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ORIGINAL ARTICLE

Economies of collaboration in build-to-model operations

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Abstract

The direct-from-model and tool-less manufacturing process of 3D printing (3DP) embodies a general-purpose technology, facilitating capacity sharing and outsourcing. Starting from a case study of a 3DP company (Shapeways) and a new market entrant (Panalpina), we develop dynamic practices for partial outsourcing in build-to-model manufacturing. We propose a new outsourcing scheme, *bidirectional partial outsourcing* (BPO), where 3D printers share capacity by alternating between the role of outsourcer and subcontractor based on need. Coupled with *order book smoothing* (OBS), where orders are released gradually to production, this provides 3D printers with two distinct ways to manage demand variability. By combining demand and cost field data with an analytical model, we find that BPO improves 3DP cost efficiency and delivery performance as the number of 3DP firms in the network increases. OBS is sufficient for an established 3D printer when alternatives to in-house manufacturing are few, or of limited capacity. Nevertheless, OBS comes at the cost of reduced responsiveness, whereas BPO shifts the cost and delivery performance frontier. Our analysis shows how BPO combined with OBS makes 3DP companies more resilient to downward movements in both demand and price levels.

KEYWORDS

3D printing, build-to-model, capacity sharing, design science research, empirical study, general purpose technology, order book smoothing

1 | INTRODUCTION

3D printing (3DP) technology changes the relationship between customers and manufacturers (Tuck, Hague, & Burns, 2007), and has led to some unlikely industrial collaborations. Being a general-purpose technology (David, 1990), 3DP is used for manufacturing prototypes, tools, customized components, complex final parts, and spare parts (Garrett, 2014; Holmström, Liotta, & Chaudhuri, 2017). Parts are fabricated directly from 3D design files that can be sent electronically to any manufacturer for production, quickly, at low transaction

cost. These characteristics allow for on-demand manufacturing and design customization (Deradjat & Minshall, 2017; Ottmeier & Hofmann, 2016), and for combining multiple parts (kits) into a single build (Achillas, Aidonis, Iakovou, Thymianidis, & Tzetzis, 2015; Ruffo, Tuck, & Hague, 2006).

In contrast to using conventional make-to-order, where supply chains are designed for a specific product type, companies may opt for a *build-to-model* mode of manufacturing, where general-purpose equipment makes it possible to delay the choice of manufacturer until the day of production. Current build-to-model practices involve designers uploading

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their data files to a preselected manufacturer's website, or requesting bids in electronic marketplaces (Eyers & Potter, 2015). Manufacturers may also exploit build-to-model by taking on more orders than in-house capacity permits, as both outsourcing and accepting subcontract work is easy compared to conventional production given that no customer-specific tooling (jigs, fixtures, etc.) is used (Baumers et al., 2013). While customers may not be too concerned with the selection of manufacturer, the manufacturing location and lead time are often essential. The homogeneity of 3DP technology makes it possible to select manufacturers close to the end customer (Khajavi, Partanen, & Holmström, 2014), while at the same time, manufacturers with assembly operations are motivated to possess in-house 3DP to reap the benefits of reduced handling, warehousing, and simplified assembly operations (Khajavi et al., 2018; Lyly-Yrjänäinen, Holmström, Johansson, & Suomala, 2016). Thus, a 3DP company can be both a customer and a provider of 3DP services.

Using a build-to-model 3DP case, we investigate how collaborative outsourcing practices compare to pure in-house production or outsourcing. We demonstrate that companies profit from partial outsourcing by maintaining capacity *while* engaging in outsourcing (Gray, Tomlin, & Roth, 2009). The outsourcing arrangement can be *unidirectional partial outsourcing* (UPO), occasionally shifting peak demand to subcontractors. Another mechanism is *bidirectional partial outsourcing* (BPO), where peak demand is outsourced, and slack capacity is offered to other firms. In this setting, each decision to outsource is an on-going operational decision, rather than a one-off strategic decision. Every time a surplus demand at one firm is matched with spare capacity at another, both profit from the trade and economies of collaboration are realized. The effect is comparable to variability pooling but does not require any centralization, as decentralized orders and capacity are traded between firms. Notably, partial outsourcing takes the variability of production requirements and diminishes their economic impact. To put this into context, we also investigate the effect of order book smoothing (OBS), which reduces the variability of orders before they reach production. OBS works by holding orders in an order book, allowing for job releases onto the shop floor at a rate steadier than demand, reducing the need for surge capacity from subcontractors. Table 1 summarizes the central concepts in this paper.

We use a multimethod approach that combines design science and case research with analytical modeling. A 3DP case study describes the collaboration between Shapeways and Panalpina World Transport Ltd. from 2014 to 2016. Shapeways is the world's leading on-line 3DP service, community, and marketplace. The company operates two 3DP factories, one in New York, the other in Eindhoven. As a third-party logistics provider, Panalpina provides traditional air and ocean

TABLE 1 Central concepts in the paper and their definitions

Concept	Description
<i>Build-to-model</i>	A manufacturing mode using the product design model for direct control of manufacturing, assembly, and logistics. General purpose resources add value as specified in the design model without set-up
<i>Order book smoothing (OBS)</i>	A practice for reducing the variability of production. The order book acts as a time buffer
<i>Unidirectional partial outsourcing (UPO)</i>	A strategy for reducing the impact of production variability. Base demand is managed by in-house capacity; peak demands are outsourced to another company. The outsourcing is unidirectional
<i>Bidirectional partial outsourcing (BPO)</i>	A strategy for reducing the impact of production variability. Firms alternate between roles as outsourcer and subcontractor. The outsourcing is bidirectional

freight solutions. To distinguish itself in the market, Panalpina also offers a range of logistics manufacturing services, one of these being 3DP. At the time of this research, Panalpina conducted their 3DP in Eindhoven; the collaboration with Shapeways facilitated their entry into the 3DP industry. Shapeways directs demand beyond their in-house capacity to a network of subcontractors, one of which is Panalpina World Transport Ltd.

We emphasize that a network of 3D printers differs from a supply chain of conventional manufacturers (Ben-Ner & Siemsen, 2017; d'Aveni, 2015) which we can understand via the performance frontier concept. The performance frontier (Schmenner & Swink, 1998; Vastag, 2000) distinguishes between the performance that is possible in principle (the asset frontier defined by the technology), and the performance achieved (the operations frontier defined by the available operational practices). Operating as a conventional supply chain leads to performance that is far from the asset frontier. Moving 3DP performance towards what is possible-in-principle requires new operational practices that account for 3DP characteristics, such as practices enabling capacity pooling (Khajavi & Holmström, 2017). The success of 3DP capacity pooling is measured by profit (or the reduction of avoidable costs) and responsiveness (lead time for the customer), defining a new operational frontier.

The literature disagrees about the future role of 3DP in supply chains, with some authors suggesting that 3DP enables vastly simplified supply chains (Mellor, Hao, & Zhang, 2014), while others highlight the possibility of

distributed manufacturing and local printing hubs (Khajavi et al., 2014; Petrick & Simpson, 2013). By considering the performance frontier, there is no contradiction in the disagreement. The future role of 3DP in supply chains depends on developing new ways of operating to simplify current supply chains and to create new types of supply structures. We contribute to the development of the latter through our proposal for partial outsourcing relying on bidirectional and dynamic sharing of capacity in a 3DP network. Excess capacity is traded between partners as needs arise. This novel form of partial outsourcing enables networks of 3DP companies to shift their operational frontier compared to in-house production or full outsourcing. Specifically, we show how BPO facilitates collaborative economies by lowering total cost without sacrificing responsiveness. In contrast, the internal practice of OBS does not shift the frontier, as lower costs are achieved through decreased responsiveness; OBS merely moves performance to a different point on the existing frontier.

The remainder of our paper is structured as follows. In Section 2, a literature review highlights how 3DP facilitates capacity sharing, examines how such operations can be managed, and identifies cost structures for 3DP. Section 3 presents our multimethod approach, while Section 4 describes the partial outsourcing arrangement between Shapeways and Panalpina. Section 5 specifies the outsourcing arrangements and order book management methods, developing analytical cost models from field data. Modeling results appear in Section 6, showing that BPO combined with OBS is the most profitable option under current market conditions and remains dominant as 3DP becomes commoditized. Section 7 discusses how BPO fits with competing approaches to production, and highlights the conditions when firms may benefit from adopting BPO. Finally, Section 8 concludes.

2 | LITERATURE REVIEW

3DP is an increasingly popular advanced manufacturing technology with unique capabilities used in the production of both prototypes and end-use parts (Wohlers, 2017). By enabling on-demand production, 3DP reduces the need to hold inventory (Holmström, Partanen, Tuomi, & Walter, 2010; Khajavi et al., 2014), increases the uptake and cost-efficiency of customization (Fogliatto, da Silveira, & Borenstein, 2012; Holmström et al., 2017; Wong & Evers, 2011), accelerates and simplifies product innovation (Weller, Kleer, & Piller, 2015), and has the potential to reduce both material use and energy consumption (Baumers, Tuck, Bourell, Sreenivasan, & Hague, 2011).

A key characteristic of the general-purpose nature of 3DP is its capability for *frictionless* manufacturing (Garrett, 2014; Holmström, Holweg, Khajavi, & Partanen, 2016), enabling production without product-specific jigs, fixtures, dies, or

cutting tools. Extensive research has shown how other general-purpose technologies benefit manufacturing operations. For example, electric drives serve as the basis for modern process-oriented factory layouts (David, 1990), while computers are a general-purpose technology in manufacturing planning and control systems (Brynjolfsson & Hitt, 2000). General-purpose manufacturing simplifies supply chain ramp-up, thereby reducing transaction costs while increasing the scope for interfirm agreement (Williamson, 1991), enabling on-demand, single item production runs. Challenges also follow with general-purpose technologies, as outsourcing is associated with a risk of copying (Tsay, Gray, Noh, & Mahoney, 2018). From a transaction cost economics perspective, these risks can be mitigated by mutual investment in manufacturing or contractual safeguards. Such mutual investment need not be in the form of assets (moving the asset frontier), but in implementing joint performance-boosting operational practices (moving the operational frontier).

The following sections focus on strategic 3DP decisions that can potentially redefine companies' operational frontier. We first explore how the characteristics of 3DP increase the available *manufacturing modes* by introducing a *build-to-model* mode. Next, we examine how 3DP supports the flexible use of *outsourcing*. Subsequently, we consider the literature on *order book smoothing*, a complementary and alternative method of outsourcing that can increase capacity utilization under variable demand. Finally, we close the section with a detailed review of 3DP *cost models*.

2.1 | Modes of manufacturing for 3DP

There is more than one way to organize the manufacture and delivery of any given product. The challenge for manufacturers is to identify and employ the most appropriate mode. In the past, mass production allowed firms to exploit economies of scale through high volume and low variety manufacturing, enabled by swift and even flow (Schmenner & Swink, 1998). Modern market requirements challenge this approach. Increasingly, the customer has greater involvement in specifying their product, leading to the development of manufacturing modes that effectively handle variety, customization, and personalization.

The rich literature on manufacturing modes includes engineer-to-order, build-to-order, assemble-to-order, make-to-stock, and ship-to-stock (Gosling, Hewlett, & Naim, 2017; Hoekstra & Romme, 1992; Konijnendijk, 1994; Naylor, Naim, & Berry, 1999; Pil & Holweg, 2004), each differing in how the customer order decoupling point separates operations that are scheduled to forecast from those performed in direct response to demand (Olhager, 2003; Rudberg & Wikner, 2004). Stock-based modes of manufacturing are either forecast-based (i.e., producing stock in response to anticipated demand), or yield-based (i.e., stocking everything a resource yields

irrespective of demand). These modes are responsive to variable market demand but incur inventory holding costs, obsolescence risks, and limit the extent of product customization (Naylor et al., 1999). Order-based modes respond to the customer's order, resulting in more opportunities for customization (Stevenson, Hendry, & Kingsman, 2005) while requiring limited stockholding. However, as responsiveness is constrained by product, process, and volume factors (Holweg, 2005), the lead time to respond to demand increases, and abilities to deal with demand variability may be constrained (Holweg & Pil, 2001).

The mutual exclusivity of “to-stock” and “to-order” manufacturing means that some benefits must be forgone for others to be gained. Postponement strategies have sought to bridge both approaches (van Hoek, Commandeur, & Vos, 1998; Yang, Burns, & Backhouse, 2004), hedging supply chain risks (Bucklin, 1965). While effective in some scenarios, postponement strategies only displace the responsiveness problem and are still reliant on holding inventory somewhere. Central to overcoming the compromise appears to be rethinking the way in which manufacturing modes are delimited by the customer order. For example, Lawson, Pil, and Holweg (2018) describe how the contrast between forecast- and order-driven manufacturing modes is reduced by implementing hybrid approaches using multimodal order fulfillment. By identifying the product attributes for which customization is desirable, manufacturers can then tailor their approaches to leverage the best of “to-stock” and “to-order” so “the distinction between BTO and build-to-forecast in the manufacturing process is no longer a critical factor” (Lawson et al., 2018).

While multimodal order fulfillment offers promising opportunities, combinations of modes (e.g., build-to-order and assembly-to-order) often rely on multiple upstream echelons of make-to-stock operations (Olhager, 2003), and so manufacturers using conventional technologies still need to invest in product-specific capacity and component inventories. By comparison, when 3DP is employed many of the traditional fulfillment activities and stockholding points can be eliminated by introducing novel ways of operating. 3DP machines fabricate parts directly from 3D design models, without human intervention. With 3DP, traditional “design for manufacturing” constraints are reduced (Eyers & Dotchev, 2010), simplifying the creation of the 3D design model. Since much of the information needed for order fulfillment is known once the 3D design is complete, an opportunity exists to extend the remit of the 3D design model. Instead of only the digital representation for manufacturing an item, the design model can be enhanced to a shared information store containing all the information needed to conduct manufacturing, assembly, and delivery. This extends the work of Främling et al. (2007) who proposed including handling instructions within digital product representations, which could then be accessed by handlers and users of the physical

product when performing their value-adding tasks. Currently, 3DP manufacturers need to rely on an additional product-centric design file that specifies handling and logistics requirements (Khajavi, Holmström, & Baumers, 2018), although all required supply chain information, in principle, could be held within a single design file.

This amalgamation of supply-chain information in a single repository, coupled with the general-purpose nature of 3DP enables the concept of build-to-model. This concept relies on the ability of 3D printers and logistics service providers to fulfill the delivery based wholly on the information provided by the model, without the need for set-up and prior development of product specific delivery capabilities. This removes supply chain concerns from vendors and designers, who can focus on design, while manufacturers can focus on developing their operations for general capability, rather than for making specific products. This advance collation of supply chain information combined with general capabilities in manufacturing make 3DP operations suitable for outsourcing. Other general-purpose technologies also match the build-to-model criteria, including CNC machining and laser cutting.

2.2 | Outsourcing of 3DP

Outsourcing offers many benefits for manufacturers, including cost reductions (Ellram, Tate, & Billington, 2008; McCarthy & Anagnostou, 2004), increased capabilities (Bhalla & Terjesen, 2013; Gottfredson, Puryear, & Phillips, 2005; Noke & Hughes, 2010), and improved flexibility (Scherrer-Rathje, Deflorin, & Anand, 2014). Due to asset specificity issues (economies of scale, tooling, and set-up costs), outsourcing is fundamentally a make-or-buy decision in conventional manufacturing settings (Williamson, 2008). Comparatively little research has explored outsourcing between the extremes of make or buy (Tsay et al., 2018), though partial outsourcing has been used to deal with demand peaks (Greaver, 1999; Scherrer-Rathje et al., 2014), and to reduce the risk of disruption (Quélin & Duhamel, 2003). Two-way partial outsourcing has received little attention in the literature, though in some situations outsourcing with a manufacturer both making and buying the same product has been proposed as a viable solution (Gray et al., 2009).

Effective outsourcing relies on manufacturers' ability to collaborate. Various collaborative capacity sharing practices are present in the literature (Nyaga, Whipple, & Lynch, 2010; Touboulic & Walker, 2015), ranging from *intensive short-term episodic collaboration* (Zacharia, Nix, & Lusch, 2011), *simple contractual arrangements* intended to promote longer-term relationships (Sluis & De Giovanni, 2016), *joint ventures* between multiple partners (Tokman, Elmadag, Uray, & Richey Jr., 2007), and *strategic alliances* with resource and knowledge sharing, including the integration of

partner resources (Gomes, Barnes, & Mahmood, 2016). Given the risks of intellectual property theft (Chopra & Sodhi, 2004), and unreliable quality (Gray, Roth, & Leiblein, 2011; Steven, Dong, & Corsi, 2014), outsourcing requires trust. While most research has focused on the outsourcer rather than the subcontractor (Baraldi, Proença, Proença, & de Castro, 2014), a risk exists of the subcontractor “climbing the value chain” to compete with the outsourcer (Noke & Hughes, 2010), necessitating strategies to limit future disruption (Lim & Tan, 2010).

Outsourcing research in 3DP is limited, and has typically investigated the potential advantages of in-house versus outsourced manufacturing (e.g., Baumer, Dickens, Tuck, & Hague, 2016; Evers & Potter, 2015; Ruffo, Tuck, & Hague, 2007). Little has been done to understand outsourcing relationships in 3DP, though existing research has focused on episodic capacity sharing to either satisfy an immediate demand (e.g., Lan, Ding, Hong, Huang, & Lu, 2008), to provide localized contact manufacturing facilities (e.g., Ryan, Evers, Potter, Purvis, & Gosling, 2017), or to enable on-line manufacturing platforms (d'Aveni, 2015; Evers & Potter, 2015). However, from practice, we observe larger companies engaging in 3DP joint ventures (e.g., BASF, Boeing), suggesting the 3DP industry is outpacing research.

Manufacturers providing an increasingly utility-like service can benefit from collaborating. 3DP demand can be outsourced to avoid hitting a capacity constraint, to access a printing technology that one does not have, or to avoid transportation lead times and costs. Furthermore, rapid technological development drives 3DP machine obsolescence (Wohlers, 2017), indicating that manufacturers should not overinvest in capacity. Nevertheless, when many suppliers are available and capacity is general-purpose, outsourcing becomes an attractive option, although the level of outsourcing depends on demand characteristics. For a manufacturer, it is prudent to use in-house capacity to meet short lead-time, operations-critical, and dependent demand. A manufacturer using 3DP in-house can produce assembly components in a single build, eliminating warehousing, and scheduling activities while also cutting lead times (Holmström et al., 2016). However, this benefit mostly disappears when part of the kit is outsourced (Khajavi, Baumer, et al., 2018). For other types of demand, the choice between in-house or outsourced manufacturing matters less.

Build-to-model facilitates outsourcing while recognizing the benefits of in-house production. Supply chain simplification and responsiveness motivate in-house manufacturing of parts for assembly, while technological obsolescence constrains in-house 3DP investment. These considerations lead us to ask, what level of outsourcing should be used for 3DP, and in what situations? From conventional manufacturing, three solutions are immediately apparent: *In-house*, where all manufacturing is done internally. *Outsource*, where all demand is outsourced for others to

produce; no 3DP machines are present in-house. *Unidirectional partial outsourcing (UPO)*, where part of the demand is done in-house, and part of the demand is outsourced to others.

A fourth option enabled by build-to-model is *bidirectional partial outsourcing (BPO)*. The general-purpose nature of 3DP blurs the distinction between in-house and outsourced manufacturing. This allows anyone with excess capacity to offer it to anyone with a design (Baumer et al., 2013), readily facilitating outsourcing between 3DP companies. BPO allows firms to conduct critical operations in-house (e.g., short lead-time assembly kits) while outsourcing other noncritical work to others in the network to cope with demand surges; in periods where a firm has excess capacity, this spare capacity can be offered to the network. BPO has commonalities with cloud manufacturing (Ren, Zhang, Wang, Tao, & Chai, 2017). In conventional manufacturing, outsourcing decisions are strategic manufacturing engineering and supply chain decisions (Fine & Whitney, 2002). In BPO, the outsourcing decision between manufacturers is operational and bidirectional, made possible by the reduced friction of build-to-model, creating opportunities for both competition and collaboration. From a manufacturer's perspective, BPO goes beyond short-term and episodic collaboration as it involves sharing of design models that are crucial for competitive advantage. To provide the dynamic capacity, BPO is likely to rely on long-term partnerships that promotes trust over episodic transactions. The risk of copying designs introduce the same difficulties and challenges present in managing conventional contract manufacturing networks (e.g., Wang, Niu, & Guo, 2013).

2.3 | Order book smoothing

An order book is a virtual queue where the randomly occurring customer orders are stored temporally before being released smoothly to the shop floor for production, allowing more efficient use of production capacity. OBS was proposed by Forrester (1961, p. 144) who recommended a proportional order book policy to smooth make-to-order production by releasing a fixed fraction of the order book in every period. Serman (2000, pp. 723–725) applies smoothing in a similar context, using a target delay to smooth the releases. Extending this to a chain of multistage service operations, Anderson, Morrice, and Lundeen (2005) use control theory and system dynamics to show that bullwhip can occur in this context, inducing capacity changes over time. An alternative proportional policy is suggested by Wikner, Naim, and Rudberg (2007), who considered an agile policy for adapting production capacity over time. Hedenstierna, Disney, and Holmström (2016) investigate the link between OBS and 3DP operations, showing how individual consumer-orientated 3DP providers can exploit the order book to manage cost, delivery time, and service levels, while improving capacity usage. Further study of Forrester

(1961, p. 144) and Hedenstierna et al. (2016) also highlights how proportional smoothing approaches cause some orders to be delivered later than promised. They propose an alternative policy that provides comparable smoothing while ensuring delivery promises are kept. Notably, the emphasis of this work was on UPO using hypothetical costs and demand, and did not consider the BPO opportunities.

2.4 | 3D printing costs

Understanding the nature of 3DP costs is complicated due to the peculiarities of 3DP technologies and product-specific attributes (Baumers et al., 2016). Early works, such as Grimm (2003), focused on the cost of producing one-off prototypes or moulds. Hopkinson and Dickens (2003) considered costs from a manufacturing perspective, focusing on the suitability of 3DP in repetitive, high volume situations, and providing a detailed cost model comprising of the machine, labor, and material costs. They argue that 3DP unit costs remain the same regardless of the quantity produced. This overlooks initial design costs and any economies of scale that may exist in pre- and post-production. It does, however, illustrate product-specific setup costs (e.g., tooling) do not need to be amortized over large demand volumes, making low volume 3DP attractive. Ruffo and Hague (2007) call out the general-purpose characteristics of 3DP and its ability to produce *different* parts in a build (rather than the repetitive production of the same item). Likewise, Atzeni, Iuliano, Minetola, and Salmi (2010) and Atzeni and Salmi (2012) question the suitability of comparing conventional and 3DP approaches, arguing that 3DP parts will be tailored to the manufacturing process.

Table 2 summarizes the main approaches to cost assessment in the 3DP literature. These cost models accommodate the individual characteristics of specific 3DP processes, though they all enjoy the basic foundations from the generic cost model presented by Gibson et al. (2015):

$$\text{Cost} = \text{Machine capital costs} + \text{Operating costs} + \text{Material costs} + \text{Labor costs.} \quad (1)$$

Machine capital costs. These relate to the machine purchase price amortized over the machine's useful life. Industrial 3DP machines can cost tens or hundreds of thousands of dollars. Almost all cost models assume that 3DP machines last for several years and estimate the proportion of time they are doing useful work (the *utilization rate*). Earlier works often overestimate machine capability, for example, Hopkinson and Dickens (2003) suggest 90% machine utilization. Recent advice is more cautious with estimates around 60% utilization (e.g., Atzeni et al., 2010; Baumers et al., 2016; Ruffo et al., 2006). This lower utilization rate recognizes machine setups,

changeovers, and maintenance are necessary. Machine capital costs are the dominant factor in the total cost of manufacturing. The *build time* (the time required to produce a part) is the dominant factor in machine capital costs. Engineering decisions, taken to minimize the build time, impact other objectives such as quality (Alexander et al., 1998). While the literature typically uses depreciation to account for technology obsolescence (e.g., Khajavi et al., 2014), this does not consider the reduced performance of older machines compared to new machines, nor potential scale economies that may affect the overall manufacturing system.

Operating costs. These are indirect costs associated with physical factory infrastructure and administration overheads. Some studies omit these as they do not contribute significantly to cost (Atzeni et al., 2010; Hopkinson & Dickens, 2003). Others (e.g., Ruffo et al., 2006) assert operating costs are significant and should be included.

Material costs. 3DP machines use specialized materials, often many times more expensive than conventional equivalents. A wide range of 3DP materials is available; the ability to process these varies by machine (Eyers & Potter, 2017).

Labor costs. 3DP machines can automatically fabricate items, but labor is required for preparatory (machine setup) and post-production activities (e.g., part finishing, quality inspection). Little consistency exists in the literature on the cost of labor. Some studies suggest 3DP requires unskilled technicians (Baumers et al., 2016; Hopkinson & Dickens, 2003; Ruffo et al., 2006); others argue 3DP requires skilled labor (Atzeni & Salmi, 2012; Atzeni et al., 2010). In practice, product being produced determines the labor required, which in turn dictates the nature of many activities in design elicitation and postprocessing (Eyers & Potter, 2017; Eyers, Potter, Gosling, & Naim, 2018).

3 | METHOD

The distinction between the technologically defined asset frontier for 3DP and the operational frontier defined by operations management practice provides a theoretical lens for our research (Schmenner & Swink, 1998; Vastag, 2000). Our starting point is that operating 3DP capacity as conventional manufacturing is likely to leave cost and delivery performance far from what is possible in principle. We seek operational practices that can improve both cost and delivery performance, contributing to a practice-based view of operations management (Bromiley & Rau, 2016).

Our case between Shapeways and Panalpina allows us to examine current operational practices and emerging field problems in the context of build-to-model manufacturing. The challenge in developing and evaluating the proposed practices of BPO and OBS in 3DP operations is twofold. First, the field problem is only now emerging. Second, while UPO from

TABLE 2 Approaches to costing of 3DP operations

Author	Focal 3D process(es)	Overhead	Labor involved in 3DP	3DP-related costs		Other notable costs	Unique contribution
				Indirect	Direct		
Alexander, Allen, and Dutta (1998)	FDM SL	–	General preprocessing and postprocessing activities	Machine depreciation	Labor Machine usage Electricity Materials	Cost of pre- and post-build resources	One of the first papers to focus on the impact of orientation on build time and therefore costs. Costs evaluated for pre-build, build, and post-build
Grimm (2003)	Wax deposition 3DP SL	–	General preprocessing and postprocessing activities (but not finishing)	Machine depreciation	Labor Material	–	Combines cost assessment with other production factors (time, quality, reliability, and ease-of-use)
Hopkinson and Dickens (2003)	FDM LS SL	Intentionally omitted	Machine setup and postprocessing	Machine purchase Ancillary equipment Machine depreciation Machine maintenance	Labor Material Support materials	Intentionally omits material recycling cost saving	Considers three 3DP technologies versus injection moulding at production volumes (up to 20,000 parts), identifying economic volumes for each approach
Byun and Lee (2006)	FDM laminated object modeling selective LS SL	–	General preprocessing and postprocessing activities	–	Machine usage Material used (parts, supports)	–	Focuses on the conflict between build time and build orientation—notes that costs differ between manufacturers, and by production volume
Ruffo et al. (2006)	LS	Production overhead Administration overhead	Machine setup and postprocessing. Full annualized salary	Software Machine depreciation Maintenance Computer hardware	Labor Material	–	Highlights that automation can replace some labor-based activities, decreasingly directly incurred costs but increasing indirect
Ruffo and Hague (2007)	LS	Production overhead Administration overhead	Machine setup and postprocessing. Full annualized salary	Software Machine depreciation Maintenance Computer hardware	Labor Material	–	Extends the Ruffo et al. (2006) model for builds containing a mixture of components
Atzeni et al. (2010)	LS	Intentionally omitted	Machine setup and postprocessing. Hourly allocated	Machine depreciation	Machine usage Labor Material	Mould	Compares conventional and additive approaches, but redesigns 3DP parts to optimize technology capabilities
Atzeni and Salmi (2012)	Direct metal LS	Intentionally omitted	Machine setup and postprocessing. Hourly allocated	Machine depreciation	Machine usage Labor Material	Mould Postprocessing	Compares conventional and 3DP approaches, with redesigned metal 3DP part to optimize technology capabilities
Gibson, Rosen, and Stucker (2015)	Generic	Factory space Factory overheads	Machine setup and postprocessing. Hourly allocated	Purchase costs Maintenance	Materials (adjusted for recycling ratios) Direct labor for preprocessing and postprocessing	Utilities	Provides a generic 3DP cost model
Baumers et al. (2016)	Electron beam melting direct metal LS	General factory costs Hardware Software	Unspecified activities. Full annualized salary	Purchase costs Maintenance costs Consumable costs	Materials Electricity Labor	–	Emphasizes system productivity through utilization rate

Shapeways to Panalpina is established, the BPO and the OBS mechanism is yet to be established. These aspects of our study are predictive and prescriptive in nature. We address the methodological challenge by using an *explorative* design science approach (Holmström, Ketokivi, & Hameri, 2009). This is a multimethod approach (Mingers & Brocklesby, 1997) providing a framework to formalize our combination of novel practice design, operations research methodologies, the expertise of the researcher, and the nature of the problem. Mingers (2003) emphasizes the problem domain and the design of the intervention in the selection of a combination of methodologies. Similar to Groop, Ketokivi, Gupta, and Holmström (2017), we combine solution design, case research, and scenario planning. However, in contrast to Groop et al. (2017), and due to the emerging nature of the 3DP industry, we have not been able to implement and evaluate the outcome of our proposed design in the case setting. Instead, based on the scenarios developed in the case context, we analytically model the outcomes of the proposed design.

We took an explorative approach to this research, cycling between understanding the problem, the problem context, and the solution. Existing 3DP research typically considers *customers* as outsourcing the production requirements; it does not consider *manufacturers* outsourcing their own work. Our initial design proposition was that 3D printers would balance supply and demand simply by managing their own order book effectively (Hedenstierna et al., 2016). Through fieldwork, we witnessed how the combination of make-to-order and general-purpose characteristics of 3DP invites companies to collaborate. The problem of interest then became, how should 3DP companies collaborate and operate to grow and expand profitably? Recognizing the opportunity for sharing general purpose capacity we designed a new operational practice, BPO to manage variability. Analyzing the outcomes in the context of the build-to-model manufacturing we find that BPO has benefits comparable to (and compatible with) OBS.

Our case identifies important qualitative and context-specific aspects of participating in the 3DP market. The collaboration between the Shapeways and Panalpina called for an explorative approach to collecting information. This is

necessary given the uniqueness of the 3DP setting and the lack of previous research on 3DP and outsourcing.

The data used for this study was collected during a 2-year government-funded academic research project with Panalpina. As part of the project, university researchers were based within Panalpina, providing an in-depth understanding of the structure and functioning of the Shapeways–Panalpina partnership. Semi-structured interviews were conducted with the Global Head of Logistics and Manufacturing and the Global Head of Additive Manufacturing of Panalpina, and Shapeways' Global Supply Chain Manager. Quantitative data, based on the regular conduct of business between the two companies, was collected and used to specify an analytical model for assessing the economic consequences of our design interventions.

Our analytical model is based on time series analysis (Box, Jenkins, Reinsel, & Ljung, 2016), with extensions for handling costs and on-time delivery performance. The model acts as the mechanism connecting the proposed design to the outcomes in the scenarios developed for the case context. The intended outcomes were the cost and delivery performance, while the emergent outcomes are our results relating to how an incumbent should operationally respond to new entrants, and how new entrants benefit from collaboration with incumbents. As the number of partners in the network increases, the total spare capacity and total excess demand available for outsourcing increases. Networks create a pooling effect where the net demand variability faced by each partner is diminished.

To sum up, our multimethod design approach develops and evaluates the design proposal for BPO with potential support for OBS in the context of an expanding network of 3D printers. Figure 1 summarizes our research using the *Context, Intervention, Mechanism, Outcome* (CIMO) framework (Denyer, Tranfield, & Van Aken, 2008). When the BPO intervention is introduced, it is expected to modify the operation of the system, shifting outsourcing from a strategic, part specific, decision to a tactical, operational, and on-going order based decision-making process. The outcomes of this change are intended outcomes, which are what the new practice is designed to achieve, and emergent outcomes, which reflect the unforeseen and systemic consequences.

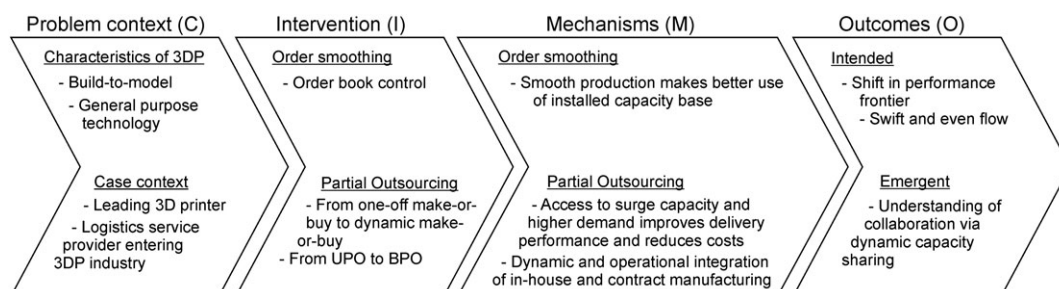


FIGURE 1 Embedding the problem in the CIMO framework

4 | THE PROBLEM IN CONTEXT: CASE DESCRIPTION

This section describes the companies, their partial outsourcing arrangement, and the resulting benefits for each company. Following this description is a detailed account of the 3DP process, includes the online ordering by customers, the build-to-model manufacturing, and outsourcing of order items.

4.1 | Case description

Shapeways is a Dutch-founded 3DP marketplace and service company. It is a spin-out of the lifestyle incubator of Royal Philips Electronics. Shapeways provides multiple categories of products to customers including gadgets, accessories, jewelry, art, home, games, miniature, and others. Serving customers in more than 140 countries, customers upload their 3D designs to Shapeways' online platform for printing and delivery. The company is headquartered in New York and maintains two facilities, in New York and Eindhoven, which operate as factories and distribution centers. Shapeways collaborates with a group of manufacturing partners (subcontractors) around the world via an online portal.

Panalpina World Transport Ltd. is a global ocean/air freight and logistics provider. It operates in 189 countries with over 15,500 employees worldwide, having customers from the telecom, automotive, chemicals, retail, energy, fashion, and healthcare industries. In recent years, Panalpina introduced Logistics Manufacturing Services to its customers, partly responding to the reshoring trend (Panalpina World Transport Ltd, 2015), embracing 3DP technology as a strategic opportunity to complement their LMS portfolio. By offering 3DP services to their existing logistics network, Panalpina hopes to provide customized and responsive product-orientated services. However, the introduction of a new manufacturing technology into a company that possesses no previous experience or knowledge is a significant challenge. The strategic partnership with Shapeways facilitated Panalpina's market entry. Panalpina invested in a 3DP facility in Eindhoven; Shapeways outsources the customer orders exceeding its capacity to Panalpina.

The partnership is governed by a regular manufacturing agreement/contract which specifies (among others) pricing, lead time performance, liabilities, and availability. From Shapeways perspective, any company that owns printers could be a partner.¹ From Panalpina's perspective, they currently operate as a facility dedicated to Shapeways, because they have not yet expanded into the B2B market, and do not wish to enter the B2C market. The contract specifies lead time commitments depending on the particular 3DP process. Every week Shapeways send Panalpina a performance report; monthly review meetings are held.

TABLE 3 Principal benefits in the Shapeways–Panalpina partnership

Shapeways	<ul style="list-style-type: none"> • Secured production partner for peak demands • Access to extra capacity • Reduced capital investment in new production facilities • Elimination of operational bottlenecks
Panalpina	<ul style="list-style-type: none"> • Induction to the 3D printing business • Knowledge and experience of set-up, operations, and maintenance • Secure minimum production output • Assistance to establish a financial performance measurement system

Table 3 summarizes the principal benefits of the companies in this partnership, based on the outcome of the semi-structured interviews described in the Section 3. The major benefits that Shapeways gains from the partnership with Panalpina stem from the trade-off between flexibility and investment. The outsourcing enables Shapeways to maintain a centralized capacity with high utilization of its equipment, and flexibility to cope with volatile demand, without the need for additional investment in warehousing, equipment, personnel, and management.

As for Panalpina, the company considered other routes into the industry: setting up their 3D printing machine as a stand-alone solution, or acquiring a 3D printing company. However, being a typical choice for a new entrant to obtain industry-specific knowledge, a strategic alliance with Shapeways partnership was Panalpina's preferred option (Cho, Kim, & Rhee, 1998). Industry knowledge gained included setting up a 3DP manufacturing facility, the operation of 3D printers, preprocessing and postprocessing, and quality control.

4.2 | The 3DP process

The 3DP process of Shapeways operates as follows. Customers place orders online, selecting or uploading 3D design models on Shapeways' website for manufacture.² A customer order may consist of some items of the same or different materials. Uploaded new designs go through a printability test. The build-to-model manufacturing of order items is either in a Shapeways' factory or distributed to their subcontractors via an online portal. Distribution is based on one or more of the following criteria: (a) the contractor possesses a specific printer which Shapeways does not have in-house, (b) the contractor can print

¹See also <https://www.shapeways.com/getting-started/global-partner-network>.

²Shapeways provides customers with two options. The customers can search on the website for existing products (designed by other designers who sell their products on the website) and ask Shapeways to print these products at the color and size of their choice. Also, customers have the option to make their own designs, upload it on Shapeways site for printability test. Shapeways supports these customers by linking them with 3D modelers, design teams for consultation and online designing tools.

in the required materials, (c) the contractor can meet the customer's time constraints.

Once items have been manufactured by the subcontractors, they go through an initial quality check (specified by Shapeways) which takes place at the subcontractor's facility. Items passing an initial quality check are shipped to Shapeways' New York or Eindhoven facility. Shapeways is responsible for the collection of the production output from its subcontractors. At the time of this research, Shapeways did not outsource the final quality control and order consolidation to its subcontractors. After orders are consolidated, often with items produced in Shapeways own facility, items are packed and shipped to the customer. The final delivery is selected from a range of Shapeways' approved 3PL providers and paid for by the customer.

Shapeways' and Panalpina's 3DP printing business uses multi-jet modeling (MJM) technology. MJM technology uses a print head to deposit photopolymers onto a platform. Wax support structures are created during the building process. An ultraviolet light solidifies the photopolymers; a post-printing process removes the wax supports. MJM advantages include high accuracy and surface finish, the capability to use different materials and colors, and the hands-free removal of support material. The disadvantages are the limited range of materials and the slow build process (Kitsakis, Moza, Iakovakis, Mastorakis, & Kechagias, 2015).

5 | SCENARIO DESIGN

This section commences with an exploration of the main operating principles currently in place in the Shapeways–Panalpina outsourcing relationship. Next, we develop an economic model from Shapeways' perspective, representing a range of outsourcing possibilities culminating in BPO. Since the performance of most outsourcing arrangements depends on order releases, we also model OBS as a dynamic practice to manage demand variability. In investigating these practices, we seek ones that affect the operational frontier. Put plainly, such practices increase profits without sacrificing other criteria, in our case the responsiveness to customers.

We consider four types of outsourcing including the extremes: (a) no outsourcing, and (b) outsourcing everything. In between are many possibilities for partial outsourcing, but here we consider two specific kinds, (c) UPO when the daily order releases exceed Shapeways' in-house capacity, and (d) BPO between a network of companies with Shapeways' cost structure. The dimension of order book control covers two options: either immediate orders release (IOR) to production or using linear OBS for production. We evaluate the experimental scenarios introduced above by developing a model of the outsourcing network and the order book, and deriving expressions for the associated production costs.

5.1 | Demand and cost structure for the Shapeways–Panalpina partnership

Our model is based on a dataset from Panalpina that contains daily demand, production, and cost information for the 14 months from November 2015 through December 2016. Panalpina's demand data was extracted from their production planning tool, encompassing a total of 5,098 parts ordered over 173 days. All demand originated from Shapeways, being the sole customer at the time. The days during the 14 months when Panalpina has no demand has no impact on our results; it is a natural consequence of the partial outsourcing mechanism. The demand data was used to infer Shapeways' demand distribution, by fitting a distribution left-censored by Shapeways' capacity. To calculate Shapeways capacity, we estimated³ the printing speed of the 3D printers using historical production data, giving an average of 5.6 cm³ (ccm) per hour (including the set-up time). The daily capacity of seven printers is then calculated as $5.6 \times 24 \times 7 = 940.8$ ccm.

If the daily production orders exceed this capacity, the surplus is outsourced to Panalpina. This approach implicitly assumes that Shapeways currently releases all orders just as they arrive, outsourcing all demand over capacity and that Panalpina is the only subcontractor for this 3DP process. The distribution fitting covered 256 observations of which 83 were left-censored and resulted in an estimated daily demand (ccm/day) following a normal distribution with $\mu_d = 1,009$ and $\sigma_d = 112$. We assume that Shapeways' daily demand, d_t , follows this distribution and is independent and identically distributed, with t denoting time counted in business days. Since $\mu_d/\sigma_d > 4$, the possibility of negative demand is negligible, and although the normal distribution only approximates the real demand process, we select it for tractability and because many statistical procedures are robust to deviations from the theoretical normal distribution (Box, Hunter, & Hunter, 1978; Tyworth & O'Neill, 1997). Additionally, the central limit theorem reasonably applies as demand originates from many independent customers. Shapeways' promised delivery times vary between 3 and 11 days depending on material and dimensions; items

³This is only an approximation for the following reasons. (a) The average production per day depends on the precise 3DP process employed. (b) Shapeways have a pool of seven machines, some of them are more modern than Panalpina's that can print up to 90% faster, therefore their capacity is not just 7 times Panalpina's capacity. (c) Cubic centimetres (ccm) is not always the right capacity measure. Shapeways monitor the vertical *shadow* of parts and the z-dimension; even then the printing speed depends on how dense the tray can be planned. (d) For each tray the expected printing time (defined by the z-dimension) is calculated. If Shapeways has more demand than daily print capacity, they look at service level commitments and make decisions to outsource or schedule for the next day's print. This is a rather complex procedure. We avoided this complexity by inspecting historical performance at Panalpina. We found, over the 14 months, 5.6 ccm/hr was printed.

TABLE 4 Basic cost components of the 3D printing operation

Cost driver		Outsourcing value	In-house value	Partial outsourcing value
c_0	Facility cost: The cost of a facility, including management and utilities, but not equipment or labor	–	€5,000/month or €240/day	€5,000/month or €240/day
c_1	Logistics cost: Variable cost of materials and shipping to the consumer	€1.67/ccm	€1.67/ccm	€1.67/ccm
c_2	Capacity cost: Cost of maintenance, electricity, labor, and contribution to machine depreciation	–	€1.52/ccm	€1.52/ccm
c_3	Outsourcing cost: Variable cost of outsourcing, excluding materials and shipping	€3.52/ccm	–	€3.52/ccm
c_4	Lost sales cost: The opportunity cost when capacity is insufficient to meet demand	–	€5.32/ccm	€5.32/ccm
p_C	Sales price to the consumer	€5.99/ccm	€5.99/ccm	€5.99/ccm

Note. No extra logistics cost is incurred under outsourcing as Panalpina and Shapeways are colocated.

with sides no greater than 50 mm have a promised delivery time of 6 days (Shapeways, 2007).

Consistent with our literature review, costs include aggregated machine, materials, personnel, transportation, and maintenance expenditures during the same period. A linear depreciation method is used to derive the daily fixed cost of equipment and investment. Energy costs are approximated by utilization and local energy prices. The cost of allocation, markup, and interest are considered to be a percentage of the variable costs. The overall cost is broken down into production volume (ccm) based on production data. Shapeways cost figures are inferred from the above results and appear in Table 4. Such inference is considered safe as the 3DP machine possessed by Panalpina is similar to the ones in Shapeways, and the operational conditions are similar in both facilities.

5.2 | Order release practices

Suppose that demand d_t must be released as production orders within Q periods to be delivered on time, where the setting $Q = 1$ (IOR) would require all orders received to be released within one working day, and $Q = 5$ (OBS) corresponds to the case of printing of items with sides less than 50 mm, as Shapeways promises delivery within 6 days and the physical lead time, $L = 1$. We call Q the *slack time*, being the difference between the promised delivery time and the actual time orders are processed. Note that daily scheduling with no additional slack has $Q = 1$, as all orders from 1 day are compounded and released at the start of the next day.

Demand is accumulated into an order book b_t that contains all received customer orders that have not yet been released to production. By letting the quantity released to production daily be denoted o_t , the order book has the difference equation

$$b_t = b_{t-1} + d_t - o_t. \quad (2)$$

Since we cannot release orders that we have not yet received, the order book will never turn negative, that is, $\sum_{t=1}^T o_t \leq b_0 + \sum_{t=1}^T d_t$ must hold. The two order release rules give orders as a function of demand. With IOR, orders are released as they arrive $o_t = d_t$, and with OBS, orders are released as a moving average of demand observations, $o_t = \beta^{-1} \sum_{n=0}^{\beta-1} d_{t-n}$, with the integer $\beta \geq 1$ being the smoothing parameter. As demand is assumed to be positive, $\beta = Q$ provides maximum smoothing while ensuring that all orders are released to production in time to meet the promised delivery time to customers. IOR is a special case of the smoothed releases with $\beta = 1$. It is convenient to let the order releases be a moving average of the demand. The orders will then have variance (Box et al., 2016)

$$\text{var}[o_t] = \beta^{-1} \text{var}[d_t]. \quad (3)$$

To see the effect of the various ways of organizing production and setting capacity, we develop cost models for the following scenarios that capture the different options of setting the in-house capacity and the presence or absence of smoothing.

5.3 | Modeling partial outsourcing interventions

In the previous section, we showed how order book control reduces the variability of the release rate. The next step is to determine the cost associated with these order releases and the available capacity by dividing the daily releases into three categories: (a) *orders produced in-house*, (b) *outsourced orders*, and (c) *orders exceeding the total network capacity*. As each successive class is a less desirable production option than the previous, the firm first allocates as much as possible to in-house production, while attempting to outsource the rest. Orders exceeding the total capacity (in-house capacity plus capacity available from subcontractors) become excess orders. Observe that the surplus capacity available from subcontractors fluctuates between periods and that each category is associated with increasing marginal costs, see Figure 2. If production releases are less than the in-house capacity, the spare capacity is offered to other firms in the BPO network.

The profit model must be capable of representing the four different scenarios of pure outsourcing, pure in-house production, UPO, and BPO, with and without OBS. We attribute costs in the following way, where the superscript denotes the firm for which the variable applies, while the subscript specifies the type of cost, price, or quantity. A fixed facility cost c_0^A applies in all scenarios except pure outsourcing. Additionally, a materials cost c_1^A applies for each ccm produced, q_Σ^A . The in-house capacity cost depends solely on the installed capacity k^A , which is optimized independently for each scenario, while the outsourcing cost c_3^A applies to each ccm of production successfully outsourced q_3^A . One part of our results take not a profit perspective, but a total cost perspective. Then we introduce a variable to compensate for lost revenue through a penalty cost of $c_4^A = p_C^A - c_1^A$ per ccm. We keep a separate

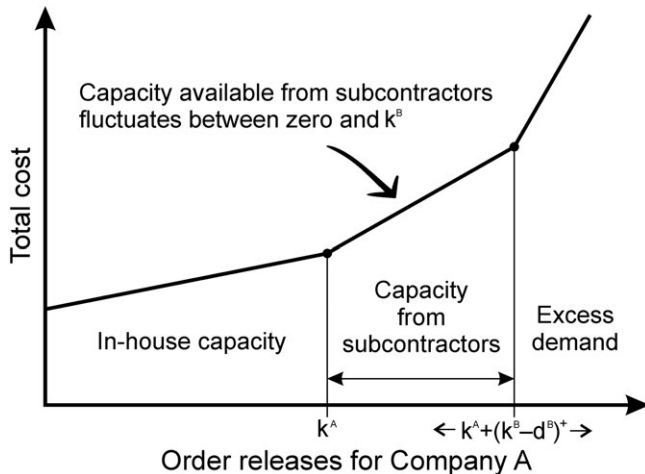


FIGURE 2 Cost structure under partial outsourcing

TABLE 5 Cost components and quantities per scenario

	Pure outsourcing	In-house production	UPO	BPO
Revenue, $p_C^A q_\Sigma^A$	$p_C^A q_\Sigma^A$	$p_C^A q_\Sigma^A$	$p_C^A q_\Sigma^A$	$p_C^A q_\Sigma^A$
Facility cost, c_0^A	—	c_0^A	c_0^A	c_0^A
Materials cost, $c_1^A q_\Sigma^A$	$c_1^A q_\Sigma^A$	$c_1^A q_\Sigma^A$	$c_1^A q_\Sigma^A$	$c_1^A q_\Sigma^A$
Capacity cost, $c_2^A k^A$	—	$c_2^A k^A$	$c_2^A k^A$	$c_2^A k^A$
Outsourcing cost, $c_3^A q_3^A$	$c_3^A q_3^A$	—	$c_3^A q_3^A$	$c_3^A q_3^A$
Subcontracting cost ^a , $c_1^A q_3^B$	—	—	—	$c_1^A q_3^B$
Subcontracting revenue ^a , $p_B^A q_3^B$	—	—	—	$p_B^A q_3^B$

^aRelated to subcontracts accepted from another firm.

tally for any outsourcing done, at q_3^B ccm, with the revenue p_B^A and a materials cost of c_1^A per ccm. Finally, the consumer revenue is the price p_C^A applied to the total production quantity q_Σ^A . Table 5 summarizes the cost components.

Since BPO contains all the cost components appearing in the other scenarios, we introduce it as a general case, as the other scenarios can be obtained by setting any irrelevant cost factors to zero. Following the description above, the total profit under BPO for Company A is

$$\pi^A = p_C^A q_\Sigma^A + (p_B^A - c_1^A) q_3^B - C^A, \quad (4)$$

where

$$C^A = c_0^A + q_\Sigma^A c_1^A + c_2^A k^A + c_3^A q_3^A. \quad (5)$$

In Appendix A, we show how to compute the expectation of (4) for almost-always-positive normally distributed demand. Under BPO the expected profit is,

$$E[\pi^A] = (p_C^A - c_1^A) \mu^A + (p_B^A - c_1^A) \int_0^{k^A} \varphi_{BA}^-(x) dx - c_0^A - c_2^A k^A - (c_3^A - c_4^A) \int_0^{k^B} \varphi_{AB}^-(x) dx - c_4^A \sigma^A G\left(\frac{k^A - \mu^A}{\sigma^A}\right), \quad (6)$$

where $G(x) = \varphi(x) - x[1 - \Phi(x)]$ is the unit normal loss function, $\varphi(x)$ is the probability density function of the standard normal distribution, and $\varphi_{AB}^-(x)$ is the probability density function of the minimum of bivariate normal variables, as defined in Appendix A.

5.4 | Extending the model to n collaborating firms

To facilitate the analysis of n firms participating in BPO, we assume they all follow demand distributions with identical parameters, that they all have the same amount of installed capacity, and that all are treated identically with respect to the matching of outsourcing requests to surplus capacity. With n as the number of firms in the network, and k as the installed capacity at each firm, the total capacity of the network is nk and the total expected lost production for all firms is $E[(D - nk)^+]$, where D represents the total network demand, or $n^{-1}E[(D - nk)^+]$ per firm. Let d equal the demand at an individual firm, giving the realized in-house production per firm $E[\min(d, k)]$. In turn, this gives the network-wide outsourced production as $E[D] - nE[\min(d, k)] - E[(D - nk)^+]$, making the expected outsourcing and subcontracting per firm equal $n^{-1}\{E[D] - nE[\min(d, k)] - E[(D - nk)^+]\}$. These quantities are applied to the costs specified in Table 5 as done in (6).

5.5 | Setting capacity levels

Apart from cost and revenue parameters, another difference between the production scenarios is the setting of the capacity level. In the case of pure *outsourcing*, there is no capacity to manage. Pure in-house production imposes a hard capacity limit on the daily capacity. For conventional *in-house production without smoothing* the capacity, k is set to produce at 60% utilization, $k = \mu_d/0.6 \approx 1.67\mu_d$, reflecting common capacity utilization in the 3DP industry (Atzeni et al., 2010; Baumers et al., 2016; Ruffo et al., 2006). Dimensioning capacity to achieve 60% utilization produces a fair amount of slack. Although giving ample room for managing internal variations in production, it comes at a high cost. For *in-house production with order book smoothing*, the production variability can be reduced dramatically, prompting us to consider more aggressive capacity settings. One way is to make capacity as small as possible while ensuring that an infeasible schedule rarely occurs. Here, we set the capacity such that an infeasible schedule is only produced in 1% of days (2–3 business days per year). That is, capacity $k^* = \mu_d + \sigma_o\Phi^{-1}(0.99) = \mu_d + \sigma_o(2.32635)$, where σ_o is the standard deviation of the order releases to production after smoothing, see (3).

Remaining are the cases where in-house production and outsourcing are combined. First, UPO; here an optimal capacity balances the costs of in-house capacity, outsourcing, and excess orders. While no closed-form solution exists and the capacity level must be optimized numerically as the maximizing argument of (6), there is an inverse-function solution to a special case and upper and lower bounds. When $c_3^A = c_4^A$, the optimal capacity is obtained as $k^* = \mu_d + \sigma_o\Phi^{-1}(1 - c_2^A/c_3^A)$, following Hosoda and Disney (2012). Intuitively, this shows that the optimal in-house capacity depends on the relative

cost of in-house production and outsourcing, with a higher relative cost of outsourcing prompting a higher in-house capacity investment. When $c_3^A \neq c_4^A$, the optimal capacity is in the range given by $\sigma_o\Phi^{-1}(1 - c_2^A/c_3^A) \leq k^* - \mu_d \leq \sigma_o\Phi^{-1}(1 - c_2^A/c_4^A)$. Under BPO, we must again find the maximizing argument of (6) numerically. In this case, k^* becomes sensitive to the installed capacity, the number of partners in the network, and the order releases of each partner.

Appendix B highlights the procedures used for validating our model. The following section puts the model into context by combining it with the case data, allowing us to test how BPO compares with other practices for managing the 3DP operation.

6 | APPLYING THE ANALYTICAL MODEL TO THE SHAPEWAYS-PANALPINA RELATIONSHIP

Realistic scenarios can be compared by applying quantitative case data to the model. Beginning with a detailed cost breakdown for nine distinct production scenarios, we see how the benefits of partial outsourcing are realized. Following this, we look at how partial outsourcing systems react to different lead times when managed with OBS. We end with an investigation of the viability of the different production modes at different price points and market sizes.

6.1 | Detailed breakdown of costs

Taking the case as a starting point, we use the cost model to test how a company with Shapeways demand, cost, and lead-time characteristics would perform under different production system configurations. Our main variable of interest is the degree of outsourcing, while we control for order book smoothing and capacity setting. These appear in Table 6, where a key result is the cost of variability, being the difference between the total cost and the smallest possible total cost if demand were constant over time. To extract this cost, revenue is not shown, but the lost revenue due to capacity shortages, that is, $p_C^A(q^A - q_\Sigma^A)$ is used instead. Under pure outsourcing and UPO, we impose no limit on the total capacity, whereas under BPO we assume a finite outsourcing capacity shared among identically configured partners, to be traded at the in-house cost c_2^A per ccm.

Table 6 shows pure outsourcing to be the least economic mode, while in-house producers can reduce cost with partial outsourcing. The main benefit comes with implementing UPO, while the marginal gain from BPO is much smaller, even when several outsourcing partners are available to absorb the variability (Configurations 7 and 9). Order book smoothing is effective in all cases where it can

TABLE 6 Cost (€/day) breakdown by production system configuration

Outsourcing strategy	Full outsourcing	In-house			UPO		BPO		
Capacity strategy	–	60% utilization	99% of periods feasible		Capacity set to minimize cost		Capacity set to minimize cost		
Configuration no.	1	2	3	4	5	6	7	8	9
Order book control	–	IOR	IOR	OBS	IOR	OBS	IOR	OBS	OBS
Subcontractors involved	≥ 1	0	0	0	≥ 1	≥ 1	4	1	4
Facility cost	–	240	240	240	240	240	240	240	240
Materials cost	1,685.03	1,685.03	1,684.4	1,684.75	1,685.03	1,685.03	1,673.10	1,673.34	1,679.70
Capacity cost	–	2,556.13	1,929.7	1,710.79	1,622.18	1,546.76	1,587.07	1,560.62	1,557.56
Outsourcing cost	3,551.68	–	–	–	125.74	56.23	77.99	18.86	34.88
Lost revenue cost	–	0	2.27	1.02	–	–	30.85	30.24	13.80
Subcontracting cost	–	–	–	–	–	–	37.00	8.95	16.55
Subcontracting revenue	–	–	–	–	–	–	(115.00)	(27.81)	(51.43)
Total cost	5,236.71	4,481.16	3,856.39	3,636.56	3,672.95	3,528.02	3,531.02	3,504.20	3,491.06
<i>Demand variability cost^a</i>	1,778.00	1,022.45	397.68	177.85	214.24	69.31	72.31	45.49	32.35
Variability on-cost over configuration 9	5,397%	3,061%	1,129%	450%	562%	114%	124%	41%	0%

^aTotal cost, less the lowest possible cost if demand were constant.

be applied, although it presupposes $Q = 5$, and hence low responsiveness.

These results can be understood intuitively by considering that in-house capacity is cheaper than outsourcing capacity and that demand has low enough variability to ensure a profitable utilization of installed capacity. Nevertheless, partial outsourcing allows for less in-house capacity, merely sufficient to handle the stable portion of demand, while the variable portion of demand can be outsourced; it is cheaper to accept lower margins on outsourced production than to maintain capacity that stands idle when there is insufficient demand.

6.2 | The interplay between partial outsourcing and order book smoothing

The foregoing analysis highlighted how a combination of order book smoothing and partial outsourcing (both UPO and BPO) permit considerable reductions of variability costs. Nevertheless, OBS requires the lead time experienced by the customer to be greater than the production lead time which instead might be used to increase responsiveness. A similar

but not evident effect, is that any additional lead time imposed by outsourcing reduces the time available for smoothing. The key is that smoothing is limited by the slack time Q , being the difference between the promised lead time to customers, less the total time for the subcontractor to complete an order. Taking the unidirectional case, we show the effect of varying Q in Table 7 where $Q = 5$ is the baseline from the case.

The difference in demand variability cost from the baseline following a change in Q tells a compelling story. Responsiveness (small Q) comes a high cost, and there is a diminishing marginal benefit of reducing it. Therefore, unless there is a willingness to pay for next-day service, companies can gain most of the smoothing cost advantages by maintaining a slack time of 3–5 working days. Customers experience the slack time plus the physical lead time, making short physical lead times imperative for maintaining responsiveness.

Table 7 also illustrates the hypothetical case of changing to an outsourcing partner with a longer lead time. To maintain the same promised lead time to customers, Shapeways would have less time to do smoothing and be forced to

TABLE 7 The effect of slack time changes on cost under UPO

	Permitted slack between physical and promised lead time, Q							
	1	2	3	4	5	6	7	8
Optimal capacity k^*	1,028.24	1,022.60	1,020.11	1,018.62	1,017.60	1,016.85	1,016.27	1,015.80
Capacity cost	1,562.92	1,554.35	1,550.56	1,548.30	1,546.76	1,545.62	1,544.73	1,544.02
Outsourcing cost	125.74	88.91	72.60	62.87	56.23	51.33	47.52	44.46
Demand variability cost	154.98	109.58	89.47	77.49	69.31	63.27	58.57	54.80
Cost difference	+124%	+58%	+29%	+12%	0%	−9%	−15%	−21%

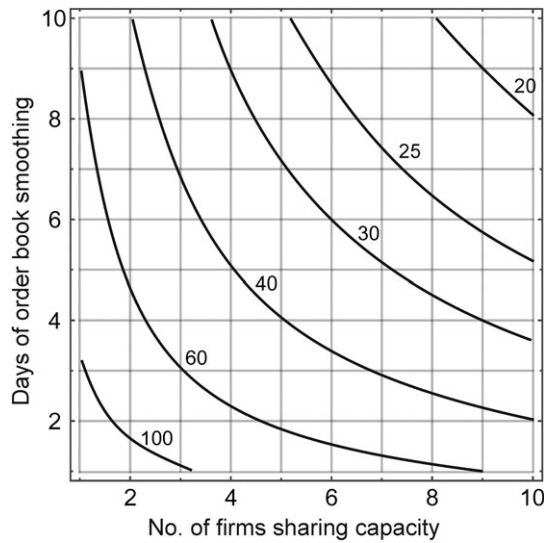


FIGURE 3 The cost of demand variability: The trade-off between the number of firms in the outsourcing network and the smoothing days in the order book

reduce Q . While a 1-day lead time increase would add 12% to the variability cost, each day of reduced slack becomes progressively more expensive.

For BPO, not only does the slack time, Q , need to be considered, but also the number of firms in the network, n . Following the earlier treatment, we assume these to be of equal size, cost parameters, while maintaining equal priority among each other. To investigate the full potential of BPO, we assume that no extra logistics costs are incurred when outsourcing. Figure 3 shows the cost contours achievable by the joint setting of n and Q . As expected, more smoothing and more partners help to reduce the variability cost, and both show diminishing returns. The preferable approach, therefore, is to have a bit of each. Another consideration coming into play with BPO is that smoothing comes at the expense of lower responsiveness, whereas a greater number of collaborating firms does not. Put

differently, BPO can decrease cost without reducing responsiveness, permitting a shift of the cost-responsiveness frontier, whereas OBS moves the tradeoff along an existing cost-responsiveness frontier.

6.3 | Market conditions and the feasibility of partial outsourcing

Moving from a cost-centric perspective to one of profitability, we now seek to find a combination of demand and price point at which production system configurations become profitable. To model different demand levels, assume demand variance to be proportional to the mean (just as in inventory consolidation; Maister, 1976), $\sigma_o^2 = 12.43\mu_d$, following the industrial case. For representative configurations (1, 2, 5, 7, and 9) from Table 6 and for each integer value $\mu_d \in [1, 800]$, the breakeven sales prices appear in Figure 4. To allow for a clearer comparison between UPO and BPO, we have changed the lost sales cost to equal the cost of outsourcing, having no impact on the dominance of any configuration over another.

We notice that for low demand (<125 ccm/day), it is most profitable to outsource the entire demand, and outsourcing is indeed the only profitable mode at most realistic price points. For demand over 125 ccm/day, BPO with $n = 5$ is the most profitable mode, especially when using OBS, although the performance without OBS is comparable but at the cost of lower responsiveness. A dedicated in-house facility is never better than UPO, but it is still preferable to pure outsourcing when demand is greater than 250 ccm/day. Note also that at the current price of €5.99/ccm, the break-even demand for BPO is 88 ccm/day, a breakeven demand 34% less than for a dedicated facility without partner firms to absorb peak volumes. Consequently, a 3DP service provider can operate profitably at lower demand levels if they engage in partial outsourcing.

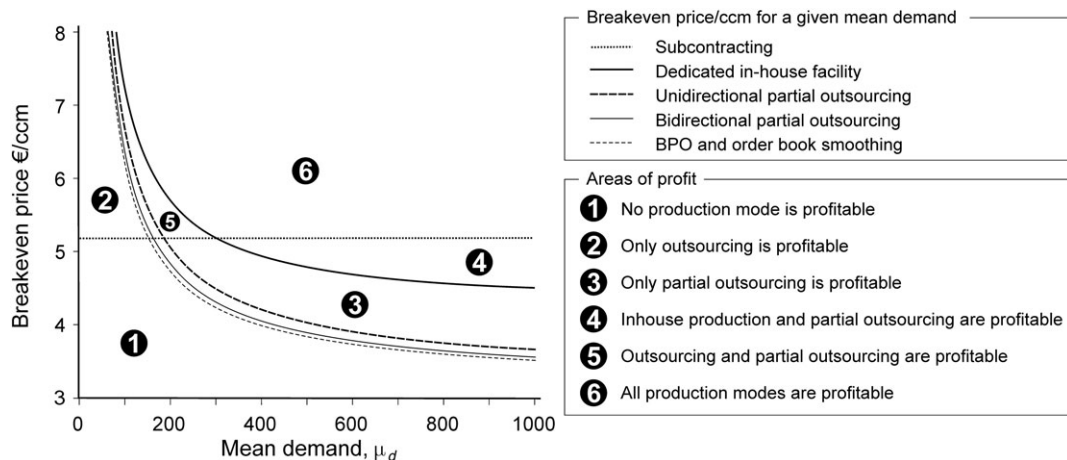


FIGURE 4 Break-even price/ccm for a given mean demand per day

Further, not only may demand change over time, but also prices. One such case is price competition when competitors undercut each other to increase their market share even if profit margins dwindle. Outsourcing is always viable as long as its variable cost is less than the market price, but at a low enough price point, outsourcing is unprofitable. For high demand a dedicated facility copes better with low prices, but not when demand is low—BPO and UPO always turns into profit at a lower price-demand combination than the dedicated facility. Partial outsourcing is therefore much more resilient in the face of faltering demand, whether it is from industrial competitors or from consumer 3DP machines. The difference in breakeven price between BPO and UPO is greatest for low demand, meaning that firms in small markets especially benefit from being able to receive outsourced demand from other firms. In a possible future setting with improved 3DP technology where we experience lower in-house equipment costs and a lower cost of outsourcing, the breakeven price will be lower, although the cost of materials and facilities moderate this decrease. For partial outsourcing, the optimal amount of in-house capacity remains the same if the outsourcing cost falls proportionally with the capacity cost, but a sharper fall in outsourcing costs, perhaps due to market saturation, will decrease the optimal in-house capacity level.

The break-even relationship illustrated in Figure 4 applies to each market that can be served by one facility, meaning that each market requires a strategy matched to the local demand, price, and local operating costs. When potential subcontractors are available, the economic choice is between pure outsourcing if demand is low, or partial outsourcing if demand is high. When no potential subcontractor is available, the only choice is to set up a new facility. This has important implications for market entry decisions. First, a 3DP provider with partial outsourcing can operate profitably in some markets, where a dedicated facility cannot, making some markets accessible only to those who engage in UPO or BPO. Second, partial outsourcing is more resilient to downward shifts in demand or price; permitting such firms to operate profitably when companies with pure in-house production are struggling.

7 | DISCUSSION

The foregoing analysis provides some key insights. First, given sufficient demand, 3DP operations benefit from engaging in partial outsourcing without sacrificing responsiveness. Second, OBS applies in most production system configurations, but requires slack between the promised lead time and the processing lead time. The cost saving from smoothing originates from exploiting existing inefficiencies or by sacrificing responsiveness to customers. Finally, BPO supports trading excess capacity at low cost, since all

companies benefit from it, and allows some revenue to be recovered by offering unused capacity.

Bromiley and Rau (2016) argue that high performance results from matching the available manufacturing assets with appropriate practices. The best available operational practices define the operational frontier (Schmenner & Swink, 1998), which can be moved by designing and implementing practices that are better suited to a context. BPO moves the operational frontier for 3DP. Given sufficient demand, introducing BPO reduces costs while keeping delivery performance constant. Our analysis shows economic benefits to all parties in the BPO arrangement. These benefits stem neither from economies of scale (which appear in 3DP only through facility costs), nor from economies of scope (which are a build-to-model characteristic), but from economies of collaboration.

When general purpose capacity is traded dynamically between firms, short-term imbalances between supply and demand can be reduced, enabling both lower costs through the better use of distributed capacity and faster response times, shifting the performance frontier. The practice of OBS enables movement of 3DP along the operational frontier, trading off delivery responsiveness for reduced cost. It can be used at any level of outsourcing in the modeled scenarios, but requires the some slack between the promised lead time and the processing lead time.

The scenario modeling and analysis produces an expected outcome in the context of individual item make-to-model manufacturing. However, this represents only a narrow segment of the potential application area of build-to-model manufacturing. Often original equipment manufacturers outsource products or modules consisting of many individual items that are assembled. The perspective of the original equipment manufacturer dominates the outsourcing literature (Tsay et al., 2018), and we now add a BPO perspective to this context. The general-purpose characteristic of 3DP changes the nature of outsourcing for an original equipment manufacturer fundamentally.

When manufacturing technology is specialized, a dedicated facility (whether in-house or with a subcontractor) is the only available alternative for an original equipment manufacturer. Profitability requires sufficient demand and introduces risk that cannot be outsourced, as subcontractors require contractual safeguards against low demand (Williamson, 2008). This makes manufacturing infeasible for low levels of demand. However, in a 3DP environment, outsourcing manufacturing does not require investment in specialized tools and assets. Taken together, these insights are represented by Figure 5, which is consistent with our breakeven analysis in Figure 4. In build-to-model manufacturing, there is no need to involve subcontractors in product development or production engineering. Outsourcing decisions that were previously one-off make-or-buy decisions and part of major new product

		Commonality of technology	
		Specialized	Generalized
Demand level	High	In-house or Outsource	Bidirectional partial outsourcing
	Low	Infeasible	Outsource

FIGURE 5 The general-purpose nature of 3DP transforms make-or-buy into make-and-buy

development and introduction projects, can become more operational and dynamic.

For low demand settings, build-to-model manufacturing offers a low risk and feasible entry to the market (Khajavi, Partanen, Holmström, & Tuomi, 2015). However, for high demand settings, partial outsourcing becomes a question of cost efficiency and responsiveness. Investing in in-house 3DP and other direct manufacturing technologies provides the opportunity to reach a new performance frontier through asset investment. In-house 3DP improves responsiveness and reduces supporting logistics and warehousing activities.

With benefits dependent on collaboration, BPO is an operational practice that we expect to reduce opportunistic behavior and supply chain risk (Christopher & Lee, 2004). In the outsourcing literature, mutual asset investment that reduces the need for contractual safeguards (Tsay et al., 2018; Williamson, 2008). The dynamic build-to-model operational practice is bidirectional and confers benefits similar to mutual investments in assets. However, the reduced performance resulting from exclusion from a collaborative network should motivate manufacturers to avoid opportunistic behavior. In a distributed network of 3DP manufacturers, partial outsourcing allows products to be offered at a price point where in-house 3DP would be unprofitable.

8 | CONCLUSION

Using demand and cost information from the outsourcing relationship between Shapeways and Panalpina we have conducted an in-depth empirical assessment on the value of partial outsourcing in build-to-model manufacturing. The partial outsourcing relationship between Shapeways and Panalpina demonstrates the potential for general purpose manufacturing technology to disrupt the conventional supply chain model. Our analytical model shows that BPO dominates unidirectional partial outsourcing, and the practice establishes a new operational frontier.

In our research we have not sought to demonstrate sustainable competitive advantage through adopting 3DP, instead we explore how to improve the performance of 3DP build-to-model manufacturing through partial outsourcing and order book smoothing. In this sense, we have subscribed to the practice-based view of operations management (Bromiley & Rau, 2016), seeking to explain performance and ways to improve performance. From a resource-based view of strategy (Barney, 2001), build-to-model manufacturing is not rare, valuable, or hard to imitate. However, the performance-based view differs from a resource-based view (Barney, 2001) in that high performance is seen as desirable, even when not providing a sustained competitive advantage.

For the digitalization of manufacturing research space more generally, our study represents build-to-model as a new mode of manufacturing operation alongside the familiar to-order production modes. In a 3D printing network, the 3D design model largely substitutes for the conventional order, and because it can be transferred easily, it facilitates BPO. From a further research perspective, more investigation of how sharing design models (rather than processing orders) differs from conventional BTO is needed, creating opportunities to develop further novel operations management practices.

We acknowledge that the full practice of BPO has not been implemented and tested in practice. The design proposal is explorative (Holmström et al., 2009), requiring further field testing and development in practice (van Aken, Chandrasekaran, & Halman, 2016). In the future, when Panalpina finds its own sources of demand in addition to that from Shapeways, then Panalpina can exploit partial outsourcing to gain benefits similar to those of Shapeways. This would enable both Panalpina and Shapeways to reap the benefits of variability pooling, without the need for one centralized capacity. The proposed operational practice of BPO allows every participating firm to improve its performance, demonstrating the potential for economies of collaboration in digital manufacturing.

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APPENDIX A: DERIVATION OF THE EXPECTED PROFIT

Exploiting the identity $q^A = q_\Sigma^A + q_4^A$, we obtain

$$\pi^A = (p_C^A - c_1^A)q^A - c_0^A + (p_B^A - c_1^A)q_3^B - c_2^A k^A - c_3^A q_3^A - (p_C^A - c_1^A)q_4^A. \quad (\text{AA1})$$

The key to determining $E[\pi^A]$ is learning the expectations of the quantities q^A , q_3^A , q_4^A , and q_3^B . Trivially, $E[q^A] = \mu^A$. The outsourced quantity q_3^A , is the minimum of our desired outsourcing and the available capacity from the subcontractor, that is, $q_3^A = (\min(q^A - k^A, k^B - q^B))^+$, that is, the minimum of bivariate random variables. Letting $\varphi_{AB}^-(x)$ be the probability density function (PDF) of $\min(q^A - k^A, k^B - q^B)$, $E[q_3^A] = \int_0^{k^B} \varphi_{AB}^-(x)xdx$. For two uncorrelated normally random variables a and b , the distribution density function of $\min(a, b)$ is given by $\varphi(x) = \frac{1}{\sigma_a} \varphi\left[\frac{x - \mu_a}{\sigma_a}\right] \Phi\left[\frac{\mu_b - x}{\sigma_b}\right] + \frac{1}{\sigma_b} \varphi\left[\frac{x - \mu_b}{\sigma_b}\right] \Phi\left[\frac{\mu_a - x}{\sigma_a}\right]$, (Disney, Gaalman, Hedenstierna, & Hosoda, 2015). Finding q_4^A seems less straightforward, but is easily obtainable if we define a variable for all orders exceeding in-house capacity $q_5^A = (q^A - k^A)^+$. Then $q_4^A = q_5^A - q_3^A$. The expectation $E[q_5^A] = \int_{k^A}^{\infty} (x - k^A)\varphi_A(x)dx$ has a convenient form under normally distributed orders, as $E[q_5^A] = \sigma^A G[(k^A - \mu^A)/\sigma^A]$, where $G(x) = \varphi(x) - x$

$[1 - \Phi(x)]$ is the unit normal loss function. Under normally distributed demand, this provides the total profit function shown in (6), where $E[q_3^B] = \int_0^{k^A} \varphi_{BA}^-(x)xdx$ can be derived in a similar manner as $E[q_3^A]$.

APPENDIX B: VALIDATION TESTS

To ensure model validity, we followed two guiding principles: The model should be fit-for-purpose, and it should be credible. The first criterion follows from building the simplest and most general model possible that produces sufficient insight about the object of study. We have ensured that no further simplifications are possible without sacrificing key results, while the model structure affords general insights about varying the degree of outsourcing. As for credibility, we have done internal consistency checks to ensure all order releases are accounted for, so that the sum of produced orders and excess orders equal the total order releases, $q^A = q_\Sigma^A + q_4^A$. We have also verified that the analytical results match a simulation of 10^5 time periods duration for each production configuration tested. Additionally, the numerical results in Section 6 show how the system reacts under a large range of variable settings, serving as sensitivity and validation tests to ensure that the model produces reasonable output for the entire range of considered inputs.