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The impact of 3D printing on manufacturer–retailer supply chains

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ABSTRACT

In this paper we consider the impact of 3D printing, or additive manufacturing, on a simple supply chain, consisting of a manufacturer and retailer, that serves stochastic customer demand. 3D printing is a relatively new manufacturing technology that is attracting attention from many firms. However, the impact of 3D printing on operations and firm relationships in a supply chain is relatively unexplored in academic research. A unique aspect of 3D printers is that they can be installed at the retailer in a supply chain, a characteristic that we highlight in our paper since it enables the supply chain to be more responsive to demand. Consequently, 3D printers can be adopted by either the manufacturer or, in a more novel situation, the retailer; we analyze the equilibrium of Stackelberg games in both cases. We characterize the economic and competitive conditions where either firm adopts 3D printing, and show that under either scenario, it is possible for both firms to earn more profit than a benchmark system without 3D printing. We identify and quantify the positive benefits associated with 3D printing, for both firms in a simple supply chain, when either firm adopts this new manufacturing technology. In many cases, the scenario where the manufacturer adopts 3D printing and installs 3D printers at the retailer results in the best profit outcomes for the manufacturer. The retailer's preference, however, depends on problem parameters. Therefore, supply chain managers should carefully consider the possibility of 3D printing products in their supply chain.

1. Introduction

3D printing, also known as additive manufacturing, is an alternative manufacturing technique that is based on producing a product layer by layer. This technique contrasts with traditional manufacturing techniques, such as milling, forging, and welding. 3D printing has received significant and growing attention in recent years by both governments and supply chain owners. Perhaps the most prominent mention of 3D printing was during President Obama's 2013 State of the Union address (Gross, 2013), where the President said *"A once-shuttered warehouse is now a state-of-the art lab where new workers are mastering the 3D printing that has the potential to revolutionize the way we make almost everything."* President Obama was referring to the National Additive Manufacturing Innovation Institute (NAMII) in Youngstown, Ohio, created in part due to a $30 million government investment, whose objective is to revolutionize manufacturing using 3D printing (www.3ders.org, 2013). In addition, the governments of Japan (www.3ders.org, 2014), China (Kyra, 2015), India (DMello, 2016), Australia (Lord, 2018), and France Hall (2016) have encouraged their industries to develop and utilize 3D printing. Prominent firms, such as GE (Smith, 2013), Mercedes Benz (3D-Printing-Progress, 2019), and Disney (Grunewald, 2016) have also invested in 3D printing technology to improve their supply chains.

One crucial reason why supply chains are investing in 3D printing technology is its ability to produce products closer to final customers (Lynch, 2019). For supply chains with a global scale, this advantage is magnified. In particular, if 3D printers are installed close enough to the final customer, it enables the supply chain to avoid transportation and inventory holding costs. Furthermore, this proximity improves a firm's ability to produce products after demand uncertainty is resolved. In other words, adopting 3D printing technology closer to final customers can facilitate a make-to-order policy.

These advantages, however, come at a cost. Two main disadvantages of 3D printing are as follows: First, 3D printing typically has lower production speed than traditional manufacturing techniques. Traditional manufacturing techniques are much faster for products with simple geometries and a low number of parts. However, their speed decreases as products' geometries get more complex or the number of parts in a product increases. Conner et al. (2014) explain that the key manufacturing attributes of a product are its

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Table 1
3D printing cost structure under different scenarios.

		3D printing purchasing cost	3D design investment cost	3D printing variable cost
Manufacturer may adopt 3D printing	Manufacturer	✓	✓	✓
	Retailer			
Retailer may adopt 3D printing	Manufacturer		✓	
	Retailer	✓		✓

complexity, customizability, and production volume; they unify these three characteristics into a Modified Complexity Factor (MCF). Next, they propose a framework that attempts to understand where 3D printing is economically feasible. Second, 3D printing requires new investment costs. 3D printing is still a relatively new technology, and adopting it requires purchasing 3D printers as well as developing 3D designs, as 3D printers require production plans that are fundamentally different from production plans for traditional manufacturing techniques.

We conclude this section by describing some practical details associated with 3D printing. 3D printing a product typically begins with a physical model that is sliced into fine layers. These layers are then turned into instructions for a 3D printer by a computer. The 3D printer then deposits material layer by layer until the model is replicated (Hannon, 2019). Therefore, there are three types of costs associated with adopting 3D printing technology; for a detailed review of the costs associated with 3D printing, we refer the reader to Baumers and Holweg (2019). First, there is the cost of purchasing 3D printers, which we denote as the *3D printers purchasing cost*. Second, there is the cost of developing 3D designs, which is a fixed cost and is independent of the number of products being 3D printed; we denote this cost as the *3D design investment cost*. Third, there is the cost of material/filament as well as energy costs, which are a linear function of the number of products being 3D printed; we denote this cost as the *3D printing variable cost*.

1.1. A supply-chain perspective

According to a Gartner poll, 65% of supply chain professionals aim to invest in 3D printing during the next five years (Alec, 2016). Therefore, in our paper, we propose and analyze stylized single-period game-theoretic models of a simple manufacturer–retailer supply chain for a single product, where 3D printing is available. We study two scenarios, described in the next two subsections.

1.1.1. Manufacturer may adopt 3D printing

We first study a scenario where the manufacturer may purchase one or more 3D printers to supplement/replace traditional manufacturing techniques. In particular, to best utilize the unique advantages of 3D printing, we consider the case where the manufacturer-owned 3D printers are installed at the retailer, in a setup similar to vendor-managed inventory. All 3D printing costs are incurred by the manufacturer. One example of this setup is BMW adopting 3D printing technology at some of its larger dealerships to produce spare parts for classic cars (Michelle, 2018). In this case, the manufacturer BMW has invested in purchasing 3D printers and has also developed the 3D designs, which allowed them to shut down the classic cars' production lines (which were only used for producing spare parts). This has enabled BMW to produce all spare parts after demand is realized; i.e., the company has switched to a make-to-order policy.

For this scenario, the manufacturer and retailer utilize a lump-sum contract, where the retailer receives a fixed sum from the manufacturer, and the manufacturer receives the remaining supply chain profit. Lump-sum contracts have been discussed and analyzed by Tsay (1999) and Corbett, Zhou, and Tang (2004) in a supply chain context, where in the latter lump-sum payments are described as *slotting fees*, which are "common among large retailers"; in contrast, we are the first to study lump-sum contracts in a context with 3D printing. The manufacturer's decisions are as follows: (1) how many of the products to traditionally manufacture, potentially at lower unit cost, (2) whether or not to adopt 3D printing, and (3) if adopting 3D printing, how many 3D printers to purchase and how many of the products to 3D print. A main trade-off in this scenario is between the potentially higher costs of 3D printing and improved responsiveness to demand.

1.1.2. Retailer may adopt 3D printing

We next study a unique arrangement where the *retailer* may utilize 3D printers; i.e., the retailer purchases and operates 3D printers on site, incurring all fixed and variable costs of 3D printing. The manufacturer bears the cost of developing 3D designs. We also allow the retailer to purchase traditionally manufactured products from the manufacturer. In other words, the retailer adopts 3D printing technology to supplement, or potentially replace, traditionally manufactured products. An example of such a retailer is Ministry of Supply (Schiffer, 2017), based in Boston, MA. As another example, 3D printing is available at many UPS stores (O'Toole, 2014), where, if supply chains are short on supply, they can request UPS to 3D print products and deliver them to the customer.

We assume the manufacturer and retailer utilize a "dual" wholesale-price contract, where the retailer pays the manufacturer for each unit of traditionally manufactured products as well as a per-unit fee for each unit the retailer 3D prints. In particular, the retailer's decisions are as follows: (1) how many of the products to order from the manufacturer, (2) whether or not to adopt 3D printing, and (3) if adopting 3D printing, how many 3D printers to purchase and how many products to 3D print. The manufacturer's decisions, on the other hand, are: (1) what should be the wholesale price for traditionally manufactured products and (2) if the retailer adopts 3D printing, what should be the per-unit fee for 3D printing a product.

We summarize this section in Table 1, by outlining which firms incur the different costs under the different scenarios.

1.2. Literature review

There is limited research in the operations management literature on the impact of 3D printing. We are aware of only a few papers that study different aspects of 3D printing. Song and Zhang (2016) study the tradeoff between 3D printing and traditional make-to-stock policies in spare-parts logistics, deriving optimal solutions in special cases which serve as high quality heuristics for a general model. Dong, Shi, and Zhang (2017) contrasts 3D printing with more traditional flexible manufacturing technologies, identifying the appropriate situations to apply 3D printing and the associated benefits. Both of these papers focus on the impact of 3D printing on a single firm; in contrast, we investigate the impact of 3D printing on a decentralized supply chain of two firms, a manufacturer and a retailer.

Westerweel, Basten, and van Houtum (2018a) focus on the lower reliability of 3D printed products. They compare 3D printing with traditional manufacturing methods using life-cycle analysis. Westerweel, Basten, and van Houtum (2018b) study the application of 3D printing in producing spare parts to reduce supply lead time and inventory cost. Sethuraman, Parlakturk, and Swaminathan (2018) focus on the fact that consumers can 3D print themselves, and they characterize the market and conditions for personal fabrication. Chen, Cui, and Lee (2018) study a centralized dual channel setting where the adoption of 3D printing is possible for each channel. In contrast to the above mentioned papers, we focus on a decentralized single channel supply chain, and study the conditions under which each player will adopt 3D printing.

In our study, the scenario where the retailer may adopt 3D printing resembles that of dual sourcing (e.g., Veeraraghavan & Scheller-Wolf (2008)). Wang, Gilland, and Tomlin (2010) characterize the optimal procurement quantities and improvement efforts for the case where a firm can source from multiple suppliers and/or exert effort to improve supplier reliability, and they study both random capacity and random yield types of supply uncertainty. JakÅ!'i and Fransoo (2018) focus on inventory systems with non-stationary stochastic demand, where there are two suppliers available for the manufacturer. The faster supply source is assumed to have stochastic capacitated delivery with zero lead time, and the slower supply source is assumed to be uncapacitated with a longer fixed lead time. The manufacturer's objective is to decide how the order should be split between the two supply sources. Inderfurth, Kelleb, and Kleber (2013) focus on the cost-effective management of two supply sources, where the source with a short lead time is characterized by a spot market with a random price, whereas the source with a large lead time is characterized by a multi-period capacity reservation contract with a fixed purchase price and reservation level. Silbermayr and Minner (2016) propose dual sourcing as a method to deal with the risks of supply disruptions. They analyze the trade-off between risk reduction via dual sourcing under disruption risk and learning benefits on sourcing costs induced by long-term relationships with a single supplier, from a buyer's perspective. Ju, Gabor, and Ommeren (2015) propose an approximation for a dual-sourcing inventory model with positive lead times and binomial yield. Chen and Yang (2014) consider a supply chain similar to what we study, and they allow the retailer to satisfy his shortages from an emergency back-up supplier. Janakiraman and Seshadri (2017) study inventory systems with backordering under dual sourcing.

The main differences between the retailer-may-adopt-3D-printing case in our study and this literature are as follows: (1) in dual sourcing one basic assumption is that the source with shorter lead time is strictly preferred to the source with longer lead time when the latter is costlier than the former; in our study, however, we do not have this assumption, and the retailer might opt for 3D printing even when it is costlier than traditionally manufactured products (due to higher responsiveness). (2) Our problem has a different cost structure; i.e., the cost of procuring the 3D printers is incurred by the retailer, and 3D printing capacity is also decided by the retailer. (3) In the dual sourcing literature, wholesale prices are exogenously set, while in our study, the manufacturer is the leader in a Stackelberg game and sets wholesale prices.

In our study, the scenario where the manufacturer may adopt 3D printing resembles that of Vendor-Managed Inventory (VMI), where the manufacturer takes control and manages the retailer's inventory. Mishra and Raghunathan (2004) study the benefits of VMI, with a focus on enhanced competition between manufacturers, which benefits the retailer. Bernstein, Chen, and Federgruen (2006) study the conditions were VMI can result in perfect supply chain coordination. Cachon and Terwiesch (2012) present a textbook discussion of how VMI can reduce the bullwhip effect in supply chains. These studies are for classical supply chains, without 3D printing, and, to the best of our knowledge, we are the first to consider VMI-type contracts in a supply chain where 3D printing plays a pivotal role.

More broadly, introducing 3D printing into a supply chain resembles investing in manufacturing to decrease the unit production cost or increase the production capacity. The problem of investing in production has long been studied in the literature. An early paper is Porteus (1985), which considers, in an EOQ setting, the set up cost as an endogenous factor that is a function of investment, and derives the optimal investment. In the flexible manufacturing literature, Van Mieghem (1998) extends the model in Fine and Freund (1990) and studies optimal investing in flexible manufacturing. Goyal and Netessine (2007) combines and studies the interaction of competition with technology investments. Our paper also considers an investment in new technology, the 3D printer, by either the manufacturer or retailer; however, we show that higher 3D printing unit production costs can still be beneficial for the supply chain under the scenario where the retailer adopts the new technology.

Another relevant literature stream concerns cooperative research and development in a supply chain. Ge, Hu, and Xia (2014) assume investment in production can take place at both the upstream supplier and the downstream manufacturer, and they derive the optimal investment strategies for both firms. Bernstein and Kök (2009) consider a problem consisting of a single assembler and multiple suppliers, and analyze the impact of different contracts on supplier investments. Ishii (2004) studies cooperative R&D from an economics perspective. Gupta (2008) studies how knowledge spillovers, resulting from manufacturer investment in process improvements, affect supply chain performance. Li, Wang, Yin, Kull, and Choi (2012) show that a manufacturer sharing cost-reduction expenses with a supplier results in increased market share and higher profit for the supply chain. Our paper also considers the cooperation between the manufacturer and retailer, albeit in a new and novel manner: the manufacturer incurs a fixed cost to develop 3D printing plans for possible use by the retailer, which pays for the right to use the plans. This unique arrangement can lead to improved profit outcomes for both firms.

Finally, a recent special issue of the Journal of Operations Management focuses on the digitization of operations and supply chains, which discusses additive manufacturing in a more general context (Baumers & Holweg, 2019; Friesike, Flath, Wirth, & Thiesse, 2019; Hedenstierna et al., 2019; Heinen & Hoberg, 2019; Roscoe, Cousins, & Handfield, 2019).

1.3. Contributions

The following is a summary of our paper's main contributions to the operations management literature.

1. To the best of our knowledge, we are the first to analyze the impact of 3D printing on a supply chain. The unique characteristics of 3D printing result in its potential adoption by either the manufacturer or retailer, resulting in new models of cash, material and information flows.
2. For the case where the manufacturer may adopt 3D printing, we analytically derive the equilibrium of the interaction between the manufacturer and retailer. We show that, if 3D printing costs are small relative to traditional manufacturing costs, then all products will be 3D printed in the equilibrium (i.e., a pure make-to-order policy). If 3D printing costs are moderate (i.e., within two thresholds), then the equilibrium consists of 3D printing in parallel with traditional manufacturing (i.e., a combination of make-to-order and make-to-stock policies). If 3D printing costs are high with respect to traditional manufacturing, then 3D printing will not be adopted in the equilibrium (i.e., a pure make-to-stock policy). Finally, if 3D printing is economically feasible for the manufacturer to utilize, then she is better off compared to a benchmark system

with no 3D printing; the retailer's outcome, however, depends on his opportunity cost.

3. For the case where the retailer may adopt 3D printing, we analytically solve the retailer's subproblem characterizing his behavior. We can then partially solve for the equilibrium under the additional assumption of uniformly distributed demand; accompanying numerical results, including for a normal distribution of demand, indicate that our analytical results closely mirror the actual equilibrium. Similar to the previous scenario, we show that there are three regions in the equilibrium: (1) pure traditional manufacturing, (2) a combination of traditionally manufactured products and 3D printed products, and (3) pure 3D printing. We further show that, in this scenario, the manufacturer is always better off compared to a benchmark supply chain with no 3D printing option available. The retailer, however, might be worst off if his opportunity cost is small and 3D printers are expensive to purchase and operate, relative to manufacturing costs; otherwise, he will also be better off.
4. Studying the above two scenarios, we first learn that 3D printing may be adopted even if the unit 3D printing cost is more than that of traditional manufacturing; this is due to the increased responsiveness of the 3D printers, allowing a make-to-order strategy. Next, comparing these two scenarios, we observe that the retailer adopting 3D printing results in larger problem parameter regions for adopting 3D printing technology, compared to that where the manufacturer adopts 3D printing. Finally, whether the manufacturer or retailer prefers each scenario depends on problem parameters; this question is studied in detail in Section 5.

2. Baseline model without 3D printing

In this section we present our benchmark model that captures the traditional situation where 3D printing is not available to firms. This model serves two purposes: (1) the constructs in this section are useful to present our results for the situation where firms have access to 3D printing, and (2) we may compare the firms' outcomes of the benchmark model with those under 3D printing.

Our benchmark model consists of a single manufacturer selling a single product to a single retailer via a wholesale-price contract with unit wholesale price $w > 0$, which is based on the model in Lariviere and Porteus (2001). The retailer, in turn, sells to (continuous) stochastic customer demand D with density f and distribution F, with support on $[0, U]$. The manufacturer's unit production cost is $c_m > 0$ and the retailer's unit selling price is $r > 0$; to avoid trivial solutions, we assume that $c_m \leq w \leq r$. The retailer's single decision, as a function of w, is to determine the order quantity $q(w) \geq 0$ that maximizes his expected profit

$$\pi_R^b(r, w) = \max_{q \geq 0} E[r \min\{q, D\}] - wq, \tag{1}$$

which is solved by the classic Newsvendor solution $q_{nv}(w) = F^{-1}\left(1 - \frac{w}{r}\right)$. The subscript R refers to the retailer (M will refer to the manufacturer) and the superscript b refers to the benchmark case in this section. We assume that the retailer participates and purchases the product if and only if his resulting profits are at least A, which represents the opportunity cost of *alternative* business opportunities.

The manufacturer, being the leader in a Stackelberg game, has a single decision of determining the appropriate wholesale price w to maximize her profits, which is determined by solving

$$\begin{aligned} \pi_M^b = \max_{w \geq 0} & (w - c_m) q_{nv}(w) \\ \text{s.t. } & \pi_R^b(r, w) \geq A, \end{aligned} \tag{2}$$

where the constraint is to make sure that the retailer's maximized profit is at least A, to ensure participation. In order to solve the manufacturer's problem cleanly, we make the standard assumption that the demand distribution F has an increasing generalized failure rate: $xf(x)/(1 - F(x))$ is increasing in x. Most common distributions (e.g., uniform, truncated normal, gamma, Pareto) satisfy this constraint; see Banciu and Mirchandani (2013) for a more complete list of distributions.

Assumption 1. The demand distribution F has an increasing generalized failure rate.

The solution to the manufacturer's problem for $A = 0$ is summarized in the following proposition.

Proposition 1. *(Lariviere & Porteus, 2001) The manufacturer's profit function $(w - c_m)q_{nv}(w)$ is strictly unimodal in w, with optimality condition*

$$(1 - F(q))\left(1 - \frac{qf(q)}{1 - F(q)}\right) = \frac{c_m}{r}. \tag{3}$$

Let q_s denote the unique solution to this optimality condition and let $w_s = r(1 - F(q_s))$ denote the associated optimal wholesale price. Note that q_s and w_s maximize the manufacturer's unconstrained problem (i.e., $A = 0$). Next, if $A > 0$, then it is useful to define the maximum wholesale price or, equivalently, the minimum order quantity that will induce the retailer to participate.

Definition 1. Let $w_m^A = \max\{w \geq 0 : \pi_R^b(r, w) \geq A\}$ and let $q_m^A = q_{nv}(w_A)$ denote the associated order quantity.

Note that w_A is the maximum wholesale price satisfying the constraint in the manufacturer's problem. Finally, Proposition 1 and Definition 1 lead us to the equilibrium solution of the manufacturer–retailer Stackelberg game in our benchmark situation, which we summarize in the following corollary. It is crucial to observe that π_M^b is concave and unimodal in w. Therefore, if $w_s < w_m^A$, then the manufacturer sets the wholesale price to w_s as an interior solution, and the retailer's participation constraint is satisfied. However, if $w_s > w_m^A$, then the optimal solution is a corner point, and the constraint in the manufacturer's problem should be binding; therefore, the manufacturer sets the wholesale price to w_m^A.

Corollary 1. *The equilibrium wholesale price is $w_b = \min\{w_s, w_m^A\}$ and the equilibrium order quantity is $q_b = q_{nv}(w_b)$, which results in retailer profit $\pi_R^b(r, w_b)$ and manufacturer profit $\pi_M^b = (w_b - c_m)q_{nv}(w_b)$.*

Finally, we make the assumption that $w_b \geq c_m$, so that the manufacturer is guaranteed to earn non-negative profit.

3. Manufacturer may purchase 3D printers

In this section we study a scenario where the manufacturer decides whether or not to adopt 3D printing technology. If 3D printing is adopted, in a setting similar to vendor managed inventory, we assume 3D printers are installed at the retailer, but the manufacturer bears the fixed and variable costs of 3D printing. The manufacturer benefits from the opportunity of implementing make-to-order policies, allowing demand to be satisfied after uncertainty is resolved. Furthermore, the manufacturer may still utilize traditionally manufactured products for a make-to-stock strategy. Hybrid solutions are also allowed. The manufacturer decides how many 3D printers to procure, how many products to 3D print, and how many products to traditionally manufacture. The manufacturer captures all revenue, except for a lump-sum payment to the retailer, which we set to the retailer's opportunity cost.

Under this scenario, the manufacturer has the option of purchasing multiple 3D printers at a unit cost of $K > 0$ per printer, to supplement/replace her traditional manufacturing capabilities.

Let $n \geq 0$ denote the number of 3D printers, which is a decision variable under the manufacturer's control. Each 3D printer has the capacity to produce $Q > 0$ units over a fixed production horizon, and the unit printing cost is $c_p > 0$. To adopt 3D printing, we assume the manufacturer must incur a fixed cost $S > 0$ to develop 3D production plans, which is independent of the number of products being printed. As discussed in the introduction, 3D printing technology requires 3D designs (or 3D schematics), which are substantially different from the plans for traditional manufacturing techniques. Note that the manufacturer only incurs the fixed cost S of developing 3D designs if she decides to adopt 3D printing technology. Next, as in our benchmark, traditional manufacturing has a unit cost c_m. The manufacturer also decides how many of the products to 3D print, which we denote as $q_p(D) \geq 0$ and how many of the products to traditionally manufacture, which we denote as $q_m \geq 0$. Note that, since products are 3D printed after demand uncertainty is resolved, the number of 3D printed products is a function of demand. Letting $\hat{A}$ denote the fixed lump-sum payment to the retailer, the manufacturer decides on n, $q_p(D)$, and q_m. Therefore, the manufacturer's profit-maximization problem is

$$\begin{aligned}\pi_M^{3D} = \max_{n, q_p(D), q_m \geq 0} & E[r \min(q_m, D)] \\ & - c_m q_m + E[(r - c_p) q_p(D)] - (nK + S \cdot \mathbb{1}\{n > 0\}) - \hat{A} \\ \text{s.t.} \quad & q_p(D) \leq \min(nQ, \max(D - q_m, 0)) \end{aligned} \tag{4}$$

The first two terms of the objective function represent the manufacturer's profit from selling the traditionally manufactured products. The third and fourth terms are her profit from selling the 3D printed products and 3D printing costs, respectively. The fifth term is the lump-sum payment to the retailer. Note that 3D design costs will be incurred only if 3D printing is adopted (i.e., $n > 0$). The first constraint represents the fact that the number of 3D printed products should be at most the minimum of the 3D printing capacity and demand spill over beyond the make-to-stock products from traditional manufacturing. The solution to the manufacturer's problem, and the resulting maximized profits, are given in the next two propositions, respectively.

Note that $c_p + K/Q$ is the effective unit production cost of a 3D printer. The conditions in the first cases of Propositions 2 and 3 imply that 3D printers are cheaper than traditional manufacturing (i.e., $c_p + \frac{K}{Q} < c_m$) and result in more manufacturer profit than the benchmark (i.e., $\pi_R^b(r - c_p, \frac{K}{Q}) - S > \pi_R^b(r, c_m)$). In this case, all products are 3D printed. In the second case, the 3D printers have a moderate cost (i.e., $c_m \leq c_p + \frac{K}{Q} \leq c_p + \frac{c_m}{r}(r - c_p)$) and still provide more manufacturer profit than the benchmark (i.e., $\pi_R^b(c_p, c_m - \frac{K}{Q}) + \pi_R^b(r - c_p, \frac{K}{Q}) - S > \pi_R^b(r, c_m)$); notably, the 3D printers are more expensive than traditional manufacturing in this case. In this case, 3D printing is utilized in parallel with traditional manufacturing. In the third case, where 3D printers have high operational costs or low manufacturer profits, all products are traditionally manufactured. Note that $\hat{A}$ does not affect the conditions of the equilibrium's three states since, in all three cases, the retailer receives $\hat{A}$ as a lump-sum payment. The development cost of the 3D designs S, however, does affect the conditions – as S increases, the parameter space that results in 3D printing shrinks.

Next, for uniformly distributed demand, we plot the optimal profits to Problem (4) in Fig. 1 for $c_p \in \{30, 50, 70\}$. On each line: (1) if $\frac{K}{Q}$ is less than the value of the circled point, then all the products will be 3D printed, representing the first case of Proposition 2, (2) if $\frac{K}{Q}$ is between the value of the circled point and the asterisked point, then 3D printing will be utilized in parallel with traditional manufacturing techniques, and (3) if $\frac{K}{Q}$ is greater than the value of the the asterisked point, then all products will be traditionally manufactured. Note that for the red line ($c_p = 70$), the 3D-printing-only region does not exist, since it is too expensive.

4. Retailer may purchase 3D printers

In this section we propose and analyze a novel scenario, where the retailer can potentially purchase 3D printers at the same cost K and unit printing cost c_p. Since the retailer adopts 3D printing technology and 3D prints the products, K and c_p are incurred by the retailer. In Section 3, however, these costs are incurred by the manufacturer, because the manufacturer is utilizing the 3D printing technology. We assume that the manufacturer sells both the physical product as well as the right to 3D print products, in

Proposition 2. *The solution to Problem (4) is*

$$(q_m^*, n^*) = \begin{cases} \left(0, \dfrac{1}{Q} F^{-1}\left(1 - \dfrac{K}{(r - c_p)Q}\right)\right), & \dfrac{K}{Q} < c_m - c_p \text{ and } \\ & \pi_R^b\left(r - c_p, \dfrac{K}{Q}\right) - S > \pi_R^b(r, c_m) \\ \left(F^{-1}\left(1 - \dfrac{c_m - \frac{K}{Q}}{c_p}\right), \dfrac{1}{Q}\left(F^{-1}\left(1 - \dfrac{K}{(r - c_p)Q}\right) - F^{-1}\left(1 - \dfrac{c_m - \frac{K}{Q}}{c_p}\right)\right)\right), & c_m - c_p \leq \dfrac{K}{Q} \leq \dfrac{c_m}{r}(r - c_p), \text{ and} \\ & \pi_R^b\left(c_p, c_m - \dfrac{K}{Q}\right) + \pi_R^b\left(r - c_p, \dfrac{K}{Q}\right) - S > \pi_R^b(r, c_m) \\ \left(F^{-1}\left(1 - \dfrac{c_m}{r}\right)\right), & \text{otherwise.} \end{cases}$$

Proposition 3. *The manufacturer's maximized profit is*

$$\pi_M^{3D} = \begin{cases} \pi_R^b\left(r - c_p, \dfrac{K}{Q}\right) - S - \hat{A}, & \dfrac{K}{Q} < c_m - c_p \text{ and} \\ & \pi_R^b\left(r - c_p, \dfrac{K}{Q}\right) - S > \pi_R^b(r, c_m) \\ \pi_R^b\left(c_p, c_m - \dfrac{K}{Q}\right) + \pi_R^b\left(r - c_p, \dfrac{K}{Q}\right) - S - \hat{A}, & c_m - c_p \leq \dfrac{K}{Q} \leq \dfrac{c_m}{r}(r - c_p), \text{ and} \\ & \pi_R^b\left(c_p, c_m - \dfrac{K}{Q}\right) + \pi_R^b\left(r - c_p, \dfrac{K}{Q}\right) - S > \pi_R^b(r, c_m) \\ \pi_R^b(r, c_m) - \hat{A}, & \text{otherwise.} \end{cases}$$

exchange for a per-unit royalty fee w_p. If the manufacturer sells the retailer the right to 3D print products, she must incur a fixed cost of S to develop the schematics.

The sequence of events is as follows. In our game theoretic model, the manufacturer first offers the pricing for both fully manufactured products as well as the royalty pricing for 3D printing: (1) the unit wholesale price of the manufactured products is w_m and (2) the unit 3D printing royalty price w_p; the retailer paying for the right to 3D print compensates the manufacturer for the fixed cost of developing them. The retailer then decides (1) how much of the manufactured products to order q_m at wholesale price w_m, (2) how many 3D printers to purchase n, and (3) conditional on buying at least one 3D printer, how many 3D printed products q_p to purchase at w_p in order to 3D print them at unit material cost c_p. As in the previous section, each 3D printer has the capacity to produce $Q > 0$ units over a fixed production horizon. Finally, since the manufacturer sets the pricing structure first, she is the leader, and the retailer is the follower in a Stackelberg game.

Remark 1. In our proposed model, one potential concern for the manufacturer would be how to prevent the retailer from printing more than q_p products once the 3D schematics are provided. In order to tackle this issue, there are some software programs, such as PaperCut (www.papercut.com), that control the number of (paper) prints for each user, and the same technology could potentially be utilized in 3D printing. Moreover, many universities audit the printing activities of students and limit them. Thus, the technology for preventing the retailer from printing more than q_p is available.

4.1. Retailer analysis

The retailer maximizes his expected profit with respect to the decisions q_m, q_p, and n for a given (w_m, w_p) pricing structure. If he decides not to buy any 3D printers, q_p must be zero. The retailer's economics are as follows: as described above, $(w_m,\ w_p)$ is the manufacturer's pricing structure, K is the fixed cost per 3D printer, c_p is the variable 3D printing cost, and r is the unit revenue. We assume that stochastic demand D is first fulfilled from the existing stock q_m (which arrives before the selling season), to avoid having left-over inventory, and remaining demand is fulfilled by the 3D printers, if any, up to their collective capacity nQ. In other words, our model is capturing and measuring the 3D printers' ability to increase the retailer's flexibility to satisfy demand. Therefore, we allow q_p to depend on the realized demand D; being closer to the consumer, it is reasonable to assume that this retailer decision can be made once demand uncertainty is resolved.

Consequently, the amount of product that is 3D printed is represented by $q_p(D)$, which is limited by the total 3D printing capacity nQ, as well as the remaining demand to be satisfied $\max\{D - q_m, 0\}$; this forms the main constraint in the retailer's profit-maximization problem:

$$\begin{aligned}\pi_R^{3D}(w_m, w_p) = \max_{q_m, q_p, n \geq 0}\ & E[r\min\{q_m, D\}] \\ & - w_m q_m + E[(r - w_p - c_p)q_p(D)] - nK \\ \text{s.t.}\ \ & q_p(D) \leq \min\{nQ, \max\{D - q_m, 0\}\}. \end{aligned} \tag{5}$$

The first two terms in the objective function are collectively the retailer's expected profit from manufactured products, and the third and fourth terms are the expected profit from 3D printed products. To avoid trivial solutions, we assume that $\max\{w_m, w_p + c_p\} < r$, so that purchasing either/both manufactured products and 3D schematics is economically feasible. The solution to the retailer's problem is presented in the following two propositions.

Proposition 4. *The optimal solution (q_m^*, n^*) to Problem (5), given the manufacturer's pricing structure (w_m, w_p), equals*

$$\begin{cases} \left(F^{-1}\left(1 - \frac{w_m}{r}\right), 0\right), & \frac{w_m}{r}(r - w_p - c_p) < \frac{K}{Q} \\ \left(F^{-1}\left(1 - \frac{w_m - \frac{K}{Q}}{w_p + c_p}\right), \frac{1}{Q}\left(F^{-1}\left(1 - \frac{K}{(r - w_p - c_p)Q}\right) - F^{-1}\left(1 - \frac{w_m - \frac{K}{Q}}{w_p + c_p}\right)\right)\right), & w_m - w_p - c_p \leq \frac{K}{Q} \leq \frac{w_m}{r}(r - w_p - c_p) \\ \left(0, \frac{1}{Q}F^{-1}\left(1 - \frac{K}{(r - w_p - c_p)Q}\right)\right), & \frac{K}{Q} < w_m - w_p - c_p, \end{cases}$$

and $q_p^*(D) = \min\{n^*Q, \max\{0, D - q_m^*\}\}$.

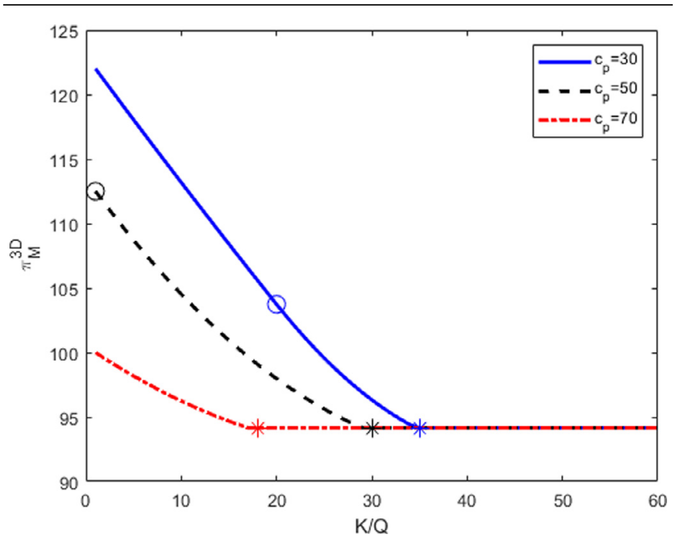


Fig. 1. Manufacturer behavior for $r = 300$, $c_m = 50$, $\hat{A} = 10$, $S = 2$.

Proposition 5. *The maximized retailer profit is*

$$\pi_R^{3D}(w_m, w_p) = \begin{cases} \pi_R^b(r, w_m), & \frac{w_m}{r}(r - w_p - c_p) < \frac{K}{Q} \\ \pi_R^b\left(w_p + c_p, w_m - \frac{K}{Q}\right) + \pi_R^b\left(r - w_p - c_p, \frac{K}{Q}\right), & w_m - w_p - c_p \leq \frac{K}{Q} \leq \frac{w_m}{r}(r - w_p - c_p) \\ \pi_R^b\left(r - w_p - c_p, \frac{K}{Q}\right), & \frac{K}{Q} < w_m - w_p - c_p. \end{cases}$$

Remark 2. Note that our modeling of the retailer adoption of 3D printing is slightly different than that of the manufacturer adopting 3D printing. In the latter case, the printed amount of product is q_p, which does not depend on the demand D, whereas in the former, $q_p(D)$ is a function of D. The reason for this is that

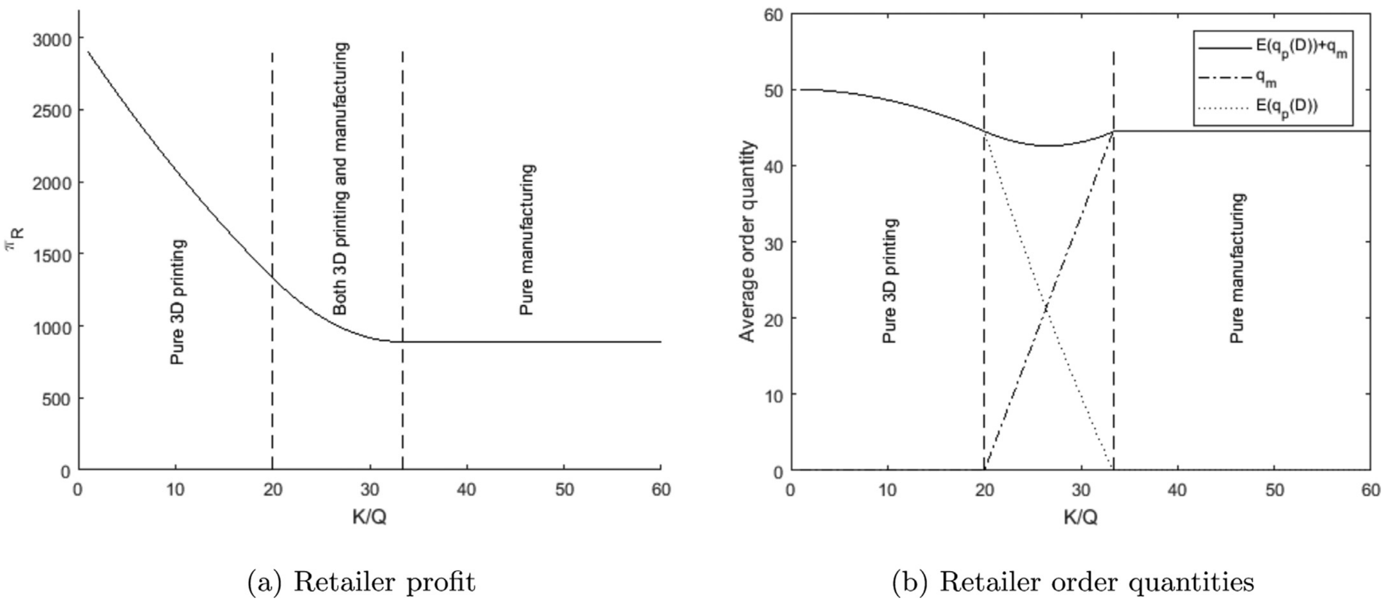


Fig. 2. Retailer behavior.

the manufacturer has a transportation lead time, where shipping typically takes place before demand is realized. However, in the former case, there is no transportation required for the products that are 3D printed at the retailer, and hence production can take place later to take advantage of realized demand, which motivates our modeling of $q_p(D)$.

Propositions 4 and 5 have been presented in terms of the amortized fixed cost of a 3D printer K/Q. In the first case, where $\frac{w_m}{r}(r - w_p - c_p) < \frac{K}{Q}$, the 3D printers are too expensive and are not utilized; we refer to this case as *pure traditional manufacturing*, since all products are made using traditional techniques. In the second case, where $w_m - w_p - c_p \le \frac{K}{Q} \le \frac{w_m}{r}(r - w_p - c_p)$, the 3D printers have a moderate cost, and they are utilized in parallel with traditional manufacturing, which is used less than in the first case (i.e., $F^{-1}\big(1 - (w_m - K/Q)/(w_p + c_p)\big) \le F^{-1}(1 - w_m/r)$); we refer to this situation as the *hybrid* case, since both manufacturing modes are utilized. In the third case, where $\frac{K}{Q} < w_m - w_p - c_p$, the 3D printers are cheap enough such that all production is 3D printed, and traditional manufacturing is not used; we refer to this case as *pure 3D printing*, since all products are 3D printed. Since the cost K/Q is decreasing as we move from the first to the third case, the maximized profits are increasing in this order; we observe this visually in Fig. 2(a). In Fig. 2(b) we observe the q_m and $E[q_p(D)]$ quantities, and notice that (1) in the pure 3D printing region, $E[q_p(D)]$ is decreasing slowly, (2) in the hybrid region, q_m is increasing and $E[q_p(D)]$ is decreasing, and (3) in the pure manufacturing region, q_m is constant (since it doesn't depend on K/Q).

In the remainder of this subsection, we explore the situation where the manufacturer is a price taker (i.e., the wholesale prices are determined exogenously) for uniformly distributed demand; the case where the manufacturer is a price setter (i.e., prices are set endongenously) is studied in the next subsection. Note that $q_m^* + E(q_p^*(D))$ is the total demand that can be satisfied by the retailer.

Proposition 6. *For a uniform demand distribution, $q_m^* + E(q_p^*(D))$ equals*

$$\begin{cases} 1 - \frac{w_m}{r}, & \frac{w_m}{r}(r - w_p - c_p) < \frac{K}{Q} \\ \frac{1}{2}\left[\left(\frac{w_m - K/Q}{w_p + c_p}\right)^2 - \left(\frac{K/Q}{r - w_p - c_p}\right)^2\right] & \\ \quad + 1 - \frac{w_m - K/Q}{w_p + c_p}, & w_m - w_p - c_p \le \frac{K}{Q} \le \frac{w_m}{r}(r - w_p - c_p) \\ \frac{1}{2}\left[\left(\frac{w_m - K/Q}{w_p + c_p}\right)^2 - \left(\frac{K/Q}{r - w_p - c_p}\right)^2\right], & \frac{K}{Q} < w_m - w_p - c_p. \end{cases}$$

It is worth mentioning that in the second case, $\frac{\partial[q_m^* + E(q_p^*(D))]}{\partial w_m} = 0$. The interpretation is that, as w_m increases, the retailer orders less of the manufactured products. At the same time, he can 3D print more products. These two effects cancel each other, and result in the retailer being insensitive to w_m.

Corollary 2. *For a uniform demand distribution, $q_m^* + E(q_p^*(D))$ is not monotone in Q.*

The transshipment literature (e.g., Dong & Rudi, 2004, Proposition 1) claims that more flexibility at the retailer results in a better balance of supply and demand. However, Corollary 2 suggests that, under 3D printing (i.e., more flexibility), supply and demand are not necessarily better matched. In fact, there are regions where 3D printing increases the mismatch between supply and demand. One example is shown in Fig. 2(b), where in the hybrid region $q_m^* + E(q_p^*(D))$ is less than q_m^* in the pure traditional manufacturing region. The reason is three fold: (1) low 3D prices compared to the manufacturing variable cost, (2) low 3D printing capacity, and (3) high 3D printer fixed cost. In such a case, 3D printing is desirable for the retailer to use; however, due to its high fixed cost and low capacity, production is limited. Therefore, under these conditions, while the retailer's profit increases in the presence of 3D printing, the match of supply and demand deteriorates.

Corollary 3. *For a uniform demand distribution, 3D printing might not be adopted even if $w_p + c_p < w_m$.*

The emergency sourcing literature assumes that if the source with longer lead times is costlier than the source with shorter lead times, the former will not be used at all. However, one can observe that in Proposition 6, 3D printing (i.e., the source with zero lead time) might not be adopted if $w_p + c_p < w_m$. This occurs due to the unique cost structure of this problem. That is, since the retailer adopts 3D printing, the printer procurement cost is incurred at the retailer. Therefore, if the 3D printing variable cost is small, but the cost of the 3D printers themselves is large, 3D printing will not be adopted, and all the products will be traditionally manufactured. In an extreme case, for example, if $w_p + c_p = 0$, and $w_m < k/Q$, then all completed products will be ordered from the manufacturer.

4.2. Manufacturer analysis

Since the manufacturer is the leader in the Stackelberg game, we assume she knows the retailer's best responses (i.e., q_m^*, $q_p^*(D)$, and n^*, as a function of w_m and w_p) when she makes her pricing decisions w_m and w_p. The manufacturer's costs are the unit traditional manufacturing cost c_m for the fully complete units the retailer orders and, if the retailer chooses to buy 3D printing schematics, the fixed cost S to develop these schematics. We again capture exogenous economic factors via the retailer's opportunity cost $A \geq 0$, where the retailer will not participate unless he is assured his expected profit is at least A. The manufacturer's profit-maximization problem is

$$\begin{aligned} \pi_M^{3D(R)} = \max_{w_m, w_p \geq 0} & (w_m - c_m)q_m^* + w_p E[q_p^*(D)] - S \cdot \mathbb{1}\{n^* > 0\} \\ \text{s.t.} \quad & (q_m^*, q_p^*(D), n^*) \text{ as defined in Proposition 4} \\ & \pi_R^{3D}(w_m, w_p) \geq A, \end{aligned} \tag{6}$$

where $\mathbb{1}\{\}$ is the indicator function. The first and second terms in the objective function represent the manufactured products and 3D schematics profits, respectively, and the third term is the fixed cost of developing 3D schematics (if $n^* > 0$). The first constraint is the retailer's best response, from Proposition 4, and the second constraint ensures the retailer's participation.

We were unable to analytically solve Problem (6) for a generic distribution F (even under the assumption that F has an increasing generalized failure rate). However, we were able to solve it for the case where demand is uniformly distributed on [0, U], the retailers opportunity cost $A = 0$, and the cost to generate 3D designs $S = 0$; we present these results next. Subsequently, we provide numerical experiments for the cases where demand is a truncated normal distribution, $A > 0$, $S > 0$, and observe results that are consistent with our analytical outcomes for the uniformly distributed demand case.

The three conditions of the retailer's best response, from Proposition 4, partition the (w_m, w_p) space into three regions. To simplify the exposition, we introduce notation for the three regions:

$$P_1 = \left\{(w_m, w_p) : \frac{K}{Q} > \frac{w_m}{r}(r - w_p - c_p)\right\}$$

$$P_2 = \left\{(w_m, w_p) : w_m - w_p - c_p \leq \frac{K}{Q} \leq \frac{w_m}{r}(r - w_p - c_p)\right\}$$

$$P_3 = \left\{(w_m, w_p) : \frac{K}{Q} < w_m - w_p - c_p\right\}.$$

Similarly, we define subproblems that are indexed by $i = 1, \ldots, 3$:

$$\begin{aligned} \pi_M^i = \max_{w_m, w_p \geq 0} \quad & (w_m - c_m)q_m^* + w_p E[q_p^*(D)] - S \cdot \mathbb{1}\{n^* > 0\} \\ \text{s.t.} \quad & (w_m, w_p) \in P_i \\ & (q_m^*, q_p^*(D), n^*) \text{ as defined in Proposition 4} \\ & \pi_R^{3D}(w_m, w_p) \geq 0, \end{aligned}$$

where $\pi_M^{3D(R)} = \max_{1 \leq i \leq 3} \pi_M^i$. We solve π_M^i, $i = 1, \ldots, 3$, in the following sequence of lemmas.

Lemma 1. *For uniformly distributed demand on* [0, U] *and* $(A, S) = (0, 0)$, $(w_m^*, w_p^*) = (\frac{r+c_m}{2}, r - c_p)$ *and* $\pi_M^1 = \frac{1}{r}(\frac{r-c_m}{2})^2 U$. *Furthermore,* $(q_m^*, n^*, q_p^*) = ((\frac{r-c_m}{2r})U, 0, 0)$ *and* $\pi_R^{3D}(w_m^*, w_p^*) = \frac{3}{2}(\frac{r-c_m}{2r})^2 Ur$.

We next present the results of the analysis of π_M^2; in order to effectively present them, we introduce some definitions that depend only on problem data, but not any decisions by either firm:

$$\begin{aligned} \hat{y} \triangleq & \frac{U}{(r+c_p)}\Bigg(\frac{K}{2Q} + \frac{(r+c_p)}{2} - c_m + c_p \\ & + \sqrt{\left(\frac{K}{2Q} + \frac{(r+c_p)}{2} - c_m + c_p\right)^2 + 2(r+c_p)\left(c_m - c_p - \frac{K}{Q}\right)}\Bigg) \end{aligned}$$

$$\Delta \triangleq (r+c_m)^2 - 4(r+c_p)\frac{K}{Q}$$

$$\xi_1 \triangleq \frac{(r + 2c_p - c_m - \sqrt{\Delta})U}{2(r+c_p)} \quad \text{(for non-negative } \Delta)$$

$$\xi_2 \triangleq \frac{(r + 2c_p - c_m + \sqrt{\Delta})U}{2(r+c_p)} \quad \text{(for non-negative } \Delta)$$

$$\begin{aligned} \psi \triangleq & U - \frac{U}{6(r-c_p)}\Bigg(\frac{K}{Q} + \left(\frac{K}{Q}\left(\sqrt{27(r-c_p)^2 + \frac{K^2}{Q^2}} - \sqrt{27}(r-c_p)\right)^2\right)^{\frac{1}{3}} \\ & + \frac{\frac{K^2}{Q^2}}{\left(\frac{K}{Q}\left(\sqrt{27(r-c_p)^2 + \frac{K^2}{Q^2}} - \sqrt{27}(r-c_p)\right)^2\right)^{\frac{1}{3}}}\Bigg) \end{aligned}$$

$$\zeta_1 \triangleq \max\{0, \min\{\psi, \hat{y}\}\}$$

$$\zeta_2 \triangleq \max\left\{\hat{y}, \left(\frac{r-c_m}{2r}\right)U\right\}$$

$$\hat{\zeta}_1 \triangleq \max\{0, \min\{\psi, \xi_2\}\} \quad \text{(for non-negative } \Delta)$$

$$\hat{\zeta}_2 \triangleq \max\left\{\xi_2, \left(\frac{r-c_m}{2r}\right)U\right\} \quad \text{(for non-negative } \Delta)$$

$$\begin{aligned} \phi \triangleq & \text{ the unique root of } \frac{(\frac{K}{Q} - c_m + c_p)^2 U^2 \frac{K}{Q}}{2\left(\frac{KU}{Q} + (U-y)(r+c_p)\right)^2} \\ & + \frac{(r-c_p)(U-y)}{U} - \frac{K}{Q} - \frac{\frac{K}{Q}y(2U-y)}{2(U-y)^2} = 0 \\ & \text{(which exists when } (K/Q - c_m + c_p)^2 K/(2Q(K/Q + r + c_p)^2) \\ & +(r-c_p) \geq K/Q) \end{aligned}$$

$$\chi_1 \triangleq \max\{\xi_1, \min\{\phi, \xi_2\}\} \quad \text{(for non-negative } \Delta \text{ and real } \phi)$$

$$\chi_2 \triangleq \begin{cases} \xi_1, & \left(\frac{r-c_m}{2r}\right)U \leq \xi_1 \\ \xi_2, & \left(\frac{r-c_m}{2r}\right)U \geq \xi_1 \\ \arg\max_{y \in \{\xi_1, \xi_2\}} \Gamma(y, y). & \end{cases} \quad \text{(for non-negative } \Delta \text{ and real } \phi)$$

It is also convenient to make the following change of variables: $x = (1 - \frac{w_m - \frac{K}{Q}}{w_p + c_p})U$, which is q_m in the second case of Proposition 4, and $y = (1 - \frac{K}{(r - w_p - c_p)Q})U$, where $n = (y - x)/Q$ in the second case of Proposition 4. The prices can be recovered using the inverse functions $w_p = r - c_p - \frac{K}{Q(1-y/U)}$ and $w_m = r(1 - x/U) - \frac{K(1-x/U)}{Q(1-y/U)} + \frac{K}{Q}$.

Lemma 2. *For uniformly distributed demand on* [0, U] *and* $(A, S) = (0, 0)$:

1. *If* $(r+c_m)^2 - 4(r+c_p)\frac{K}{Q} < 0$, *then* $y^* = (\frac{r-c_m}{2r})U$, $x^* = y^*$, *and the manufacturer profit is* $\pi_M^2 = \frac{1}{r}(\frac{r-c_m}{2})^2 U$.

2. *If* $(r+c_m)^2 - 4(r+c_p)\frac{K}{Q} \geq 0$, *then:*

(a) *If* $\frac{K}{Q} - c_m + c_p \geq 0$, *then:*

i. *If* $\frac{(\frac{K}{Q} - c_m + c_p)^2 \frac{K}{Q}}{2(\frac{K}{Q} + (r+c_p))^2} + (r - c_p) < \frac{K}{Q}$, *then* $y^* = \xi_1$, $x^* = \left(\frac{K}{Q} - c_m + c_p\right)/\left(\frac{r+c_p}{U} - \frac{K}{Q(U-\xi_1)}\right)$, *and the manufacturer profit is* $\pi_M^2 = \frac{1}{2}\frac{\left(\frac{K}{Q} - c_m + c_p\right)^2}{\left(\frac{r+c_p}{U} - \frac{K}{Q(U-\xi_1)}\right)} + (r - c_p - \frac{KU}{Q(U-\xi_1)})(\xi_1 - \frac{\xi_1^2}{2U})$.

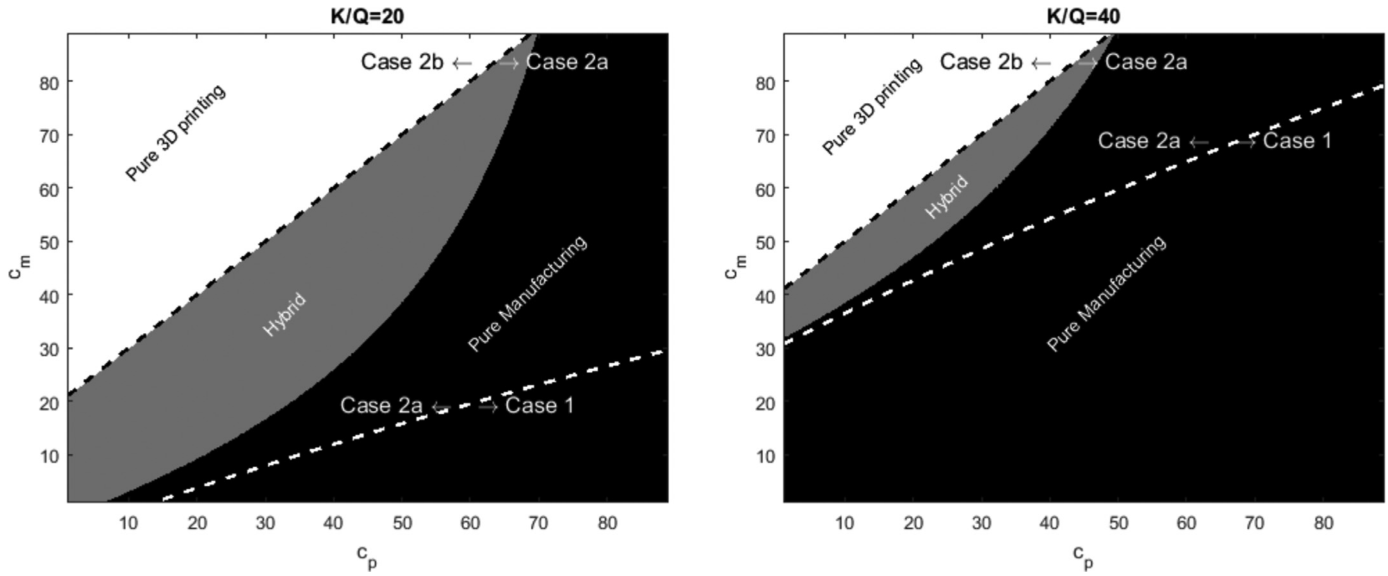


Fig. 3. Equilibrium outcomes compared with cases of Proposition 7.

ii. *If* $\frac{(\frac{K}{Q}-c_m+c_p)^2\frac{K}{Q}}{2(\frac{K}{Q}+(r+c_p))^2}+(r-c_p)\geq\frac{K}{Q}$, *then*

$$y^*=\begin{cases}\chi_1, & -\frac{1}{2}\frac{(\frac{K}{Q}-c_m+c_p)^2}{(\frac{K}{Q(U-\chi_1)}-\frac{(r+c_p)}{U})}-\left(\frac{KU}{Q(U-\chi_1)}-r+c_p\right)(\chi_1-\frac{\chi_1^2}{2U}) \\ & \geq(\frac{r}{U}(U-\chi_2)-c_m)\chi_2 \\ \chi_2, & \text{otherwise.}\end{cases},$$

$$x^*=\begin{cases}-(\frac{K}{Q}-c_m+c_p)/(\frac{K}{Q(U-y^*)}-\frac{r}{U}-\frac{c_p}{U}), & \xi_1<y^*<\xi_2 \\ y^*, & y^*\leq\xi_1 \text{or} y^*\geq\xi_2\end{cases},$$

and the manufacturer profit is $\pi_M^2=-\frac{1}{2}((\frac{K}{Q}-c_m+c_p)^2)/((\frac{K}{Q(U-y^*)}-\frac{(r+c_p)}{U}))+(r-c_p-\frac{KU}{Q(U-y^*)})(y^*-\frac{(y^*)^2}{2U})$.

(b) *If* $\frac{K}{Q}-c_m+c_p<0$, *then:*

i. *If* $\xi_2\leq\hat{y}$, *then* $y^*=\begin{cases}\zeta_1, & \left(r-c_p-\frac{KU}{Q(U-\zeta_1)}\right)\left(\zeta_1-\frac{\zeta_1^2}{2U}\right) \\ & \geq\left(\frac{r}{U}(U-\zeta_2)-c_m\right)\zeta_2 \\ \zeta_2, & \text{otherwise.}\end{cases}$,

$x^*=\begin{cases}0, & y^*\in[0,\hat{y}] \\ y^*, & y^*\in(\hat{y},U]\end{cases}$, *and the manufacturer profit is* $\pi_M^2=\begin{cases}\left(r-c_p-\frac{KU}{Q(U-y^*)}\right)\left(y^*-\frac{(y^*)^2}{2U}\right), & y^*\in[0,\hat{y}] \\ \left(\frac{r}{U}(U-y^*)-c_m\right)y^*, & y^*\in(\hat{y},U]\end{cases}$.

ii. *If* $\xi_2>\hat{y}$, *then* $y^*=\begin{cases}\hat{\zeta}_1, & \left(r-c_p-\frac{KU}{Q(U-\hat{\zeta}_1)}\right)\left(\hat{\zeta}_1-\frac{\hat{\zeta}_1^2}{2U}\right) \\ & \geq\left(\frac{r}{U}(U-\hat{\zeta}_2)-c_m\right)\hat{\zeta}_2 \\ \hat{\zeta}_2, & \text{otherwise.}\end{cases}$,

$x^*=\begin{cases}0, & y^*\in[0,\xi_2] \\ y^*, & y^*\in(\xi_2,U]\end{cases}$, *and the manufacturer profit is* $\pi_M^2=\begin{cases}\left(r-c_p-\frac{KU}{Q(U-y^*)}\right)\left(y^*-\frac{(y^*)^2}{2U}\right), & y^*\in[0,\xi_2] \\ \left(\frac{r}{U}(U-y^*)-c_m\right)y^*, & y^*\in(\xi_2,U]\end{cases}$.

In all cases, the retailer profit is

$$\pi_R^{3D}(w_m^*,w_p^*)=\frac{K}{2Q(U-y^*)}((y^*)^2-(x^*)^2)+\frac{r(x^*)^2}{2U}.$$

Lemma 3. *For uniformly distributed demand on* $[0,\ U]$ *and* $(A,S)=(0,0)$, $y^*=\max\{0,\psi\}$, $x^*=0$, *the manufacturer profit is* $\pi_M^3=\left(r-c_p-\frac{KU}{Q(U-y^*)}\right)\left(y^*-\frac{(y^*)^2}{2U}\right)$ *and the retailer profit is* $\pi_R^{3D}(w_m^*,w_p^*)=\frac{(y^*)^2K}{2Q(U-y^*)}$.

The following proposition assembles and simplifies the results from Lemmas 1–3.

Proposition 7. *For uniformly distributed demand on* $[0,\ U]$ *and* $(A,S)=(0,0)$*:*

1. *If* $(r+c_m)^2-4(r+c_p)\frac{K}{Q}<0$, *then* $\max\{\pi_M^1,\pi_M^3\}$ *determines the equilibrium.*
2. *If* $(r+c_m)^2-4(r+c_p)\frac{K}{Q}\geq 0$, *then:*
   (a) *If* $\frac{K}{Q}-c_m+c_p\geq 0$, *then* $\max\{\pi_M^1,\pi_M^2,\pi_M^3\}$ *determines the equilibrium.*
   (b) *If* $\frac{K}{Q}-c_m+c_p<0$, *then* $\max\{\pi_M^1,\pi_M^3\}$ *determines the equilibrium.*

Proposition 7 has been proved, but is incomplete; unfortunately, we found it intractable to make more analytical progress. We next present our conjectured solution, which is subsequently supported by numerical experiments.

Conjecture 1. *For uniformly distributed demand on* $[0,\ U]$ *and* $(A,S)=(0,0)$*:*

1. *If* $(r+c_m)^2-4(r+c_p)\frac{K}{Q}<0$, *then the equilibrium is pure traditional manufacturing.*
2. *If* $(r+c_m)^2-4(r+c_p)\frac{K}{Q}\geq 0$, *then:*
   (a) *If* $\frac{K}{Q}-c_m+c_p\geq 0$, *then:*
      i. *If* c_m *is not too large and* c_p+K/Q *is not too small, then the equilibrium is pure traditional manufacturing.*
      ii. *Otherwise, the equilibrium is a hybrid utilizing both traditional manufacturing and 3D printing.*
   (b) *If* $\frac{K}{Q}-c_m+c_p<0$, *then the equilibrium is pure 3D printing.*

In Fig. 3 we numerically evaluate the equilibrium outcomes (pure 3D printing, pure manufacturing, and hybrid) for $(c_p,\ c_m)\in[0,\ r]^2$ for $K/Q\in\{20,\ 40\}$ and $r=90$. We superimpose the conditions of Proposition 7, in order to compare the induced partition of $(c_p,\ c_m)$ space with those of the actual equilibrium. Increasing K/Q further continues the dynamic apparent in Fig. 3 (i.e., shrinking regions corresponding to cases 2a and 2b, and a growing region corresponding to case 1).

We observe that cases 1 and 2b of Proposition 7 exactly correspond to the actual equilibrium outcomes: in case 1, the equilibrium is pure manufacturing, and in case 2b, the equilibrium is pure 3D printing. However, in case 2a, there are two possible

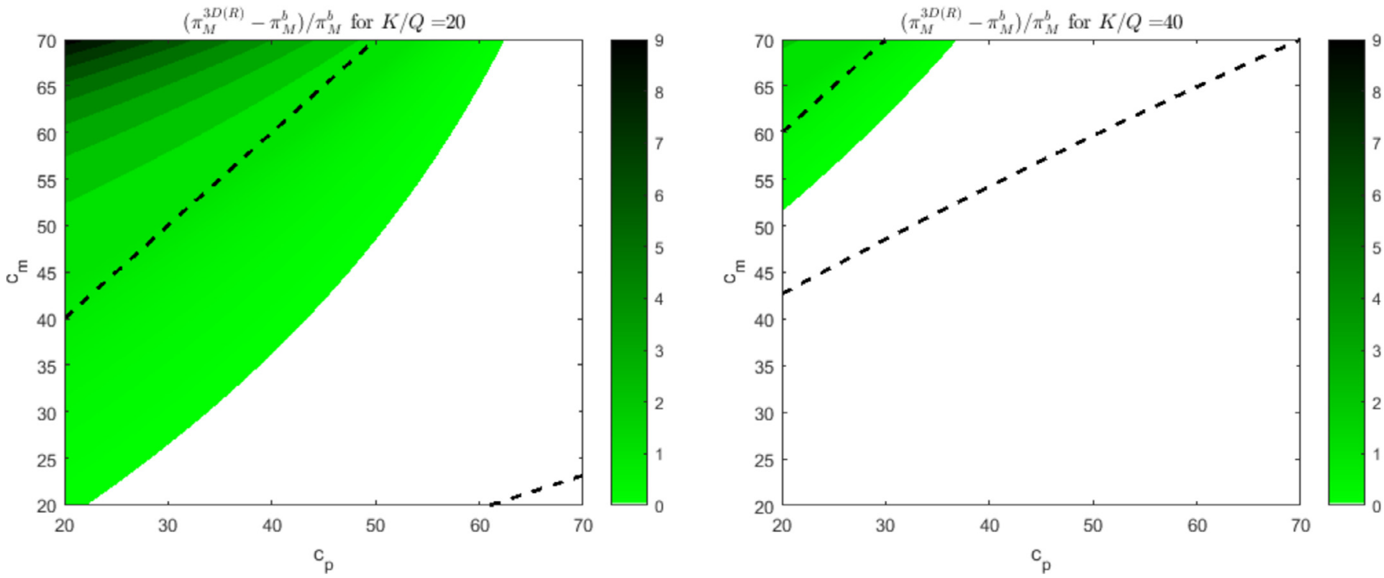


Fig. 4. Ratios of manufacturer profit under 3D printing to benchmark manufacturer profit.

equilibria not precisely captured by our analysis: (1) pure manufacturing or (2) a hybrid of manufacturing and 3D printing. We attempt to capture these equilibria in the sub-cases i–ii of case 2a in Conjecture 1, and we next provide a discussion of them.

The condition of case 1 can be manipulated to obtain a clear interpretation:

$$(r+c_m)^2 - 4(r+c_p)\frac{K}{Q} < 0 \Rightarrow \frac{r+c_m}{2} < \sqrt{(r+c_p)\frac{K}{Q}} \Rightarrow \frac{r+c_m}{2} < \frac{r+c_p+\frac{K}{Q}}{2},$$

where the second implication is due to the inequality of arithmetic and geometric means, and the last inequality can be simplified to $c_m < c_p + \frac{K}{Q}$. In other words, the condition of case 1 implies that the unit cost of traditional manufacturing is strictly less than the unit cost of 3D printing, which leads to pure manufacturing in equilibrium. In case 2a, the inequality $c_m \le c_p + \frac{K}{Q}$ holds, but due to the restriction $(r+c_m)^2 - 4(r+c_p)\frac{K}{Q} \ge 0$, traditional manufacturing can not be too much cheaper than 3D printing, leading to a hybrid equilibrium in a portion of the 2a region; the use of 3D printing, despite its higher cost, is due to the additional flexibility it provides in reacting to demand after it is realized. Case 2b considers the region where 3D printing has a strictly smaller unit printing cost than traditional manufacturing, $c_p + \frac{K}{Q} < c_m$, which results in the equilibrium being pure 3D printing. Finally, note that the additional cases i–ii for case 2a in Conjecture 1 are consistent with these interpretations.

In Fig. 4, we provide the percentage improvement in the manufacturer's profit, with respect to the benchmark profit: $(\pi_M^{3D(R)} - \pi_M^b)/\pi_M^b$. The setup is similar to above, except we consider $(c_p, c_m) \in [20, 70]^2$, where $r = 90$, in order to eliminate extreme cases of very cheap or very expensive unit costs (which can result in 3D printing improving benchmark profits by an unrealistic multiple of 1000). From the graphs, it is evident that as c_m increases and c_p (or K/Q) decreases, the benefit of 3D printing improves, an intuitive finding. What is perhaps less intuitive is the growth rate of improvement: observing the scale of contour plot, we see that the benefit of 3D printing increases very fast as c_m decreases or c_p increases, approaching an improvement of approximately 900% when $(r, c_m, c_p, K/Q) = (90, 70, 20, 20)$. While this exact point might not be realistic, our results suggest that substantial increases in manufacturer profit, due to the adoption of 3D printing, are possible.

In Fig. 5, we provide the percentage improvement in the retailer's profit, with respect to the benchmark profit: $(\pi_R^{3D} - \pi_R^b)/\pi_R^b$. We first observe that "win–win" situations are possible: when $c_p + K/Q$ is small and c_m is large (the top left corner of the left plot), the retailer's profit under 3D printing is strictly greater than its benchmark profit, just as in the manufacturer's case; however, the retailer's lift is not nearly as great as the manufacturer's. Unfortunately, the retailer can also lose a substantial amount of profit, whenever the equilibrium is a hybrid solution, as well as when the equilibrium is pure 3D printing with the additional condition that c_m is not too large with respect to $c_p + K/Q$. Therefore, the retailer benefits from 3D printing whenever the production economics are very much in its favor (i.e., when c_m is large with respect to $c_p + K/Q$). Of course, these negative outcomes can be prevented by increasing the retailer's reservation profit from $A = 0$ to a larger value; we shortly provide additional numerical results that study how the equilibrium changes as A is increased.

4.2.1. Relaxing the assumptions of $S = 0$ and $A = 0$

Fig. 6 presents the optimal firm profits under 3D printing, as well as the optimal benchmark profits, as a function of S, the cost to develop 3D designs from traditional manufacturing plans, for $(A, K, Q, c_m, c_p) = (0, 150, 15, 40, 40)$. We observe that there exists a threshold value of S, after which both firm profits are independent of S since 3D printing is not the equilibrium (it is too expensive), and before which the manufacturer's profit is decreasing in S and the retailer's profit does not depend on S; therefore, when 3D printing forms part of the equilibrium, the cost to develop 3D designs is incurred solely by the manufacturer, and no costs are passed on to the retailer. However, note that, in this experiment, the benchmark manufacturer profit is 250, yet the manufacturer's profit under 3D printing is larger than this benchmark for S up to 300; note that this occurs even though the unit cost of manufacturing, $c_m = 40$, is strictly less than that of 3D printing, $c_p + K/Q = 50$. In addition, in passing through the threshold value of S, the manufacturer's profit is continuous, but the retailer experiences a substantial drop; near this transition point, the retailer may consider a lump sum payment to subsidize the manufacturer's cost S, in order to avoid the drop in profit.

Fig. 7 presents the optimal firm profits under 3D printing, as well as the optimal benchmark profits, for different economic conditions, as represented by the retailer's opportunity cost A, for $(S, K, Q, c_m, c_p) = (0, 150, 15, 40, 40)$. We observe that there

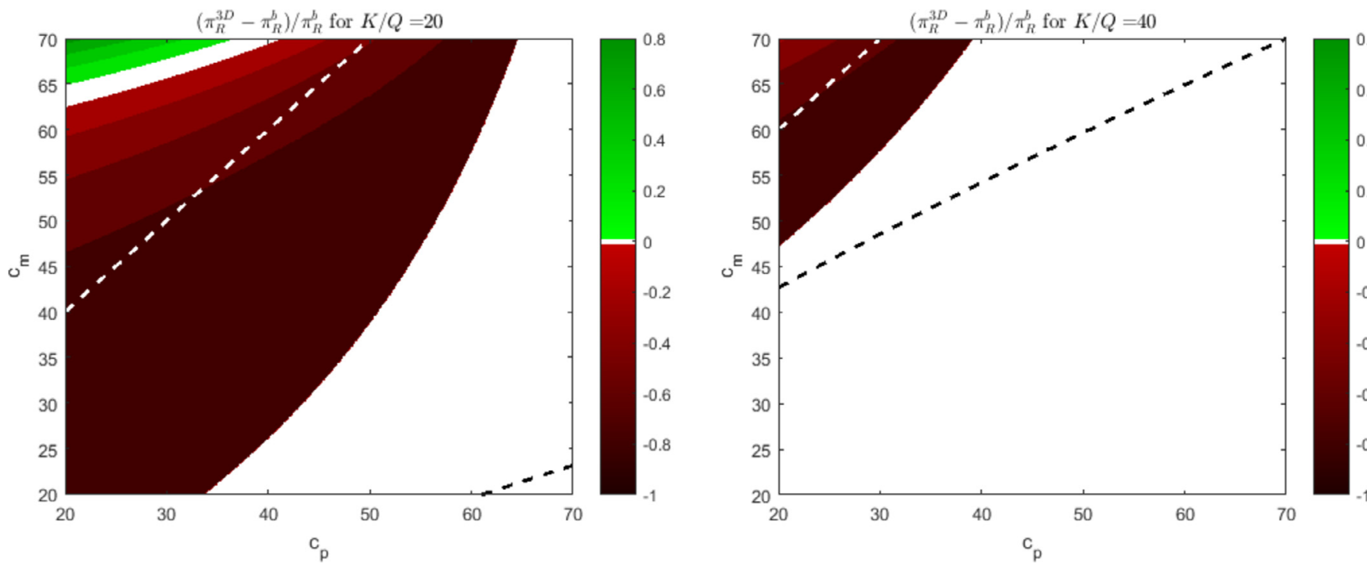


Fig. 5. Ratios of retailer profit under 3D printing to benchmark retailer profit.

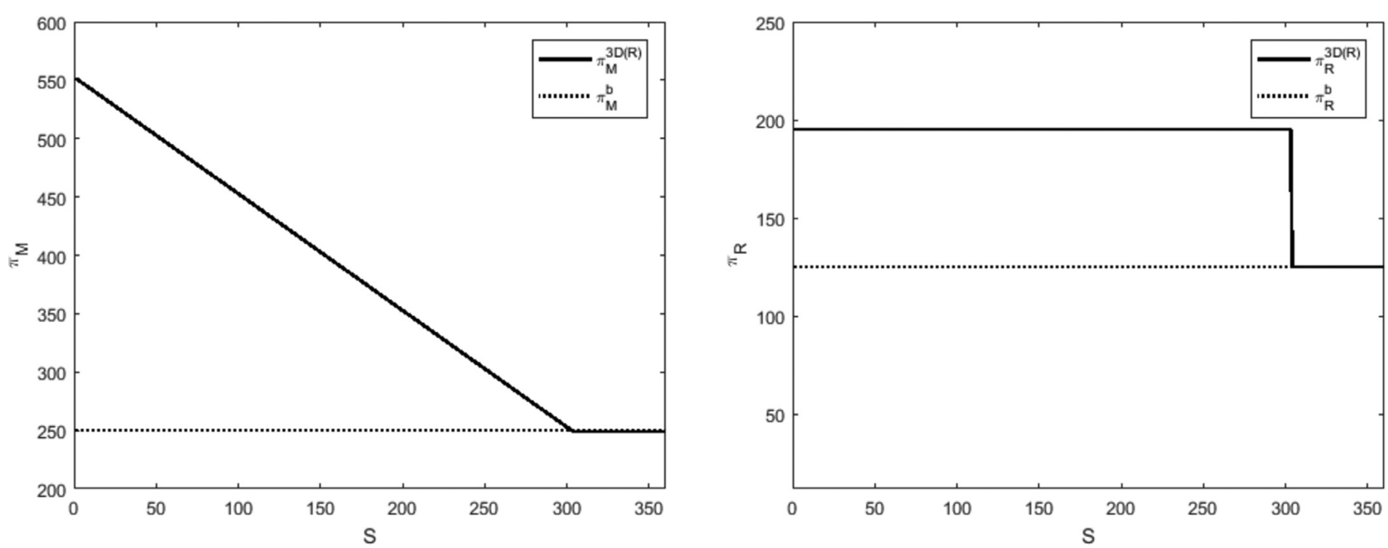


Fig. 6. Optimal firm profits as a function of *S*.

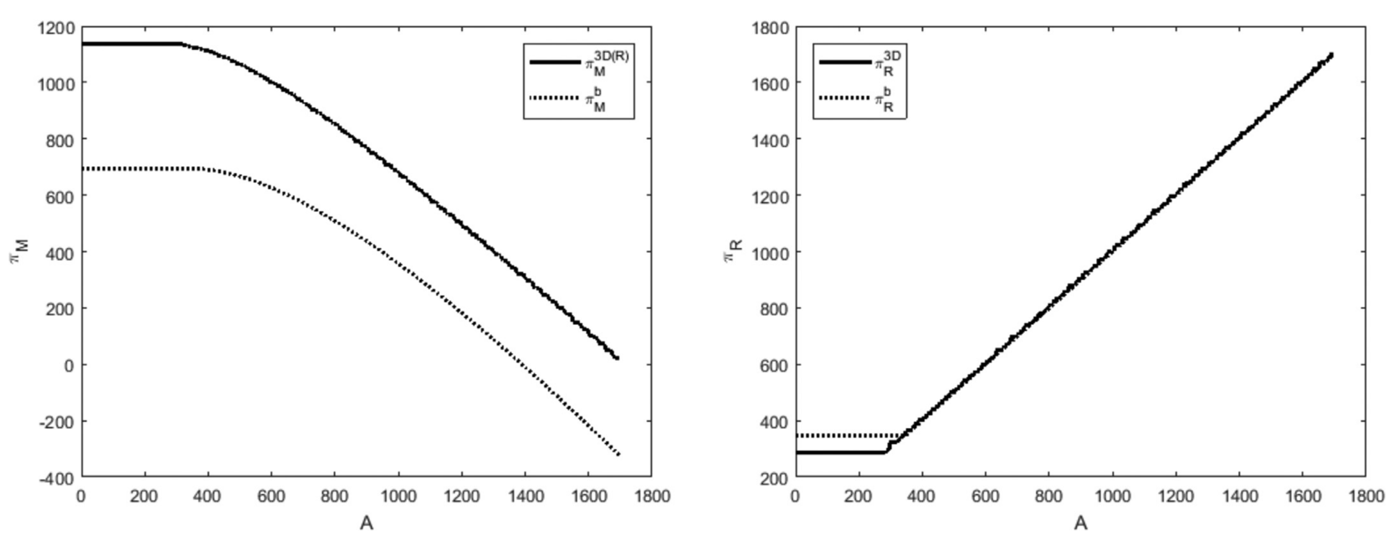


Fig. 7. Optimal firm profits as a function of *A*.

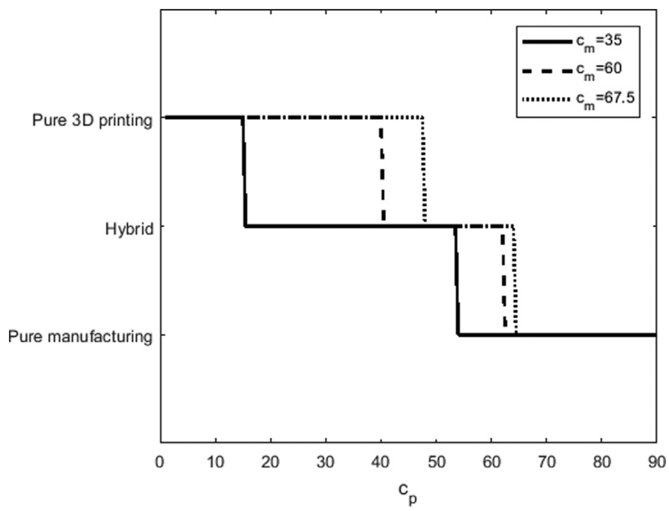


Fig. 8. Equilibrium outcomes for a normal distribution of demand.

exists a threshold value of A, before which both firm profits are independent of A (the retailer is earning more than A), and after which the manufacturer's profit is decreasing in A and the retailer's profit is increasing in A; this threshold is slightly higher in the benchmark case. When A is large enough, the retailer is ambivalent between 3D printing and traditional manufacturing, whereas the manufacturer always prefers 3D printing.

4.2.2. Relaxing the assumption of uniform demand

In this section we consider the case where demand is normally distributed (truncated at zero), rather than uniformly distributed, and we (numerically) show that the equilibrium is qualitatively similar. Since we were unable to make analytical progress for the manufacturer's behavior for any distribution other than the uniform, we resorted to purely numerical evaluation of the equilibrium. We found the time requirements prohibitive to generate contour plots for the normal distribution, as in Figs. 3–5; we estimate 500 hours per contour plot for comparable resolution; thus, an additional contribution of our previous analytical results, for the uniform distribution, is the ability to efficiently generate Figs. 3–5. Consequently, for the normal distribution of demand, we provide "slices" of the contour plots, which still allow comparisons with the uniform distribution results. In particular, we provide evidence that our analytical results are not fully dependent on the uniform distribution, and that the insights we generate are applicable to other distributions.

The experimental design is similar to that above, except that the demand is normally distributed, truncated at zero, with the same mean of $\mu = 50$, and the standard deviation is $\sigma = 15$. In Fig. 8 we identify the equilibrium as a function of c_p for $c_m \in \{35, 60, 67.5\}$ and $K/Q = 20$; these values of c_m were selected in order to compare with qualitatively different behaviors in the uniform distribution case. Comparing with horizontal slices of Fig. 3, at the same values of c_m considered here, we see that the equilibrium outcomes are effectively identical. For instance, the solid line represents the case where $c_m = 35$. In this case, the equilibrium is: (1) pure 3D printing if $0 \le c_p < 11$, (2) hybrid if $11 \le c_p < 55$, and (3) pure traditional manufacturing if $55 \le c_p \le 90$.

In Fig. 9, we plot, on the left, $(\pi_M^{3D(R)} - \pi_M^b)/\pi_M^b$, and, on the right, $(\pi_R^{3D} - \pi_R^b)/\pi_R^b$, for the normal distribution of demand, which allow comparisons with slices of the left plots in Figs. 4 and 5 (for $K/Q = 20$); the experimental setup is identical to that of Fig. 8. For the manufacturer, we see identical behaviors in the uniform and normal cases: the ratio decreases in c_p to zero, where the equilibrium is pure manufacturing; furthermore, we observe that, in the left plots of both Figs. 4 and 9, the slope is steeper for larger values of c_m. Similar behaviors are observed for the retailer when comparing the left plot of Fig. 5 (where $K/Q = 20$) with the right plot of Fig. 9. Consequently, we conjecture that most of the insights generated for the uniform distribution are qualitatively applicable to other distributions of demand.

5. Manufacturer versus retailer adoption of 3D printing

In this section we compare firm and system performance of the manufacturer adopting 3D printing (MAP) scenario, as analyzed in Section 3, with the retailer adopting 3D printing (RAP) scenario, as analyzed in Section 4, under the following three cases: 1) $A = \hat{A} = 0$, 2) $A = \hat{A} > 0$, and 3) $\hat{A} > A > 0$.

1. $A = \hat{A} = 0$. Note that, in this case, the retailer's profit under MAP is zero, whereas he is a profit maximizer under RAP. Therefore, he always prefers RAP. Next, our numerical results show that, although the cost of purchasing 3D printers (i.e.,

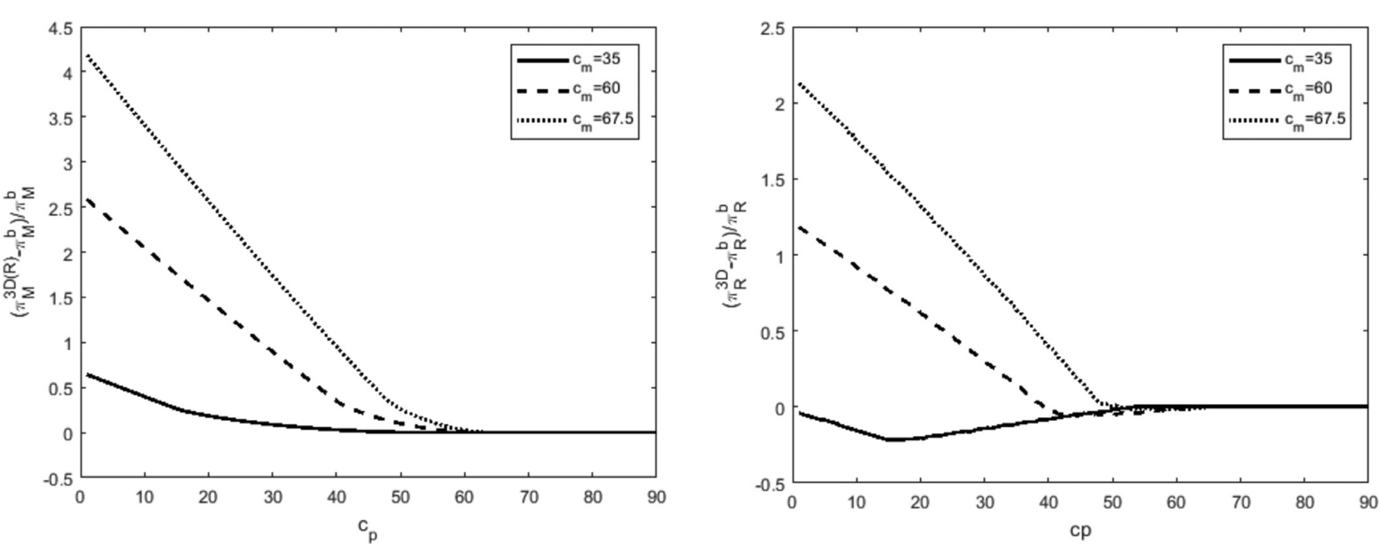
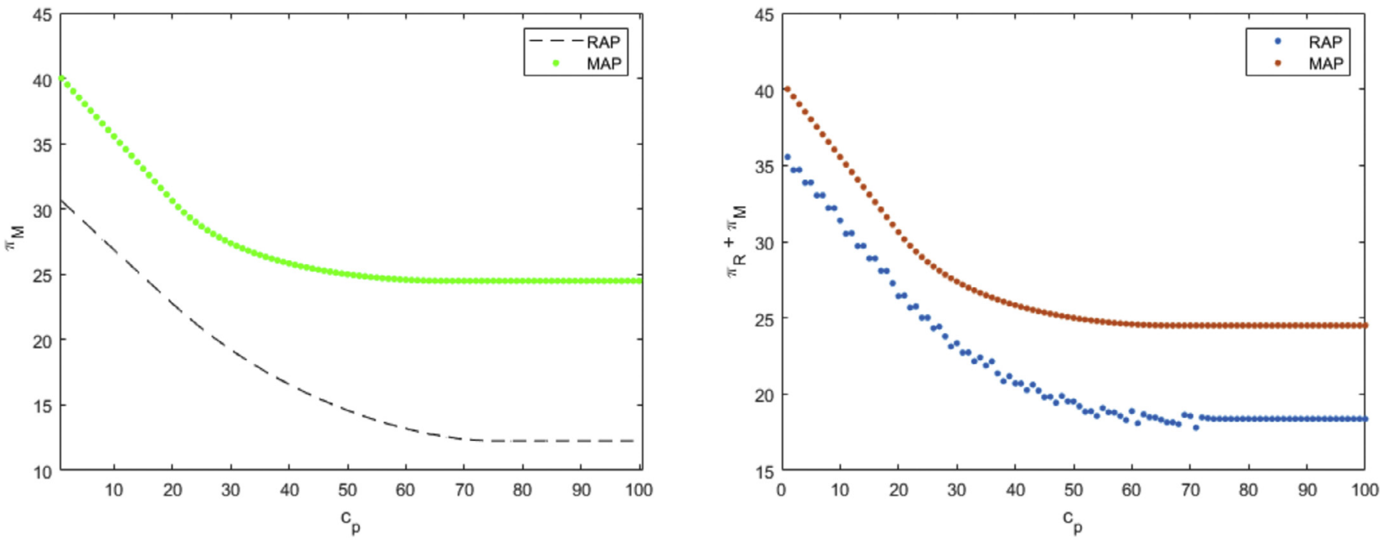
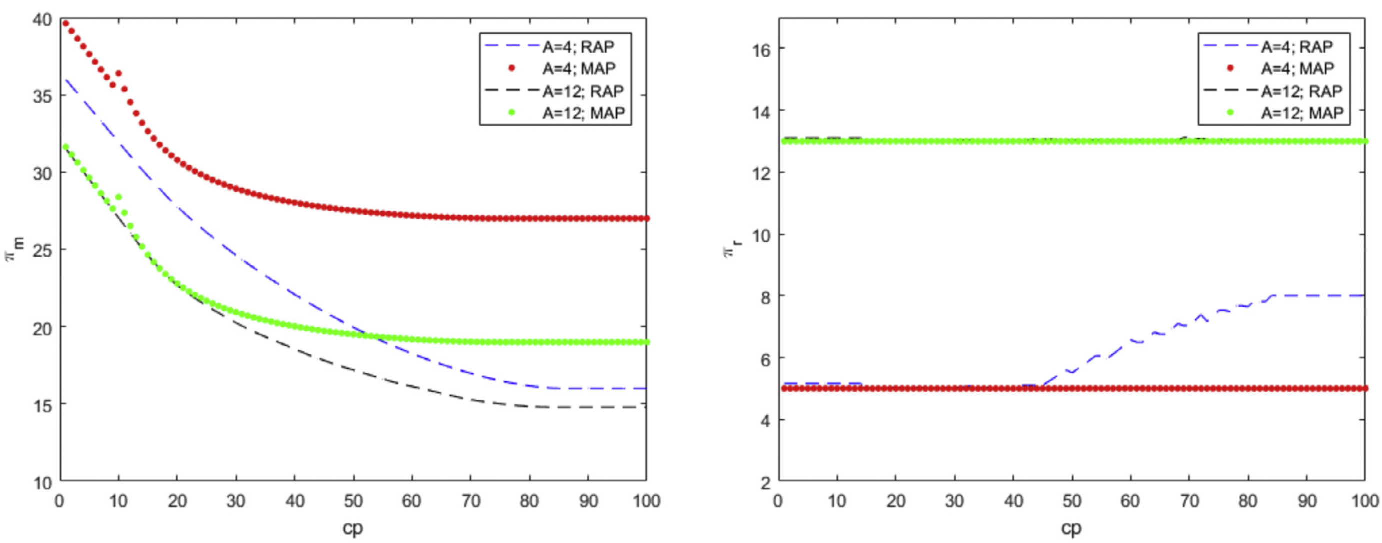


Fig. 9. Ratios of firm profits under 3D printing to benchmark firm profits.



(a) Manufacturer profit (b) System profit

Fig. 10. Optimal profits as a function of c_p for $S = 0$, $c_m = 20$, $r = 100$, $K = 40$, $Q = 40$, and $A = \hat{A} = 0$.



(a) Manufacturer profit (b) Retailer profit

Fig. 11. Optimal firms profits as a function of c_p for $S = 0$, $c_m = 20$, $r = 100$, $K = 40$, $Q = 40$ and $A = \hat{A} \in \{4, 12\}$.

nK) is incurred by the manufacturer under MAP (whereas this cost is incurred by the retailer under RAP), the manufacturer is always better off under MAP. One can observe this in Fig. 10(a). Next, we define the supply chain profit as the sum of manufacturer and retailer profit. In Fig. 10(b), 3D printing is not adopted where the lines are horizontal; in other regions, 3D printing is adopted. In the regions where 3D printing is not adopted, the optimal order quantity for the red line (i.e., MAP scenario) is $F^{-1}(1 - \frac{c_m}{r})$, the optimal order quantity for the blue line (i.e., RAP scenario) is $F^{-1}(1 - \frac{w_m^*}{r})$, and the vertical difference between the two profits (i.e., the blue line and the red line where they are both horizontal) is due to the double marginalization effect. Note also that as c_p decreases, 3D printing technology is adopted and the vertical difference between the two profits decreases.

2. $A = \hat{A} > 0$. In this case, as shown in Fig. 11(a), if A is small, the manufacturer always strictly prefers MAP. The retailer's decision, however, depends on the 3D printing variable cost (i.e, c_p), as shown in Fig. 11(b). If c_p is small, then the retailer is indifferent between MAP and RAP, because in both scenarios 3D printing is adopted. If c_p is relatively large and A is relatively small, however, then the retailer prefers RAP because he has the power to control 3D printing technology. Next, if A is large, then the manufacturer still (weakly, for small c_p) prefers MAP and the retailer is indifferent, because he earns A in both scenarios.
3. $\hat{A} > A > 0$. In this case, if $\hat{A}$ is sufficiently larger than A, then the retailer always prefers MAP, as shown in Fig. 12(b). Next, if c_p is small, then in the equilibrium both MAP and RAP will adopt 3D printing technology, and the manufacturer prefers RAP to avoid the more expensive lump sum cost of $\hat{A}$. If c_p is high, then the manufacturer prefers MAP to avoid double marginalization, as shown on Fig. 12(a). In this case, both the manufacturer and retailer prefer MAP when $c_p \in [34, 76]$, within which 3D printing technology is still adopted.

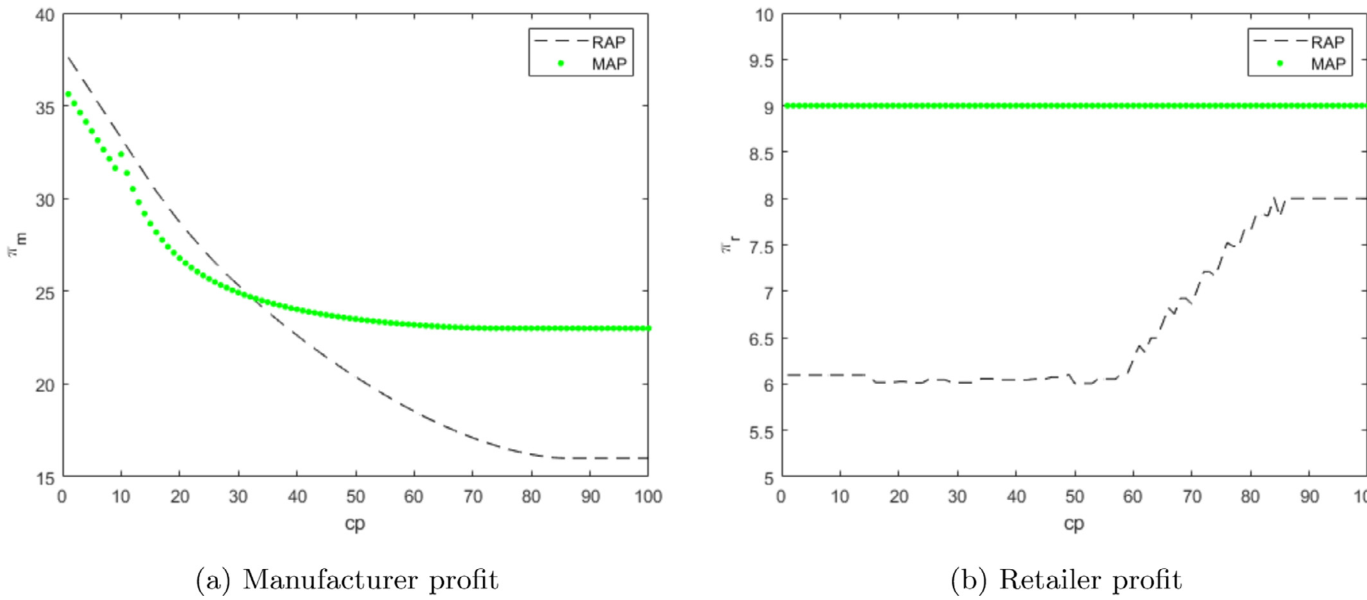


Fig. 12. Optimal firms profits as a function of c_p for $S = 0$, $c_m = 20$, $r = 100$, $K = 40$, $Q = 40$, $A = 6$ and $\hat{A} = 1.5A$.

6. Conclusion

3D printing, or additive manufacturing, is a relatively new manufacturing technique, which in contrast to traditional manufacturing techniques, can be utilized closer to the final customers (i.e., at the retailer). The costs associated with adopting 3D printing technology are: (1) 3D printer purchasing cost, (2) 3D design investment cost, and (3) 3D printing variable cost. In this paper, we have studied the trade off between the costs associated with 3D printing and its benefit in a simple supply chain consisting of a manufacturer and retailer. Due to the unique characteristics of 3D printing, either the manufacturer or retailer can adopt it. In our paper we have characterized the economic and competitive situations where either firm would adopt 3D printing, and we report on the resulting profits, for both firms, with respect to a benchmark supply chain without 3D printing.

We first study the case where the manufacturer may adopt 3D printing technology. If the technology is adopted, to take advantage of its benefit, 3D printers are installed at the retailer, similar to vendor managed inventory. In this case, the manufacturer and retailer utilize a lump-sum contract. We derive the equilibrium for a generic demand distribution. We show that there exist some problem parameter regions where both firms are better off under this scenario compared to a benchmark supply chain with no 3D printing available. We next show that, if 3D printing costs are small relative to traditional manufacturing costs, all products are 3D printed (i.e., a pure make-to-order policy). If 3D printing costs are moderate (i.e., within two thresholds), the equilibrium consists of 3D printing in parallel with traditional manufacturing (i.e., a combination of make-to-order and make-to-stock policies). If 3D printing costs are high with respect to traditional manufacturing, all products are traditionally manufactured (i.e., a pure make-to-stock policy).

Next, we study the case where the retailer may adopt 3D printing technology. In this case, the manufacturer and retailer utilize a wholesale price contract, for which we find the retailer's best response to the manufacturer's wholesale price strategy, for a generic demand distribution. Under a few simplifying assumptions, we find the equilibrium for a uniform demand distribution, and through a set of numerical studies, we show that the manufacturer is always better off compared to a benchmark supply chain with no 3D printing available. The retailer, however, might be better off or worst off, depending on problem parameters. Similar to the first scenario, pure traditional manufacturing, a hybrid of traditional manufacturing and 3D printing, and pure 3D printing are possible, depending on problem parameters.

Next, by comparing the above two cases, we conclude the following results. (1) If, in an extreme case, the retailer's opportunity cost and lump-sum payment are zero, then both the manufacturer and the whole supply chain prefer the first scenario (i.e., MAP). The retailer, however, prefers the second scenario (i.e., RAP). (2) If the lump-sum payment equals the retailer's opportunity cost, and both are positive, then: (a) given a small 3D printing variable cost, as compared to traditional manufacturing unit cost, the retailer is indifferent between the two scenarios whereas the manufacturer prefers the first scenario (i.e., MAP), and (b) given a large 3D printing variable cost, the manufacturer is indifferent between the two scenarios whereas the retailer prefers the second scenario (i.e., RAP). (3) If the lump-sum payment is greater than the retailer's opportunity cost, then the retailer always prefers the first scenario (i.e., MAP). The manufacturer's decision, however, depends on the 3D printing variable cost; if it is small, then the manufacturer prefers the second scenario (i.e., RAP); otherwise, the first scenario (i.e., MAP) is preferred.

Finally, we acknowledge that, as one of the first studies of 3D printing in the context of supply chains, our research has several limitations. Addressing these limitations can lead to valuable future research. On the quality side, researchers can allow for lower revenue for 3D printed products since their quality is not necessarily the same as traditionally manufactured products. Addressing this question adds another level of complexity to our problem. To simplify the problem, researchers can assume 3D printing capacity is exogenous, similar to Chen et al. (2018). On the demand side, researchers can utilize price-dependent demand models to optimize over the selling price. One such model is utilized in Sethuraman et al. (2018). However, future researchers should be mindful that in such a case, the retailer can ask for a premium because 3D printed products can be customized to each customer. Moreover, researchers may also want to consider the positioning of the 3D printing technology: researchers can consider the case where both the manufacturer and the retailer have the option of adopting 3D printing technology.

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Supplementary material

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