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Evaluating the Role of 3D Printing in Decentralized Supply Chains: A Stackelberg Framework for Optimal Manufacturing Decisions

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Abstract

The advent of 3D printing is transforming the manufacturing landscape, enabling flexible, on-demand production with minimal setup costs. This study examines the impact of 3D printing on the manufacturer-retailer supply chain, focusing on a Stackelberg framework with two product scenarios. We analyze the conditions under which 3D printing becomes a viable alternative to traditional manufacturing, considering factors such as customer demand, production costs, and capacity constraints. Our research highlights the complex trade-offs involved in adopting 3D printing, including reduced inventory holding costs, improved customer satisfaction, and increased flexibility, versus higher variable costs and slower production rates. We also explore the implications of 3D printing for supply chain coordination, including the potential for double marginalization. The study contributes to the growing literature on 3D printing in supply chains, offering actionable recommendations for businesses navigating this evolving landscape. Our findings provide valuable insights for manufacturers and retailers seeking to leverage 3D printing to improve their supply chain operations and stay competitive in today's dynamic market.

Keywords
3D Printing, Supply Chain Management, Stackelberg Game.

1. Introduction
The advent of 3D printing, also known as additive manufacturing, has significantly transformed the manufacturing landscape. Unlike traditional production methods such as molding, casting, and machining, which rely on economies of scale and large production runs, 3D printing allows for flexible, on-demand production with minimal setup costs. This technological shift enables manufacturers to move from standardized, mass production toward highly customizable and agile production systems. Such flexibility is particularly valuable in supply chain management, where manufacturers and retailers face increasing pressures to meet dynamic consumer demand, reduce lead times, and control costs.

Traditional manufacturing methods often involve high fixed costs and significant lead times due to reliance on extensive tooling and setup processes. In contrast, 3D printing eliminates many of these barriers by enabling the production of small batches with little to no retooling effort. As a result, 3D printing has been widely adopted across industries, ranging from aerospace and automotive to healthcare. For example, companies like BMW have embraced 3D printing to streamline operations, particularly for producing spare parts for legacy products. By adopting this technology, BMW has been able to close outdated production lines, reducing costs while maintaining its ability to produce parts for older vehicle models.

In traditional supply chain setups, the manufacturer sells products to the retailer at a wholesale price, while the retailer manages uncertainties in customer demand through inventory and pricing strategies. This decentralized structure is typically governed by a wholesale price contract, under which each entity operates independently with distinct objectives. Manufacturers focus on maximizing profits by setting wholesale prices, while retailers optimize order quantities to balance purchasing costs and demand uncertainties. For instance, Lariviere and Porteus (2001) analyzed such supply chain arrangements, highlighting the strategic interplay between manufacturers and retailers. However, the introduction of 3D printing disrupts this traditional framework by introducing new dynamics, such as the ability to produce multiple products on demand and the need to manage capacity constraints associated with 3D printing equipment.

The motivation for this study stems from the challenges faced by companies producing spare parts for legacy products. Maintaining production lines for such parts is often costly and inefficient, particularly when demand is low or irregular. By adopting 3D printing, these companies can transition away from traditional manufacturing while still meeting customer needs. For example, BMW's adoption of 3D printing for legacy car parts demonstrates how firms can enhance flexibility and cost efficiency. However, the decision to adopt 3D printing is not straightforward. Manufacturers must weigh the benefits of customization and responsiveness against the fixed costs of acquiring 3D printers and the capacity limitations inherent to the technology.

In this paper, we examine how 3D printing impacts the manufacturer-retailer supply chain by focusing on two scenarios. In the first scenario, we analyze a supply chain involving two distinct products under a Stackelberg framework. In this setup, the manufacturer, acting as the leader, decides whether to adopt 3D printing and sets wholesale prices for each product. The retailer, as the follower, observes these prices and determines the optimal order quantities based on customer demand. This hierarchical decision-making structure allows us to explore how 3D printing influences equilibrium outcomes, including the conditions under which it becomes a viable alternative to traditional manufacturing. We also derive the equilibrium outcomes for cases where customer demand follows a uniform distribution.

The integration of 3D printing into supply chains introduces trade-offs that must be carefully evaluated. On the one hand, 3D printing enables manufacturers to respond quickly to market changes and produce customized products, making it particularly advantageous in volatile or niche markets. This flexibility can reduce inventory holding costs and improve customer satisfaction through shorter lead times and tailored offerings. On the other hand, the relatively high variable costs of 3D printing, coupled with its slower production rates compared to traditional methods, present challenges. Capacity limitations, in particular, require manufacturers to prioritize products with higher profitability or strategic value, potentially leaving lower-demand items unproduced.

Furthermore, the adoption of 3D printing changes the dynamics of supply chain coordination. Traditional wholesale price contracts may no longer be sufficient to align the objectives of manufacturers and retailers in a 3D printing-enabled supply chain. The decentralized decision-making process can lead to inefficiencies, such as double marginalization, where both parties independently mark up prices, reducing overall supply chain profit. Therefore, new contract mechanisms or pricing strategies may be necessary to ensure coordination and maximize the benefits of 3D printing.

This study aims to provide insights into these complex trade-offs and their implications for supply chain design and management. By analyzing two product scenarios under a Stackelberg framework, we aim to highlight the conditions under which 3D printing becomes a competitive alternative to traditional manufacturing. The findings of this research contribute to the growing body of literature on 3D printing in supply chains.

In conclusion, the integration of 3D printing into supply chains is not merely a technological upgrade but a paradigm shift that reshapes traditional roles, decision-making processes, and profitability structures. By examining these changes through a rigorous analytical framework, this study aims to provide actionable insights for businesses navigating the evolving landscape of supply chain management.

While this paper assumes that demand follows a uniform distribution, this represents a notable limitation. Recent advancements in computer science offer promising tools to estimate demand distributions more accurately from empirical datasets. Future research could investigate the application of computational intelligence algorithms, such as LSTM-CNN frameworks (e.g., Golchin and Riahi, 2021) and generative AI models (e.g., Golchin and Rekabdar, 2024; Wang et al., 2024; Bai and Xu, 2021), to derive realistic demand distributions. These advanced methods, which leverage large-scale emotional and sentiment data from social media, have the potential to reveal hidden patterns in consumer behavior and preferences, which could result in accurately forecasting the demand. By incorporating such insights into predictive analytics, researchers can better capture the intricacies of demand dynamics. This approach has the potential to significantly enhance the accuracy of demand forecasting, streamline inventory management, and improve overall supply chain performance.

1.1.Objectives

The primary objective of this study is to examine the impact of 3D printing on decentralized manufacturer-retailer supply chains, focusing on the trade-offs between traditional and additive manufacturing methods. It aims to identify the conditions under which 3D printing becomes a viable alternative by analyzing cost structures, demand variability, and capacity constraints using a Stackelberg framework. Additionally, the research seeks to derive equilibrium solutions that guide manufacturers and retailers in optimizing pricing, production, and coordination strategies in the presence of 3D printing technology.

2. Literature Review

The intersection of 3D printing (additive manufacturing) and supply chain management has garnered increasing attention in recent years due to the transformative potential of this technology. This section reviews the relevant literature in three domains: 3D printing in operations management, supply chain contracting, and supply chain investment, positioning this study within these streams.

3D Printing in Operations Management The literature on 3D printing’s impact on supply chain dynamics is growing, with a focus on reducing lead times, enhancing customization, and lowering inventory costs. Conner et al. (2014) explored its economic feasibility, highlighting its strengths in high-complexity, low-volume products. Dong et al. (2017) demonstrated that 3D printing offers full flexibility at lower costs compared to traditional flexible technologies, which are often costlier to scale. Westerweel et al. (2018) emphasized 3D printing’s value in reducing inventory and lead times for spare parts, particularly in scenarios where large inventories are impractical. Song and Zhang (2019) examined the transition to make-to-order production enabled by 3D printing, noting reductions in excess inventory. Similarly, Chen et al. (2020) studied 3D printing’s integration in multi-channel supply chains, showing its adaptability to meet demand in both online and offline contexts. Sethuraman et al. (2018) highlighted the disruptive potential of “personal fabrication,” where consumers use 3D printers to bypass traditional supply chain models.

Most of these studies focus on centralized supply chains, whereas our research examines decentralized supply chains. A key related study is by Arbabian and Wagner (2020), who analyzed single-product supply chains incorporating 3D printing. They showed that retailer adoption of 3D printing can, under certain conditions, eliminate double marginalization, echoing some findings in our study. Additional contributions include Hall (2016) on the economic conditions for self-replicating 3D printers and Kretschmer (2015) on decentralized manufacturing enabled by 3D printing, which reduces transportation costs. Unlike these studies, our research investigates supply chains producing and selling multiple products.

Ahmed et al. (2023) applied stochastic optimization to optimize additive manufacturing (AM) deployment under demand uncertainties, while Cantini et al. (2022) developed decision support systems for balancing cost, lead time, and service levels in AM adoption for spare parts. During the COVID-19 pandemic, Ivanov (2021) proposed “supply chain viability,” emphasizing redundancy and flexibility. Top et al. (2023) examined AM’s environmental benefits and challenges, highlighting its role in sustainable manufacturing despite adoption barriers.

Our research differs by examining cost structures through wholesale price contracts where the cost of 3D-printed products is endogenous. Kucukkoc (2019) optimized scheduling in AM environments using Mixed-Integer Linear Programming (MILP), enhancing workload balance. Unlike these studies, our paper considers the adoption of 3D printing as a decision variable rather than assuming its preexistence.

Supply Chain Contracting Supply chain contracting literature has extensively examined how contracts coordinate decentralized supply chains to address issues like double marginalization. Cachon and Lariviere (2005) demonstrated the effectiveness of revenue-sharing contracts. Tsay (1999) highlighted quantity-flexibility contracts as another coordination mechanism. However, 3D printing introduces complexities to traditional contracting models. Arbabian (2022) argued against adopting 3D printing if its variable costs exceed traditional manufacturing. Our study counters this by showing that even with higher costs, the flexibility and customization offered by 3D printing can justify its adoption in multi-product supply chains.

Chen et al. (2019) examined wholesale-price contracts' role in incentivizing 3D printing adoption in decentralized supply chains, providing a framework to balance traditional and 3D printing manufacturing methods. Our work builds on these studies by integrating wholesale-price contracts with endogenous cost structures in multi-product supply chains.

Supply Chain Investment Investments in 3D printing parallel broader manufacturing technology investments aimed at reducing costs or enhancing capacity. Porteus (1985) analyzed investments in setup cost optimization, while Fine and Freund (1990) extended this to flexible manufacturing systems. Goyal and Netessine (2007) examined how competition affects technology investment, noting that firms often underinvest due to competitive pressures.
Our research contributes by modeling the fixed cost of acquiring 3D printers and analyzing investment decisions based on demand variability, product complexity, and cost structures. Similar to Ge et al. (2014), who studied supplier and manufacturer investment strategies, we focus on optimal investment strategies for 3D printing technology adoption. This approach is aligned with identifying conditions that make 3D printing investments viable within decentralized supply chains.

Finally, machine learning techniques have shown significant potential for optimizing supply chains and manufacturing processes. For example, Golchin and Rekabdar (2024) and Wang et al., 2024 utilized reinforcement learning for anomaly detection, highlighting its applicability in dynamic decision-making such as capacity planning in 3D printing. Similarly, Golchin and Riahi (2021) demonstrated the effectiveness of combining deep learning models for analyzing complex data, which could be adapted to model demand patterns and improve coordination in decentralized supply chains. Incorporating such methods into the Stackelberg framework can enhance its predictive power, offering new avenues for managing the trade-offs between traditional and additive manufacturing.

3. Methods

In this section, we examine a scenario where the manufacturer employs traditional production methods to create two distinct products. The unit production costs for these products are denoted as $\left(c_{m,1}, c_{m,2}\right)$.The manufacturer supplies the products to the retailer at wholesale prices (w_1, w_2), respectively. The retailer, in turn, encounters stochastic demand for each product, characterized by probability density functions $f_i(x) = 1; i \in \{1,2\}$, and their corresponding cumulative distribution functions $F_i(x) = \frac{1}{x}; i \in \{1,2\}$. The retailer sells the products to end customers at prices (r_1, r_2). In this setup, consistent with our benchmark case, the retailer's optimization problem is as follows:

$$\pi_R = \max_{q_i \geq 0} r_1 \int_0^1 \min(q_1, x) dx - w_1 q_1 + r_2 \int_0^1 \min(q_2, x) dx - w_2 q_2.$$

Following the Newsvendor's results, the optimal order quantities are as follows.

$$(\mathrm{q}_1(w_1), \mathrm{q}_2(w_2)) = \left(\left(1 - \frac{w_1}{r_1}\right), \left(1 - \frac{w_2}{r_2}\right)\right).$$

In the context of 3D printing, the manufacturer gains the option to invest in a 3D printer at a fixed cost $K > 0$, with unit printing costs $c_{p,1}$ and $c_{p,2}$, as an alternative to traditional manufacturing. This option is particularly relevant in scenarios involving high complexity, extensive customizability, and/or low production volumes. A notable example is seen in car manufacturers like BMW, which are incorporating 3D printing technology into their production processes. Traditionally, even after discontinuing a car model, manufacturers often retain legacy production lines to produce spare parts for those models. By adopting 3D printing, companies can phase out these obsolete production lines and replace them with more efficient 3D printing systems.

We introduce $z \in \{0,1\}$ to represent the manufacturer's binary decision on whether to adopt 3D printing technology. If 3D printing is adopted ($z = 1$), traditional manufacturing is entirely replaced. For instance, it would be inefficient for BMW to maintain old production lines solely for spare parts while simultaneously using 3D printing for the same purpose. However, a limitation of 3D printing is its constrained production capacity Q compared to traditional manufacturing methods. Conversely, if 3D printing is not adopted ($z = 0$), the manufacturer relies exclusively on traditional manufacturing.

Given these considerations, the manufacturer's profit-maximizing problem in the presence of 3D printing is as follows:

$$\begin{aligned} \pi_M = \max_{w_i \geq 0, v \in \{0,1\}} \quad & \left(w_1 - zc_{p,1} - (1-z)c_{m,1}\right)\left(1 - \frac{w_1}{r_1}\right) + \left(w_2 - zc_{p,2} - (1-z)c_{m,2}\right)\left(1 - \frac{w_1}{r_1}\right) - Kz \\ s.t. \quad & q_{nv}(w_1) + q_{nv}(w_2) \leq (1-z)M + zQ. \end{aligned}$$

The first term in the above objective function represents the profit from selling product 1. If 3D printing is not adopted ($z = 0$), this term simplifies to the benchmark profit for product 1. However, if 3D printing is adopted ($z = 1$), the first term becomes $\left(w_1 - c_{m,1}\right)\left(1 - \frac{w_1}{r_1}\right)$, representing the manufacturer's profit from selling the 3D-printed version of product 1. A similar interpretation applies to the second term, which captures the profit from selling product 2 under the respective manufacturing approach. The final term in the objective function accounts for the fixed cost of adopting or investing in 3D printing technology.

In the constraint in equation (4), M denotes a large numerical value. This constraint ensures that if 3D printing is adopted, the retailer's cumulative optimal order quantities comply with the capacity limitation imposed by the 3D printing process.

Before moving forward, we make one simplifying assumption. That is, without loss of generality, we normalize Q to 1. With this assumption, the manufacturer's problem simplifies to

$$\begin{aligned} \pi_M = \max_{w_i \geq 0, v \in \{0,1\}} \quad & \left(w_1 - zc_{p,1} - (1-z)c_{m,1}\right)\left(1 - \frac{w_1}{r_1}\right) + \left(w_2 - zc_{p,2} - (1-z)c_{m,2}\right)\left(1 - \frac{w_1}{r_1}\right) - Kz \\ s.t. \quad & q_{nv}(w_1) + q_{nv}(w_2) \leq (1-z)M + z. \end{aligned}$$

Next, in the following sections, we find the equilibrium to the above problem.

3.1 Case 1: z=0.

In this section, we analyze the scenario where 3D printing is not adopted ($z = 0$). Under this condition, the manufacturer's problem simplifies to:

$$\begin{aligned} \pi_M^{3D} = \max_{w_i \geq 0} \quad & \left(w_1 - c_{m,1}\right)\left(1 - \frac{w_1}{r_1}\right) + \left(w_2 - c_{m,2}\right)\left(1 - \frac{w_2}{r_2}\right) \\ s.t. \quad & \left(1 - \frac{w_1}{r_1}\right) + \left(1 - \frac{w_2}{r_2}\right) \leq M, \end{aligned}$$

In this scenario, the constraint becomes redundant, making the problem similar to that of the Newsvendor. The primary distinction lies in the retailer ordering two distinct products. Consequently, the optimal solution can be determined using the following proposition.

Proposition 1. *The unique optimal solution to the manufacturer's problem is*

- $(q_1^{cm}, q_2^{\text{cm}}) = \left(-\frac{(c_{m,1} - r_1)}{2r_1}, -\frac{(c_{m,2} - r_2)}{2r_2}\right)$,
- $(w_1^{cm}, w_2^{\text{cm}}) = \left(r_1\left(1 + \frac{c_{m,1} - r_1}{2r_1}\right), r_2\left(1 + \frac{c_{m,2} - r_2}{2r_2}\right)\right)$,

- $\pi_M^{\mathrm{cm}} = \frac{r_1^2\, r_2 + (r_2^2 + (-2c_{m,1} - 2c_{m,2})r_2 + c_{m,2}^2)r_1 + c_{m,1}^2 r_2}{4r_1 r_2}$.

The subscript *cm* in the above proposition refers to the fact that all the products are being produced using conventional ways of manufacturing. Also, as one may observe, because in this case 3D printing is not adopted, the optimal order quantities and the optimal wholesale prices are similar to that of the Newsvendor's.

3.2 Case 2: z=1.

In this section, we examine the scenario where 3D printing is adopted (i.e., $z = 1$). Under this condition, the manufacturer's problem simplifies to:

$$\pi_M = \max_{w_i \geq 0} \quad (w_1 - c_{p,1})\left(1 - \frac{w_1}{r_1}\right) + (w_2 - c_{p,2})\left(1 - \frac{w_2}{r_2}\right) - K$$

$$s.t. \qquad \left(1 - \frac{w_2}{r_2}\right) + \left(1 - \frac{w_2}{r_2}\right) \leq 1,$$

Note that because we normalized 3D printing capacity (i.e., Q) to 1, the right hand side of the constraint is 1. Next, to find the optimal solutions for the case where $z = 1$, we divide the solution space into two regions.

Region 1: $\mathbf{1 > \left(1 - \frac{w_1}{r_1}\right) + \left(1 - \frac{w_2}{r_2}\right)}$**.** In this scenario, the constraint in the above problem becomes redundant, and the problem admits an interior solution. This represents a situation where 3D printing is employed but operates below its maximum capacity. The following lemma provides the solution that maximizes the manufacturer's profit within this region.

Lemma 1. The unique optimal solution to the above problem is as follows.

- $(\mathrm{q}_1^{\mathrm{3D}}, \mathrm{q}_2^{\mathrm{3D}}) = \left(\left(1 - \frac{c_{p,1}}{r_1}\right), \left(1 - \frac{c_{p,2}}{r_2}\right)\right)$
- $(w_1^{\mathrm{3D}}, w_2^{\mathrm{3D}}) = \left(r_1(1 - \mathrm{q}_1^{\mathrm{3D}}), r_2(1 - \mathrm{q}_2^{\mathrm{3D}})\right)$
- $\pi_M = \left(w_1^{\mathrm{3D}} - c_{p,1}\right)\left(1 - \frac{c_{p,1}}{r_1}\right) + (w_2^{\mathrm{3D}} - c_{p,2})\left(1 - \frac{c_{p,2}}{r_2}\right) - K$

The subscript *cm* in this case refers to the fact in this region 3D printing is adopted!

Region 2: $\mathbf{\left(1 - \frac{w_1}{r_1}\right) + \left(1 - \frac{w_2}{r_2}\right) \leq 1}$. In this scenario, the constraint in the manufacturer's problem is binding, resulting in a corner solution. This reflects a situation where 3D printing operates at its maximum capacity. Consequently, $\left(1 - \frac{w_1}{r_1}\right) + \left(1 - \frac{w_2}{r_2}\right) = 1$, which implies $q_1 + q_2 = 1 \rightarrow q_2 = 1 - q_1$. Thus, manufacturer's problem simplifies to:

$$\pi_M = \max_{w_i \geq 0} \left(w_1 - c_{p,1}\right)\left(1 - \frac{w_1}{r_1}\right) + \left(w_2 - c_{p,2}\right)\left(1 - \left(1 - \frac{w_2}{r_2}\right)\right) - K$$

Next, the retailer's optimal order quantity is $\left(1 - \frac{w_2}{r_2}\right) = 1 - \mathrm{q}_2$. Therefore, $w_2 = r_2 \mathrm{q}_1$. Finally, the above problem, simplifies to

$$\pi_M = \max_{q_1} \left(r_1(1 - q_1) - c_{p,1}\right)\mathrm{q}_1 + \left(r_2 q_1 - c_{p,2}\right)(1 - \mathrm{q}_1) - K$$

Lemma 2. The unique optimal solution to the above problem is as follows.

- $(q_1^{3D1}, q_2^{3D1}) = \left(\frac{(2r_2 - c_{p,1} + c_{p,2} + r_1 - r_2)}{2(r_2 + r_1)}, \frac{((c_{p,1} - c_{p,2} - r_1 + r_2) + 2r_1)}{2(r_2 + r_1)}\right)$,

- $(w_1^{3D1}, w_2^{3D1}) = \left(-\frac{r_1\left(\left(-c_{p,1}+c_{p,2}-r_1-r_2\right)\right)}{2(r_2+r_1)}, -\frac{r_2\left(\left(c_{p,1}-c_{p,2}-r_1-r_2\right)\right)}{2(r_2+r_1)}\right)$,
- $\pi_M^{3D1} = \frac{\left(\left(c_{p,1}-c_{p,2}-r_1+r_2\right)^2 - 4r_2\left(c_{p,1}-r_1\right)\right)U_1 - 4r_1\left(\left(c_{p,2}-r_2\right)+r_2\right)}{4r_2+4r_1} - K$.

Finally, the optimal solution to the manufacturer's problem when $z = 1$ is proposed in the following proposition.

Proposition 2. *The unique optimal solution to the manufacturer's Problem when* $z = 1$ *is:*

$$
(q_1, q_2) = \begin{cases} \left(\frac{1}{2}\left(1-\frac{c_{p,1}}{r_1}\right), \frac{1}{2}\left(1-\frac{c_{p,2}}{r_2}\right)\right), & \left(1-\frac{c_{p,1}}{r_1}\right)+\left(1-\frac{c_{p,2}}{r_2}\right) < 2 \\ \left(\frac{\left(2r_2 - c_{p,1} + c_{p,2} + r_1 - r_2\right)}{2(r_2+r_1)}, \frac{\left(\left(c_{p,1} - c_{p,2} - r_1 + r_2\right) + 2r_1\right)}{2(r_2+r_1)}\right), & \text{otherwise.} \end{cases}
$$

$$
(w_1, w_2) = \begin{cases} \left(r_1\left(1+\frac{c_{p,1}-r_1}{2r_1}\right), r_2\left(1+\frac{c_{p,2}-r_2}{2r_2}\right)\right), & \left(1-\frac{c_{p,1}}{r_1}\right)+\left(1-\frac{c_{p,2}}{r_2}\right) < 2 \\ \left(-\frac{r_1\left(\left(-c_{p,1}+c_{p,2}-r_1-r_2\right)\right)}{2(r_2+r_1)}, -\frac{r_2\left(\left(c_{p,1}-c_{p,2}-r_1-r_2\right)\right)}{2(r_2+r_1)}\right), & \text{otherwise.} \end{cases}
$$

$$
\pi_M = \begin{cases} \frac{r_1^2 r_2 + \left(r_2^2 + \left(-2c_{p,1} - 2c_{p,2}\right)r_2 + c_{p,2}^2\right)r_1 + c_{p,1}^2 r_2}{4r_1 r_2} - K, & \left(1-\frac{c_{p,1}}{r_1}\right)+\left(1-\frac{c_{p,2}}{r_2}\right) < 2 \\ \frac{\left(\left(c_{p,1}-c_{p,2}-r_1+r_2\right)^2 - 4r_2\left(c_{p,1}-r_1\right)\right) - 4r_1\left(\left(c_{p,2}-r_2\right)+r_2\right)}{4r_2+4r_1} - K, & \text{otherwise.} \end{cases}
$$

3.3 The Equilibrium

In this section we find the Stackelberg equilibrium of the game between the manufacturer and the retailer, which is derived by taking the maximum of the profit in Proposition 2 and Proposition 3.

$$
(q_1^*, q_2^*, z^*) = \begin{cases} \left(\frac{\left(21r_2 - c_{p,1} + c_{p,2} + r_1 - r_2\right)}{2(r_2+r_1)}, \frac{\left(\left(c_{p,1}-c_{p,2}-r_1+r_2\right)+2r_1\right)}{2(r_2+r_1)}, 1\right), & \left(1-\frac{c_{p,1}}{r_1}\right)+\left(1-\frac{c_{p,2}}{r_2}\right) > 2 \\ \quad \text{and } \frac{\left(\left(c_{p,1}-c_{p,2}-r_1+r_2\right)^2 - 41r_2\left(c_{p,1}-r_1\right)\right) - 41r_1\left(\left(c_{p,2}-r_2\right)+1r_2\right)}{4r_2+4r_1} - K > \frac{r_1^2 r_2 + \left(r_2^2 + \left(-2c_{m,1} - 2c_{m,2}\right)r_2 + c_{m,2}^2\right)r_1 + c_{m,1}^2 r_2}{4r_1 r_2} & \\ \left(\frac{1}{2}\left(1-\frac{c_{p,1}}{r_1}\right), \frac{1}{2}\left(1-\frac{c_{p,2}}{r_2}\right), 1\right), & \left(1-\frac{c_{p,1}}{r_1}\right)+\left(1-\frac{c_{p,2}}{r_2}\right) \le 2 \\ \quad \textit{and } \frac{r_1^2 r_2 + \left(r_2^2 + \left(-2c_{p,1} - 2c_{p,2}\right)r_2 + c_{p,2}^2\right)r_1 + c_{p,1}^2 r_2}{4r_1 r_2} - K > \frac{r_1^2 r_2 + \left(r_2^2 + \left(-2c_{m,1} - 2c_{m,2}\right)r_2 + c_{m,2}^2\right)r_1 + c_{m,1}^2 r_2}{4r_1 r_2} & \\ \left(-\frac{\left(c_{m,1}-r_1\right)}{2r_1}, -\frac{\left(c_{m,2}-r_2\right)}{2r_2}, 0\right), & \textit{otherwise} \end{cases}
$$

In the first scenario of Proposition 3, 3D printing proves to be more profitable, leading to the adoption of 3D printing technology (i.e., $z^* = 1$). However, due to the limited capacity of 3D printing, the retailer's optimal order quantity depends on this capacity and is given by:

$$q_i^* = \frac{(r_{i^-} - c_{p,i} + c_{p,i^-} + r_i)}{2(r_{i^-} + r_i)}$$

In the second scenario of Proposition 3, 3D printing remains more profitable, and the technology is still adopted (i.e., $z^* = 1$). In this case, the capacity of 3D printing is no longer a constraint. As a result, the retailer's optimal order quantity resembles that of the Newsvendor model:

$$q_i^* = \frac{1}{2}\left(1 - \frac{c_{p,i}}{r_i}\right)$$

In the third scenario of Proposition 3, 3D printing is not profitable. As a result, the problem reduces to the Benchmark case. Finally, in the Numerical Study section, we analyze the effects of various parameters on the equilibrium.

To understand the equilibrium better, we show the results of the case where $(c_{m,1}, c_{m,2}, r_1, r_2, K) = (0.9,1.9,1,2,0.05)$ on Figure 1 for different values of $c_{p,1}$ and $c_{p,2}$. This graph represents the equilibrium conditions across varying values of $c_{p,1}$ and $c_{p,2}$, depicting two key dimensions. On the left panel, the color gradient showcases the firm's profit π_M , where warmer tones (red) indicate higher profits and cooler tones (blue) represent lower profits. The profit distribution is strongly influenced by the interplay of $c_{p,1}$ and $c_{p,2}$, which reflect the cost parameters of two competing entities. This visualization highlights how the profit landscape shifts with changes in these parameters, offering insights into the firm's strategic positioning and the economic environment in which it operates.

The right panel categorizes the equilibrium into three cases: Case 1 (red), where 3D printing is utilized with no capacity constraint, Case 2 (green), where 3D printing is utilized at capacity, and Case 3 (blue), where 3D printing is not used at all. These equilibrium zones are defined based on the specific conditions derived from the underlying model, where each region corresponds to distinct optimal strategies for the competing entities. The segmentation illustrates the critical thresholds at which the system transitions between equilibria, emphasizing the dynamic and conditional nature of strategic interactions. Together, these plots provide a comprehensive view of the equilibrium structure, blending quantitative performance insights with strategic classifications.

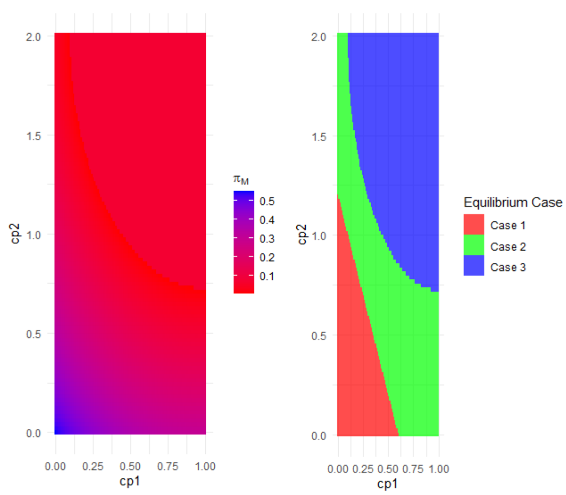

Figure 1. Comparing the total cost of different policies; Case 1: 3D printing used at capacity, Case 2: 3D printing used with no capacity constraint, Case 3: 3D printing not used.

4. Results and Discussion

In this section, we perform a numerical analysis of the equilibrium to gain deeper insights into the optimal strategies for supply chain owners in the context of 3D printing technology. The parameters used in this study are presented in Table 1. The selected parameters are designed to comprehensively cover the entire problem parameter space. This includes scenarios where 3D printing might be more or less cost-effective to operate, as well as cases where the technology might be considered either inexpensive or expensive to adopt. By exploring these varied conditions, we aim to provide a holistic understanding of the trade-offs and opportunities presented by 3D printing. Our focus is on highlighting novel findings, while omitting the discussion of straightforward results, such as the impact of $\boldsymbol{c_{m,i}}$ on the equilibrium.

Table 1. Joint Replenishment Policy total cost

$r1$	$r2$	$c_{m,1}$	$c_{m,2}$	$c_{p,1}$	$c_{p,2}$	K
50	$\left\{\frac{1}{2}r1, r1, 2r1\right\} = \{25,50,100\}$	$\{1, \ldots, r_1\}$	$\{1, \ldots, r_2\}$	$\{1, \ldots, r_1\}$	$\{1, \ldots, r_2\}$	$\{0, .1, \ldots, 6\}$

First, we investigate the effect of $c_{p,1}$ and $c_{p,2}$ on the equilibrium in Figure 2. This graph illustrates the influence of $c_{p,1}$ and $c_{p,2}$ on the equilibrium, categorizing the outcomes into three distinct cases. Case 1 (red region), where 3D printing is utilized with no capacity constraint, arises when both parameters $c_{p,1}$ and $c_{p,2}$ are relatively low. In this region, the equilibrium reflects a scenario where the supply chain benefits from competitive production costs, leading to a higher reliance on 3D printing as a viable manufacturing strategy. The lower values of $c_{p,1}$ and $c_{p,2}$ allow for a cost-effective balance in production, which influences the firms' optimal decisions to remain in this equilibrium state.

As $c_{p,1}$ and $c_{p,2}$ increase, the equilibrium transitions through Case 2 (green region), where 3D printing is utilized at capacity, and eventually into Case 3 (blue region), where 3D printing is not used at all. Case 2 represents an intermediate scenario where one or both cost parameters reach moderate levels, limiting the viability of 3D printing but still maintaining some balance between traditional and advanced manufacturing methods. Finally, in Case 3, where $c_{p,1}$ and $c_{p,2}$ are high, the equilibrium shifts entirely, indicating that the cost advantage of 3D printing diminishes. This region highlights the dominance of traditional manufacturing as high $c_{p,1}$ and $c_{p,2}$ make 3D printing economically unfavorable. The boundaries between these regions demonstrate the sensitivity of the equilibrium to variations in production costs, emphasizing the critical role of $c_{p,1}$ and $c_{p,2}$ in determining the optimal strategies.

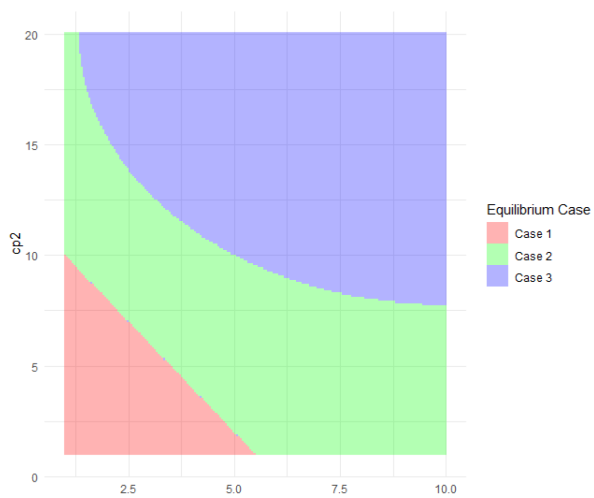

Figure 2. Equilibrium cases when $\boldsymbol{(c_{m,1}, c_{m,2}, r_1, r_2, K) = (5, 10, 10, 20, 0)}$

Next, Figure 3 compares the profit trends $(\pi_M^{3D1}, \pi_M^{3D}, \pi_M^{\text{cm}})$ as a function of $c_{p,2}$, illustrating how changes in the second cost parameter affect profitability across three scenarios. The red line (π_M^{cm}) represents a baseline profit level, which remains constant regardless of $c_{p,2}$. In contrast, the blue line (π_M^{3D1}) and green line (π_M^{3D}) show a decreasing trend, indicating a negative correlation between $c_{p,2}$ and profitability in these cases. Notably, the steep decline in profits for these cases highlights the sensitivity of profit outcomes to higher production costs.

The vertical red dashed line marks a critical threshold of $c_{p,2} = 10$. To the left of this threshold, both π_M^{3D1} exhibit significantly higher profits, with π_M^{3D1} outperforming π_M^{3D}. However, as $c_{p,2}$ increases beyond the threshold, all profits converge to lower levels, underscoring the diminishing profitability of these scenarios as costs rise.

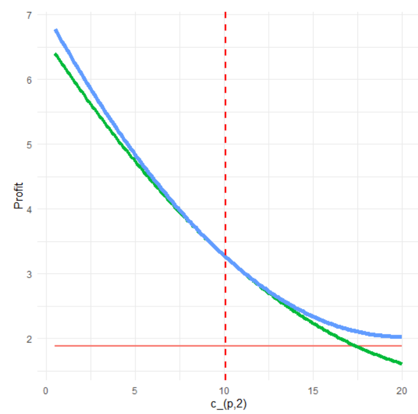

Figure 3. Equilibrium cases when $\left(\boldsymbol{c_{m,1}}, \boldsymbol{c_{m,2}}, \boldsymbol{r_1}, \boldsymbol{r_2}, \boldsymbol{K}, \boldsymbol{c_{p,1}}\right) = (\mathbf{5}, \mathbf{10}, \mathbf{10}, \mathbf{20}, \mathbf{0}, \mathbf{1})$.

5. Conclusion

This study provides a comprehensive analysis of the implications of 3D printing on decentralized manufacturer-retailer supply chains, with a focus on two-product scenarios modeled under a Stackelberg framework. By comparing traditional manufacturing and 3D printing, we highlight the strategic trade-offs businesses face when considering this disruptive technology. While 3D printing offers significant benefits, such as reduced inventory costs, enhanced flexibility, and improved responsiveness to demand variability, its adoption introduces challenges like higher variable costs and capacity limitations.

Our findings reveal that 3D printing can be a viable alternative to traditional manufacturing under specific conditions, particularly when demand patterns favor customization and agility. Moreover, the results emphasize the importance of aligning supply chain coordination mechanisms to fully capitalize on the benefits of 3D printing while minimizing inefficiencies such as double marginalization. The derived equilibrium solutions underscore the dynamic interplay between cost structures, pricing strategies, and capacity constraints in determining the optimal manufacturing approach.

Through numerical analysis, we further illustrate how critical parameters such as production costs, demand variability, and capacity influence the equilibrium strategies for manufacturers and retailers. These insights provide actionable guidance for businesses evaluating the adoption of 3D printing as part of their supply chain strategy, enabling them to balance cost efficiency with market responsiveness effectively.

In conclusion, 3D printing represents a paradigm shift in manufacturing and supply chain management, offering both opportunities and challenges. By rigorously analyzing these dynamics, this research contributes to the growing body of literature on additive manufacturing and its role in transforming modern supply chains. Future research could expand on these findings by exploring multi-product scenarios or integrating environmental sustainability into the decision-making framework, further enriching the understanding of 3D printing's potential in complex supply chain ecosystems.

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