This is the preprint version of the following article: Guo, S., Choi, T.-M., & Chung, S.-H. (2022). Self-design fun: Should 3D printing be employed in mass customization operations? European Journal of Operational Research, 299(3), 883-897, which is available at https://dx.doi.org/10.1016/j.ejor.2021.07.009.

Self-design Fun: Should 3D Printing be Employed in Mass Customization Operations?

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Date: 22 December, 2020.

Abstract

Today, in the market with ever-changing consumer preferences, three-dimensional (3D) printing is becoming an overwhelming trend. In this paper, we explore the use of 3D printing in mass customization (MC) programs. We consider the case when 3D printing brings extra self-design fun to consumers, which is highlighted in MC practices of the auto company BMW and the furniture company Poltrona Frau, and also changes the cost formula (i.e., the marginal product variety cost) of the MC product. In addition, the roles played by the risk attitudes of the MC manufacturer and consumers, consumer returns, as well as consumers' time sensitive behaviors, are also uncovered. We find that although integrating 3D printing into MC can lead to a maximized product variety level, it can benefit both the MC manufacturer and the consumers only when the consumer's self-design fun is sufficiently large and the product variety marginal cost is not too large. In particular, a high self-design fun presents the superior performance in contributing to a higher level of MR benefits to the MC manufacturer and also a higher level of consumer surplus under the risk-seeking attitudes of the MC manufacturer and consumers. The high flexibility and responsiveness of 3D printing also shows its advantages in remanufacturing the consumer returned MC items and enhancing MC programs' overall lead-time. Finally, applying 3D printing in creating molds can also help the MC manufacturer tackle demand uncertainties. These findings all provide a good reference to the application of 3D printing in MC operations.

***Keywords**:* Supply Chain Management; 3D Printing, Mass Customization, Risk attitudes, Self-Design Fun.

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[*] The corresponding author. The authors sincerely thank the editor and reviewers for their critical comments on this paper, especially during the difficult time with COVID-19 pandemic. They wish the editor and all reviewers safe from the virus. Thanks.

[1] Tsan-Ming Choi's research is partially supported by Research Grants Council (Hong Kong) under the General Research Fund (No.: PolyU 152294/16E).

1. Introduction

1.1. Background and Motivation

Mass customization (MC), under which consumers can tailor a standard product into their unique tastes, has been tremendously adopted across various firms for many years. As far back as 1999, Levi Strauss & Co. has successfully made a name for itself through offering an ‘Original Spin’ process at its retail stores, which was indeed a pioneering practice in MC. In recent years, given the popularity of various advanced manufacturing technologies, firms like Kraft, M&Ms, Wrigley, Nike, and Zazzle also adopt MC. For instance, Nike’s FlyKnit knitting technology is well known for its ability to support extreme consumer-generated designs in MC which can even be a thread-level customization. Despite the strength of advanced technologies to allow a rampant product variety level (e.g., the thread-level customization via FlyKnit) and improve product design in MC, however, the customization process in MC is viewed as a cause for cost and feasibility concerns in operations. The extreme of unlimited product variety level can also dilute the advantage of customization in taste match. This makes us wonder, to what extent should customization be employed in MC, and how could the extent of customization impact the performance of MC? Here, following the classic product variety literature like Fisher and Ittner (1999) and Ramdas (2003), we define product variety as the “peripheral differences” (e.g., color, and accessories) of the product in the design dimension (i.e., components) which will not influence product quality (defined as minimum performance requirements). As an example, either spring-clip terminals or sturdier binding-post terminals can be utilized for a speaker as both can meet minimum performance requirements. This is also in line with the real practices in other industries such as computers, toys, and automobiles.

In the meanwhile 3D printing, also known as additive manufacturing (AM), is becoming an emerging trend under Industry 4.0 over the recent years. According to Knowledge Sourcing Intelligence[2], the 3D printing market is even expected to reach a market size of US$39.640 billion by the year 2024, compared with the size of US$9.190 billion in 2018. The reason behind is the widespread application of 3D printing in the production of functional parts across various industries, given its dominant advantages in tolerating large part variety (Song and Zhang, 2019; Olsen and Tomlin, 2020). Industries like consumer electronics, fashion and automotive are all

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[2] See https://www.knowledge-sourcing.com/report/3d-printing-market. (Accessed March, 2020)

the major industry players that are driving the market for 3D printing. For instance, as 3D printing makes it possible to create shapes without molds (Sun et al., 2020), consumers can easily customize their own fashion produce elements of an extreme intricacy (like a particular button in the fashion product (Pasricha and Greeninger, 2018)) that one could not reach otherwise. This allows the fashion brand to produce on-demand with realistic parameter settings (referring to both the flexibility in small scale production and high customization capabilities), and also achieve the complementarity between stock and print in cost minimization. As a case in point, Adidas uses 3D printing to produce midsole for its Futurecraft 4D range. In the auto industry, General Electric also establishes the collaboration with Sigma Labs for the 3D printing supported production of jet engine components such as fuel nozzles.[3] Given 3D printing's inherent flexibility and the advantage in eliminating manufacturing diseconomies of product variety, 3D printing is also currently more attractive than conventional manufacturing methods in MC operations.

Table 1. Features of traditional and 3D printing MC production systems.

	The basic product		**The final MC product**	
Traditional MC System	Operational feature(s)	Mass production.	Operational feature(s)	1) Customized by the traditional manufacturing system (e.g., computer-aided-design (CAD)); 2) Consumers customize their products within a set of ready-made product variety offerings. *3) Examples: Nike By You (previously titled NikeID), My M&M'S, and Zazzle.com.*
	Cost structure	A per-unit production cost of each standard product.	Cost structure	The extra flexibility cost for MC (i.e., extra product variety cost) is in the format of an overall variety dependent cost.
MC System with 3D Printing	Operational feature(s)	Mass production.	Operational feature(s)	1) Customized by the 3D printing technology; 2) Consumers enjoy the extra self-design fun with innovative customization which is beyond the ready-made product variety offerings in the traditional MC. 3) *Examples: HP Metal Jet, MINI Yours Customised in German group BMW, and Razor Maker™ in Procter and Gamble.*
	Cost structure	A per-unit production cost of each standard product.	Cost structure:	The extra flexibility cost for MC (i.e., extra product variety cost) includes both the fixed 3D printers purchasing cost, and the 3D printing development cost for 3D designs (or 3D schematics) and production plans[4].

Comparisons between the traditional MC and the 3D printing supported MC are listed in Table 1. As an example, HP established its partnership with the auto manufacturer GKN in 2018 to deploy 3D printing to

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[3] See http://3dprintingreviews.blogspot.com/2013/06/ge-aviation-to-grow-better-fuel-nozzles.html. (Accessed March, 2020)

[4] Notice that although in the traditional MC system, the materials utilized can influence the overall production cost, the final cost also depends on other factors like the firm's degree of production flexibility as highlighted in product variety literature like Dewan et al. (2003). The flexibility cost in production therefore is highlighted in this paper as the extra product variety cost for MC.

produce functional metal parts of its MC auto products.[5] Similar practices are also popular in the German group BMW, which uses 3D printing to support its MINI MC customers. Pieces are printed individually and can be available in just a few days, which offers more freedom in terms of functionality and product design. Besides, product design nowadays has already expanded to include hobbyists and prosumers (innovative users who both produce and consume a product) to develop their own customized products (Petrick and Simpson, 2013). The National Survey Data released in Gambardella et al. (2017), for instance, shows that millions of users (around 3.7% to 6.1% citizens of the involved developed countries) collectively investing billions of dollars annually for developing or modifying the products to better serve their own needs. To capture the additional innovation enjoyment in product design (Kleer and Piller, 2019), we follow the user innovation theory [6] and self-congruency theory[7] and incorporate the value of mass customization experience (i.e., the self-design fun) brought by 3D printing into the consumer utility function. We explore how 3D printing affects the practices of MC from the aspects of the self-design fun and the product variety design (e.g., the manufacturing flexibility). In practice, the self-design fun is emphasized across various industries. For instance, the 3D printing supported MC launched by the German group BMW allows consumers to self-design the passenger-side sideband and the side inserts of their own vehicles.[8] Consumers' self-design experience to the furniture pieces is also highlighted as a major selling point in the high-end furniture company Poltrona Frau's 3D printing supported MC project.[9] In addition, 3D printing as a new technology becoming popular in recent years, both the MC manufacturer and consumers may have limited knowledge towards 3D printing. This leads to a higher level of uncertainties, like the product uncertainty regarding how well the final MC product matches with consumers' own self-concept and their idealized version. Given that risk is an important consideration in front of new technologies (Smith and Ulu, 2017), the roles played by the risk attitudes of MC manufacturer and consumers towards the application of 3D printing in MC are also uncovered in this paper.

1.2. Research Questions and Key Findings

Given the widespread application of 3D printing in MC operations (e.g., in the auto industry and the fashion industry) and the identified research gap, we address the following research questions (RQs) in this paper:

RQ1: Should 3D printing be employed in MC operations? What are the influences of 3D printing?

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[5] See https://press.ext.hp.com/us/en/press-releases/2018/hp-launches-worlds-most-advanced-metals-3d-printing-technology.html and http://www.scdigest.com/ontarget/18-09-11-1.php?cid=1466. (Accessed March, 2020)

[6] According to user innovation theory, innovative users do not wait for the manufacturer to capture their needs, but are incentivized to actively apply manufacturing technologies (e.g. CAD or other design software) to turn their needs into a fitting product specification (von Hippel et al., 2011; Gambardella et al., 2017). 3D printing, which provides the flexibility and the experience to design the MC product with innovative customization beyond the ready-made product variety offerings in the traditional MC, thus has a profound influence on user innovation.

[7] The self-congruency theory suggests that consumers value how well the purchased product expresses their personalities and match with their self-concept when making purchasing decisions (Merle et al., 2010; Çil and Pangburn, 2017). Self-expressiveness value differs from uniqueness value inherently as the individual is seeking to own a product that fits his/her self-image rather than trying to display his/her difference (Merle et al., 2010). Accordingly, different from the value of mass-customized product, the mass customization experience can bring an additional value.

[8] See https://www.3dnatives.com/en/bmw-3d-printing-additive-manufacturing-241220184/. (Accessed March, 2020)

[9] See https://protocube.it/portfolio/configuratore-3d-poltrona-frau/?lang=en. (Accessed May, 2020)

RQ2: How could the risk attitudes of the MC manufacturer and consumers affect the performance of 3D printing in MC?

RQ3: Can 3D printing help address consumers returns in MC as well as the customization lead-time in the traditional MC?

To answer these RQs, we consider a monopolist MC manufacturer who directly sells a new MC product to individual consumers by adopting either the traditional MC or the 3D printing supported MC. As shown in Table 1, without the support of 3D printing, the customization process is based on conventional methods like CAD. While under the 3D printing supported MC, given the unique capacity to create shapes without molds, 3D printing is applied to print different end-use product variants (i.e., components) based on the customization requirements from the consumers. Examples of these 3D printed components can be the jet engine components in General Electric, the functional metal parts in HP, and the passenger-side sideband or the side inserts in BMW. Respective characteristics of these two different MC strategies are considered (like the zero costly up-front investment in molds under the 3D printing supported MC), and comparisons are conducted. In addition, we also address the roles played by the risk attitudes of the MC manufacturer and consumers, the existence of consumer returns, consumers' time sensitive behaviors, as well as the application of "*3D printing in molding*"[10].

Regarding the influences of 3D printing (RQ1), we find that adopting 3D printing can always contribute to a maximum product variety level of the MC product. While integrating 3D printing into MC can be beneficial to both the MC manufacturer and consumers only when the consumer's self-design fun is sufficiently large and the marginal cost of product variety is not too large. The reason behind is that consumers not only consider their congruency with the MC product, but also put some weight on the self-design fun as well as the final retail price. This implies that the MC manufacturer should pay close attention to the overall cost of the MC product after adopting the 3D printing technology, which can finally influence the retail price of the MC product. This is also true even under the consideration of the risk attitudes of the MC manufacturer and consumers, as well as the influences of other operational factors like consumers returns and the time sensitive behaviors of consumers. In addition, under new advanced technologies, individual consumers may face the product uncertainty regarding how well the purchased MC product matches with their self-concept as well as their "ideal product", and the MC manufacturer may accordingly face market uncertainties. We therefore have RQ2. It is revealed that compared to the risk-averse and risk-neutral attitudes, the risk-seeking attitude (of the MC manufacturer and individual consumers) can lead to a more distinct advantage of self-design fun in helping achieve a MC program that brings more benefits to the MC manufacturer and consumers. That is because the risk-seeking customer's incentive to take the risks of product uncertainties makes them value the self-design fun more and be more willing to pay higher premiums for it. This can then make a 3D printing based MC (i.e., for end-use product variants printing)

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[10] Here, 3D printing in molding means employing 3D printing technologies to create molds.

more successful. On the other hand, a customer who is less risk-seeking or more risk-averse prefers to receive the traditional MC product and therefore shows fewer interests in self-design fun. This also explains our finding that applying 3D printing in molding can bring more benefits to both the MC manufacturer and consumers in a market with risk seeking consumers than the market with risk averse consumers, as long as the traditional MC's standard cost for each mold is high but the customization cost on the 3D printed mold is small. Concerning RQ3, we show that launching the full refund policy may reduce the optimal product variety level in the traditional MC if the consumers are less risk averse or more risk seeking. This problem, however, can be successfully solved via introducing 3D printing into MC, given the beauty of 3D printing's materials parsimony. That is, the nature of single-material usage in 3D printing can reduce the complexity of the MC product and consequently ensure the flexibility of remanufacturing the consumer returned items. Furthermore, this paper also proves the capability of 3D printing in enhancing the speed of MC programs' overall lead-time. All of these findings show that 3D printing has dominant advantages in overcoming the common challenges in the traditional MC (e.g., the diversified consumers' preferences of self-concept, the limited product variety level, the complexity of MC products, the high molding cost, as well as the customization lead-time). The MC manufacturer therefore should consider to integrate 3D printing into the MC programs for creating different product variants, if he can achieve a high self-design fun and a relatively low product variety marginal cost under the 3D printing supported MC.

1.3. Contribution Statement and Paper's Structure

Advancements in 3D printing, such as the flexibility in product variety and the capacity to create shapes without molds, have unlocked a broad spectrum of production applications like MC. To the best of our knowledge, this paper is the first study which theoretically explores how 3D printing supported MC program performs compared to the traditional MC program. The effects of risk attitudes, consumer returns and consumers' time sensitive behaviors are uncovered. The application of "*3D printing in molding*" is also discussed. The findings not only contribute to the literature but also provide valuable guidance to practitioners for improving MC operations. In addition, innovation by consumers has been underexplored in standard microeconomic modeling for innovative products and services (Syam and Pazgal, 2013). The consideration on the unique self-design fun brought by 3D printing, which highlights the experience and additional self-expressiveness enjoyment to design the MC product with innovative customization beyond the ready-made product variety offerings, therefore also contributes to the extant knowledge on the innovative market.

This paper is organized as follows. In Section 2, relevant literature is reviewed, referring to the domains of mass customization supply chains, 3D printing in operations, and decision making with risk attitudes. Section 3 presents the basic models, which includes MC operations both without and with the support of 3D printing. The optimal strategies and influences of 3D printing are then explored in Section 4. Afterwards, Section 5 extends

Section 4 by discussing how different behaviors of the MC manufacturer and consumers can influence the MC operations. Aspects like risk attitudes, consumer returns, and consumers' time sensitive behaviors are analyzed. Besides, the application of "*3D printing in molding*" is also explored. Finally, Section 6 concludes the paper by summarizing the key managerial insights. To enhance readability, supplementary tables are placed in the Appendix A while all technical proofs are placed in the Online Supplementary Appendix.

2. Literature Review

This paper relates to three areas: mass customization supply chains, 3D printing in operations, as well as decision making with risk attitudes.

2.1. Mass Customization Supply Chains

In the field of mass customization supply chains, several extant literature can be found covering topics like market competition (e.g., Alptekinoğlu and Corbett (2008), Mendelson and Parlaktürk (2008b)), brand system (e.g., Çil and Pangburn (2017)), consumer returns (e.g., Choi and Guo (2018), Guo et al. (2020)), and consumers' time sensitive behaviors (e.g., Mendelson and Parlaktürk (2008a), Alptekinoğlu and Corbett (2010)). Among them, Alptekinoğlu and Corbett (2008) address the influences of firms' production costs based on the price and product variety competition between the traditional firm (i.e., the mass producer) and the MC firm. They reveal that the traditional firm can achieve profitable competition if the MC firm has limited production cost advantages in product variety. Differently, Mendelson and Parlaktürk (2008b) explore the case when both the competing firms can choose either to adopt MC or not. The authors show that compared to uniform prices of MC products, setting differentiated retail prices for different product configurations can lead to a broader adoption of MC. For brand system, Çil and Pangburn (2017) focus on MC's potential in improving the alignment of the product with regard to consumer tastes and explore the product-specific and brand-level components in the consumer utility function. The authors demonstrate that differentiating retail prices by offering a reduced price to the consumers with extreme tastes while providing a higher price to those with more mainstream tastes can be optimal for the MC firm. As can be seen from these research works, the specific tastes or preferences of consumers and the cost of product variety play a vital role in MC operations. Similar to above studies, we also consider these two factors. While differently, we simultaneously integrate the roles of self-design fun and consumer returns.

For consumer returns, the MC literature Choi and Guo (2018) investigate the value of quick response (QR) supply in MC systems with the consideration of consumer returns. The authors find that QR supply can help reduce the MC system's environmental cost associated with consumer returns. Guo et al. (2020) explore impacts of different salvage values of unused inventories and consumer returns in MC. The authors study the optimal product quality improvement decisions. Both Choi and Guo (2018) and Guo et al. (2020) provide evidence regarding the significant impacts of consumer returns in MC systems. To this end, we complement the extant MC literature such as Choi and Guo (2018) and Guo et al. (2020) by providing new insights regarding the flexibility of 3D printing in remanufacturing the consumer returned MC items. In addition, the customization lead-time and consumers' time sensitive behaviors, which are emphasized in Mendelson and Parlaktürk (2008a) and Alptekinoğlu and Corbett (2010), are also considered in this paper. In particular, Mendelson and Parlaktürk (2008a) consider the lead-time delay in duopoly competition between the customizing firm and traditional firm. The authors find that shorter customization times can make MC less profitable while customization delays can soften the competition. Alptekinoğlu and Corbett (2010) study the influences of the customization lead-time on the optimal product line design. The authors highlight that the tradeoff between customization lead-time and product variety is complex and the MC firm should pay close attention to factors such as consumer dispersion and operational scale. Different from Mendelson and Parlaktürk (2008a)'s and Alptekinoğlu and Corbett (2010)'s focus on the lead-time-variety tradeoff in the operations of the traditional MC, we innovatively investigate the application of 3D printing in MC for addressing the consumers' time sensitive behaviors.

2.2. 3D Printing in Operations

Concerning the application of 3D printing in operations, there is literature investigating the fields of market response effectiveness (e.g., Arbabian and Wagner (2020)), spare parts inventory management (e.g., Song and Zhang (2019)), pricing strategy (Sun et al. (2020)), and market competition (e.g., Kleer and Piller (2019)). Arbabian and Wagner (2020) analyze the impacts of 3D printing on a supply chain that serves a stochastic demand, in which either the manufacturer or the retailer may adopt 3D printing. They find that 3D printing can still be a desirable strategy even if the unit 3D printing cost is higher than traditional manufacturing, given its increased responsiveness to the make-to-order strategy. By comparing the 3D printing supported on-demand mode with the traditional manufacture-to-stock mode, Song and Zhang (2019) study the application of 3D printing in addressing the stochastic demands of spare parts in logistics design. The authors indicate that the cost savings enabled by 3D printing show its advantages in tolerating large part variety and improving inventory management of the critical parts. Sun et al. (2020) explore the pricing strategy of a 3D printing based platform, which provides both standard and customized products (with different qualities). The authors highlight that when the unit labour cost of the designer is low, the final price of the customized product increases with its own quality while decreases with the quality of the standard product. Kleer and Piller (2019) investigate the effects of 3D printing on a dynamic market with both user innovation and spatial competition. Consumers' transportation cost is considered and as revealed in Kleer and Piller (2019), the more consumers place a premium on the instant availability of the products, the more advancements in 3D printing will shift production of these products from a centralized production system to a local one. These studies all reveal the dominant advantages of 3D printing in improving operations efficiency. This paper complements the findings among these studies by exploring the advantages of 3D printing in handling consumer returns and addressing the consumers' time sensitive behaviors. Besides, although 3D printing has plenty of advantages, it also comes with risks. Therefore, the risks attitudes behavior towards 3D printing, which are neglected in the above literature, are originally addressed in this paper.

2.3. Decision Making with Risk Attitudes

This paper is also related to the domain of decision making with risk attitudes. Specifically, Yang et al. (2018) investigate the inventory risks under the service and demand uncertainty and extend the classic newsvendor models to the considerations on the risk averse preference of both the supplier and the retailer. The authors highlight that pull can outperform push if the supplier and the retailer hold a same risk-averse level, while push can induce a higher optimal order quantity than pull if the supplier is more risk-averse than the retailer. Besides, other aspects such as supply uncertainty (e.g., Demirel et al. (2018)), technology adoption (e.g., Smith and Ulu (2017)), and warranty claim (e.g., Gallego et al. (2015)) are also emphasized in the extant risk attitude literature. For example, Demirel et al. (2018) discuss the roles of supply disruption risks in the manufacturer's sourcing and inventory strategies, and address the supplier's risk attitudes towards whether to serve as a backup supplier or not. The authors find that having a backup supplier can benefit the suppliers, while it is not necessarily beneficial to the manufacturer and the supply chain. Smith and Ulu (2017) address the uncertain benefits of technology and study the impacts of the decision maker's risk attitudes on technology adoption. They point out that if the decision maker is risk-averse, it may be optimal to gather more information about the technology first before make adoption decisions of the technology. By designing a constant absolute risk aversion model, Gallego et al. (2015) characterize the impacts of consumers' strategic claim behavior and risk attitudes on the residual value warranties provided by the service provider. The authors highlight that under the residual value warranties, the total cost of repair and refunds can be surprisingly lower for more risk-averse customers. In line with these research works, this paper also considers the uncertainty-related costs. In contrast to external factors like supply disruption and supply chain structures, however, this paper focuses on the risk attitudes that are related to the inevitable and inherent uncertainty in MC given the extra customization action and the potential adoption of the 3D printing technology.

3. Base Model

3.1. Traditional MC Operations without 3D Printing

We first consider a monopolist MC manufacturer adopts the traditional MC and directly supplies the new MC product to end consumers. No new technologies are applied. The MC manufacturer simultaneously makes optimal decisions of the product variety level v $(0 \leq v \leq 1)$ and the retail price p of the MC product to maximize the expected profit. The per-unit production cost of each standard product is c. In the meantime, product customization is never free (Squire et al., 2006). Accordingly, the manufacturer has an extra flexibility cost for MC[11] as $C_{\overline{3D}}(v) = \frac{kv^2}{2}$, which includes the product development cost for product variety and the labor learning cost. It is product variety dependent, with k as the sensitivity of the product variety cost with respect to the MC product's variety level v. We define product variety as the "peripheral differences" (e.g., color, and accessories) of the product that the MC manufacturer allows the consumers to match their distinct tastes. Flexibility and cost efficiency have been known as conflicting objectives. Such a quadratic cost structure captures the diseconomies of product variety, and reflects the fact that the marginal customization expenditure increases as the product variety level increases. The cost structure is in line with the extant MC literature like Dewan et al. (2003), Takagoshi and Matsubayashi (2013), and Jost and Süsser (2020), and can be supported by the product variety literature such as Draganska and Jain (2005) and Xiao et al. (2014). For instance, Draganska and Jain (2005) empirically prove that yogurt firms incur a quadratic cost in the number of varieties (yogurt flavors). This is in fact also why MC manufacturers like Dell provide only a limited range of custom product configurations in practice (Dewan et al. 2003).

Market demand: In the target market, consumers have perfect information about the MC product, and each consumer buys at most one unit. Following the extant literature (e.g., Huang et al. (2014), and Wang et al. (2019)), each consumer holds his own valuation (i.e., the consumer's willingness to pay) as u, which follows a probability distribution function $g(u)$ and a cumulative distribution function $G(u)$. Consumer heterogeneity in product valuations is captured by taking u to be uniformly distributed over $[0, a]$. Notice that the central question addressed in this paper is whether a MC manufacturer should apply 3D printing in its product line for associated customization services, rather than the product misfit. To this end, we exclude the non-uniformity of the consumer preference distribution as a possible explanation of product positioning and assume consumer types are distributed uniformly. That is, every consumer type has a distinct ideal MC product (regarding the product variety level rather than the quality). Given that consumer types follow uniform distribution, their ideal products are also distributed uniformly. As a result, when the MC manufacturer chooses to provide a certain product variety level, it is not because more consumers have that product variety level as their ideal MC product than any other (i.e., demand-side variety). Instead, it will be the result of the MC manufacturer's manufacturing flexibility considerations (i.e., supply-side variety). Similar practices of the uniformly distributed consumer valuations can also be found in various extant operational research like Perdikaki and Swaminathan (2013), Jiang et al. (2017), Kremer et al. (2017), Letizia et al. (2018), and Wu (2019).

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[11] Given that the flexibility cost for MC is defined as the cost induced by the product variety level of final MC products, we use the term "*the product variety cost*" interchangeably throughout the whole paper.

By providing a variety level v, the MC manufacturer enhances the consumer's willingness to pay by θv (i.e., *the ready-made product variety enjoyment*)[12], where θ is the consumer's willingness to pay for the variety level of the MC product. Such a product variety-induced consumer preference is supported by literature like Bohlmann et al. (2002). Accordingly, a consumer gets the utility of $U_{\overline{3D}} = u - p + \theta v$ from purchasing the MC product without the integration of the 3D printing technology. As a result, we can get the demand of the MC product as $d_{\overline{3D}} = \int_{p-\theta v}^{a} g(u)du = \frac{1}{a}(a + \theta v - p)$. In addition, to ensure a profitable business of MC, we have $a > c$ in this paper; as otherwise, a consumer will never purchase if their willingness to pay for the MC product is low. We can then have the objective function of the MC manufacturer and the consumer surplus as:

$$\max_{v \geq 0, p \geq 0} \pi_{\overline{3D}} = (p - c)d_{\overline{3D}} - \frac{kv^2}{2}. \tag{1}$$

$$CS_{\overline{3D}} = \int_{p-\theta v}^{a} U_{\overline{3D}} g(u)du = \frac{1}{2a}[a - (p - \theta v)]^2. \tag{2}$$

3.2. MC Operations with 3D Printing

Given the overwhelming trend of 3D printing across various industries nowadays (e.g., the automotive industry and the fashion industry), we next consider the new MC operations mode with the support of 3D printing for the customization process.[13] As illustrated in Table 1, the basic product is mass produced, which is the same as the traditional MC. While given the unique capacity to create shapes without molds, 3D printing rather than the traditional manufacturing system is then applied to support MC by printing different end-use product variants (i.e., components) based on the individual consumer's customization requirement. The extra flexibility cost for MC (i.e., the product variety cost) with the use of 3D printing is $C_{3D}(v) = F + \alpha v$, where F is the fixed 3D printers purchasing cost, and αv is the 3D printing development cost for 3D designs (or 3D schematics) and production plans. The developing cost, with α as the sensitivity of the cost with respect to the MC product's variety level v, is linear in the MC product's variety level. This addresses the practices that 3D printing begins with a 3D CAD file and creates the product by adding layers of materials to the 3D printer (e.g., polymers, resins, or powders) until the final shape is complete (Erickson, 2019; Song and Zhang, 2019). The 3D printing development cost therefore is linear to the MC product's variety level while independent of the quantity of end-use product variants being printed. That is, 3D printing makes it economically feasible for customization (Weller et al., 2015; Friesike et al., 2019) and offers the product variety at (close to) zero marginal cost of

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[12] The traditional MC is known as offering consumers a customization choice from a set of ready-made offerings, based on a standardized range of components or allowable features (Ramdas, 2003). In this paper, we define this as *the ready-made product variety enjoyment*, which captures the value of the mass-customized product and reflects the limited engagement that consumers can have in the product design process of the traditional MC. To enhance clarity, detailed definitions are provided in Table A3 in Appendix A.

[13] Notice that although we exclusively compare the pure 3D printing system with the pure traditional manufacturing system for the customization process in MC, we also explore the hybrid customization process which includes both in Section 5.4. Besides, detailed comparisons on the respective operational features of traditional and 3D printing MC systems and relevant model formulations are provided in Table A4 in Appendix A.

diseconomies (Baumers and Holweg, 2019). The reliability of such a cost structure can be reflected in the applications of 3D printing in the single-unit or very low-volume production across a variety of sectors ranging from prosthetics, dental implants, and hearing aids (Petrick and Simpson, 2013), and is also supported by the literature like Arbabian and Wagner (2020).

In addition, product design nowadays has already expanded to include hobbyists and prosumers. Empirical research such as Lakhani and Wolf (2005), Franke et al. (2010), and Raasch and von Hippel (2013) has extensively shown that users derive extra fun from engaging in innovation processes. 3D printing provides consumers the flexibility to engage in the design process of the MC product with innovative customization which is beyond the ready-made product variety offerings provided by the MC manufacturer. Following user innovation theory and the self-congruency theory, the consumers enjoy extra *self-design fun* by a utility f, $f > 0$.[14] *The self-design fun* is defined as the value of mass customization experience and reflects the additional self-expressiveness enjoyment brought by the flexibility of innovative customization design under 3D printing. *The self-design fun* is hence inherently different from *the ready-made product variety enjoyment* in the traditional MC. In practice, the German group BMW and the high-end furniture company Poltrona Frau also highlight the additional self-design fun under their 3D printing supported MC programs. As the enjoyment is for the mass customization experience in the product design process regardless of the outcome, the self-design fun is reflected as a constant. As a result, the utility that a consumer gets from purchasing the 3D printing supported MC product follows $U_{3D} = u - p + \theta v + f$. Accordingly, the demand for the MC product is updated as $d_{3D} = \int_{p-\theta v-f}^{a} g(u)du = \frac{1}{a}(a + \theta v + f - p)$. We then have the objective function of the MC manufacturer and the consumer surplus as:

$$\max_{v\geq 0, p\geq 0} \pi_{3D} = (p - c)d_{3D} - (F + \alpha v). \tag{3}$$

$$CS_{3D} = \int_{p-\theta v-f}^{a} U_{3D}\, g(u)du = \frac{1}{2a}[a - (p - \theta v - f)]^2. \tag{4}$$

4. Optimal Strategies and Influences of 3D Printing

We first explore RQ 1: Should 3D printing be employed in MC operations? What are the influences of 3D printing? Comparisons between the cases with and without 3D printing are conducted next.

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[14] Notice that extending to the case with two different segments of consumers ($j = H, L$) (e.g., by following Iyer (1998) and Jain and Bala (2018)) which vary in their willingness to pay for the variety level of the MC product and the self-design fun does not influence the reliability of our results. Specifically, innovative consumers ($j = H$, with the proportion of α) enjoy the self-design fun (f) and hold a higher willingness to pay for the variety level (θ^H). While traditional consumers ($j = L$, with the proportion of $(1 - \alpha)$) do not benefit from the self-design fun and hold a lower willingness to pay for the variety level (θ^L). The exogenous and static proportion of innovative consumers (α) captures the empirical results in the National Survey Data as released in Gambardella et al. (2017). We can then derive the demand for the MC product as $d_{3D} = \int_{p-\theta v-f}^{a} g(u)du = \frac{1}{a}\{a + [\alpha\theta^H + (1-\alpha)\theta^L]v + \alpha f - p\}$. It can therefore be proved that our findings are robust.

4.1. Optimal Strategies

With the condition of $k > \frac{\theta^2}{2a}$ for the case without 3D printing, we have the respective optimal strategies under both case without 3D printing and the case with 3D printing as Table 2.

Table 2. Optimal strategies in basic models.

	MC without 3D Printing	MC with 3D Printing
Optimal product variety level	$v^*_{\overline{3D}} = \frac{\theta(a-c)}{2ak-\theta^2}$;	$v^*_{3D} = 1$;
Optimal retail price	$p^*_{\overline{3D}} = \frac{ak(a+c)-\theta^2 c}{2ak-\theta^2}$;	$p^*_{3D} = \frac{a+c+f+\theta}{2}$;
Market demand	$d^*_{\overline{3D}} = \frac{k(a-c)}{2ak-\theta^2}$;	$d^*_{3D} = \frac{a+f+\theta-c}{2a}$;
Expected profit of the MC manufacturer	$\Pi^*_{\overline{3D}} = \frac{k(a-c)^2}{2(2ak-\theta^2)}$;	$\Pi^*_{3D} = \frac{(a+f+\theta-c)^2}{4a} - F - \alpha$;
Consumer surplus	$CS^*_{\overline{3D}} = \frac{ak^2(a-c)^2}{2(2ak-\theta^2)^2}$;	$CS^*_{3D} = \frac{(a+f+\theta-c)^2}{8a}$.

4.2. Influences of 3D Printing

By comparing the optimal strategies shown in Table 2, we have Proposition 1.[15]

Proposition 1. a) $d^*_{3D} > d^*_{\overline{3D}}$ if and only if $f > \frac{\theta^2(a-c)-\theta(2ak-\theta^2)}{2ak-\theta^2}$, otherwise $d^*_{3D} < d^*_{\overline{3D}}$; b) $\Pi^*_{3D} > \Pi^*_{\overline{3D}}$ if and only if $\alpha < \frac{(2ak-\theta^2)(a+f+\theta-c)^2-2ak(a-c)^2}{4a(2ak-\theta^2)} - F$, otherwise $\Pi^*_{3D} < \Pi^*_{\overline{3D}}$; c) $CS^*_{3D} > CS^*_{\overline{3D}}$ if and only if $f > \frac{\theta^2(a-c)-\theta(2ak-\theta^2)}{2ak-\theta^2}$, otherwise $CS^*_{3D} < CS^*_{\overline{3D}}$.

As a common belief, when the product variety level increases, the distance between a consumer's taste and the MC product decreases, which should benefit the consumer (Çil and Pangburn, 2017). As an example, the traditional footwear products of Adidas for everyday consumers come in single form and discrete size. While with 3D printing, Adidas can customize its everyday footwear products into the same comfort and performance even as the ones for elite athletes, by taking into account the unique feet-shapes of consumers, as well as their weights, postures, and even styles of walking.[16] Proposition 1, however, reveals that 3D printing can either be beneficial or harmful. As can be seen from Table 2, although adopting 3D printing can contribute to a maximum product variety level (i.e., $v^*_{3D} = 1$), a higher consumer's willingness to pay for the traditional ready-made product variety enjoyment may not necessarily contribute to more consumer surplus. Instead, 3D printing can

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[15] As a remark, assuming the "traditional MC" and "3D printing supported MC" both follow linear regression or both follow quadratic regression does not influence the insights of this paper. In fact, by making $C_{\overline{3D}}(v) = kv$ and $C_{3D}(v) = F + \alpha v$ (for linear regression) or $C_{\overline{3D}}(v) = \frac{kv^2}{2}$ and $C_{3D}(v) = F + \frac{\alpha v^2}{2}$ (for quadratic regression, with $\alpha < k$), our analysis shows that we have similar findings such as: 1) When the self-design fun f is sufficiently large, $d^*_{3D} > d^*_{\overline{3D}}$, $CS^*_{3D} > CS^*_{\overline{3D}}$; 2) When the flexibility cost for MC in the 3D Printing supported MC is sufficiently small, $\Pi^*_{3D} > \Pi^*_{\overline{3D}}$.

[16] Consumers feet are different and their strides also vary, both of which can thus influence the performance of footwear products. In addition, even with the same product size, a consumer with the weight of 250 pounds will need different foot-support than a consumer weighing 150 pounds. This variety challenge, however, can be addressed by 3D printing. The midsole in the Futurecraft 4D series of Adidas, for instance, is a 3D-printed polyurethane elastomer. Its lattice structure varies in density, and therefore can flexibly give the consumer better foot support and cushioning than other everyday series like the regular Ultra Boosts in Adidas, the midsole of which is made of single-density foam.

stimulate a larger market demand and more consumer surplus if and only if the self-design fun is sufficiently large. This appeals the MC manufacturer's close attention to the role of the self-design fun. The finding that adopting 3D printing can help achieve a higher profit level to the MC manufacturer only when the restructured marginal cost with respect to the MC product's variety level is not too large also reveals another restricted advantage of a high product variety level in MC. Proposition 1 thus complements the extant MC literature by revealing that in addition to the costs (e.g., for product variety as emphasized in Alptekinoğlu and Corbett (2008)), the MC manufacturer should also pay close attention to the self-design fun (i.e., the mass customization experience) in MC. This complements the extant research on MC.

Theorem 1. *A maximized product variety level brought by 3D printing may not necessarily contribute to the success of MC. Instead, emphasizing the self-design fun can bring obvious advantages to 3D printing supported MC programs*.

Theorem 1 critically highlights the different roles of the value of the mass-customized product (i.e., the traditional ready-made product variety enjoyment) and the value of the mass customization experience for innovative customization design (i.e., the self-design fun). While the traditional ready-made product variety enjoyment has been widely emphasized in MC, the attention to the self-design fun for innovative customization design remains relatively limited. Theorem 1 is thus of great importance to MC operations, especially for the MC manufacturers who emphasize affordable MC products, an example of which is Adidas.

4.3. Values of Self-Design Fun and Product Variety Level

In this subsection, we explore *the values of 3D printing* (i.e., Δd, $\Delta \Pi$ and ΔCS) with respect to self-design fun (i.e., f) and the variety level of the MC product (i.e., θ), which are shorted for *the value of self-design fun* and *the value of product variety* for better presentation in later discussions, respectively. Define:

$\Delta d = d_{3D}^{*} - d_{\overline{3D}}^{*}$,

$\Delta \Pi = \Pi_{3D}^{*} - \Pi_{\overline{3D}}^{*}$, and

$\Delta CS = CS_{3D}^{*} - CS_{\overline{3D}}^{*}$.

Proposition 2. *For the values of self-design fun (i.e., f): a)* $\frac{d\Delta d}{df} > 0$*; b)* $\frac{d\Delta \Pi}{df} > 0$*; c)* $\frac{d\Delta CS}{df} > 0$.

Proposition 2 explains further how the self-design fun helps MC practices. For instance, together with Proposition 1, we know that when the MC manufacturer's product variety marginal cost under 3D printing is not too large (i.e., $\alpha < \frac{(2ak-\theta^2)(a+f+\theta-c)^2-2ak(a-c)^2}{4a(2ak-\theta^2)} - F$), a higher level of self-design fun ($f > \frac{\theta^2(a-c)-\theta(2ak-\theta^2)}{2ak-\theta^2}$) can contribute to *a higher value of 3D printing* with respect to the MC manufacturer's optimal profit and consumer surplus (i.e., $\Delta\Pi$ and ΔCS).[17] While when the traditional MC brings more profits to the MC manufacturer (when $\alpha > \frac{(2ak-\theta^2)(a+f+\theta-c)^2-2ak(a-c)^2}{4a(2ak-\theta^2)} - F$), the self-design fun can also help reduce the profit difference and the consumer surplus difference between the traditional MC model and the 3D printing MC model. Proposition 2 therefore provides a valuable guideline regarding how to make full use of 3D printing in MC. For instance, in addition to the enhanced manufacturing flexibility, the MC manufacturer should also consider the high-end companies' strategies of highlighting the consumers' experience of actively engaging in the MC product's design process with innovative customization (i.e., the self-design fun) under the 3D printing supported MC (e.g., as emphasized by the high-end auto company BMW and the high-end furniture company Poltrona Frau).

Proposition 3. *For the values of product variety (i.e., θ): a)* $\frac{d\Delta d}{d\theta} > 0$ *if and only if* $c > \frac{4\theta a^2 k-(2ak-\theta^2)}{4\theta ak}$*; b)* $\frac{d\Delta\Pi}{d\theta} > 0$ *if and only if* $f > \frac{2\theta ak(a-c)^2-\left(2ak-\theta^2\right)^2(a-c+\theta)}{(2ak-\theta^2)^2}$ *; c)* $\frac{d\Delta CS}{d\theta} > 0$ *if and only if* $f > \frac{8\theta a^2k^2(a-c)^2-\left(2ak-\theta^2\right)^3(a-c+\theta)}{4a(2ak-\theta^2)^3}$.

Proposition 3 reveals that although 3D printing can contribute to the maximum product variety level (i.e., $v_{3D}^* = 1$ as is shown in Proposition 1), a higher consumer willingness to pay for the MC product's variety level does not necessarily guarantee *a higher value of 3D printing* (i.e., Δd, $\Delta\Pi$ and ΔCS). Instead, only when the self-design fun is sufficiently high (i.e., $f > \max(\frac{2\theta ak(a-c)^2-\left(2ak-\theta^2\right)^2(a-c+\theta)}{(2ak-\theta^2)^2}, \frac{8\theta a^2k^2(a-c)^2-\left(2ak-\theta^2\right)^3(a-c+\theta)}{4a(2ak-\theta^2)^3})$), can a higher consumer willingness to pay for the MC product's variety level achieve *a higher value of 3D printing* regarding the MC manufacturer's optimal profit and consumer surplus (i.e., $\Delta\Pi$ and ΔCS). Proposition 3, together with Proposition 1 and Proposition 2, thus highlights the critical role of the self-design fun in increasing *the value of 3D printing* in MC.

5. Extended Models

Although both MC and 3D printing have the potentials to improve a MC product's alignment with regard to the consumer tastes, they are also at the risk of increasing product uncertainty (regarding how well the product matches the consumer's self-concept and their idealized version). This increased product uncertainty can induce market uncertainties (Dong et al., 2018) and influence MC operations. In this section, we therefore explore how different behaviors of the MC manufacturer and consumers can influence MC operations. Aspects like risk

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[17] As a remark, it can be proved that when $a > c$, $\frac{\theta^2(a-c)-\theta(2ak-\theta^2)}{2ak-\theta^2} > c - \theta - a$ always holds.

attitudes, consumer returns, and the time sensitive behaviors of consumers, and 3D printing in molding will be examined next.

5.1. Risk Attitudes

In the basic model, we exclude the risk attitudes of the MC manufacturer and the consumers. In reality, however, new technologies are associated with uncertainties and risks. Decision makers may also exhibit different risk attitudes towards uncertainties and new technologies (Ma et al., 2009; Smith and Ulu, 2017). Given the uncertainties behind MC and the 3D printing technology, therefore, we focus on RQ2 next by addressing the influences brought by the risk attitudes of the MC manufacturer and the consumers. In following discussions, we define the risk that the individual consumer may face as the “product uncertainty”, which refers to how well the purchased MC product matches their own self-concept as well as their idealized version of the final product. While for the MC manufacturer, the operational risk is basically induced by the market uncertainty.

Model A (A denotes for the attitude towards risks) is discussed next, under which both consumers and the MC manufacturer can be risk averse, risk neutral, or even risk seeking towards the product uncertainties and market uncertainties brought by MC and 3D printing. Following the mainstream literature like Chen et al. (2018), without loss of generality, we assume the market includes N consumers who are interested in the MC product where N is a random variable following a symmetric distribution with mean μ_d and variance σ_d. Under the case without 3D printing, each consumer will buy the MC product if the sum of their valuation u and the willingness to pay for the MC product’s variety level θv is larger than the retail price p plus a risk premium measured by their risk attitude parameter λ_C and the standard deviation of u (σ_u), i.e., $U_{\overline{3D}} = u + \theta v - p - \lambda_C \sigma_u > 0$. The risk attitude parameter λ_C is positive if the consumer is risk averse, 0 if the consumer is risk neutral, and negative if the consumer is risk seeking. The property of a constant risk attitude parameter is commonly adopted in risk attitude literature like Gallego et al. (2015). For a given retail price p, therefore, the number of consumers who will buy the MC product is $d_{\overline{3D}}^{MA} = N \int_{(p+\lambda_C \sigma_u)-\theta v}^{a} g(u) du$. N is randomly distributed with mean μ_d. Taking expectation with respect to N, the expected number of consumers who will buy the MC product at a retail price p for the case without 3D printing is: $E\left[d_{\overline{3D}}^{MA}\right] = E(\int_{(p+\lambda_C \sigma_u)-\theta v}^{a} g(u) du) = \frac{\mu_d}{a}[a + \theta v - (p + \lambda_C \sigma_u)]$. Similar to previous discussions, to ensure a profitable business of MC, we have $a > c + \lambda_C \sigma_u$ in later sections. We have the MC manufacturer’s profit as: $\pi_{\overline{3D}}^{MA} = N(p - c) \int_{(p+\lambda_C \sigma_u)-\theta v}^{a} g(u) du - \frac{kv^2}{2}$. The operational risk is quantified by the variance of the MC manufacturer’s profit $V\left(\pi_{\overline{3D}}^{MA}\right)$. Taking variance with respect to N, we have: $V\left(\pi_{\overline{3D}}^{MA}\right) = [\sigma_d (p - c) \int_{(p+\lambda_C \sigma_u)-\theta v}^{a} g(u) du]^2$. It is straightforward that the standard deviation of the MC manufacturer’s profit is:

$SD(\pi_{3D}^{MA}) = \sqrt{V(\pi_{3D}^{MA})}$. We denote the MC manufacturer's risk attitude parameter as λ_M. Similarly, we have $\lambda_M > 0$ if the MC manufacturer is risk averse, $\lambda_M = 0$ if the MC manufacturer is risk neutral, and $\lambda_M < 0$ if the MC manufacturer is risk seeking. Besides, in order to make (5) and (6) reasonable, the MC manufacturer's risk attitude parameter λ_M cannot be extremely big, which is bounded by $\lambda_M < \frac{\mu_d}{\sigma_d}$. Following Chiu and Choi (2016), we define the mean-risk (MR) objective function of the MC manufacturer for the case without 3D printing as Φ_{3D}^{MA}, which shows the MC manufacturer's trade-off between "expected profit" and the risks related to "variance of profit". To enhance the presentation, we use the term "MR benefit" (MRB) to denote the MR objective function value.

$$\Phi_{3D}^{MA} = E[\pi_{3D}^{MA}] - \lambda_M SD(\pi_{3D}^{MA}) = (\mu_d - \sigma_d\lambda_M)(p-c)\int_{(p+\lambda_C\sigma_u)-\theta v}^{a} g(u)du - \frac{kv^2}{2} \quad . \tag{5}$$

Following the same logic, with 3D printing, the expected market demand of the MC product and the MRB function of the MC manufacturer become:

$$E[d_{3D}^{MA}] = \int_{(p+\lambda_C\sigma_u)-\theta v-f}^{a} g(u)du = \frac{\mu_d}{a}[a + \theta v + f - (p + \lambda_C\sigma_u)].$$

$$\Phi_{3D}^{MA} = E[\pi_{3D}^{MA}] - \lambda_M SD(\pi_{3D}^{MA}) = (\mu_d - \sigma_d\lambda_M)(p-c)\int_{(p+\lambda_C\sigma_u)-\theta v-f}^{a} g(u)du — (F + \alpha v) \quad . \tag{6}$$

With the condition of $k > \frac{\theta^2(\mu_d - \sigma_d\lambda_M)}{2a}$ for the case without 3D printing, the optimal strategies under the case without 3D printing and the case with 3D printing are then given as Table 3.

Table 3. Optimal strategies under Model *A*.[18]

	MC without 3D Printing	**MC with 3D Printing**
Optimal product variety level	$v_{3D}^{MA*} = \frac{\theta(\mu_d-\lambda_M\sigma_d)(a-c-\lambda_C\sigma_u)}{2ak-\theta^2(\mu_d-\lambda_M\sigma_d)}$;	$v_{3D}^{MA*} = 1$;
Optimal retail price	$p_{3D}^{MA*} = \frac{ak(a+c)-\theta^2(\mu_d-\lambda_M\sigma_d)c-ak\lambda_C\sigma_u}{2ak-\theta^2(\mu_d-\lambda_M\sigma_d)}$;	$p_{3D}^{MA*} = \frac{a+\theta+f-\lambda_C\sigma_u+c}{2}$;
Market demand	$E[d_{3D}^{MA*}] = \frac{\mu_d k(a-c-\lambda_C\sigma_u)}{2ak-\theta^2(\mu_d-\lambda_M\sigma_d)}$;	$E[d_{3D}^{MA*}] = \frac{\mu_d(a+\theta+f-\lambda_C\sigma_u-c)}{2a}$;
Expected profit of the MC manufacturer	$E[\Pi_{3D}^{MA*}] = \frac{k(a-c-\lambda_C\sigma_u)^2[2\mu_d ak-\theta^2(\mu_d-\lambda_M\sigma_d)^2]}{2[2ak-\theta^2(\mu_d-\lambda_M\sigma_d)]^2}$;	$E[\Pi_{3D}^{MA*}] = \frac{\mu_d(a+\theta+f-\lambda_C\sigma_u-c)^2}{4a} - F - \alpha$;
Optimal MR benefits of the MC manufacturer	$\Phi_{3D}^{MA*} = \frac{(\mu_d-\lambda_M\sigma_d)k(a-c-\lambda_C\sigma_u)^2}{2[2ak-\theta^2(\mu_d-\lambda_M\sigma_d)]}$;	$\Phi_{3D}^{MA*} = \frac{(\mu_d-\lambda_M\sigma_d)(a+\theta+f-\lambda_C\sigma_u-c)^2}{4a} - F - \alpha$;
Consumer surplus	$E[CS_{3D}^{MA*}] = \frac{\mu_d ak^2(a-c-\lambda_C\sigma_u)^2}{2[2ak-\theta^2(\mu_d-\lambda_M\sigma_d)]^2}$;	$E[CS_{3D}^{MA*}] = \frac{\mu_d(a+\theta+f-\lambda_C\sigma_u-c)^2}{8a}$;

Proposition 4. *a) If the self-design fun f is sufficiently large (i.e., $f > \underline{f}^{MA}$), $E[d_{3D}^{MA*}] > E[d_{3D}^{MA*}]$; b) If the MC product's 3D printing supported marginal variety cost α is sufficiently small (i.e., $\alpha < \overline{\alpha}^{MA}$), $E[\Pi_{3D}^{MA*}] > E[\Pi_{3D}^{MA*}]$; c) If the self-design fun f is sufficiently large (i.e., $f > \underline{f}^{MA}$), $E[CS_{3D}^{MA*}] > E[CS_{3D}^{MA*}]$.*

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[18] The optimal strategies under the considerations of the MC manufacturer's risk attitude only (*Model A1*) and the ones under the considerations of the consumers' risk attitude only (Model *A2*) are provided in Appendix B. Based on the results shown in Appendix B, it can be found that the findings under both Model *A1* and Model *A2* (as two special cases of Model *A*) are similar to Model *A*. We therefore only present Model *A* in the mainbody.

Proposition 4 proves the robustness of our findings in Proposition 1 and Theorem 1 under the consideration of the risk attitudes behaviors of the MC manufacturer and the consumers, which can be risk averse, risk neutral or risk seeking. For instance, when the self-design fun is sufficiently low, the MC manufacturer should in fact consider the traditional MC program regardless of the achievement of a higher product variety level under 3D printing. Especially, this also helps to avoid a higher operations risk level induced by a higher demand variation.

Proposition 5. *For the MR benefits of the MC manufacturer: When the 3D supported MC product's marginal variety cost* α *is sufficiently small (i.e.,* $\alpha < \overline{\alpha}_B^{MA}$*),* $\Phi_{3D}^{MA*} > \Phi_{\overline{3D}}^{MA*}$.

Proposition 5 again addresses the MC literature's concerns on cost and effectiveness of product variety (e.g., Alptekinoğlu and Corbett (2008)) and reveals that taking the risk attitudes into considerations, 3D printing can bring more benefits to the MC manufacturer also only when the MC product's marginal variety cost under 3D printing is sufficiently small. This is consistent with the cost concern of MC as raised in Proposition 1. Together with previous findings, Proposition 5 offers a valuable insight that despite the risk attitudes of the MC manufacturer and consumers, the product variety cost and variety extensions should always be carefully weighed in MC operations, no matter whether it is supported by new technologies like 3D printing or not.

Proposition 6. *a) For the values of self-design fun (i.e.,* f*):* $\frac{d\Delta\Phi^{MA}}{df} > 0$, *and* $\frac{d\Delta E[CS]^{MA}}{df} > 0$*; b) For the values of product variety (i.e.,* θ *):* $\frac{d\Delta\Phi^{MA}}{d\theta} > 0$ *if and only if* $f > \frac{2\theta ak(a-c-\lambda_C\sigma_u)^2(\mu_d-\sigma_d\lambda_M)-[2ak-\theta^2(\mu_d-\sigma_d\lambda_M)]^2(a-c+\theta-\lambda_C\sigma_u)}{[2ak-\theta^2(\mu_d-\sigma_d\lambda_M)]^2}$, $\frac{d\Delta E[CS]^{MA}}{d\theta} > 0$ *if and only if* $f > \frac{8\theta a^2k^2(a-c-\lambda_C\sigma_u)^2(\mu_d-\sigma_d\lambda_M)-[2ak-\theta^2(\mu_d-\sigma_d\lambda_M)]^3(a-c+\theta-\lambda_C\sigma_u)}{[2ak-\theta^2(\mu_d-\sigma_d\lambda_M)]^3}$.

Proposition 6 proves the robustness of Proposition 2 and Proposition 3. As can be seen from above, the decision of introducing 3D printing into MC is not always beneficial. Instead, it should be carefully evaluated by taking the values of self-design fun and product variety into considerations. In particular, Proposition 6 and Proposition 5 together also highlight a new implication which complements base models. Under a sufficiently small marginal product variety cost (i.e., $\alpha < \overline{\alpha}_B^{MA}$), the risk-seeking attitudes (of the MC manufacturer and consumers) can contribute to a more distinct advantage of self-design fun than the risk-averse and risk-neutral attitude counterparts in helping realize a higher level of MRB to the MC manufacturer and achieve more consumer surplus.[19] That is, the risk-seeking customer's incentive to take the risks of product uncertainties makes them value self-design fun more and be more willing to pay higher premiums for it. This can make a 3D printing based MC more successful. While a customer who is less risk-seeking or more risk-averse prefers the traditional MC product and shows fewer interest in self-design fun. These findings provide important

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[19] This can be derived by comparing the case when $\lambda_M < 0$ ($\lambda_C < 0$) to the cases when $\lambda_M > 0$ ($\lambda_C > 0$) and $\lambda_M = 0$ ($\lambda_C = 0$), for $\frac{d\Delta\Phi^{MA}}{df}$ and $\frac{d\Delta E[CS]^{MA}}{df}$.

implications in tackling the risks induced by demand uncertainties, which is emphasized in the literature (e.g., see, Asian and Nie (2014)). Theorem 2 summarizes the core findings.

Theorem 2. *Compared to the scenario when the MC manufacturer and consumers are risk averse or risk neutral: With the marginal product variety cost is sufficiently small (resp. big), a higher self-design fun can yield a higher (resp. lower) level of MRB to the MC manufacturer and also a higher level of consumer surplus when the MC manufacturer and consumers are risk seeking.*

5.2 Consumer Returns: Circular Economy and Sustainability

We previously do not consider consumer returns. Given the popularity of full refund policies in MC practices (e.g., "Nike By You"), we next explore RQ 3 and investigate the impacts of consumer returns (Model *CR*, with *CR* denotes for consumer returns). A full refund policy is applied under both the cases without and with 3D printing, and the role of 3D printing in addressing the low salvage value of consumer returns (owing to the customization action) is discussed. The risk attitudes of consumers are still considered below given the inevitable uncertainty associated with MC products. As consumer returns increases operational risks (Xu et al. 2015), we also continue to take into account of the MC manufacturer's risk attitude in the following discussions. Implications for the case with a risk-neutral MC manufacturer (or risk-neutral consumers) can be found by setting $\lambda_M = 0$ (or $\lambda_C = 0$). Besides, prior literature like Pinçe et al. (2016) show that the consumer return rates in practice are similar across all brands, which is consistently in the range of 8–12%. We therefore consider an exogenous consumer return rate γ. This is also supported by the literature like Li and Rajagopalan (1998).

a) Consumer Returns under Traditional MC (without 3D Printing)

Following the literature, we consider a zero salvage value of the consumer returned items under the traditional MC. Accordingly, the MRB function of the MC manufacturer is:

$$\Phi_{\overline{3D}}^{CR} = E\left[\pi_{\overline{3D}}^{CR}\right] - \lambda_M SD\left(\pi_{\overline{3D}}^{CR}\right) = (\mu_d - \sigma_d \lambda_M)[(1-\gamma)p - c] \int_{(p+\lambda_C\sigma_u)-\theta v}^{a} g(u)du - \frac{kv^2}{2} \quad . \tag{7}$$

b) Consumer Returns under the 3D Printing supported MC

As a recent report published in California Management Review, Unruh (2018) shows that one dominant beauty of 3D printing is materials parsimony, given that 3D printing use primarily one material only to produce the product and the end-of-life product can be substantially reused to print another product. A company called Local Motors, for instance, 3D prints 80% of its cars from a single material; and at the end of the automobile's life, it can collect as high as 80% of that vehicle and put it back into the manufacturing process for another vehicle, or some other products. In the technical white paper of 'HP Metal Jet technology'[20], HP also has highlights the high reusability of materials in its 3D printing MC program. To address this unique advantage of 3D printing, therefore, we assume a salvage value of s can be achieved from each consumer returned product under the 3D

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[20] See https://h20195.www2.hp.com/v2/getpdf.aspx/4AA7-3333ENW.pdf. (Accessed May, 2020)

printing supported MC ($0 < s < c$), which can be the unite cost saving in production for another new MC product under the circular economy. Such a positive cost saving through remanufacturing is also supported by the literature (e.g., Hong et al. (2017)). Consequently, we have the MRB function of the MC manufacturer as:

$$\Phi_{3D}^{CR} = E\left[\pi_{3D}^{CR}\right] - \lambda_M SD\left(\pi_{3D}^{CR}\right) = (\mu_d - \sigma_d\lambda_M)[(1-\gamma)p - c + \gamma s]\int_{(p+\lambda_C\sigma_u)-\theta v-f}^{a} g(u)du - (F + \alpha v)\ . \quad (8)$$

Accordingly, we have the optimal strategies as given in Table 4. Similarly, for the case without 3D printing, the results are under the condition of $k > \frac{\theta^2(1-\gamma)(\mu_d-\sigma_d\lambda_M)}{2a}$, and we always have a consumer willingness to pay as $a > \frac{c+(1-\gamma)\lambda_C\sigma_u}{(1-\gamma)}$.

Table 4. Optimal strategies under Model *CR*.

	MC without 3D Printing	**MC with 3D Printing**
Optimal product variety level	$v_{3D}^{CR*} = \frac{\theta(1-\gamma)(\mu_d-\lambda_M\sigma_d)[(1-\gamma)(a-\lambda_C\sigma_u)-c]}{2ak(1-\gamma)-\theta^2(1-\gamma)^2(\mu_d-\lambda_M\sigma_d)}$;	$v_{3D}^{CR*} = 1$;
Optimal retail price	$p_{3D}^{CR*} = \frac{ak(1-\gamma)(a+c-\lambda_C\sigma_u)-\theta^2(1-\gamma)(\mu_d-\lambda_M\sigma_d)c}{2ak(1-\gamma)-\theta^2(1-\gamma)^2(\mu_d-\lambda_M\sigma_d)}$;	$p_{3D}^{CR*} = \frac{(1-\gamma)(a+\theta+f-\lambda_C\sigma_u)+c-\gamma s}{2(1-\gamma)}$;
Optimal MR benefits of the MC manufacturer	$\Phi_{3D}^{CR*} = \frac{(\mu_d-\lambda_M\sigma_d)k[(1-\gamma)(a-\lambda_C\sigma_u)-c]^2}{2[2ak(1-\gamma)-\theta^2(1-\gamma)^2(\mu_d-\lambda_M\sigma_d)]}$;	$\Phi_{3D}^{CR*} = \frac{(\mu_d-\lambda_M\sigma_d)[(1-\gamma)(a+\theta+f-\lambda_C\sigma_u)-c+\gamma s]^2}{4a(1-\gamma)} - F - \alpha$;
Consumer surplus	$E[CS_{3D}^{CR*}] = \frac{\mu_d ak^2[(1-\gamma)(a-\lambda_C\sigma_u)-c]^2}{2[2ak(1-\gamma)-\theta^2(1-\gamma)^2(\mu_d-\lambda_M\sigma_d)]^2}$;	$E[CS_{3D}^{CR*}] = \frac{\mu_d[(1-\gamma)(a+\theta+f-\lambda_C\sigma_u)-c+\gamma s]^2}{8a(1-\gamma)^2}$;

Proposition 7. *a)* $v_{3D}^{MA*} = v_{3D}^{CR*} = 1$; *b)* $v_{3D}^{MA*} > v_{3D}^{CR*}$ *if and only if* $\lambda_C < \frac{2a^2k-c\theta^2(\mu_d-\lambda_M\sigma_d)}{2ak\sigma_u}$.

Results in Table 4 shows the robustness of previous findings concerning the advantages of 3D printing in achieving a higher benefit level to both the MC manufacturer and the consumers under the condition of a high self-design fun and a relatively low product variety marginal cost.[21] While in addition to that, taking into account the consumer returns, another new insight is also generated. As can be seen from Proposition 7, a 3D printing supported MC can help achieve a maximized product variety level of the MC product even in front of the full refund policy and the inevitable consumer returns. That is, the risks induced by consumer returns will not influence the MC manufacturer's optimal decision on the product variety level. While for the traditional MC, launching the full refund policy may reduce the optimal product variety level if the consumers are less risk averse or more risk seeking (i.e., $\lambda_C < \frac{2a^2k-c\theta^2(\mu_d-\lambda_M\sigma_d)}{2ak\sigma_u}$). Furthermore, as we can see from Table 4, a higher salvage value of the 3D printing supported MC product can bring more MRB to the MC manufacturer and yield a higher level of consumer surplus. The findings in Proposition 7 thus proves the beauty of 3D printing in materials parsimony as highlighted in Unruh (2018). This innovative finding can contribute to the development of circular economy and sustainability of MC programs under uncertainties, and serve as an important guideline to the MC manufacturer who offers full refund policies (e.g., Nike). Besides, it also relates to the sustainability

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[21] This can be proved by following the same logic as Proposition 1 and Proposition 4. As the results are similar, we do not repeatedly show the discussions.

literature on the recycling of consumer returns (e.g., Feng et al. (2017)) as well as the salvage values of products (e.g., Shi et al. (2018), and Li et al. (2019)). Theorem 3 presents the results.

Theorem 3. *The flexibility of 3D printing in remanufacturing the consumer returned items ensures its unique capability in achieving a maximized product variety level of the MC product even under the consideration of the operational risks induced by consumer returns.*

5.3 Time Sensitive Behaviors: Customization Lead-time in the Digital Age

Given the nature of the make-to-order step for MC products, the customization lead-time is viewed as an important shortcoming of MC (Mendelson and Parlaktürk, 2008a). In this subsection, we consider an average customization lead-time of t in the traditional MC (Model L, with L denoting the customization lead-time), which can however be eliminated in a 3D printing supported MC program. For instance, prior literature such as Berman (2012) shows that 3D printers can produce simple objects (e.g., a gear) in less than one hour. Besides, as released in an official report in HP Press Centre[22], its Metal Jet 3D printing platform shows superb performance in unlocking the speed of its MC programs' overall lead-time (e.g., by reducing the cycle time for the production of different parts). Implementing HP Metal Jet 3D printing technique, the German automaker Volkswagen, for instance, is known for its shortened lead-time spent on building extra custom tooling for new parts production of its MC vehicles. Following Mendelson and Parlaktürk (2008a), we assume that the consumer is sensitive to the waiting time (i.e., the customization lead-time in this paper). The consumer's disutility of the waiting time is ξt, where ξ ($\xi > 0$) is the consumer's sensitivity parameter of waiting. Accordingly, the expected market demand and the MRB function of the MC manufacturer under the traditional MC become:

$$E\left[d_{3D}^{ML}\right] = \int_{(p+\lambda_C\sigma_u+\xi t)-\theta v}^{a} g(u)du = \frac{\mu_d}{a}[a + \theta v - (p + \lambda_C\sigma_u + \xi t)].$$

$$\Phi_{3D}^{ML} = E\left[\pi_{3D}^{ML}\right] - \lambda_M SD\left(\pi_{3D}^{ML}\right) = (\mu_d - \sigma_d\lambda_M)(p - c)\int_{(p+\lambda_C\sigma_u+\xi t)-\theta v}^{a} g(u)du - \frac{kv^2}{2} \quad . \tag{9}$$

Following the same logic as previous sections, with the condition of $k > \frac{\theta^2(\mu_d-\sigma_d\lambda_M)}{2a}$ and $a > c + \lambda_C\sigma_u + \xi t$, we have the optimal strategies of the traditional MC under Model L as:

$$v_{3D}^{ML*} = \frac{\theta(\mu_d-\lambda_M\sigma_d)(a-\lambda_C\sigma_u-c-\xi t)}{2ak-\theta^2(\mu_d-\lambda_M\sigma_d)};\ p_{3D}^{ML*} = \frac{ak(a+c-\lambda_C\sigma_u-\xi t)-\theta^2(\mu_d-\lambda_M\sigma_d)c}{2ak-\theta^2(\mu_d-\lambda_M\sigma_d)};$$

$$\Phi_{3D}^{ML*} = \frac{(\mu_d-\lambda_M\sigma_d)k(a-\lambda_C\sigma_u-c-\xi t)^2}{2[2ak-\theta^2(\mu_d-\lambda_M\sigma_d)]};\ E\left[CS_{3D}^{ML*}\right] = \frac{\mu_d ak^2(a-\lambda_C\sigma_u-c-\xi t)^2}{2[2ak-\theta^2(\mu_d-\lambda_M\sigma_d)]^2}.$$

Proposition 8. *a)* $v_{3D}^{ML*} < v_{3D}^{MA*}$; *b)* $\frac{d\Delta\Phi^{ML}}{dt} > 0$; *c)* $\frac{d\Delta E[CS]^{ML}}{dt} > 0$.

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[22] https://press.ext.hp.com/us/en/press-releases/2018/hp-launches-worlds-most-advanced-metals-3d-printing-technology.html. (Accessed April, 2020)

Comparing with Model *A*, we can see that the previously highlighted conditions of achieving a profitable 3D printing supported MC also hold under Model *L*.[23] Besides, Proposition 8 innovatively reveals an important finding regarding the advantage of 3D printing under the considerations of consumers' time sensitive behaviors. Specifically, in the decision making process, a risk- and time-sensitive consumer trades off the sacrifice from her ideal MC product (which includes the self-design fun and product variety), disutility of product price, product uncertainties, as well as customization waiting. The long customization lead-time in tradition MC programs can therefore reduce the degree of separation between the customized product and the standard product, which weakens the advantages of MC. Prior MC literature like Agrawal et al. (2001) also confirm such a separation in practice. Proposition 8, however, shows that the long customization lead-time in the traditional MC can contribute to more values of 3D printing in MC, as long as it can achieve a high self-design fun and a relatively low marginal product variety cost. This not only provides a crucial implication to the MC manufacturer who is suffering from the long customization lead-time, but also addresses the critical concerns in the manufacturing systems literature with production lead-time and uncertain demand considerations (e.g., Shi et al. (2014)).

Findings in Proposition 8 also address other challenges in MC like supply chain integration. Given that different components in traditional MCs are usually sourced from multiple suppliers (Berman, 2012), it requires a high degree of supply chain integration so as to avoid supply chain disruption. This problem however, can be solved by integrating 3D printing into MC since only a small number of materials are needed (rather than a highly-integrated supply chain), which means relatively low sourcing risks. We then have Theorem 4.

Theorem 4. *Applying 3D printing in MC can enhance the speed of traditional MC programs' overall lead-time. Therefore, 3D printing benefits the MC manufacturer, when the self-design fun is high and the marginal cost of product variety is relatively low.*

5.4 MC With 3D Printing: Molding

Previous discussions explore the application of 3D printing for directly printed end-use product variants (i.e., components) in MC, which address the unique capacity of 3D printing to create shapes without molds. It is widely adopted in manufacturing firms like General Electric, HP, as well as BMW. In practice, the 3D printed parts can also serve as a mold in MC for further customization, rather than the end-use parts. Typical examples can be the clear aligner and retainer market in dentistry (e.g., the dental products by Formlabs)[24] and the custom earbuds market in audiology (e.g., Formlabs' Standard Clear Resin)[25]. This subsection thus considers the application of 3D printing in molding and we call the respective scenario Model *M* (*M* denotes for molding).

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[23] This can be proved by following the same logic as Proposition 4 and Proposition 5.

[24] See https://dental.formlabs.com/indications/thermoformed-clear-aligners-retainers/. (Accessed May, 2020)

[25] Detailed information can be found in https://formlabs.com/industries/audiology/. (Accessed May, 2020)

a) Molding in Traditional MC (without 3D Printing)

Given the long lead-time under the traditional MC, in addition to the standard product, the MC manufacturer also prepares a mold in advance for each MC product, which is for further customization and holds a standard per unit cost m. m includes both the per unit production cost of each mold, together with the inventory holding cost. Accordingly, the MRB function of the MC manufacturer is:

$$\varPhi_{3D}^{MM} = (\mu_d - \sigma_d \lambda_M)(p - c - m) \int_{(p+\lambda_C \sigma_u)-\theta v}^{a} g(u)du - \frac{kv^2}{2}. \tag{10}$$

b) Molding under the 3D Printing supported MC

With the help of 3D printing, the MC manufacturer adopts on-demand printing for each mold based on specific consumer requirements, which consequently induces an overall product variety cost $\tilde{\alpha} v + \frac{\tilde{k} v^2}{2}$. Here, notice that the fixed cost F is the same as the one in previous discussions (e.g., Section 3.2), given that it is for purchasing 3D printers, which should thus be the same no matter whether it is for creating molds or for directly producing the end-use variants. While in the meantime, the extra 3D printing development cost for each mold is updated to be $\tilde{\alpha} v$, and the ("afterwards") customization cost on the 3D printed mold becomes $\frac{\tilde{k} v^2}{2}$. As a result, we have the new MRB function of the MC manufacturer as follows:

$$\varPhi_{3D}^{MM} = (\mu_d - \sigma_d \lambda_M)(p - c) \int_{(p+\lambda_C \sigma_u)-\theta v-f}^{a} g(u)du — (F + \tilde{\alpha} v + \frac{\tilde{k} v^2}{2}). \tag{11}$$

Accordingly, we have the optimal strategies as listed in Table 5, with the condition of $k > \frac{\theta^2(\mu_d - \sigma_d \lambda_M)}{2a}$ for the traditional MC and the condition of $\tilde{k} > \frac{\theta^2(\mu_d - \sigma_d \lambda_M)}{2a}$ for the 3D printing supported MC. In addition, we have a consumer willingness to pay as $a > c + m + \lambda_C \sigma_u$ for the traditional MC and $a > \frac{\tilde{k}(c+\lambda_C \sigma_u - f)+\theta\tilde{\alpha}}{\tilde{k}}$ for the 3D printing supported MC.

Table 5. Optimal strategies under Model *M*.

	MC without 3D Printing	**MC with 3D Printing**
Optimal product variety level	$v_{3D}^{MM*} = \frac{\theta(\mu_d-\lambda_M\sigma_d)(a-c-m-\lambda_C\sigma_u)}{2ak-\theta^2(\mu_d-\lambda_M\sigma_d)}$;	$v_{3D}^{MM*} = \frac{\theta(\mu_d-\lambda_M\sigma_d)(a+f-c-\lambda_C\sigma_u)-2a\tilde{\alpha}}{2a\tilde{k}-\theta^2(\mu_d-\lambda_M\sigma_d)}$;
Optimal retail price	$p_{3D}^{MM*} = \frac{a^2k+[ak-\theta^2(\mu_d-\lambda_M\sigma_d)](c+m)-ak\lambda_C\sigma_u}{2ak-\theta^2(\mu_d-\lambda_M\sigma_d)}$;	$p_{3D}^{MM*} = \frac{a^2\tilde{k}+[a\tilde{k}-\theta^2(\mu_d-\lambda_M\sigma_d)]c+a\tilde{k}(f-\lambda_C\sigma_u)-a\tilde{\alpha}\theta}{2a\tilde{k}-\theta^2(\mu_d-\lambda_M\sigma_d)}$;
Market demand	$E[d_{3D}^{MM*}] = \frac{\mu_d k(a-c-m-\lambda_C\sigma_u)}{2ak-\theta^2(\mu_d-\lambda_M\sigma_d)}$;	$E[d_{3D}^{MM*}] = \frac{\mu_d[\tilde{k}(a+f-c-\lambda_C\sigma_u)-\tilde{\alpha}\theta]}{2a\tilde{k}-\theta^2(\mu_d-\lambda_M\sigma_d)}$;
Optimal MR benefits of the MC manufacturer	$\varPhi_{3D}^{MM*} = \frac{(\mu_d-\lambda_M\sigma_d)k(a-c-m-\lambda_C\sigma_u)^2}{2[2ak-\theta^2(\mu_d-\lambda_M\sigma_d)]}$;	$\varPhi_{3D}^{MM*} =$ $\frac{(\mu_d-\lambda_M\sigma_d)(a+f-c-\lambda_C\sigma_u)[\tilde{k}(a+f-c-\lambda_C\sigma_u)-2\tilde{\alpha}\theta]+2a\tilde{\alpha}^2}{2[2a\tilde{k}-\theta^2(\mu_d-\lambda_M\sigma_d)]} - F$;
Consumer surplus	$E[CS_{3D}^{MM*}] = \frac{\mu_d a k^2(a-c-m-\lambda_C\sigma_u)^2}{2[2ak-\theta^2(\mu_d-\lambda_M\sigma_d)]^2}$;	$E[CS_{3D}^{MM*}] = \frac{\mu_d a[\tilde{k}(a+f-c-\lambda_C\sigma_u)-\tilde{\alpha}\theta]^2}{2[2a\tilde{k}-\theta^2(\mu_d-\lambda_M\sigma_d)]^2}$;

Define : $\Delta v^{MM} = v_{3D}^{MM*} - v_{\overline{3D}}^{MM*}$, $\Delta\varPhi^{MM} = \varPhi_{3D}^{MM*} - \varPhi_{\overline{3D}}^{MM*}$, and $\Delta CS^{MM} = CS_{3D}^{MM*} - CS_{\overline{3D}}^{MM*}$.

Proposition 9. *a)* $v_{3D}^{MM*} = 1$ *if and only if* $f = \frac{2a(\tilde{k}+\tilde{\alpha})-\theta(\mu_d-\lambda_M\sigma_d)(a+\theta-c-\lambda_C\sigma_u)}{\theta(\mu_d-\lambda_M\sigma_d)}$ *; otherwise, if* $f < \frac{2a(\tilde{k}+\tilde{\alpha})-\theta(\mu_d-\lambda_M\sigma_d)(a+\theta-c-\lambda_C\sigma_u)}{\theta(\mu_d-\lambda_M\sigma_d)}$, $v_{3D}^{MM*} < 1$; *b)* $v_{3D}^{MM*} > v_{\underline{3D}}^{MM*}$ *if and only if* $m > \frac{[2a\tilde{\alpha}-\theta(\mu_d-\lambda_M\sigma_d)f][2ak-\theta^2(\mu_d-\lambda_M\sigma_d)]-2a\theta(k-\tilde{k})(\mu_d-\lambda_M\sigma_d)(a-c-\lambda_C\sigma_u)}{\theta(\mu_d-\lambda_M\sigma_d)[2a\tilde{k}-\theta^2(\mu_d-\lambda_M\sigma_d)]}$; *c)* $\frac{d\Delta v^{MM}}{d\lambda_C} > 0$ *if and only if* $k < \tilde{k}$ *, otherwise* $\frac{d\Delta v^{MM}}{d\lambda_C} < 0$.

Similar to other subsections, the optimal strategies in Table 5 verify the robustness of previous findings on the conditions of when 3D printing can help achieve a higher benefit level to both the MC manufacturer and consumers. In the meantime, Proposition 9a) reveals an important finding that different from the end-use product variants printing, applying 3D printing in molding does not always stimulate the maximized product variety level (i.e., $v_{3D}^{MM*} = 1$) of MC. Instead, the MC manufacturer should pay attention to the self-design fun of individual consumers when deciding the optimal product variety level. Besides, according to Proposition 9b), when the standard per unit cost for each mold under the traditional MC (i.e., m) is sufficiently large, having the support of 3D printing can contribute to a higher product variety level of the MC product. In addition, Proposition 9c) indicates that as long as the ("afterwards") customization cost on the 3D printed mold is sufficiently small (i.e., $\tilde{k} < k$), the risk seeking behavior of individual consumers can lead to a larger product variety difference between the traditional MC and the 3D printing supported MC compared to the risk averse counterpart. Proposition 9b) and Proposition 9c) together therefore show that when the target consumers are risk seeking, 3D printing is a catalyst in molding for achieving a higher product variety level of MC (than the traditional MC), if the standard per unit cost for each mold under the traditional MC is high while the afterwards customization cost on the 3D printed mold is low. The healthcare (e.g., dental) products are facing rapidly growing demands with an ever-expanding variety of indications. Proposition 9 thus explains the reasons behind the widespread applications of 3D printing in molding in healthcare (e.g., dentistry and audiology) MCs nowadays. According to the published data in Formlabs, for instance, 3D printing custom jigs via Pankl Racing Systems can significantly reduce molding costs by 12 times (i.e., \$9 - \$28) than the traditionally CNC machined ones (i.e., \$45 - \$340).[26] In addition, the distinct advantage of 3D printing in reducing the overall lead-time under molding is also highlighted in Formlabs, which is reported to be 48 times faster (i.e., 5 to 9 hours) when compared with the 2 to 3 weeks lead-time under the CNC machined MC. This also addresses the significance of our findings in Section 5.3 even under the case for 3D printing in molding.

Proposition 10. *a)* $\Phi_{3D}^{MM*} > \Phi_{\underline{3D}}^{MM*}$ *if and only if* $F < \frac{A(\mu_d-\lambda_M\sigma_d)+[2a\tilde{\alpha}^2-2\tilde{\alpha}\theta(\mu_d-\lambda_M\sigma_d)(a+f-c-\lambda_C\sigma_u)][2ak-\theta^2(\mu_d-\lambda_M\sigma_d)]}{2[2ak-\theta^2(\mu_d-\lambda_M\sigma_d)][2a\tilde{k}-\theta^2(\mu_d-\lambda_M\sigma_d)]}$; *b)* $\frac{d\Delta\Phi^{MM}}{d\lambda_C} > 0$ *if and only if* $m <$

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[26] Interested readers can refer to https://formlabs.com/industries/manufacturing/ for more details. (Accessed May, 2020)

$\frac{(k-\tilde{k})\theta^2(\mu_d-\lambda_M\sigma_d)(a-c-\lambda_C\sigma_u)-(\theta\tilde{\alpha}-\tilde{k}f)[2ak-\theta^2(\mu_d-\lambda_M\sigma_d)]}{k[2a\tilde{k}-\theta^2(\mu_d-\lambda_M\sigma_d)]}$, $\frac{d\Delta\Phi^{MM}}{d\lambda_C} < 0$ *if and only if* $m > \frac{(k-\tilde{k})\theta^2(\mu_d-\lambda_M\sigma_d)(a-c-\lambda_C\sigma_u)-(\theta\tilde{\alpha}-\tilde{k}f)[2ak-\theta^2(\mu_d-\lambda_M\sigma_d)]}{k[2a\tilde{k}-\theta^2(\mu_d-\lambda_M\sigma_d)]}$.

Proposition 10a) highlights the significance of the fixed purchasing cost of the 3D printing technology. In the meantime, Proposition 10b) confirms the finding in Proposition 9 that under a high standard per unit cost for each mold under the traditional MC, the risk seeking behavior of consumers, which may lead to a higher market demand uncertainty level, can make 3D printing in molding bring more "MR beneficial" to the MC manufacturer than the case with risk averse consumers.

Proposition 11. *a)* $CS_{3D}^{MM*} > CS_{\overline{3D}}^{MM*}$ *if and only if* $m > \frac{(\theta\tilde{\alpha}-\tilde{k}f)[2ak-\theta^2(\mu_d-\lambda_M\sigma_d)]-(k-\tilde{k})\theta^2(\mu_d-\lambda_M\sigma_d)(a-c-\lambda_C\sigma_u)}{k[2a\tilde{k}-\theta^2(\mu_d-\lambda_M\sigma_d)]}$, $CS_{3D}^{MM*} < CS_{\overline{3D}}^{MM*}$ *if and only if* $m < \frac{(\theta\tilde{\alpha}-\tilde{k}f)[2ak-\theta^2(\mu_d-\lambda_M\sigma_d)]-(k-\tilde{k})\theta^2(\mu_d-\lambda_M\sigma_d)(a-c-\lambda_C\sigma_u)}{k[2a\tilde{k}-\theta^2(\mu_d-\lambda_M\sigma_d)]}$;*b)* $\frac{d\Delta CS^{MM}}{d\lambda_C} > 0$ *if and only if* $k < \tilde{k}$, $\frac{d\Delta CS^{MM}}{d\lambda_C} < 0$ *if and only if* $k > \tilde{k}$.

Proposition 11 provides further supports for Proposition 9, by revealing the efficiency of 3D printing for producing molds when the standard per unit cost for each mold under the traditional MC is high and consumes are risk seeking. Based on Propositions 9, 10 and 11, we have core insights summarized in Theorem 5.

Theorem 5. *When the traditional MC's standard cost for producing each mold is high but the "afterwards" customization cost on the 3D printed mold is small, applying 3D printing in molding is more beneficial to both the MC manufacturer and consumers in a market with risk seeking consumers than a market with risk averse consumers.*

6. Concluding Remarks and Future Studies

Motivated by the widespread application of 3D printing in MC programs across various industries (e.g., the auto industry and the fashion industry) and the identified research gap, we explore the influences of 3D printing in MC operations. To the best of our knowledge, this paper is the first to investigate the application of 3D printing in MC programs. Conditions of when a 3D printing supported MC program can contribute to more benefits to the MC manufacturer and a higher level of consumer surplus are investigated. In addition, we specifically discuss the roles played by the risk attitudes of the MC manufacturer and consumers, the existence of consumer returns, as well as consumers' time sensitive behaviors. The application of "*3D printing in molding*" is also explored. Operational implications are discussed in the following, together with the directions for future studies.

6.1 Operational Implications

a) ***Values of 3D printing in MC***: Our analyses show that adopting the 3D printing technology can contribute to a maximized product variety level of the MC product. In the meanwhile, however, integrating 3D printing into MC can increase the MC manufacturer's profit level (or MRB for the case when the MC manufacturer is risk sensitive) and consumer surplus only when the consumer's self-design fun is sufficiently large while the marginal product variety cost is not too large. The reason behind is that consumers consider not only on their congruency with the finalized MC product, but also on the self-design fun of 3D printing and the retail price. This appeals the MC manufacturer's close attention to the overall cost of the MC product in practice, which is also true with the consideration of other operational factors like the risk attitudes of the MC manufacturer and the consumers, consumer returns as well as the time sensitive behaviors of consumers.

b) ***Risk attitudes of the MC manufacturer and the consumers***: We find that compared to the risk-averse and risk-neutral attitudes, the risk-seeking behaviors (of the MC manufacturer and consumers) can contribute to a more distinct advantage of self-design fun in helping the MC manufacturer achieve a higher level of MRB and increase consumer surplus. That is because the risk-seeking customer's incentive to take the risks of product uncertainties makes them value self-design fun more, which can make a 3D printing based MC more successful.

c) ***Consumer returns***: Findings in this paper indicate that if the consumers are less risk averse or more risk seeking, offering the full refund policy may reduce the optimal product variety level of the MC product under the traditional MC. This problem, however, can be solved by the beauty of 3D printing's materials parsimony. That is, given that 3D printing use primarily one material to produce the product, it can reduce the complexity of the MC product, which consequently ensure the flexibility of remanufacturing the consumer returned items.

d) ***Time sensitive behaviors***: Applying 3D printing in MC can unlock the speed of traditional MC programs' overall lead-time. 3D printing therefore is of great benefits to the MC manufacturer who is suffering from the long customization lead-time in the traditional MC program, as long as the MC manufacturer can achieve a high self-design fun and a relatively low marginal cost of product variety under the 3D printing supported MC.

e) ***3D printing in molding***: In practice, 3D printing can be applied in MC either for end-use product variants printing or for molding (i.e., creating molds). When the traditional MC's standard cost for each mold is high but the "afterwards" customization cost on the 3D printed mold is small, applying 3D printing in molding can bring more benefits to both the MC manufacturer and consumers in a market with risk seeking consumers than a market with risk averse consumers. Thus, to judge whether 3D printing in molding is especially pertinent relates to the risk attitudes of consumers in the market.

6.2 Limitations and Future Studies

While our model addresses the common challenges like risk attitudes and consumer returns in MC operations, other aspects should be considered in the future. First, we restrict our attention to the application of 3D printing in MC while other new technologies are not considered. In the future, we may explore the application of other advanced technologies and compare the performance with 3D printing. The reliability of advanced technologies (e.g., the probability of failure as emphasized in Nie et al. (2009)) can also be examined. Second, we examine MC operations with symmetric information. However, in practice, the MC manufacturer or the consumers may not obtain all the related information. It therefore can be interesting to examine MC operations in an information asymmetric situation and explore the value of information sharing (Teunter et al. 2018; Zhao et al. 2018). Third, this paper focuses on the economic performance of MC programs at the MC manufacturer level. Given the increasing public emphasis on sustainability over the recent years, the social and environmental benefits of applying new technologies in MC deserve further research, and the role of local governments may also be discussed. For instance, given the increasing number of worldwide disasters and catastrophes over recent decades (Farahani et al. (2020)), the application of 3D printing in MC programs for the emergency events (e.g., COVID-19 pandemic) will be a very interesting topic to explore in future research.

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Appendix A – Supplementary Tables

Table A1. Abbreviations.

$\underline{f}^{MA} = \frac{\theta^2(\mu_d - \lambda_M\sigma_d)(a - c - \lambda_C\sigma_u) - \theta[2ak - \theta^2(\mu_d - \lambda_M\sigma_d)]}{2ak - \theta^2(\mu_d - \lambda_M\sigma_d)}$	$\overline{\alpha}^{MA} = \frac{\mu_d[2ak - \theta^2(\mu_d - \lambda_M\sigma_d)]^2(a + f + \theta - c - \lambda_C\sigma_u)^2 - 2ak(a - c - \lambda_C\sigma_u)^2[2\mu_d ak - \theta^2(\mu_d - \lambda_M\sigma_d)^2]}{4a[2ak - \theta^2(\mu_d - \lambda_M\sigma_d)]^2} - F$
$\overline{\alpha}_B^{MA} = \frac{(\mu_d - \lambda_M\sigma_d)\{[2ak - \theta^2(\mu_d - \lambda_M\sigma_d)](a + f + \theta - c - \lambda_C\sigma_u)^2 - 2ak(a - c - \lambda_C\sigma_u)^2\}}{4a[2ak - \theta^2(\mu_d - \lambda_M\sigma_d)]} - F$	$A = \tilde{k}(a + f - c - \lambda_C\sigma_u)^2[2ak - \theta^2(\mu_d - \lambda_M\sigma_d)] - k(a - c - m - \lambda_C\sigma_u)^2[2a\tilde{k} - \theta^2(\mu_d - \lambda_M\sigma_d)]$

Table A2. Some detailed examples of 3D printing supported MC programs.

MC programs	Details	
HP Metal Jet	*The 3D printing manufacturer:*	HP.
	Product category:	Functional metal parts for auto.
	MC details:	Available mass-customizable parts include items such as individualized key rings as well as exterior-mounted name plates.
	Link: https://press.ext.hp.com/us/en/press-releases/2018/hp-launches-worlds-most-advanced-metals-3d-printing-technology.html	
MINI Yours Customised	*The 3D printing manufacturer:*	The BMW Group.
	Product category:	Vehicles and components.
	MC details:	Consumers can self-design selected components such as indicator inlays and dashboard trim strips, and the components will then be 3D-printed to specification.
	Link: https://www.press.bmwgroup.com/global/article/detail/T0286895EN/	
Razor Maker™ in Procter and Gamble	*The 3D printing manufacturer:*	Formlabs.
	Product category:	The shaving supply and razor brand of Procter and Gamble.
	MC details:	It offers customizable 3D-printed handles of Procter and Gamble razors to consumers, e.g., the look, color and style.
	Link: https://news.pg.com/press-release/pg-corporate-announcements/gillette-partners-formlabs-–-boston-startup-defining-3d-pri	
Poltrona Frau	*The 3D printing manufacturer:*	Protocube Reply.
	Product category:	Furniture and accessories.
	MC details:	Consumers can virtually touch and redefine the selected configuration options in the catalog.
	Link: https://protocube.it/poltrona-frau-new-eshop-3d-configurator/?lang=en	

Table A3. Definitions.

MC systems	Traditional MC System	MC System with 3D Printing
Definitions	*The ready-made product variety enjoyment*: Defined as the value of the mass-customized product. It reflects the limited engagement that consumers can have in the product design process of the traditional MC.	*The self-design fun*: Defined as the value of mass customization experience. It refers to the additional self-expressiveness enjoyment brought by the flexibility of innovative customization design under 3D printing.

Table A4. Respective operational features and model formulation of traditional and 3D printing MC systems.

Operational features	Traditional MC System *Examples: Nike By You (previously titled NikeID), My M&M'S, and Zazzle.com.*	MC System with 3D Printing *Examples: HP Metal Jet, MINI Yours Customised in BMW, and Razor Maker™ in Procter and Gamble.*
Customization technologies	Customized by traditional manufacturing technologies (e.g., computer-aided-design). *Model formulation*: The flexibility cost for product variety is quadratic due to the diseconomies of product variety in production.	Customized by the 3D printing technology. *Model formulation*: The flexibility cost for product variety is linear, given the fact that product variety will not magnify the cost under 3D printing.
Consumer utility	By customizing the products within a set of ready-made product variety offerings, consumers gain the traditional ready-made product variety enjoyment. That is, consumers can only enjoy the value of the mass-customized product. *Model formulation*: Consumers' willingness to pay for the ready-made product variety enjoyment is related to the design outcome of the product. It	In addition to the traditional ready-made product variety enjoyment, consumers also have extra self-design fun with innovative customization beyond the ready-made offerings. Accordingly, consumers can enjoy both the value of the mass-customized product and the value of the mass customization experience. *Model formulation*: The self-design fun is for the flexibility of innovative customization design (i.e., the

	therefore increases with the variety level of the MC product.	product design process itself regardless of the outcome). It is thus reflected as a constant.
Reusability of consumer returns	Due to the complex structure of customized items, consumer returns have limited reusability. *Model formulation*: The salvage value of consumer returned items is zero.	Given that 3D printing use primarily one material only to create the product, consumer returns can be substantially reused. *Model formulation*: Additional salvage value can be achieved from each consumer returned item.
Customization lead-time	Given the nature of the make-to-order step for MC products, the customization lead-time is viewed as an important shortcoming of the traditional MC. *Model formulation*: Consumers wait for the additional customization lead-time.	3D printing shows superb performance in unlocking the speed of its MC programs' overall lead-time (e.g., by reducing the cycle time for the production of different parts). *Model formulation*: The customization lead-time is zero.
Molding in MC	Given the long lead-time, the MC manufacturer prepares molds in advance for further customization of each MC product. *Model formulation*: Extra inventory holding cost is induced for each mold.	The MC manufacturer adopts on-demand printing for each mold based on specific consumer requirements. *Model formulation*: No additional inventory holding cost is caused for each mold.

Appendix B – Models and Results w.r.t Risk Attitudes

Table B1. Definitions of different models.

	Considerations on the MC Manufacturer's risk attitude	**Considerations on the consumers' risk attitude**
Model A (MA)	✓	✓
Model A1 (MA1)	✓	✗
Model A2 (MA2)	✗	✓

Table B2a. Equilibrium results under Model A1.

(The equilibrium results in the case without 3D printing are under the condition of $k > \frac{\theta^2(\mu_d - \sigma_d\lambda_M)}{2a}$.)

	MC without 3D Printing	**MC with 3D Printing**
Optimal product variety level	$v_{3D}^{MA1*} = \frac{\theta(\mu_d - \lambda_M\sigma_d)(a-c)}{2ak - \theta^2(\mu_d - \lambda_M\sigma_d)}$;	$v_{3D}^{MA1*} = 1$;
Optimal retail price	$p_{3D}^{MA1*} = \frac{ak(a+c) - \theta^2(\mu_d - \lambda_M\sigma_d)c}{2ak - \theta^2(\mu_d - \lambda_M\sigma_d)}$;	$p_{3D}^{MA1*} = \frac{a+c+f+\theta}{2}$;
Market demand	$E[d_{3D}^{MA1*}] = \frac{\mu_d k(a-c)}{2ak - \theta^2(\mu_d - \lambda_M\sigma_d)}$;	$E[d_{3D}^{MA1*}] = \frac{\mu_d(a+f+\theta-c)}{2a}$;
Expected profit of the MC manufacturer	$E[\Pi_{3D}^{MA1*}] =$ $\frac{k(a-c)^2[2\mu_d ak - \theta^2(\mu_d - \lambda_M\sigma_d)^2]}{2[2ak - \theta^2(\mu_d - \lambda_M\sigma_d)]^2}$;	$E[\Pi_{3D}^{MA1*}] = \frac{\mu_d(a+f+\theta-c)^2}{4a} - F - \alpha$;
Optimal MV benefits of the MC manufacturer	$\Phi_{3D}^{MA1*} = \frac{(\mu_d - \lambda_M\sigma_d)k(a-c)^2}{2[2ak - \theta^2(\mu_d - \lambda_M\sigma_d)]}$;	$\Phi_{3D}^{MA1*} = \frac{(\mu_d - \lambda_M\sigma_d)(a+f+\theta-c)^2}{4a} - F -$ α;
Consumer surplus	$E[CS_{3D}^{MA1*}] = \frac{\mu_d ak^2(a-c)^2}{2[2ak - \theta^2(\mu_d - \lambda_M\sigma_d)]^2}$;	$E[CS_{3D}^{MA1*}] = \frac{\mu_d(a+f+\theta-c)^2}{8a}$;

Table B2b. Equilibrium results under Model A2.

(The equilibrium results for case without 3D printing are under the condition of $k > \frac{\theta^2\mu_d}{2a}$.)

	MC without 3D Printing	**MC with 3D Printing**

Optimal product variety level	$v_{\overline{3D}}^{MA2*}=\frac{\mu_d\theta(a-c-\lambda_C\sigma_u)}{2ak-\mu_d\theta^2};$	$v_{3D}^{MA2*}=1;$
Optimal retail price	$p_{\overline{3D}}^{MA2*}=\frac{ak(a-\lambda_C\sigma_u)+(ak-\mu_d\theta^2)c}{2ak-\mu_d\theta^2};$	$p_{3D}^{MA2*}=\frac{a+\theta+f-\lambda_C\sigma_u+c}{2};$
Market demand	$E[d_{\overline{3D}}^{MA2*}]=\frac{\mu_d k(a-c-\lambda_C\sigma_u)}{2ak-\mu_d\theta^2};$	$E[d_{3D}^{MA2*}]=\frac{\mu_d(a+\theta+f-\lambda_C\sigma_u-c)}{2a};$
Expected profit of the MC manufacturer	$E[\Pi_{\overline{3D}}^{MA2*}]=\frac{k\mu_d(a-c-\lambda_C\sigma_u)^2}{2(2ak-\mu_d\theta^2)};$	$E[\Pi_{3D}^{MA2*}]=\frac{\mu_d(a+\theta+f-\lambda_C\sigma_u-c))^2}{4a}-F-\alpha;$
Consumer surplus	$E[CS_{\overline{3D}}^{MA2*}]=\frac{\mu_d ak^2(a-c-\lambda_C\sigma_u)^2}{2(2ak-\mu_d\theta^2)^2};$	$E[CS_{3D}^{MA2*}]=\frac{\mu_d(a+\theta+f-\lambda_C\sigma_u-c))^2}{8a};$