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

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**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 under the case with a low consumer’s willingness to pay for the traditional “ready-made product variety enjoyment” (RPVE), even the maximized product variety level and the additional self-design fun cannot make the 3D printing based MC more profitable. In addition, compared to the markets with risk-averse and risk-neutral consumers, the 3D printing based MC can increase more MRBs and a higher consumer surplus by simultaneously highlighting the high self-design fun and the high RPVE in a market with risk-seeking 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.

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]](#footnote-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, 2020; Olsen and Tomlin, 2020). Industries like consumer electronics, fashion and automotive are all 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]](#footnote-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]](#footnote-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 produce functional metal parts of its MC auto products.[[5]](#footnote-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]](#footnote-6) and self-congruency theory[[7]](#footnote-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]](#footnote-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]](#footnote-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**

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?

**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]](#footnote-10). Our results 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).

**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 Online Supplementary Appendix A while all technical proofs are placed in the Online Supplementary Online Supplementary Appendix C.

1. **Literature Review**

This paper relates to four areas, namely mass customization supply chains, 3D printing in operations, decision making with risk attitudes, as well as product co-creation and consumer customization.

**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. However, different from them, we make a novel contribution to this research field by considering the “integrated-roles” of self-design fun and consumer returns.

The concept of self-design fun is relatively new in the OR literature and it makes a critical impact on consumer surplus and MC firms’ strategies. 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 the focal points on lead-time-variety tradeoffs in traditional MC operations such as Mendelson and Parlaktürk (2008a) and Alptekinoğlu and Corbett (2010), we innovatively investigate the applications of 3D printing in MC for addressing the consumers’ time sensitive behaviors. This is critical for MC practices and has not yet been examined by the consumer returns related literature in the field of MC.

**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 (2020)), 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 (2020) 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 managing the consumers’ time sensitive behaviors. This addresses the popularity of consumer returns policies in practice and the widely acknowledged advantages of 3D printing in overcoming the customization lead-time and achieving the circular economy. Besides, although 3D printing has plenty of advantages, it also comes with risks. Therefore, the risk attitudes and behaviors towards 3D printing, which are neglected in the above reviewed literature, are also important and should be highlighted in this paper. In other words, this paper takes a first step towards understanding both the advantages and challenges of 3D printing.

**2.3. Decision Making with Risk Attitudes**

This paper is also related to the domain of decision making with risk attitudes. Regarding demand uncertainty, Yang et al. (2018) investigate the inventory risks 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. Delaney (2021) discusses the investment risks with the considerations of market incompleteness and uncertainty associated with product development time. The authors show that the optimal investment threshold is concave in the degree of market incompleteness. They also prove that the case with market incompleteness and risk aversion can lead to less stringent investment criteria than the case with market completeness and risk neutrality. Focusing on the dynamic interaction between futures and spot prices, Oliveira and Ruiz (2021) examine the procurement risks in the electricity supply chain consisting of risk-averse generators and retailers. The authors find that although introducing future market prices can reduce generators’ profitability in the risk-neutral case, it can increase the generators’ profit in the risk-averse case. 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. Rather than studying external factors like supply disruptions and supply chain structures, this paper focuses on exploring the risk attitudes that are related to the inevitable and inherent uncertainty induced by customization and technology adoption (e.g., 3D printing) in MC. With a view to examine models with these inherent factors, this paper is significantly different from the above reviewed literature.

**2.4. Product Co-Creation and Consumer Customization**

Despite the increasing popularity in practice, product co-creation is relatively under-explored in the OR literature. In this emerging field, Syam and Pazgal (2013) model the interaction between a monopolist firm and consumers and explore the pricing strategy of the firm. They find that the pricing structure affects customers’ incentive to participate in product co-creation and a single price may benefit the firm more than adopting the price discrimination strategy. Gu and Tayi (2015) explore the firm’s strategic trade-off between enhancing consumers’ customizing capability and increasing the value of the standardized product in the consumer co-creation problem. The authors highlight that although the customizable product can bring consumers a greater surplus than the standardized product, the firm obtains a greater profit only if consumer customizability is sufficiently high. Modelling the co-design process by the firm’s co-design capability and the consumers’ co-design efforts, Basu and Bhaskaran (2018) investigate the effects of co-design on the firm’s optimal strategies of product line and product quality. The authors mention that only in the situation when both standard and customizable products are available to the consumers will the consumers engage in the co-design process. While the above literature illustrates the growing significance of product co-design, they do not answer the question of how consumers’ motivation to participate in the co-design process influences the application of 3D printing. Our paper contributes to this literature by introducing the consumers’ co-design interest (i.e., the self-design fun) as a significant factor. We also examine its effects on the MC manufacturer’s decisions of whether or not to adopt 3D printing in MC. Moreover, different from prior studies such as Gu and Tayi (2015) that focuses on IT products (which is less costly for customization owing to their digital nature), we are interested in investigating the flexibility cost for product variety of non-IT products. Our paper therefore can provide important insights for MC practitioners in other industries.

1. **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 () and the retail price of the MC product to maximize the expected profit. The per-unit production cost of each standard product is . In the meantime, product customization is never free (Squire et al., 2006). Accordingly, the manufacturer has an extra flexibility cost for MC[[11]](#footnote-11) as , which includes the product development cost for product variety and the labor learning cost. It is product variety dependent, with as the sensitivity of the product variety cost with respect to the MC product’s variety level . 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. The classic flexible manufacturing system of MC in practice is largely based on flexible production lines which are designed and equipped with changeable configurations to meet different product variety needs. The traditional MC operations in BMW’s Mini factory, for instance, rely on individual mobile production cells with standardized robotic units (known as “MobiCells”) (Gray and Mortimer, 2007). In such systems, a higher product variety level requires more frequent changeovers, more complicated tooling and machinery, and even higher energy consumption. This unavoidably leads to higher variable costs for product development and decreases cost efficiency of MC. This is also why MC manufacturers like Dell would provide only a limited range of custom product configurations in practice (Dewan et al., 2003). It is therefore reasonable to apply a quadratic cost structure, which captures the diseconomies of product variety in the traditional MC and reflects the fact that the marginal customization expenditure increases as the product variety level increases. In practice, for instance, such a quadratic cost (with respect to the number of product varieties) can be also observed from the yogurt firms (regarding the variety of its yogurt flavors) (Draganska and Jain, 2005). In addition, the quadratic 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 Xiao et al. (2014). Grounded on these observed practices and prior studies, we also employ the quadratic cost structure in our model.

***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 , which follows a probability distribution function and a cumulative distribution function . Consumer heterogeneity in product valuations is captured by taking to be uniformly distributed over . 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), Wu (2019), and Zhang et al. (2021).

By providing a variety level , the MC manufacturer enhances the consumer’s willingness to pay by (i.e., *the ready-made product variety enjoyment* (RPVE))[[12]](#footnote-12), where 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 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 . In addition, to ensure a profitable business of MC, we have 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:

. (1)

. (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]](#footnote-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 , where is the fixed 3D printers purchasing cost, and is the 3D printing development cost for 3D designs (or 3D schematics) and production plans. The developing cost, with as the sensitivity of the cost with respect to the MC product’s variety level , is linear in the MC product’s variety level. This addresses the fact that 3D printing begins with a 3D CAD file and creates the product by adding layers of materials to the 3D model until the final shape is formed (e.g., as reflected in the practices of HP Metal Jet technology, Nike Flyprint, and IKEA's Omedelbar)[[14]](#footnote-14). The process is free of any retooling or mold changes. 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) a zero marginal cost of 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 (e.g., see Arbabian and Wagner, 2020).

In addition, product design nowadays has already expanded to include hobbyists and prosumers. Empirical research such as Franke et al. (2010) has reported experimental evidence that users would 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 , .[[15]](#footnote-15) *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 RPVE* 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 . Accordingly, the demand for the MC product is updated as . We then have the objective function of the MC manufacturer and the consumer surplus as:

. (3)

. (4)

1. **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.

**4.1. Optimal Strategies**

With the condition of 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** | ; | ; |
| **Optimal retail price** | ; | ; |
| **Market demand** | ; | ; |
| **Expected profit of the MC manufacturer** | ; | ; |
| **Consumer surplus** | ; | . |

**4.2. Influences of 3D Printing**

By comparing the optimal strategies shown in Table 2, we have Proposition 1.[[16]](#footnote-16)

**Proposition 1.** a) If , and ; If , both and if and only if , otherwise and ; b) If , ; If , if and only if , otherwise .

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.[[17]](#footnote-17) Proposition 1, however, reveals that the maximized product variety level under 3D printing (i.e., ) can either be beneficial or harmful. As we can see from Proposition 1, if the consumer’s willingness to pay for the traditional RPVE is relatively low (i.e., ), although 3D printing can yield a higher consumer surplus, it reduces the MC manufacturer’s profits. That is, under the case with a low consumer’s willingness to pay for the traditional RPVE, the profit increase is insufficient to cover the cost increase due to the increased product variety. In this case, even the additional self-design fun cannot make the 3D printing based MC more profitable. While if the consumer’s willingness to pay for the traditional RPVE is relatively high (i.e., ), the 3D printing based MC can bring a higher consumer surplus and also increase the MC manufacturer’s profits if and only if the self-design fun is sufficiently large (i.e., ). This means 3D printing can make the MC program more beneficial to the consumers and MC manufacturer if the consumers find the maximized product variety level and the self-design fun both attractive enough. While if any of these two sources of customer-perceived value is low, applying 3D printing into MC may reduce either consumer surplus or MC manufacturer’s profits (when compared with the traditional MC). This is surprising.

As we explained earlier, 3D printing’s two main advantages are its zero-marginal cost of diseconomies in product variety and the extra self-design fun. The thresholds mentioned above (e.g., the consumer’s willingness to pay for the traditional RPVE) capture how 3D printing’s different advantages influence the results of whether or not the traditional MC can outperform the 3D printing based MC, respectively. For example, if the MC manufacturer offers a complete customized product in the 3D printing based MC program, the only factors to attract consumers are the self-design fun and the retail price. This will consequently transfer all the benefits of customization (i.e., the traditional RPVE) to the consumers. Engaging in complete customization therefore does not necessarily benefit the MC manufacturer. Note that it is true even when there is no purchasing cost of 3D printers (i.e., ). In other words, although 3D printing can make it economically feasible for customization, the traditional MC can still outperform the 3D printing based MC. Factors like the consumer’s willingness to pay for the traditional RPVE therefore should be the MC manufacturer’s major concern when making an optimal decision on whether or not to adopt 3D printing. The interesting implication above complements the knowledge from the extant literature (such as Syam and Pazgal (2013)) which emphasizes that a firm’s profit from co-creation can always dominate its profit in a no co-creation environment.

In addition, the finding that even the maximized product variety level under 3D printing (i.e., ) can not necessarily make the MC program more beneficial reveals the restricted advantages of the unlimited design freedom in MC. This also explains why different from some proposals that 3D printing will be dominating, we only observe its presence in a limited number of product lines in practice. Use the example of the MC manufacturer Nike, it limits its 3D-printed offerings to the performance footwear product lines such as Nike Zoom Vaporfly Elites. In the available product lines, Nike also restricts the 3D printing application into some specially selected product variants (i.e., components) rather than at a full product variety level. For instance, Nike only applies the customizable 3D-printed textile upper (known as Nike Flyprint) into the product line of Nike Zoom Vaporfly Elites. For the product line Futurecraft 4D, the MC manufacturer Adidas also limits its 3D printing customization service into sneaker midsoles. Similarly, the furniture giant IKEA only offers a few 3D-printed collections like “OMEDELBAR” (for coat hangers and jewelry holders) and limited 3D-printing models for its customizable add-ons (e.g., handles, switches, and zippers)[[18]](#footnote-18). Proposition 1 thus appeal the MC manufacturer’s attention and complements the extant MC literature.

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

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

,

, and

.

**Proposition 2.** *For the values of self-design fun: a) ; b) and it is monotonically increasing in; c) and it is monotonically increasing in.*

Proposition 2 provides a valuable guideline regarding how to make full use of the self-design brought by 3D printing in MC operations. For instance, it is interesting to see that the value of self-design fun is increasing in the consumer’s willingness to pay for the traditional RPVE for all cases. Together with Proposition 1, we can then know that if the consumer’s willingness to pay for the traditional RPVE is relatively high () and continues to increase, the MC manufacturer should in fact consider highlighting the self-design fun. This can effectively contribute to more increases in the MC manufacturer’s optimal profit and consumer surplus because they are increasing in self-design fun. This finding may explain why the high-end auto company BMW and the high-end furniture company Poltrona Frau both put strong emphasis on the self-design fun because doing so is beneficial to the companies and consumers.

**Proposition 3.** *For the values of product variety: a) if and only if ; b) if and only if ; c) if and only if ; d) Both and are monotonically increasing in.*

Propositions 1 and 2 above show that a high consumer’s willingness to pay for the traditional RPVE (i.e., ) not only may help the 3D printing based MC program achieve higher consumer surplus and profits than the traditional MC, but also bring a high level of self-design fun. A natural question arises on whether a higher consumer’s willingness to pay for the traditional RPVE is always better for the 3D printing based MC. Proposition 3 addresses this concern and reveals that a higher consumer willingness to pay for the traditional RPVE does not necessarily guarantee more value is generated by 3D printing (i.e., , and ). Instead, only when the self-design fun is sufficiently high (i.e., ), can a higher consumer willingness to pay for the traditional RPVE achieve *a higher value of 3D printing* regarding the MC manufacturer’s optimal profit and consumer surplus (i.e., and ). In addition, it is critical to notice from Proposition 3 that a higher value of self-design fun can also make a higher consumer willingness to pay for the traditional RPVE more beneficial. Proposition 3, together with Proposition 1 and Proposition 2, thus provides an important guideline that the MC manufacturer should simultaneously highlight the customer-perceived values of the traditional RPVE and the self-design fun and make both more attractive when introduce 3D printing. Theorem 1 below summarizes the findings in Propositions 1, 2 and 3.

**Theorem 1.** *The maximized product variety level does not guarantee the 3D printing based MC can be more successful than the traditional MC. Instead, the value of 3D printing depends on the joint effect of customer-perceived values of the traditional RPVE and the self-design fun.*

Theorem 1 critically highlights that in addition to the costs (e.g., for product variety as emphasized in MC literature like Alptekinoğlu and Corbett (2008)), the MC manufacturer should also pay close attention to the customer-perceived values of both the MC product (i.e., the traditional RPVE) and the MC experience for innovative customization design (i.e., the self-design fun). While the traditional RPVE 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 provide 3D-printed MC products without mentioning the self-design fun (P.S.: An example of which is Adidas).

1. **Extended Models**

Although both MC and 3D printing can potentially 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 behaviors of the MC manufacturer and consumers can influence MC operations. Aspects like risk attitudes, consumer returns, and the time sensitive behaviors of consumers, and 3D printing in molding will be examined.

**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. (2021), 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 and variance . Under the case without 3D printing, each consumer will buy the MC product if the sum of their valuation and the willingness to pay for the MC product’s variety level is larger than the retail price plus a risk premium measured by their risk attitude parameter and the standard deviation of (), i.e., . The risk attitude parameter 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 , therefore, the number of consumers who will buy the MC product is . *N* is randomly distributed with mean . Taking expectation with respect to *N*, the expected number of consumers who will buy the MC product at a retail price for the case without 3D printing is: . Similar to previous discussions, to ensure a profitable business of MC, we have in later sections. We have the MC manufacturer’s profit as: . The operational risk is quantified by the variance of the MC manufacturer’s profit . Taking variance with respect to *N*, we have: It is straightforward that the standard deviation of the MC manufacturer’s profit is: We denote the MC manufacturer’s risk attitude parameter as . Similarly, we have if the MC manufacturer is risk averse, if the MC manufacturer is risk neutral, and if the MC manufacturer is risk seeking. Besides, in order to make (5) and (6) reasonable, the MC manufacturer’s risk attitude parameter cannot be extremely big, which is bounded by . Following Chiu and Choi (2016), we define the mean-risk (MR) objective function of the MC manufacturer for the case without 3D printing as , 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.

. (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:

.

. (6)

With the condition of 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*.[[19]](#footnote-19)**

|  |  |  |
| --- | --- | --- |
|  | **MC without 3D Printing** | **MC with 3D Printing** |
| **Optimal product variety level** | ; | ; |
| **Optimal retail price** | ; | ; |
| **Market demand** | ; | ; |
| **Optimal MRBs of the MC manufacturer** | *;* | *;* |
| **Consumer surplus** | ; | ; |

**Proposition 4.** *a) If , and ; If , both and if the self-design fun is sufficiently large (i.e., ); b) If , ; If , if and only if , otherwise .*

Proposition 4 proves the robustness of our findings in Proposition 1 and Theorem 1 with the consideration of the risk attitudes of the MC manufacturer and consumers. For instance, it is interesting to see that 3D printing can also bring a higher consumer surplus to risk-averse consumers as long as their willingness to pay for the traditional RPVE and the self-design fun are both high. While if the consumer’s willingness to pay for the traditional RPVE is relatively low (i.e., ), the MC manufacturer in fact should consider the traditional MC program even when both the MC manufacturer and consumers are risk seeking.

In the meantime, new findings are generated. In a risk-neutral environment, it is straightforward that a higher variety level of the MC product adds more value to the consumers when they hold a higher willingness to pay for the traditional RPVE. With risk considerations, however, increasing product variety may also lead to higher uncertainties. Offering a higher variety level of the MC product therefore may not necessarily increase consumer surplus and the MC manufacturer’s MRBs even if the consumers hold a high willingness to pay for the traditional RPVE. The self-design fun then comes for help, which is for the MC experience and is free from the risks associated with product uncertainty. As an example, if the consumer’s willingness to pay for the traditional RPVE is relatively high (i.e., ), the MC manufacturer can make the 3D printing based MC more beneficial than the traditional one by highlighting the self-design fun instead of highlighting the extremely high product variety level. This also helps to avoid a higher operations risk level induced by product uncertainty.

**Proposition 5.** *For the values of self-design fun (i.e., ): a) , and ; b) Both and are monotonically increasing in and , but monotonically decreasingin .*

Proposition 5 shows the robustness of Proposition 2 and Proposition 4. For instance, Proposition 5 proves that a higher value of the self-design fun can considerably increase more MRBs to the MC manufacturer and a higher consumer surplus in a larger market filled with consumers who have a higher willingness to pay for the traditional RPVE. This is true no matter whether the consumers are risk averse, risk neutral or risk seeking. Simultaneously, Proposition 5 also highlights a new implication which complements our base models and Proposition 4 above. It indicates that compared with the risk-averse and risk-neutral attitude counterparts of consumers, the risk-seeking attitude of consumers can contribute to a more distinct advantage of the self-design fun in achieving more MRBs and a higher consumer surplus.[[20]](#footnote-20) That is, the risk-seeking customer’s incentive to take the risks of product uncertainties also 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. Devoting more efforts to advertising the high self-design fun to risk-seeking consumers therefore is recommending strategy for 3D printing based MC programs. These findings provide important implications in tackling the risks associated with market uncertainties, which is emphasized in the literature (e.g., see, Asian and Nie (2014)).

**Proposition 6.** *For the values of product variety (i.e., ): a) if and only if ; b) if and only if ; c) Both and are monotonically increasing in; d) If , both and are are monotonically decreasing in.*

Proposition 6 supports and complements the findings in Proposition 3 and Proposition 4. As we can see above, a high risk averse level of the consumers () can limit the 3D printing’s effectiveness in increasing the MC manufacturer’s MRBs and consumer surplus by increasing the consumer’s willingness to pay for the traditional RPVE. The decision of introducing 3D printing into MC therefore should be carefully evaluated by taking the consumers’ risk attitudes into considerations. Proposition 6 and Proposition 5 together hence highlight another important implication that 3D printing’s effectiveness in bringing more benefits than the traditional MC can be restricted by the degree of risk-aversion of customers. In particular, it can be more difficult to motivate a consumer who is less risk-seeking or more risk-averse to purchase the 3D-printed MC product by advertising the high self-design fun and high RPVE. These findings indicate the significant influences of the market structure (regarding the consumers’ risk preferences) on the success of the 3D printing based MC. Theorem 2 summarizes the core findings.

**Theorem 2.** *Compared to the markets with risk-averse and risk-neutral consumers, the 3D printing based MC can increase more MRBs and a higher consumer surplus by highlighting the high self-design fun and the high RPVE in a market with risk-seeking consumers.*

Theorem 2 explains how to make the full use of 3D printing’s different characteristics in an uncertain MC market. Specifically, in a market with risk-seeking consumers, simultaneously highlighting the high self-design fun and the high RPVE can effectively make the 3D printing based MC more beneficial than the traditional one. While under the scenario with less risk-seeking or more risk-averse consumers, the major characteristic that distinguishes the 3D printing based MC is its natural flexibility. Accordingly, the MC manufacturer can increase the MRBs by including more designs into product assortment without increasing the unit development cost.

**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 (or ). 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 . 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:

. (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’[[21]](#footnote-21), HP also 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 can be achieved from each consumer returned product under the 3D printing supported MC (), 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:

. (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 , and we always have a consumer willingness to pay as .

**Table 4. Optimal strategies under Model *CR*.**

|  |  |  |
| --- | --- | --- |
|  | **MC without 3D Printing** | **MC with 3D Printing** |
| **Optimal product variety level** | ; | ; |
| **Optimal retail price** | ; | ; |
| **Optimal MRBs of the MC manufacturer** | *;* | *;* |
| **Consumer surplus** | ; | ; |

**Proposition 7.** *a) ; b) if and only if , otherwise .*

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 high RPVE.[[22]](#footnote-22) In addition, taking into account the consumer returns, another new insight is generated. As can be seen from Proposition 7, a 3D printing supported MC can help achieve the 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., ). Furthermore, as we can see from Table 4, a higher salvage value of the 3D printing supported MC product can bring more MRBs 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 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 the 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 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[[23]](#footnote-23), 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 , where () 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:

.

. (9)

Following the same logic as previous sections, with the condition of and , we have the optimal strategies of the traditional MC under Model *L* as:

; ;

*;* .

**Proposition 8.** *a) ; b) ; c) ; d) Both and are monotonically decreasingin .*

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*.[[24]](#footnote-24) 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. This not only provides a crucial implication to the MC manufacturer who is suffering from the long customization lead-time, but also addresses the concerns on production lead-time and uncertain demand among the manufacturing systems literature (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.** *The 3D printing based MC can bring more MRBs and a higher consumer surplus when the customization lead-time (in the traditional MC) becomes longer. In particular, such benefits can be more obvious in the market with risk-seeking consumers (compared to the markets with risk-averse and risk-neutral consumers).*

**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)[[25]](#footnote-25) and the custom earbuds market in audiology (e.g., Formlabs’ Standard Clear Resin)[[26]](#footnote-26). This subsection thus considers the application of 3D printing in molding and we call the respective scenario Model *M* (*M* denotes for molding).

**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 . 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:

. (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 . Here, notice that the fixed cost 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 , and the (“afterwards”) customization cost on the 3D printed mold becomes . As a result, we have the new MRB function of the MC manufacturer as follows:

. (11)

Accordingly, we have the optimal strategies as listed in Table 5, with the condition of for the traditional MC and the condition of for the 3D printing supported MC. In addition, we have a consumer willingness to pay as for the traditional MC and 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** | ; | ; |
| **Optimal retail price** | ; | ; |
| **Market demand** | ; | ; |
| **Optimal MRBs of the MC manufacturer** | *;* | *;* |
| **Consumer surplus** | ; | ; |

The optimal strategies in Table 5 reveal similar conditions on the customer-perceived values of traditional RPVE and the self-design fun regarding when 3D printing can help achieve more MRBs and a higher consumer surplus. This verifies the robustness of our findings in previous subsections. Instead of repeating similar discussions, we therefore focus more on the influences of the standard per unit cost for each mold under the traditional MC (i.e.,) and the (“afterwards”) customization cost on the 3D printed mold in the following discussions. Define : , , and .

**Proposition 9.** *a) if and only if ; otherwise, if, ; b) if and only if ; c) if and only if , otherwise .*

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., ) 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), 3D printing can contribute to a higher product variety level of the MC product only when the standard per unit cost for each mold under the traditional is sufficiently large. In addition, Proposition 9c) indicates that as long as the (“afterwards”) customization cost on the 3D printed mold is sufficiently small (i.e., ), 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 than the risk averse counterpart. Proposition 9b) and Proposition 9c) together thus show that when the target consumers are risk seeking, 3D printing is a catalyst in molding for achieving a higher product variety level (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).[[27]](#footnote-27) 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.** *if and only if , otherwise.*

Proposition 10 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) if and only if , if and only if ;b) if and only if , if and only if .*

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.*

1. **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 surplusare 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 the maximized product variety level of MC product. In the meanwhile, however, under the case with a low consumer’s willingness to pay for the traditional RPVE, even the maximized product variety level and the additional self-design fun cannot make the 3D printing based MC more profitable. On the contrary, if the consumer’s willingness to pay for the traditional RPVE is relatively high, the 3D printing based MC can bring a higher consumer surplus and also increase the MC manufacturer’s profits if and only if the self-design fun is also sufficiently large. The MC manufacturer therefore should simultaneously highlight the customer-perceived values of the traditional RPVE and the self-design fun and make both more attractive when it introduces 3D printing. This calls for the MC manufacturer’s close attention. In particular, it is of great importance to the MC manufacturers who provide 3D-printed MC products but without mentioning the self-design fun, an example of which is Adidas. These findings also apply to the cases with the consideration of other operational factors like 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***: With the risk considerations, increasing the product variety is also at the risk of increasing product uncertainty. Offering a higher variety level of the MC product therefore may not necessarily increase consumer surplus and the MC manufacturer’s MRBs even if the consumers hold a high willingness to pay for the traditional RPVE. The self-design fun then comes for the rescue. As an example, if the consumer’s willingness to pay for the traditional RPVE is relatively high, the MC manufacturer can make the 3D printing based MC more beneficial by highlighting the self-design fun rather than highlighting the extremely high product variety level. In addition, compared to the markets with risk-averse and risk-neutral consumers, the 3D printing based MC can increase more MRBs and a higher consumer surplus by highlighting the high self-design fun and the high RPVE in a market with risk-seeking consumers.

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. In particular, the 3D printing based MC can bring more MRBs and a higher consumer surplus when the customization lead-time (in the traditional MC) becomes longer. 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, especially in the market environment with risk-seeking consumers.

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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1. \* 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.” [↑](#footnote-ref-1)
2. See <https://www.knowledge-sourcing.com/report/3d-printing-market>. (Accessed March, 2020) [↑](#footnote-ref-2)
3. See <http://3dprintingreviews.blogspot.com/2013/06/ge-aviation-to-grow-better-fuel-nozzles.html>. (Accessed March, 2020) [↑](#footnote-ref-3)
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. [↑](#footnote-ref-4)
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) [↑](#footnote-ref-5)
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. [↑](#footnote-ref-6)
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. [↑](#footnote-ref-7)
8. See <https://www.3dnatives.com/en/bmw-3d-printing-additive-manufacturing-241220184/>. (Accessed March, 2020) [↑](#footnote-ref-8)
9. See <https://protocube.it/portfolio/configuratore-3d-poltrona-frau/?lang=en>. (Accessed May, 2020) [↑](#footnote-ref-9)
10. Here, 3D printing in molding means employing 3D printing technologies to create molds. [↑](#footnote-ref-10)
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. [↑](#footnote-ref-11)
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 Online Supplementary Appendix A. [↑](#footnote-ref-12)
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 Online Supplementary Appendix A. [↑](#footnote-ref-13)
14. See <https://h20195.www2.hp.com/v2/getpdf.aspx/4AA7-3333ENW.pdf> for HP Metal Jet technology, <https://news.nike.com/news/nike-flyprint-3d-printed-textile> for Nike Flyprint, and <https://ikea.today/brave-new-3d-world/> for IKEA's Omedelbar. (Accessed April, 2021) [↑](#footnote-ref-14)
15. Notice that extending to the case with two different segments of consumers () (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 (, with the proportion of ) enjoy the self-design fun () and hold a higher willingness to pay for the variety level (). While traditional consumers (, with the proportion of ()) do not benefit from the self-design fun and hold a lower willingness to pay for the variety level (). The exogenous and static proportion of innovative consumers () 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 . It can therefore be proved that our findings are robust. [↑](#footnote-ref-15)
16. 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 and (for linear regression) or and (for quadratic regression, with ), our analysis shows that we have similar findings such as: 1) When the self-design fun is sufficiently large, , ; 2) When the flexibility cost for MC in the 3D Printing supported MC is sufficiently small, . [↑](#footnote-ref-16)
17. 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. [↑](#footnote-ref-17)
18. More details can be found at [https://www.3dnatives.com/en/ikea-3d-printed-chair150620184/#](https://www.3dnatives.com/en/ikea-3d-printed-chair150620184/)! and <https://www.3dprintingmedia.network/ikea-thisables-3d-printed-accessible/>. (Accessed April, 2021) [↑](#footnote-ref-18)
19. 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 Online Supplementary Appendix B. Based on the results shown in Online Supplementary 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. [↑](#footnote-ref-19)
20. This can be derived by comparing the case when to the cases when and , for and . [↑](#footnote-ref-20)
21. See <https://h20195.www2.hp.com/v2/getpdf.aspx/4AA7-3333ENW.pdf>. (Accessed May, 2020) [↑](#footnote-ref-21)
22. 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. [↑](#footnote-ref-22)
23. <https://press.ext.hp.com/us/en/press-releases/2018/hp-launches-worlds-most-advanced-metals-3d-printing-technology.html>. (Accessed April, 2020) [↑](#footnote-ref-23)
24. This can be proved by following the same logic as Proposition 4 and Proposition 5. [↑](#footnote-ref-24)
25. See <https://dental.formlabs.com/indications/thermoformed-clear-aligners-retainers/>. (Accessed May, 2020) [↑](#footnote-ref-25)
26. Detailed information can be found in <https://formlabs.com/industries/audiology/>. (Accessed May, 2020) [↑](#footnote-ref-26)
27. Interested readers can refer to <https://formlabs.com/industries/manufacturing/> for more details. (Accessed May, 2020) [↑](#footnote-ref-27)