Int. J. Production Economics 268 (2024) 109103

Contents lists available at ScienceDirect

International Journal of Production Economics

journal homepage: www.elsevier.com/locate/ijpe

Customizing customization in a 3D printing-enabled hybrid manufacturing supply chain

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ARTICLE INFO

Keywords:
3D printing
Customization degree
Supply chain configuration
Channel preference
Stackelberg game theory

ABSTRACT

At-scale manufacture of customized products often requires both traditional processes and 3D Printing (3DP)-enabled additive manufacturing. Such hybrid manufacturing supports varying degrees of product customization achieved through variance in the mix of traditional and 3DP processes. Further, it supports the customization of the configuration of the 3DP-enabled supply chain. Our research investigates decision-making by 3DP manufacturers to obtain optimal profits based on the degree of customization. A two-echelon manufacturer-retailer supply chain that distributes customized products online and offline based on customers' channel preferences is considered. The Stackelberg Game model was used to study decision-making between the leader (manufacturer) and the follower (retailer). We analyzed two models: the centralized manufacturer-customized model and the decentralized retailer-customized model. The key findings of our study are as follows: Firstly, when the unit production cost is relatively small, it is optimal for the 3DP provider to offer consumers fully 3DP customized products. Secondly, with both the manufacturer-customized and the retailer-customized model, an increase in consumers' offline channel preference, will reduce the overall profits. Thirdly, in the retailer-customized model, the optimal selling price and profits are not affected by the ratio of the manufacturer's unit production cost and the total unit production cost. Finally, when the unit production cost increases with the customization degree, the optimal customization degree is relatively insensitive to potential market size changes. Our findings have practical relevance for firms seeking to gain a competitive advantage by deciding on the degree of customization and supply chain configuration strategies for 3DP manufacturing.

1. Introduction

Three-dimensional printing (3DP), or direct digital manufacturing, applies additive processes to produce solid 3D objects directly from digital design files (Candi and Beltagui 2019). In industry, 3DP has evolved from prototyping to production technology and has become a standard practice in contemporary product development and manufacturing (Gardan, 2016; Delic et al., 2019). In contrast to the intrinsic cost issues with traditional customization, 3DP-enabled customization provides affordable solutions for manufacturers to offer improved flexibility and product choices to satisfy customers' desires (Long et al., 2017). Previously, due to technical limitations such as reduced choices for materials and colors (Cozmei and Caloian, 2012), 3DP manufacturing remained an emerging technology and has been seen as a complementary method to conventional production. As the technology advances and gets mature, 3DP is now capable of new material options, better processing speeds, and greater autonomy (Achillas et al., 2017). Increasingly, manufacturers are shifting towards 3DP-enabled customization production to cater to customers' choices and stay ahead of the competition (Verboeket and Krikke, 2019).

At the process level, most manufacturing operations consist of a hybrid of traditional and 3DP operations. The 3DP is adopted alongside traditional mould-based production technologies to finalize the production. Traditional mass customization manufacturing, which relies on using different combinations of pre-assembled modular parts, may still be cost-effective and efficient for many types of products, especially

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https://doi.org/10.1016/j.ijpe.2023.109103
Received 8 February 2023; Received in revised form 8 November 2023; Accepted 19 November 2023
Available online 28 November 2023

those that involve production in large volumes (Berman, 2012). However, for products requiring relatively smaller degrees of customization production and lower production volume, the cost and time advantages of conventional mass customization decrease, because moulds and large inventory are required. For these volume manufacturing, increasing the adoption of 3DP in hybrid manufacturing may bring additional value, such as improved product functionality, higher production efficiency, greater customization, and shorter time to market, which may outweigh 3DP's higher production costs (PWC, 2018). HOYA, a global leading med-tech company started using 3DP to customize the glass in accordance with the patient's visual, comfort and aesthetic requirements. Frame design, colour and finish can all be chosen to match the customer's individual style. These are complemented by a choice of a lens solution. However, considering the cost of 3DP technology adoption, the company may decide to customize the whole glasses or only frames. In such circumstances, 3DP-enabled customization presents a paradox for companies who need to assess at what point it becomes economically attractive to use 3DP over traditional customized manufacturing and to what extent 3DP should be used to combine with conventional manufacturing.

At the supply chain level, in contrast to traditional "economies of scale" models, where production stages are separated and geographically dispersed (Cotteleer and Joyce, 2014), 3DP has the advantage of "minimum efficient scale" (Long et al., 2017; Braziotis et al., 2019). Thus, local flexible manufacturing is enabled by going into production at or near the point of use. The location of production thus becomes less sensitive and there could be a re-shuffle of production facilities (Chan et al., 2018). Depending on where the adoption of 3D printing technology takes place, the 3DP supply chain can be configured as the centralized manufacturer-customized model (at the manufacturer) or decentralized retailer-customized production model (at the retailer). In a decentralized retailer-customized production model, manufacturers outsource the 3DP production to retailers to better meet the needs of customers. For example, Adidas has introduced 3D-printed high-end customized sneakers through the *Adidas Futurecraft* series. Retailer stores can promptly respond to customers' requirements by scanning consumers' feet and 3D printing the sneaker's sole (Boute et al., 2022; Kim, 2018). The flexible location of production creates a new paradigm of distributed manufacturing (Khajavi et al., 2014).

Arguably, this emerging supply chain configuration will leverage the operations innovation brought about through the transformation in manufacturing (from traditional to 3DP) and test their implications on profitability. Manufacturers must decide whether to implement 3DP operations on their own or to decentralize the production sites to get closer proximity to market locations.

To date, the extant literature on 3DP manufacturing has predominantly focussed on the effects of 3DP on production costs, whilst decision-making related to complex supply chain configuration has often been ignored. Moreover, a complex hybrid manufacturing process comprising both 3DP and traditional manufacturing makes it even more difficult to manage 3DP manufacturing. With the diffusion of 3DP in the industry, 3DP participation in different degrees of customization production is increasingly paving the way for mainstream manufacturing. 3DP has the advantage of minimum batch-size production, whilst conventional customization possesses the cost advantage of economies of scale. Concerning the middle scale of production where both 3DP and mass conventional customization could be adopted, a question remains as to how one may determine the mix of both 3DP and traditional manufacturing in the hybrid production model and optimize the supply chain configuration. Academics and practitioners still lack a model to assess the economic feasibility of combing different levels of 3DP with conventional manufacturing to match demand. In this context, there is a pressing need for research considering the degree of 3DP adoption, together with the supply chain configuration strategies of 3DP manufacturing supply chains and their implications on profitability.

Given the widespread application of 3DP and the identified research gaps, we investigate the following research questions.

(1) The conditions under which the manufacturer or the retailer may provide 3DP customization?
(2) In either the centralized manufacturer-customized model or the decentralized retailer-customized production model, what degree of 3DP customization should be provided to achieve optimal profitability?

To answer these questions, the *Stackelberg Game* model is used to study decision-making in a non-cooperative game mode between two players – the leader (manufacturer) and the follower (retailer). These two players model our two-echelon manufacturer-retailer supply chain for 3DP manufacturing. In supply chain management literature, Game Theory has almost exclusively been applied to the study of traditional production planning (e.g., Gray et al., 2009; Wang et al., 2014), bilevel supply chain arrangements for platform products (Leng et al., 2014; Zhang and Huang, 2010) and dual channel (Wang et al., 2020), including online/offline supply channels (Ma et al., 2021; Mehrabani and Seifi, 2021). In the context of sustainable supply chain management, Bhuniya et al. (2023) developed a Stackelberg game policy where the manufacturer is the Stackelberg leader and selects the mark-up, product quality and greening costs for maximum profitability, followed by the retailer (the Stackelberg follower) who selects mark-up with its's strategy. The main objective of the model was to find the best strategy for profit maximization which considers factors such as variable demand, trade credit, revenue sharing and green investment.

The paper contributes to the literature in the following ways (see Table 1).

The remainder of this paper is organized as follows. A review of the literature on 3DP customization is included in section 2. Section 3 presents the formulation of our original analytical models and their assumptions and notation. The results and numerical analysis are presented in Section 4, 5 and 6 respectively. Section 7 concludes the paper with an outline of the key research contributions and their managerial implications, research limitations and future research directions.

2. Literature review

Our study contributes to the operations and supply chain management literature on the impact of 3DP. It specifically concerns production planning, considering different customization degrees, supply chain configurations and customers' channel preferences. Our work takes inspiration from closed-loop supply chain modelling studies on remanufacturing which have considered differentiation between new and remanufactured products (Taleizadeh et al., 2023). Some of this work also considers differentiation brought about through the commitment of supply chain partners to reduce carbon emissions. For example, the study by Dey et al. (2023) refers to the scenario where damage to products from the manufacturer during transportation could potentially be repaired in the retailer's facility and sold as new products. It could be argued that the degree of remanufacturing required here is associated with the degree of damage to the original product. As such, it could be loosely associated with the concept of customization degrees since both refer to the degree of change from the standard manufactured product. In a similar vein, Ullah et al. (2021) investigated the optimal remanufacturing strategy for a sustainable closed-loop supply chain where products could be returned. They present the concept of hybrid manufacturing-remanufacturing where partial demand is met by retailers through remanufacturing while the remainder is fulfilled from the manufacturer's side.

Our literature review positions our contributions within these literature streams.

2.1. Customization degree in 3DP manufacturing

The essence of customization is rooted in a company's ability to explore latent market niches and meet the different needs of these target customers (Jiao et al., 2003). Manufacturers offer customization based on market demand and their desire to fulfil customer needs for custom-made products; however, they must bear the potential costs incurred by the wider variety of customized production (Hegde et al., 2005; Um et al., 2017). Therefore, successful customization resides with the balance between providing the right variety of customized products and quick responsiveness to market demand or efficient production (Dong et al., 2012).

Based on firms' customization objectives and operation performance (e.g., production cost and delivery performance), customization can be pursued to different degrees; in doing so, it should consider the product variability offered to the market (Da Silveira et al., 2001). In current customization research, customization degree has been classified into various types following a standardization/customization continuum (Amaro et al., 1999; Da Silveira et al., 2001; Duray et al., 2000; Gilmore and Pine, 1997; Lampel and Mintzberg, 1996; Poulin et al., 2006), so that companies can manage their product design and customization production combining different market demands with their own production objectives and capabilities (Fogliatto et al., 2012).

In literature, customization degree has been broadly studied from product, process, and customer perspectives.

Product perspective: Customization degree is considered as the fraction of attributes of the product that a manufacturer chooses to customize. In this vein, Syam and Kumar (2006) characterize products with two attributes. The manufacturer determines the level of customization by choosing whether and which attribute(s) to customize in a duopoly setting.

Process perspective: Customization degree is also explored from a process view and defined as the degree of production flexibility. The customization degree thus depends on the part of the supply chain in which the customization is made. Rather than considering customization and standardization as alternatives, Lampel and Mintzberg (1996) delineated customization provisions along a standardization/customization continuum. They defined a manufacturing supply chain in four stages: design, fabrication, assembly, and distribution. Depending on the part of the supply chain in which the customization is made, five customization degrees are proposed: pure standardization, segmented standardization, customized standardization, tailored customization, and pure customization. This definition was also adopted in studies by Suomala et al. (2002) and Lyons et al. (2020).

Customer perspective: In marketing literature, the degree of customization is determined by how far consumers are involved in the customization production process (Duray et al., 2000; Wong and Lesmono, 2013). Jost and Suesser (2020) modelled consumers as active co-producers who define the level of customization. In Dewan et al. (2003), consumer preferences are distributed along Salop (1979)'s circular market-based mode and a manufacturer can choose to produce a standard or customized product. In this case, the manufacturer determines its customization scope represented as an arc on the circle.

The higher customization degree may lead to higher complexity in the manufacturing processes since it increases the number of product components or product varieties (Soltysova and Bednar, 2015; Zhang et al., 2005). It can also cause increased production costs (Modrak et al., 2014; Hu et al., 2011). Extra profits cannot always be guaranteed by additional resource inputs such as labor and materials. Mendelson and Parlaktürk, 2008 extended the analysis of firms' investments in customization under competition and found that investment in achieving a high level of customization should be avoided when unit costs and quality of the products do not have the advantage. Bardakci and Whitelock (2003) discovered that a higher level of mass customization would increase the prices of customized products, reducing customer satisfaction and affecting demand. This result was also echoed by Cavusoglu et al. (2007).

To mitigate the conflict between product variety and production costs, companies predominantly rely on controlling variation in the production of customized goods or use of modular and platform strategies to reduce the complexity and costs of product development, sourcing, and manufacturing (Baldwin and Clark, 1997; Pil and Holweg, 2004; Salvador et al., 2002). Many studies have attempted to investigate how various attributes influence the optimal customization degree, such as production cost and product structure (Spahi, 2008). Nevertheless, the aforementioned studies on degrees of customization have been undertaken in the context of mass customization. The relationship between customization degree and other influence factors on operation performance in specific 3DP manufacturing contexts has not been investigated.

3DP was first more extensively applied for small quantity customization, but now the possibility of application in hybrid manufacturing (3DP combined with conventional customization) is being explored and practised (Achillas et al., 2017; Beltagui et al., 2020; Oh et al., 2020). This is especially true for producing final parts (Khajavi et al., 2014) and end-use products (Achillas et al., 2017; Chen et al., 2021). Compared to the conventional approach to mass customization, 3DP provides innovative and improved product platforms by offering many derivatives with different features (Heradio et al., 2016), allowing for unprecedented customization options. 3DP lifts geometric limitations for manufacturers, enabling manufacturing efficiency with low volumes. From a product perspective, 3DP reaches the extreme of full customization (Baumers et al., 2017). Unlike Duray et al. (2000), who considered customization degree from a customer involvement perspective, we assume that the degree of customization is endogenous. Thus, in this study, considering 3DP's unique features, we adopt a process view to define customization degree as the involvement of the 3DP application within the customization production process. The higher the customization degree, the more the adoption of 3DP technology in the production process.

Many studies have confirmed the benefits of the 3DP application. 3DP may help a manufacturer to capture consumer surplus with enhanced flexibility to offer customization (Weller et al., 2015), customized production and transportation (Afshari et al., 2020; Eyers et al., 2018; Niaki and Nonino, 2017), as well as reduction of inventory (Knofius et al., 2019; Kunovjanek and Reiner, 2020). Despite the various advantages of 3DP, it has its limitation. While the initial investment for 3D printing may be lower than other manufacturing methods, once scaled up to produce large volumes for mass production, the cost per unit does not reduce as it would with injection moulding. For middle-volume production, both 3DP and mass production have advantages and disadvantages. The adoption of 3DP by manufacturers is a gradual process, whereby the manufacturing will consist of a hybrid combination of 3DP and traditional tool-based manufacturing. However, to what extent can 3DP be applied to customization production or become a viable economical alternative to traditional manufacturing in a hybrid manufacturing setting has hardly been investigated.

2.2. 3DP supply chain configuration decisions

3DP production can be implemented at any location and is anticipated to profoundly affect the supply chain configuration (Braziotis et al., 2019). 3DP will support both centralized and decentralized production configurations (Huang et al., 2013). In centralized manufacturing, 3DP production is centralized at the manufacturer facilities to serve multiple demand locations (Bogers et al., 2016; Braziotis et al., 2019). In this mode, economies of scale may be achieved by pooling demand from various service or market locations. However, the disadvantage is that production facilities are distant from service locations or end customers, resulting in increased response times and transportation costs (Huang et al., 2013; Hibbert, 2014; Braziotis et al., 2019).

In a decentralized configuration, 3DP production can be implemented locally next to potential customers (Bogers et al., 2016; Ben-Ner and Siemsen, 2017), with the extreme case of consumers owning 3D printers at home (Kleer and Piller, 2019). 3DP creates improved consumer welfare as customers are often concerned with manufacturing location and lead time (Hedenstierna et al., 2019; Kleer and Piller, 2019). In the case of 3DP-enabled decentralized supply chains, lower inventory, logistic costs, and faster deliveries in response to customer orders can be achieved (Holmström et al., 2010; Huang et al., 2013; Khajavi et al., 2014). A decentralized model also increases opportunities for collaboration and co-creation with customers (Kunovjanek and Reiner, 2020; Liu et al., 2014; Weller et al., 2015).

Interestingly, there is a contradiction regarding the economic feasibility of the decentralized configuration, owing to its high operating costs associated with the proliferation of 3DP production facilities at each service site and low-capacity utilization (Khajavi et al., 2014). However, there is limited research in the operations management literature exploring the trade-off between these two configurations. Jia et al. (2016) compare the financial viability of manufacturer 3D printing and retailer 3D printing models using simulation and find the manufacturer gains more profits in the manufacturer-dominant customization model. Under the retailer 3DP production model, Arbabian and Wagner (2020) characterize the economic and competitive conditions where either firm or retailer covers the costs for 3D printers and costs for materials. However, the model *(ibid.)* does not reflect the increase in customer utility brought about by customization, and the increase in the proportion of 3D printed products cannot directly expand market demand. In our paper, the customization degree we consider is not constrained by demand, and the market demand increases with the customization degree. Subsequent work by Arbabian (2022), conducted in a similar setting, characterizes the possible cost subsidy to induce 3DP adoption either at the manufacturer or at the retailer. Chen et al. (2021) evaluated the impact of 3DP on a firm's product variety, pricing, and inventory decisions in dual-channel settings where the adoption of 3DP can take place online and in-store. Unlike these studies which focus on 3DP fully customized products, we study the supply chain configuration strategy where the customized product is manufactured by combining 3DP technology and conventional manufacturing methods. Thus, 3DP may only be adopted in certain segments of the production process. However, how 3DP can be combined with conventional manufacturing in novel combinations to obtain operational benefits and its implication on supply chain configuration remains unexplored and is crucial for the deployment of 3DP (Holmström and Romme, 2012; Holmström et al., 2016).

2.3. 3DP customers' channel preferences

According to Mehrabani and Seifi (2021), customers' preference for online/offline channels can significantly affect sales and pricing, affecting manufacturers' distribution strategies. However, manufacturers and retailers can achieve a win-win scenario under a dual-channel supply chain. Thus, to reflect the real-world distribution landscape of 3DP manufactured products, we modelled online/offline retailing in our study. To maintain the competitive advantage and create extra value in the supply chain, manufacturers across a wide range of industries often utilize both direct and indirect channels to distribute customized products to achieve a balance between efficiency and flexibility. As both online and offline distribution has been considered in our study, we are building on a realistic distribution system where 3DP products are available for final customers.

In summary, scholars have studied the production planning decision considering customization degree, but they mainly consider customized products within mass customization not in the context of the application of 3D printing customization and have not yet linked with the 3DP supply chain configuration. The main achievement of our research is to explore production planning by evaluating customized strategy and supply chain configuration based on a realistic supply chain setting.

Table 2 shows the positioning of our study compared with the literature.

3. Models and notations

3.1. Problem description

In this research, we propose and analyze the Stackelberg game theoretic models of a 3DP supply chain consisting of a manufacturer, a retailer, and customers with different channel preferences. A customized product composed of standardized and 3DP customized parts is produced through a hybrid manufacturing method (production is carried out under both traditional and 3D printing technologies) and will be offered through an online channel in addition to the offline retail channel with potential market size a. D_t and D_o represent demand in offline and online channels, respectively. A monopolistic setting is applied with each agent trying to maximize its profit. This allows the examination of various issues related to both production and marketing factors without any interference from market competition. The leader (manufacturer) holds a dominant position in the hierarchical decision problem as it occupies more knowledge and has the advantage of experience in the 3DP application; the follower (retailer) reacts rationally to the leader's decision (Gibbons, 1992).

Similar to Jia et al. (2016) and Arbabian and Wagner (2020)'s supply chain configuration setting, the application of 3DP technology can take place either at the centralized manufacturer's facility or on the premises of a retailer. The latter is referred to as decentralized manufacturing. Thus, two 3DP customization models are considered: the centralized manufacturer-customized model (Model M) and the decentralized retailer-customized model (Model R). In Model M, the manufacturer produces both 3DP parts using 3DP technology and standard parts using traditional manufacturing methods, then assembles the parts to finalize the production. The 3DP customized products will be sold to the retailer via a wholesale-price contract with a unit wholesale price w_M , which is based on the model by Lariviere and Porteus (2001). The manufacturer simultaneously makes optimal decisions regarding the customization degree (3DP application level) e_M with the objective to maximize the expected profit. The retailer sells the customized products to customers at the offline selling price $p_{t|M}$, whilst the manufacturer sells customized products to customers through its online channel at the selling price $p_{o|M}$. A simplified model structure is shown in Fig. 1.

In a decentralized retailer-customized model (Model R), 3D printers are installed at the retailer facility; the manufacturer manufactures standard parts and supplies them to the retailer together with other 3D

Table 1
Authors' Statement of contribution.

Contribution Type	Statement of Contributions
Contribution to Theory	Our study considers both the customization degree and 3DP supply chain configuration in the context of 3DP manufacturing. Please refer to Table 2 (Section 2) for the contribution of the work in relation to the existing literature.
Contribution to Methodology	Our work presents a game-theoretical model that allows for the analytical assessment of the extent to which 3DP-enabled customization could be applied in hybrid customization manufacturing under centralized and decentralized supply chain configuration.
Contribution to Practice	Our work also contributes to practice; it offers practical managerial tools - a more developed and relevant game model to inform stakeholders on the degree of customization and the resultant profitability, thus assisting in better decision-making, which then contributes to bettering strategic business deployment of various stakeholders in 3DP supply chain.

Table 2
Summary of literature.

Representative papers	Customization degree	3DP supply chain configuration
Lampel and Mintzberg (1996)	✓	
Duray et al. (2000)	✓	
Suomala et al. (2002)	✓	
Dewan et al. (2003)	✓	
Syam and Kumar, 2006	✓	
Mendelson and Parlaktürk, 2008	✓	
Wong and Lesmono (2013)	✓	
Jost and Suesser (2020)	✓	
Lyons et al. (2020)	✓	
Huang et al. (2013)		✓
Weller et al. (2015)		✓
Bogers et al. (2016)		✓
Jia et al. (2016)		✓
Braziotis et al. (2019)		✓
Kleer and Piller (2019)		✓
Arbabian and Wagner (2020)	[a]	✓
Chen et al. (2021)		✓
Mehrabani and Seifi (2021)		✓
Arbabian (2022)		✓
Contribution of our paper	✓	✓

[a] **Note:** In Arbabian and Wagner (2020), it is arguable that the proportion of products that are 3D printed can be interpreted as the degree of customization. However, in our study we consider the scenario where both conventional and 3DP manufacturing methods are used in producing every unit of product.

customized schematics at a unit wholesale price w_R (see Fig. 2). The retailer prints the customized parts with the customization degree e_R and assembles them with standard parts to finalize the production at local stores. The retailer then sells the customized products through its stores and online channel directly to the customers at prices $p_{t|R}$ and $p_{o|R}$, respectively.

Different customized models result in different production cost structures (as shown in Table 3 below). Building on Baumers and Holweg (2019)'s cost categories, our model further considers the cost of standard parts and assembly due to the hybrid nature of the product. In Model M, the manufacturer incurs unit production cost c_{m1}. It includes the costs towards purchasing 3D printers and 3DP raw materials, investment related to 3D customized design, and costs related to standard parts and assembly. In Model R, the total unit production cost is $c_T = c_{m2} + c_r$. The manufacturer incurs unit production cost of 3D customized design investment and standard parts c_{m2}. And the retailer incurs unit production cost c_r which consist of the cost of 3D printers, 3DP raw materials and assembly. The cost variation coefficient is defined as $n = \frac{c_T}{c_{m1}}$ $(n > 0)$ to represent the total unit production cost ratio between Model R and Model M. We also denote the cost composition ratio $q = \frac{c_{m2}}{c_T}$ $(0 < q < 1)$ as the ratio between the manufacturer's unit production cost and the total unit production cost in Model R. In addition, in Chen et al.'s (2021) model, the cost of 3D technology adoption is a fixed parameter. In our research, the firm incurs the cost of 3D technology adoption to set up 3D printers and employee training. It is presented as a 3DP customized variable cost me_j^2 which considers the customization degree, and m $(m > 0)$ represents the cost efficiency of the 3D technology application (Dewan et al., 2003; Li et al., 2015). This reflects a positive relationship between the cost of 3D technology adoption and customization degree.

Finally, the optimal expected profits solution in the two 3DP customization models are compared, and the results determine whether the manufacturer or retailer adopts 3DP customization production. The optimal customization degree in the two models is analyzed, considering the individual profit maximization motive of the agents.

3.2. Assumptions and notations

The variable symbols and definitions of our models are presented in Table 4.

Table 3
Cost structure under different models.

	Centralized Manufacturer-customized model		Decentralized Retailer-customized model	
	Manufacturer	Retailer	Manufacturer	Retailer
3D printers purchasing cost	✓			✓
3DP raw materials cost	✓			✓
3D customized design investment cost	✓		✓	
The production cost of standard parts	✓		✓	
Assembly cost	✓			✓
3DP customized variable cost	✓			✓

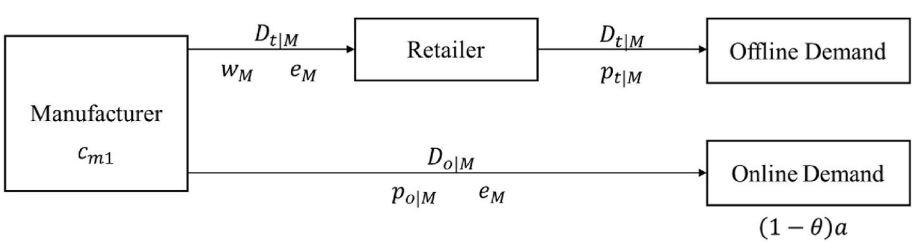


Fig. 1. Centralized Manufacturer-customized model (Model M).

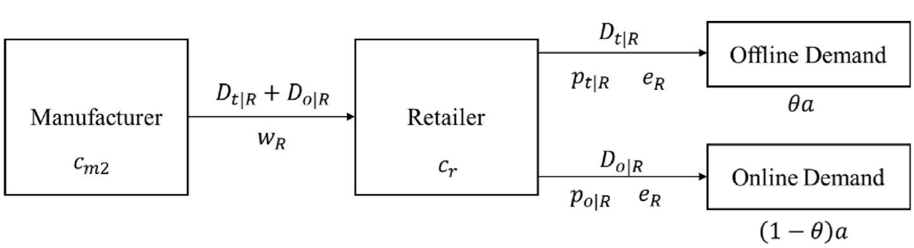


Fig. 2. Decentralized Retailer-customized model (Model R).

In this research, the following assumptions are made.

Assumption 1. To ensure that in each production model, the profit made by the manufacturer or retailer from each product is greater than zero, Thus, we assume that: In Model M, $w_M < p_{t|M}$ and $c_{m1} < w_M < p_{o|M}$; in Model R, $c_{m2} < w_R$, $w_R + c_r < p_{t|R}$, and $w_R + c_r < p_{o|R}$.

Assumption 2. 3DP technology will be used in the manufacturing process of customized products. $e_j (0 < e_j \leq 1)$ is the degree of customization defined as the level of 3DP application in the customization process. If $0 < e_j < 1$, it implies the product is a partial 3DP customized product. Thus, final products are assembled using standard parts (produced with traditional manufacturing technology) and 3DP customized parts. If $e_j = 1$, it implies the product is fully 3DP manufactured. τ ($\tau > 0$) is the customer preference coefficient for customization.

Assumption 3. Customers' preference for offline channels is greater than 0 and less than 1: $0 < \theta < 1$ (Chiang et al. (2003); Hua et al. (2010). Assumption 3 ensures that both online and offline channels will exist in Model M and Model R.

Assumption 4. The magnitude of self-price sensitivity is greater than cross-price sensitivity : $\beta > \alpha$ (Hanssens et al., 2001; Kurata et al., 2007).

Assumption 5. The demand of each sales channel has a linear relationship with the sales price and customization degree of products (Tsay and Agrawal, 2000; Chiang et al., 2003; Wang and He, 2022). it implies (i) each sales channel's demand is decreasing in its own price and increasing in customization degree, and (ii) one sales channel's price increase can increase the other sales channel's demand.

Table 4
Model notation.

Symbol	Description
superscript j	$j =$ M and $j =$ R represent manufacturer-customized model and retailer-customized model, respectively
Decision variables	
e_j	Customization degree under model j
w_M	Unit wholesale price for customized products under Model M
w_R	Unit wholesale price for 3D customized schematics, standard parts under Model R
$p_{t|j}$	Unit selling price from the offline channel under model j
$p_{o|j}$	Unit selling price from the online channel under model j
Model parameters	
a	Total potential market size
θ	Customer preference of offline channel
β	Coefficient of self-price sensitivity
α	Coefficient of cross-price sensitivity
τ	Customer preference coefficient for customization
m	Cost efficiency of 3DP technology adoption
c_{m1}	Unit cost of customized products under Model M (3D printers, 3DP raw materials, 3D customized design investment, standard parts, and assembly)
c_{m2}	Unit cost of 3D customized design investment and standard parts under Model R
c_r	Unit cost of 3D printers, 3DP raw materials, and assembly under Model R
c_T	The total unit production cost in Model R, $c_T = c_{m2} + c_r$
n	The total unit production cost ratio between Model R and Model M, $n = \frac{c_T}{c_{m1}}$
q	The ratio between the manufacturer's unit production cost and the total unit production cost in Model R, $q = \frac{c_{m2}}{c_T}$
Other notations	
$D_{t|j}$	Customer demand from the offline channel under model j
$D_{o|j}$	Customer demand from the online channel under model j
$\pi_{m|j}$	Profit for the manufacturer under model j
$\pi_{r|j}$	Profit for the retailer under model j

3.3. Demands and profits functions

According to assumption 5, the demand functions associated with offline and online retail channels are as follows:

The demand function for the offline channel is:

$$D_{t|j} = \theta a - \beta p_{t|j} + \alpha p_{o|j} + \tau e_j \tag{1}$$

The demand function for the online channel is:

$$D_{o|j} = (1-\theta)a - \beta p_{o|j} + \alpha p_{t|j} + \tau e_j \tag{2}$$

The profit function of the manufacturer and the retailer are as follows:

In Model M, the profit function for the manufacturer is:

$$\pi_{m|M} = (w_M - c_{m1})D_{t|M} + \left(p_{o|M} - c_{m1}\right)D_{o|M} - m{e_M}^2 \tag{3}$$

The profit function for the retailer is:

$$\pi_{r|M} = \left(p_{t|M} - w_M\right)D_{t|M} \tag{4}$$

In Model R, the profit function for the manufacturer is

$$\pi_{m|R} = (w_R - c_{m2})\ (D_{t|R} + D_{o|R}) \tag{5}$$

The profit function for the retailer is

$$\pi_{r|R} = \left(p_{t|R} - w_R - c_r\right)D_{t|R} + \left(p_{o|R} - w_R - c_r\right)D_{o|R} - m{e_R}^2 \tag{6}$$

4. Analysis

4.1. The centralized manufacturer-customized model (model M)

In Model M, the sequence of decisions in the game in our basic model is as follows:

The manufacturer simultaneously determines the customization degree e_M, the wholesale price of products w_M and online selling price $p_{o|M}$. Then, the retailer determines the offline selling price $p_{t|M}$.

In the above game, we can derive Equilibrium solutions using the standard backward induction technique. (To simplify the expression and presentation , we put the specific expression of symbols $L_1 \sim L_{14}$ in Appendix B)

$$w_M = \frac{L_4 - 2c_{m1}L_2(\tau^2 L_3 - 4\beta m L_1)}{2L_2 L_{10}}$$

$$p_{o|M} = \frac{L_5 - 2c_{m1}L_2(\tau^2 L_3 - 4\beta m L_1)}{2L_2 L_{10}}$$

$$p_{t|M} = \frac{L_6 - 2c_{m1}L_2(\tau^2 L_3 - 2mL_1L_2)}{2L_2 L_{10}}$$

$$e_M = \frac{\tau(a(2\beta - \theta L_1) - c_{m1}L_1L_3)}{L_{10}}$$

According to $e_M = \frac{\tau(a(2\beta - \theta L_1) - c_{m1}L_1L_3)}{L_{10}}$, we know that c_{m1} has a negative effect on e_M, and $e_M = 0$ when $c_{m1} = \frac{a(2\beta - \theta L_1)}{L_1 L_3}$. With c_{m1} continues to increase, e_M remains unchanged at 0; $e_M = 1$ when $c_{m1} = \frac{\tau a(2\beta - \theta L_1) + L_3\tau^2 - 8\beta m L_1}{\tau L_1 L_3}$. With c_{m1} continues to decrease, e_M remains unchanged at 1. Let $c_a = \frac{a(2\beta - \theta L_1)}{L_1 L_3}$, $c_b = \frac{\tau a(2\beta - \theta L_1) + L_3\tau^2 - 8\beta m L_1}{\tau L_1 L_3}$, when $m < m_a = \frac{L_3\tau^2 + a\tau(2\beta - \theta L_1)}{8\beta L_1}$, $c_b > 0$. And $c_a - c_b = \frac{8\beta m L_1 - \tau^2 L_3}{\tau L_3 L_1} > 0$.

The degree of customization can be rewritten as:

$$e_M = \begin{cases} 1 & 0 < c_{m1} \leq c_b \\ \frac{\tau(a(2\beta - \theta L_1) - c_{m1}L_1L_3)}{L_{10}} & c_b < c_{m1} < c_a \end{cases}$$

then, the online and offline demand functions can be rewritten as:

$$D_{t|M} = \begin{cases} \theta a - \beta p_{t|M} + \alpha p_{o|M} + \tau 0 < c_{m1} \le c_b \\ \theta a - \beta p_{t|M} + \alpha p_{o|M} + \tau e_M c_b < c_{m1} < c_a \end{cases}$$

$$D_{o|M} = \begin{cases} (1-\theta) a - \beta p_{o|M} + \alpha p_{t|M} + \tau 0 < c_{m1} \le c_b \\ (1-\theta) a - \beta p_{o|M} + \alpha p_{t|M} + \tau e_M c_b < c_{m1} < c_a \end{cases}$$

Therefore, in Model M, the manufacturer's optimal degree of customization, optimal pricing and profit are e_M^*, w_M^*, $p_{o|M}^*$ and $\pi_{m|M}^*$, the customized product sales volume of the offline channel and the online channel are $D_{t|M}^*$ and $D_{o|M}^*$, the retailer' s optimal pricing and profit are $p_{t|M}^*$ and $\pi_{r|M}^*$:

$$e_M^* = \begin{cases} 1 \quad 0 < c_{m1} \le c_b \\ \dfrac{\tau(a(2\beta - \theta L_1) - c_{m1} L_1 L_3)}{L_{10}} c_b < c_{m1} < c_a \end{cases} \tag{7}$$

$$w_M^* = \begin{cases} \dfrac{a(\alpha + \theta L_1) + \tau L_2 + c_{m1} L_1 L_2}{2 L_1 L_2} 0 < c_{m1} \le c_b \\ \dfrac{L_4 - 2 c_{m1} L_2 (\tau^2 L_3 - 4\beta m L_1)}{2 L_2 L_{10}} c_b < c_{m1} < c_a \end{cases} \tag{8}$$

$$p_{o|M}^* = \begin{cases} \dfrac{a(\beta - \theta L_1) + t L_2 + c_{m1} L_1 L_2}{2 L_1 L_2} 0 < c_{m1} \le c_b \\ \dfrac{L_5 - 2 c_{m1} L_2 (\tau^2 L_3 - 4\beta m L_1)}{2 L_2 L_{10}} c_b < c_{m1} < c_a \end{cases} \tag{9}$$

$$p_{t|M}^* = \begin{cases} \dfrac{a(2\beta\alpha + \theta L_1 L_3) + t L_2 (3\beta - \alpha) + c_{m1} L_2^2 L_1}{4\beta L_1 L_2} 0 < c_{m1} \le c_b \\ \dfrac{L_6 - 2 c_{m1} L_2 (\tau^2 L_3 - 2 m L_1 L_2)}{2 L_2 L_{10}} c_b < c_{m1} < c_a \end{cases} \tag{10}$$

$$D_{t|M}^* = \begin{cases} \dfrac{a\theta + \tau - c_{m1} L_1}{4} 0 < c_{m1} \le c_b \\ \dfrac{\beta(4am\theta L_1 - a\tau^2(2\theta - 1) - 4 c_{m1} m L_1^2)}{2 L_{10}} c_b < c_{m1} < c_a \end{cases} \tag{11}$$

$$D_{o|M}^* = \begin{cases} \dfrac{a(\beta(2-\theta) - \theta L_1) + (2\beta + \alpha)(\tau - c_{m1} L_1)}{4\beta} 0 < c_{m1} \le c_b \\ \dfrac{L_7 - 4 c_{m1} m L_1^2 (2\beta + \alpha)}{2 L_{10}} c_b < c_{m1} < c_a \end{cases} \tag{12}$$

$$\pi_{m|M}^* = \begin{cases} \dfrac{L_9 - c_{m1} L_1 L_2 L_3 (2\tau - c_{m1} L_1)}{8\beta L_1 L_2} 0 < c_{m1} \le c_b \\ \dfrac{L_8 - 4 c_{m1} m L_1 L_2 (2a(2\beta - \theta L_1) + c_{m1} L_1 L_3)}{4 L_2 L_{10}} c_b < c_{m1} < c_a \end{cases} \tag{13}$$

$$\pi_{r|M}^* = \begin{cases} \dfrac{(a\theta + \tau - c_{m1} L_1)^2}{16\beta} 0 < c_{m1} \le c_b \\ \dfrac{\beta(4 c_{m1} m L_1^2 + a\tau^2(2\theta - 1) - 4am\theta L_1)^2}{4 L_{10}^2} c_b < c_{m1} < c_a \end{cases} \tag{14}$$

Under Model M, according to the above equilibrium results, we derive constraint on m: $m_b < m < min\{m_a, m_1, m_2\}$. m_b is the lower limit of cost efficiency of 3DP technology adoption. We conduct the analysis under this constraint in order to ensure the practical significance of the research.

The above equilibrium results are summarized as follows.

Theorem 1. The equilibrium solutions under Model M are summarized in Table 5.

Proposition 1. *Under Model M, the following hold*:

(1) If $0 < c_{m1} \le c_b$, the optimal degree of customization $e_M^* = 1$, and e_M^* is not affected by the unit production cost c_{m1}.
(2) If $c_b < c_{m1} < c_a$, the optimal degree of customization $e_M^* \in (0, 1)$, and e_M^* decreases when the unit production cost c_{m1}.

Proposition 1 states that under Model M, when the unit production cost c_{m1} is relatively small (i.e., $0 < c_{m1} \le c_b$), the manufacturer uses 3DP technology for production and the unit production cost c_{m1} has no effect on the optimal degree of customization. When the unit production cost c_{m1} is relatively large (i.e.,$c_b < c_{m1} < c_a$), the manufacturer uses both 3DP technology and traditional manufacturing technology for production at the same time, and the optimal customization degree of products decreases with increasing the unit production cost c_{m1}, which implies that the proportion of production using 3DP technology decreases. If the unit production cost c_{m1} is relatively large, the increase in sales revenue brought about through the improvement of customization degree will be proportionately lower than the increase in the investment cost of 3DP technology. In other words, the larger the unit production cost c_{m1}, the less the increase in sales revenue. Thus, the manufacturer can only decrease the optimal degree of customization to reduce the negative effects of the high investment cost of 3DP technology.

Proposition 2. Under Model M, when customers' preference for offline channel θ increases, its effect on the optimal decisions is shown in Table 6.

In Model M, when the unit production cost of customized products c_{m1} is relatively small (i.e., $0 < c_{m1} \le c_b$), customers' preference for offline channel θ does not affect the optimal customization degree. When the unit production cost c_{m1} is relatively large (i.e., $c_b < c_{m1} < c_a$), the customization degree will decrease when θ increases. This is because when the unit production cost c_{m1} is relatively small, the manufacturer tends to offer fully customized products regardless of whether they will be distributed through the online channel or the offline channel (hence, the customization degree is always 1). However, if the unit production cost c_{m1} is relatively large, when θ increases, more products would sell through the offline channel compared to the online channel. This will affect the manufacturer's total profits as they always decrease in such a scenario. In other words, the positive change caused by growth in offline sales is not sufficient to offset the loss from fewer online sales. In this situation, the manufacturer tends to decrease customization degree and thus saves from customized fixed costs in the pursuit of higher profitability.

Proposition 3. *Under Model M,*

(1) *Online sales volume $D_{o|M}^*$ is always larger than offline sales volume $D_{t|M}^*$, and the volume difference increases when the unit production cost c_{m1} increases.*
(2) *When the unit production cost c_{m1} is relatively small, the online selling price $p_{o|M}^*$ would be less than the offline selling price $p_{t|M}^*$, and the price difference increases when the unit production cost c_{m1} increases.*

According to the constraint $p_{t|M}^* > w_M^*$, we can obtain $0 < \theta < \frac{1}{2}$.This means that the market demand for offline channels is always less than online channels, so offline sales volume will not exceed online sales volume. Proposition 3(2) explores how the unit production cost c_{m1} affects both the manufacturer's and the retailer's pricing strategy. When the unit production cost c_{m1} is relatively small, since the manufacturer cannot increase market demands by increasing the degree of customization, higher market demands can only be achieved through lowering the product price. While, the retailer will charge a higher price to increase unit profit. When the unit production cost c_{m1} is relatively large, both the manufacturer and the retailer may take the opposite pricing strategies. As the unit production cost c_{m1} decreases, the difference between distribution channels would decrease, accompanied by fiercer price competition.

4.2. The decentralized retailer-customized model (model R)

In Model M, the sequence of decisions in the game is as follows:

The manufacturer determines the wholesale price w_R. Then, the retailer simultaneously determines the customization degree e_R, online selling price $p_{o|R}$ and offline selling price $p_{t|R}$.

We solve the game by backward induction.

$$w_R = \frac{a+2L_1(c_{m2}-c_r)}{4L_1}$$

$$p_{t|R} = \frac{L_{12}-2c_T(\tau^2-mL_1)L_1L_2}{4L_2L_1L_{14}}$$

$$p_{o|R} = \frac{L_{11}-2c_T(\tau^2-mL_1)L_1L_2}{4L_1L_2L_{14}}$$

$$e_R = \frac{\tau(a-2L_1c_T)}{4L_{14}}$$

According to $e_R = \frac{\tau(a-2L_1c_T)}{4L_{14}}$, we know that c_T has a negative effect on e_R , and $e_R = 0$ when $c_T = \frac{a}{2L_1}$. With c_T continues to increase, e_R remains unchanged at 0; $e_R = 1$ when $c_T = \frac{a\tau+4\tau^2-8mL_1}{2n\tau L_1}$, with c_T continues to decrease, e_R remains unchanged at 1. Let $c_c = \frac{a}{2L_1}$, $c_d = \frac{a\tau+4\tau^2-8mL_1}{2n\tau L_1}$, when $m < m_c = \frac{4\tau^2+a\tau}{8L_1}$, $c_d > 0$, and $c_c - c_d = \frac{2(2mL_1-\tau^2)}{\tau L_1} > 0$.

The degree of customization can be rewritten as:

$$e_R = \begin{cases} 1 & 0 < c_T \le c_d \\ \dfrac{\tau(a-2L_1(c_{m2}+c_r))}{4L_{14}} & c_d < c_T < c_c \end{cases}$$

then, the online and offline demand functions can be rewritten as:

$$D_{t|R} = \begin{cases} \theta a - \beta p_{t|R} + \alpha p_{o|R} + \tau & 0 < c_T \le c_d \\ \theta a - \beta p_{t|R} + \alpha p_{o|R} + \tau e_R & c_d < c_T < c_c \end{cases}$$

$$D_{o|R} = \begin{cases} (1-\theta)a - \beta p_{o|R} + \alpha p_{t|R} + \tau & 0 < c_T \le c_d \\ (1-\theta)a - \beta p_{o|R} + \alpha p_{t|R} + \tau e_R & c_d < c_T < c_c \end{cases}$$

Therefore, in Model R, the optimal pricing and profit of the manufacturer are w_R^* and $\pi_{m|R}^*$, the demand for customized products in offline channels and online channels are $D_{t|R}^*$ and $D_{o|R}^*$, the optimal degree of customization, price and profit for retailers are e_R^*, $p_{o|R}^*$, $p_{t|R}^*$ and $\pi_{r|R}^*$:

$$e_R^* = \begin{cases} 1 & 0 < c_T \le c_d \\ \dfrac{\tau(a-2L_1c_T)}{4L_{14}} & c_d < c_T < c_c \end{cases} \tag{15}$$

$$w_R^* = \begin{cases} \dfrac{a+2\tau+2L_1(c_{m2}-c_r)}{4L_1} & 0 < c_T \le c_d \\ \dfrac{a+2L_1(c_{m2}-c_r)}{4L_1} & c_d < c_T < c_c \end{cases} \tag{16}$$

$$p_{o|R}^* = \begin{cases} \dfrac{a(5\beta+\alpha)+4a\theta L_1+6\tau L_2+2L_1L_2c_T}{8L_1L_2} & 0 < c_T \le c_d \\ \dfrac{L_{11}-2c_T(\tau^2-mL_1)L_1L_2}{4L_1L_2L_{14}} & c_d < c_T < c_c \end{cases} \tag{17}$$

$$p_{t|R}^* = \begin{cases} \dfrac{a(\beta+5\alpha)+4a\theta L_1+6\tau L_2+2L_1L_2c_T}{8L_1L_2} & 0 < c_T \le c_d \\ \dfrac{L_{12}-2c_T(\tau^2-mL_1)L_1L_2}{4L_2L_1L_{14}} & c_d < c_T < c_c \end{cases} \tag{18}$$

$$D_{t|R}^* = \begin{cases} \dfrac{a(4\theta-1)+2\tau-2L_1c_T}{8} & 0 < c_T \le c_d \\ \dfrac{amL_1(4\theta-1)-a\tau^2(2\theta-1)-2mc_TL_1^2}{4L_{14}} & c_d < c_T < c_c \end{cases} \tag{19}$$

$$D_{o|R}^* = \begin{cases} \dfrac{a(3-4\theta)+2\tau-2L_1c_T}{8} & 0 < c_T \le c_d \\ \dfrac{a\tau^2(2\theta-1)-amL_1(4\theta-3)-2mc_TL_1^2}{4L_{14}} & c_d < c_T < c_c \end{cases} \tag{20}$$

$$\pi_{m|R}^* = \begin{cases} \dfrac{(a+2\tau-2L_1c_T)^2}{16L_1} & 0 < c_T \le c_d \\ \dfrac{m(a-2L_1c_T)^2}{8L_{14}} & c_d < c_T < c_c \end{cases} \tag{21}$$

$$\pi_{r|R}^* = \begin{cases} \dfrac{L_{13}-4L_1L_2c_T(a+2\tau-c_TL_1)}{32L_1L_2} & 0 < c_T \le c_d \\ \dfrac{L_{12}-4mL_1L_2c_T(a-L_1c_T)}{16L_2L_{14}} & c_d < c_T < c_c \end{cases} \tag{22}$$

Under Model R, according to the above equilibrium results, we derive constraint on m: $m_d < m < min\{m_c, m_3, m_4\}$. m_d is the lower limit of cost efficiency of 3DP technology adoption. We conduct the analysis under this constraint to ensure the practical significance of the research.

The above equilibrium results are summarized as follows.

Theorem 2. The equilibrium solutions under Model R are summarized in Table 7.

Proposition 4. Under Model R:

(1) If $0 < c_T \le c_d$, the optimal degree of customization $e_R^* = 1$, and e is not affected by the total unit production cost c_T.

(2) If $c_d < c_T < c_c$, the optimal degree of customization $e_R^* \in (0,1)$, and e_R^* decreases when the total unit production cost c_T increases.

Proposition 4 shows that under Model R, when the total unit production cost c_T is relatively small (i.e., $0 < c_T \le c_d$), the retailer uses 3DP technology for production. The total unit production cost c_T has no effect on the optimal degree of customization. When the total unit production cost c_T is relatively large (i.e., $c_d < c_T < c_c$), the optimal customization degree of products decreases when the unit production cost increases, which means that the proportion of 3DP customization will decrease.

Combined with Proposition 1, the difference between Model R and Model M is that whether the retailer adopts traditional manufacturing technology for partial customization production is not only affected by the retailer's unit production cost c_r is also affected by the manufacturer's unit production cost c_{m2}.

Proposition 5. Under Model R, when customers' preference for offline channel θ increases, its effect on the optimal decisions is shown in Table 8.

In Model R, when customers' preference for offline channel θ increases, the retailer's profit will decrease, while the customization degree and the manufacturer's wholesale price and profitability remain unaffected. Based on *Eq. (5)*, the manufacturer's total profit is the multiplied sum of the wholesale price and the total market demand (online plus offline, which is stable and irrelevant to consumer's preference for offline channel). In other words, given stable total market demand, the manufacturer's optimal decision will not be affected by the customer's preference for the offline channel. Under Model R, the wholesale price set by the manufacturer influences the retailer's optimal customization degree, which changes sales volumes through online/offline channels and fixed costs for customization. In contrast, the online and offline prices of the retailer would affect both sales volume and unit profit. Hence, the optimal customization degree is not affected by customers' preference for distribution channels.

Proposition 6. *Under Model R,*

(1) The online sales volume $D^*_{o|R}$ is always larger offline sales volume $D^*_{t|R}$. The volume difference is not affected by total unit production cost c_T.
(2) The online selling price $p^*_{o|R}$ is always higher than the offline selling price $p^*_{t|R}$. The price difference is not affected by the total unit production cost c_T.

Similar to Proposition 3, in Proposition 6(1), given $p^*_{o|R} > w^*_R$, we can obtain $0 < \theta < \frac{1}{2}$, meaning the market demand for the offline channel is less than for the online channel; hence the offline sales volume will not exceed the online sales volume. As the online channel is preferred by customers and generates more orders, under Model R, the retailer can always set a higher online sales price than offline price, as indicated in Proposition 6(2). This is because in model R, the degree of customization and the prices in two channels are determined by the retailer, and the change of unit cost will not affect the pricing strategy.

4.3. Comparing model M and model R

Proposition 7. *: Comparing the optimal degrees of customization between Model M and Model R under different threshold conditions.*

(1) *If* $m_e \le m < m_c$ and $n_1 \le n \le n_2$, $0 < e_R{}^* < e_M{}^* < 1$ when $c_b \le c_{m1} < c_g$; $0 < e_M{}^* \le e_R{}^* < 1$ when $c_g \le c_{m1} < c_a$; if $m_e \le m < m_c$ and $n_2 < n \le n_3$, $0 < e_R{}^* < e_M{}^* < 1$ when $c_b \le c_{m1} < c_e$

In Proposition 7(1), if the cost efficiency of 3DP technology adoption m is relatively large and the cost variation coefficient n is relatively small, then when c_{m1} is relatively small, the optimal degree of customization under Model R is lower than that under Model M; when c_{m1} is relatively large, the optimal degree of customization under Model R is higher than that under Model M. If both the cost efficiency of 3DP technology adoption m and the cost variation coefficient n are relatively large, the optimal degree of customization under Model R is always lower than that under Model M.

(2) If $m_d < m < m_e$ and $n_4 < n \le n_2$, $0 < e_M{}^* < e_R{}^* < 1$ when $c_f \le c_{m1} < c_a$; if $m_d < m < m_e$ and $n_2 < n \le n_1$, $0 < e_M{}^* < e_R{}^* < 1$ when $c_f \le c_{m1} < c_g$; $0 < e_R{}^* \le e_M{}^* < 1$ when $c_g \le c_{m1} < c_e$.

In *Proposition 7(2)*, if both the cost efficiency of 3DP technology adoption *m* and the cost variation coefficient *n* are relatively small, the optimal degree of customization under Model M is always lower than that under Model R. If the cost efficiency of 3DP technology adoption *m* is relatively small and the cost variation coefficient *n* is relatively large, then when c_{m1} is relatively small, the optimal degree of customization under Model M is lower than that under Model R; when c_{m1} is relatively large, the optimal degree of customization under Model M is higher than that under Model R.

Proposition 8. *Under Model R*:

(1) The optimal selling prices $p^*_{o|R}$ and $p^*_{t|R}$, and the optimal profits $\pi^*_{m|R}$ and $\pi^*_{r|R}$ are not affected by the cost composition ratio q.
(2) If $0 < c_{m1} \le c_f$, $p^*_{o|R}$ and $p^*_{t|R}$ increase, when the cost variation coefficient n increases; if $c_f < c_{m1} < c_e$, $p^*_{o|R}$ and $p^*_{t|R}$ decrease with increasing the cost variation coefficient n when $m_d < m < m_5$, $p^*_{o|R}$ and $p^*_{t|R}$ increase with increasing the cost variation coefficient n when $m_5 \le m < m_c$. $\pi^*_{m|R}$ and $\pi^*_{r|R}$ decrease with increasing the cost variation coefficient n all the time when $0 < c_{m1} < c_e$.

Proposition 8 states that under Model R, the optimal selling prices and the optimal profits are not affected by the cost composition ratio q, but are affected by the cost variation coefficient n. In other words, the retailer would pay more attention to the total unit production cost c_T rather than his own the unit production cost c_r.

Hence, if the retailer offers partially customized products to the customers, the increase of the cost variation coefficient n will reduce the optimal selling prices, when the cost efficiency of 3DP technology adoption m is relatively small; The increase of the cost variation coefficient n will increase the optimal selling prices when the cost efficiency of 3DP technology adoption m is relatively large. If the retailer offers fully customized products to customers, the optimal selling prices always increase with the increase of cost variation coefficient n. We prove that the retailer needs to consider not only production costs but also the 3DP raw materials, 3D printers cost and standard parts, so he has the incentive to collaborate with the manufacturer to carry out research and development (R&D), the manufacturer should also consider how to collaborate with the retailer.

5. Numerical analysis

In this section, we conduct numerical experiments to further investigate the impact of unit production cost c_{m1} on the optimal customization degree, manufacturer's and retailer's optimal profits through sensitivity analysis. We also compare the manufacturer's and the retailer's optimal profits and customization strategies under different models. To make the models feasible and meaningful, all the values of the chosen parameters satisfy the model constraints. Under the condition of satisfying all model constraints, we assume that the base values of the parameters are $a = 100$; $\theta = 0.4$; $\alpha = 1.5$; $\beta = 6.5$; $\tau = 20$ (Bian et al., 2017; Wang and He, 2022). To illustrate more scenarios within the constraints and verify the analysis in Table 9 and Table 10 above, we investigate the impact of unit production cost on supply chain decision-making when the cost variation coefficient is small, moderate or large.

In Fig. 3, under Model M, if $m = 65$, the manufacturer offers fully customized products when $0 < c_{m1} \le 6.43$, the manufacturer offers partially customized products when $6.43 < c_{m1} \le 9.23$. Under Model R, if $m = 65$ and $n = 0.8$, the retailer offers fully customized products when $0 < c_{m1} \le 6.25$, the retailer offers partially customized products when $6.25 < c_{m1} \le 10.58$ (Fig. 3a); if $m = 65$ and $n = 1$, the retailer offers fully customized products when $0 < c_{m1} \le 5$, the retailer offers partially customized products when $5 < c_{m1} \le 8.46$ (Fig. 3b); if $m = 65$ and $n = 1.6$, the retailer offers fully customized products when $0 < c_{m1} \le 3.13$, the retailer offers partially customized products when $3.13 < c_{m1} \le 5.29$ (Fig. 3c).

In Fig. 4, under Model M, if $m = 45$, the manufacturer offers fully customized products when $0 < c_{m1} \le 8.9$, the manufacturer offers partially customized products when $8.9 < c_{m1} \le 9.78$. Under Model R, if $m = 45$ and $n = 1$, the retailer offers fully customized products when $0 < c_{m1} \le 9$, the retailer offers partially customized products when $9 < c_{m1} \le 9.56$ (Fig. 4a); if $m = 45$ and $n = 0.94$, the retailer offers fully customized products when $0 < c_{m1} \le 9.57$, the retailer offers partially customized products when $9.57 < c_{m1} \le 10.17$ (Fig. 4b); if $m = 45$ and $n = 0.7$, the retailer offers fully customized products when $0 < c_{m1} \le 12.86$, the retailer offers partially customized products when $12.86 < c_{m1} \le 13.56$ (Fig. 4c). Figs. 3 and 4 show the analysis results in Table 7, Table 8 and *Proposition 7*.

It can be seen from Fig. 5 that if the cost efficiency of 3DP technology adoption *m* is relatively large, the manufacturer chooses to let the retailer conduct customized production only when the cost variation coefficient *n* is relatively small and the unit production cost c_{m1} is relatively large.

As can be seen from Fig. 6, if the cost efficiency of 3DP technology adoption *m* and the unit production cost c_{m1} are relatively small, regardless of the cost-efficiency of 3DP technology adoption *m*, the

Table 5
Equilibrium solutions under Model M.

	$0 < c_{m1} \le c_b$	$c_b < c_{m1} < c_a$
e_M^*	1	$\frac{\tau(a(2\beta - \theta L_1) - c_{m1}L_1L_3)}{L_{10}}$
w_M^*	$\frac{a(\alpha+\theta L_1) + \tau L_2 + c_{m1}L_1L_2}{2L_1L_2}$	$\frac{L_4 - 2c_{m1}L_2(\tau^2L_3 - 4\beta mL_1)}{2L_2L_{10}}$
$p_{o\|M}^*$	$\frac{a(\beta - \theta L_1) + tL_2 + c_{m1}L_1L_2}{2L_1L_2}$	$\frac{L_5 - 2c_{m1}L_2(\tau^2L_3 - 4\beta mL_1)}{2L_2L_{10}}$
$p_{t\|M}^*$	$\frac{a(2\beta\alpha + \theta L_1L_3) + tL_2(3\beta - \alpha) + c_{m1}{L_2}^2L_1}{4\beta L_1L_2}$	$\frac{L_6 - 2c_{m1}L_2(\tau^2L_3 - 2mL_1L_2)}{2L_2L_{10}}$
$D_{t\|M}^*$	$\frac{a\theta + \tau - c_{m1}L_1}{4}$	$\frac{\beta(4am\theta L_1 - a\tau^2(2\theta - 1) - 4c_{m1}m{L_1}^2)}{2L_{10}}$
$D_{o\|M}^*$	$\frac{a(\beta(2 - \theta) - \theta L_1) + (2\beta+\alpha)(\tau - c_{m1}L_1)}{4\beta}$	$\frac{L_7 - 4c_{m1}m{L_1}^2(2\beta+\alpha)}{2L_{10}}$
$\pi_{m\|M}^*$	$\frac{L_9 - c_{m1}L_1L_2L_3(2\tau - c_{m1}L_1)}{8\beta L_1L_2}$	$\frac{L_8 - 4c_{m1}mL_1L_2(2a(2\beta - \theta L_1) + c_{m1}L_1L_3)}{4L_2L_{10}}$
$\pi_{r\|M}^*$	$\frac{(a\theta + \tau - c_{m1}L_1)^2}{16\beta}$	$\frac{\beta(4c_{m1}m{L_1}^2 + a\tau^2(2\theta - 1) - 4am\theta L_1)^2}{4{L_{10}}^2}$

Table 6
Effects brought by increased $\boldsymbol{\theta}$ on optimal decisions (Model M).

	e_M^*	w_M^*	$p_{o\|M}^*$	$p_{t\|M}^*$	$D_{o\|M}^*$	$D_{t\|M}^*$	$\pi_{m\|M}^*$	$\pi_{r\|M}^*$
$0 < c_{m1} \le c_b$	–	↑	↓	↑	↓	↑	↓	↑
$c_b < c_{m1} < c_a$	↓	~	↓	~	↓	↑	↓	~

" – " no effect; "↓" negative effect; "↑"positive effect; "~" non-linear effect.

manufacturer does not choose to let the retailer conduct customized production. Combining Figs. 5 and 6, we can know that if the unit production cost c_{m1} is small, regardless of the cost-efficiency of 3DP technology adoption m and the cost variation coefficient n, the manufacturer will choose to produce fully customized products by itself.

6. Extended models

Westerweel et al. (2018) argue that the application of 3DP may have various impacts on different types of costs; for example, in some cases, the development cost of 3DP components is higher than that of conventional components; in other cases, the shorter production lead time enabled through 3DP can reduce costs towards logistics. There is also a debate on the impact of 3DP adoption on variable costs. 3DP can lead to higher or lower variable costs depending on the type of product being manufactured.

Therefore, in this section, based on the basic model in Section 3, we further relax the hypothesis and consider the scenarios where the customization degree of 3DP products affects the unit production cost. Specifically, we investigate two cases: (A) as the degree of customization increases, the unit production cost decreases; (B) as the degree of customization increases, the unit production cost increases. Based on the new hypothesis, we find that the equilibrium solution becomes complex and the influence path of the relevant cost on the customization strategy cannot be obtained. Irrespective of this limitation, we make some interesting findings by analyzing the impact of the potential market size of the product on the customization degree and the profits of supply chain members.

According to the new hypothesis, we introduce the parameter φ ($0 < \varphi < 1$) as the cost variation coefficient, that is, the coefficient of the effect of an increase in the customization degree on the unit production cost. In the above two cases, we also consider the manufacturer's (M) and retailer's (R) customization models, respectively, and solve the optimal customization degree. We explore four models as follows:

(1) Model MA: Centralized Manufacturer-customized model considering that the unit production cost decreases when the customization degree increases;

Table 8
Effects brought by increased $\boldsymbol{\theta}$ on optimal decisions (Model R).

	e_R^*	w_R^*	$p_{o\|R}^*$	$p_{t\|R}^*$	$D_{o\|R}^*$	$D_{t\|R}^*$	$\pi_{m\|R}^*$	$\pi_{r\|R}^*$
$0 < c_T \le c_d$	–	–	↓	↑	↓	↑	–	↓
$c_d < c_T \le c_c$	–	–	↓	↑	↓	↑	–	↓

"– "no effect; "↓" negative effect; "↑" positive effect.

Table 7
Equilibrium solutions under Model R.

	$0 < c_T \le c_d$	$c_d < c_T < c_c$
e_R^*	1	$\frac{\tau(a - 2L_1c_T)}{4L_{14}}$
w_M^*	$\frac{a + 2\tau + 2L_1(c_{m2} - c_r)}{4L_1}$	$\frac{a + 2L_1c_T}{4L_1}$
$p_{o\|R}^*$	$\frac{a(5\beta+\alpha) + 4a\theta L_1 + 6\tau L_2 + 2L_1L_2c_T + c_r}{8L_1L_2}$	$\frac{L_{11} - 2c_T(\tau^2 - mL_1)L_1L_2}{4L_1L_2L_{14}}$
$p_{t\|R}^*$	$\frac{a(\beta+5\alpha) + 4a\theta L_1 + 6\tau L_2 + 2L_1L_2c_T}{8L_1L_2}$	$\frac{L_{12} - 2c_T(\tau^2 - mL_1)L_1L_2}{4L_2L_1L_{14}}$
$D_{t\|R}^*$	$\frac{a(4\theta - 1) + 2\tau - 2L_1c_T}{8}$	$\frac{amL_1(4\theta - 1) - a\tau^2(2\theta - 1) - 2mc_T{L_1}^2}{4L_{14}}$
$D_{o\|R}^*$	$\frac{a(3 - 4\theta) + 2\tau - 2L_1c_T}{8}$	$\frac{a\tau^2(2\theta - 1) - amL_1(4\theta - 3) - 2mc_T{L_1}^2}{4L_{14}}$
$\pi_{m\|R}^*$	$\frac{(a + 2\tau - 2L_1c_T)^2}{16L_1}$	$\frac{m(a - 2L_1c_T)^2}{8L_{14}}$
$\pi_{r\|R}^*$	$\frac{L_{13} - 4L_1L_2c_T(a + 2\tau - c_TL_1)}{32L_1L_2}$	$\frac{L_{12} - 4mL_1L_2c_T(a - L_1c_T)}{16L_2L_{14}}$

Table 9
Customization strategy when $m_e \le m < m_c$.

$m_e \le m < m_c$								
$n_1 \le n \le n_2$			$n_2 < n \le n_3$			$n > n_3$		
	$e_M{}^*$	$e_R{}^*$		$e_M{}^*$	$e_R{}^*$		$e_M{}^*$	$e_R{}^*$
$0 < c_{m1} < c_f$	1	1	$0 < c_{m1} < c_f$	1	1	$0 < c_{m1} < c_f$	1	1
$c_f \le c_{m1} < c_b$	1	$(0,1)$	$c_f \le c_{m1} < c_b$	1	$(0,1)$	$c_f \le c_{m1} < c_e$	1	$(0,1)$
$c_b \le c_{m1} < c_a$	$(0,1)$	$(0,1)$	$c_b \le c_{m1} < c_e$	$(0,1)$	$(0,1)$	$c_e \le c_{m1} < c_b$	1	\
$c_a \le c_{m1} < c_e$	\	$(0,1)$	$c_e \le c_{m1} < c_a$	$(0,1)$	\	$c_b \le c_{m1} < c_a$	$(0,1)$	\

Table 10
Customization strategy when $m_d < m < m_e$.

$m_d < m < m_e$								
$n_2 < n \le n_1$			$n_4 < n \le n_2$			$n \le n_4$		
	$e_M{}^*$	$e_R{}^*$		$e_M{}^*$	$e_R{}^*$		$e_M{}^*$	$e_R{}^*$
$0 < c_{m1} < c_b$	1	1	$0 < c_{m1} < c_b$	1	1	$0 < c_{m1} < c_b$	1	1
$c_b \le c_{m1} < c_f$	$(0,1)$	1	$c_b \le c_{m1} < c_f$	$(0,1)$	1	$c_b \le c_{m1} < c_a$	$(0,1)$	1
$c_f \le c_{m1} < c_e$	$(0,1)$	$(0,1)$	$c_f \le c_{m1} < c_a$	$(0,1)$	$(0,1)$	$c_a \le c_{m1} < c_f$	\	1
$c_e \le c_{m1} < c_a$	$(0,1)$	\	$c_a \le c_{m1} < c_e$	\	$(0,1)$	$c_f \le c_{m1} < c_e$	\	$(0,1)$

Table 11
Optimal customization degrees under Model MA, RA, MB, and RB.

	$a_1 < a < a_2$	$a > a_2$
e_M^{A*}	$\frac{(\tau + c_{m1}\varphi L_1)(c_{m1}(3\beta^2 - 2\beta\alpha - \alpha^2) - a(2\beta - \theta L_1))}{c_{m1}{}^2\varphi^2 L_1{}^2 L_3 + 2c_{m1}\varphi\tau(3\beta^2 - 2\beta\alpha - \alpha^2) - 8\beta m L_1 + \tau^2 L_3}$	1
	$a_3 < a < a_4$	$a > a_4$
e_R^{A*}	$\frac{(\tau + c_r\varphi L_1)(2c_T L_1 - a)}{4(c_r\beta^2 c_T L_1{}^2 + \varphi\tau(c_T + c_r)L_1 - 2mL_1 + \tau^2)}$	1
	$a_5 < a < a_6$	$a > a_6$
e_M^{B*}	$\frac{(\tau - c_{m1}\varphi L_1)(c_{m1}(3\beta^2 - 2\beta\alpha - \alpha^2) - a(2\beta - \theta L_1))}{c_{m1}{}^2\varphi^2 L_1{}^2 L_3 - 2c_{m1}\varphi\tau(3\beta^2 - 2\beta\alpha - \alpha^2) - 8\beta m L_1 + \tau^2 L_3}$	1
	$a_7 < a < a_8$	$a > a_8$
e_R^{B*}	$\frac{(\tau - c_r\varphi L_1)(2c_T L_1 - a)}{4(c_r\beta^2 c_T L_1{}^2 - \varphi\tau(c_T + c_r)L_1 - 2mL_1 + \tau^2)}$	1

(2) Model RA: Decentralized Retailer-customized model considering that the unit production cost decreases when the customization degree increases;
(3) Model MB: Centralized Manufacturer-customized model considering that the unit production cost increases when the customization degree increases;
(4) Model RB: Decentralized Retailer-customized model considering that the unit production cost increases when the customization degree increases.

In Model MA, the profit function for the manufacturer is:

$$\pi_{m|M}^A = \left(w_M - (1-\varphi e_M)c_{m1}\right)D_{t|M} + \left(p_{o|M} - (1-\varphi e_M)c_{m1}\right)D_{o|M} - m e_M{}^2 \tag{23}$$

The profit function for the retailer is:

$$\pi_{r|M}^A = \left(p_{t|M} - w_M\right)D_{t|M} \tag{24}$$

in Model RA, the profit function for the manufacturer is

$$\pi_{m|R}^A = \left(w_R - (1-\varphi e_R)c_{m2}\right)\left(D_{t|R} + D_{o|R}\right) \tag{25}$$

The profit function for the retailer is

$$\pi_{r|R}^A = \left(p_{t|R} - w_R - (1-\varphi e_R)c_r\right)D_{t|R} + \left(p_{o|R} - w_R - (1-\varphi e_R)c_r\right)D_{o|R} - m e_R{}^2 \tag{26}$$

in Model MB, the profit function for the manufacturer is:

$$\pi_{m|M}^B = \left(w_M - (1+\varphi e_M)c_{m1}\right)D_{t|M} + \left(p_{o|M} - (1+\varphi e_M)c_{m1}\right)D_{o|M} - m e_M{}^2 \tag{27}$$

The profit function for the retailer is:

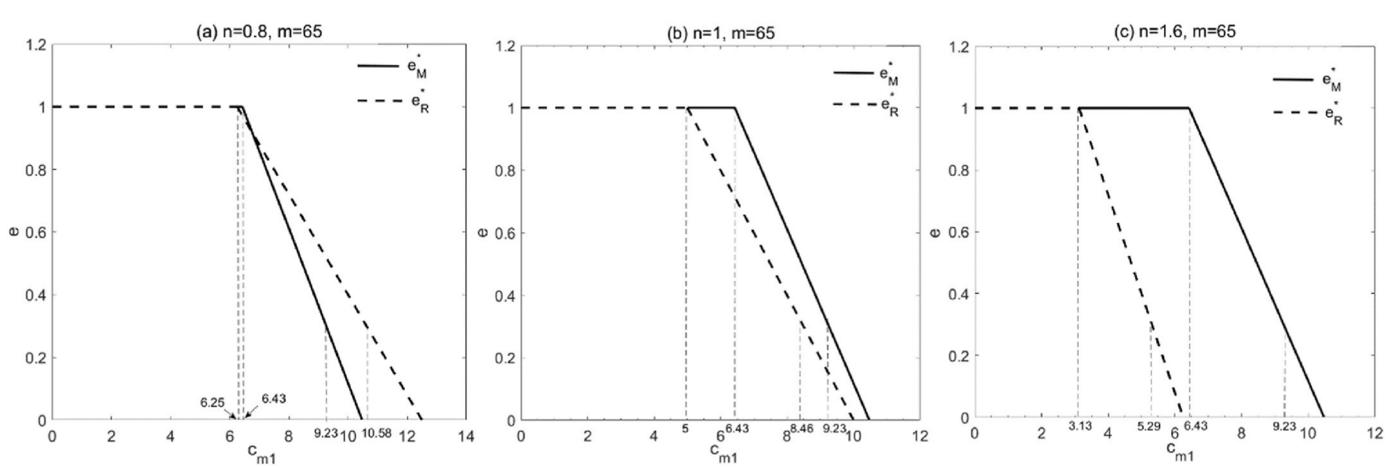


Fig. 3. Optimal degree of customization ($m = 65$).

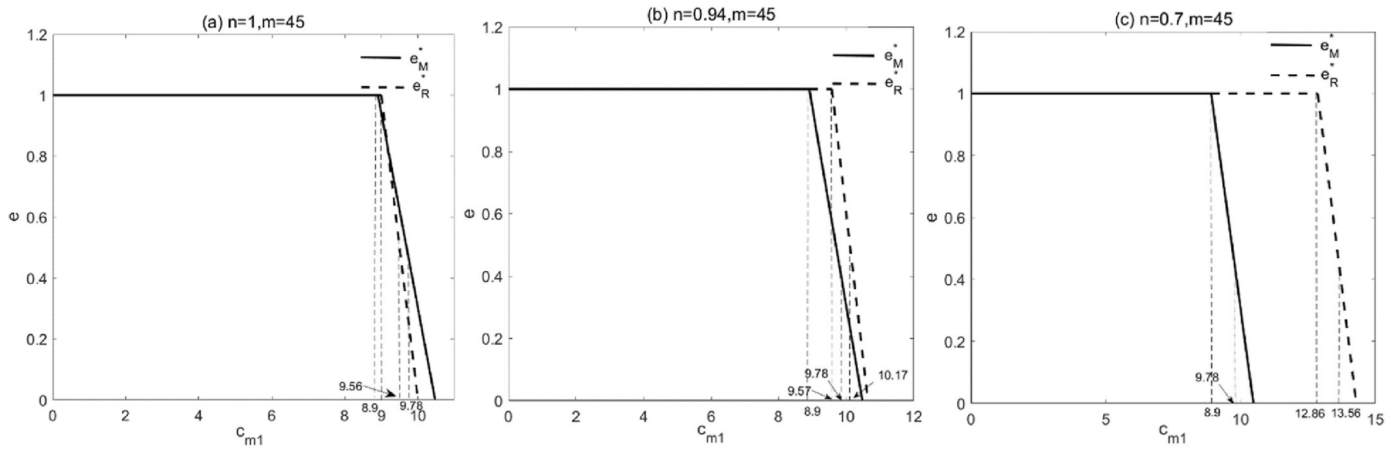


Fig. 4. Optimal degree of customization ($m = 45$).

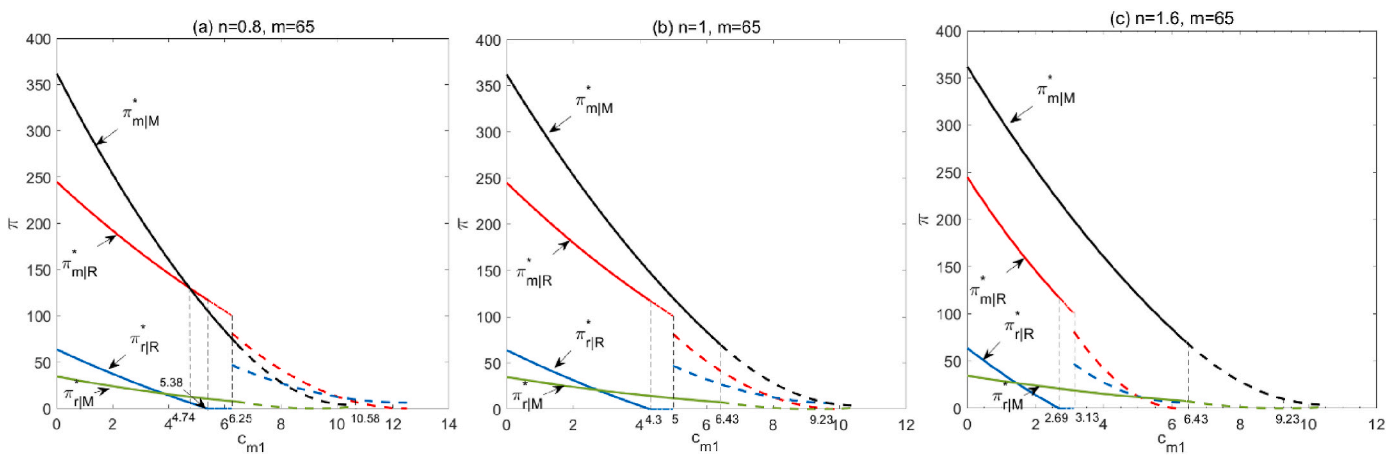


Fig. 5. Comparison of optimal customized strategy in Model M and Model R ($m = 65$).

(i) In Fig. 5a, if $n = 0.8$ and $m = 65$, the manufacturer should choose the fully customized strategy under Model M when $0 < c_{m1} \leq 4.74$; the manufacturer should choose the fully customized strategy under Model R when $4.74 < c_{m1} \leq 6.25$; the manufacturer should choose the partially customized strategy under Model R when $6.25 < c_{m1} \leq 10.58$.

(ii) In Fig. 5b, if $n = 1$ and $m = 65$, the manufacturer should choose the fully customized strategy under Model M when $0 < c_{m1} \leq 6.43$; the manufacturer should choose the partially customized strategy under Model M when $6.43 < c_{m1} \leq 9.23$.

(iii) In Fig. 5c, if $n = 1.6$ and $m = 65$, the manufacturer should choose the fully customized strategy under Model M when $0 < c_{m1} \leq 6.43$; the manufacturer should choose the partially customized strategy under Model M when $6.43 < c_{m1} \leq 9.23$.

$$\pi^B_{r|R} = \left(p_{t|M} - w_M\right) D_{t|M} \tag{28}$$

in Model RB, the profit function for the manufacturer is

$$\pi^B_{m|R} = (w_R - (1 + \varphi e_R) c_{m2}) \left(D_{t|R} + D_{o|R}\right) \tag{29}$$

The profit function for the retailer is

$$\pi^B_{r|R} = \left(p_{t|R} - w_R - (1 + \varphi e_R) c_r\right) D_{t|R} + \left(p_{o|R} - w_R - (1 + \varphi e_R) c_r\right) D_{o|R} - m e_R{}^2 \tag{30}$$

Theorem 3. . The optimal customization degrees under Model MA, RA, MB, and RB are summarized in Table 11.

We conduct numerical experiments to analyze the impact of potential market size on customization strategy and production models. According to Section 5 numerical analysis, we assume the base values of parameters are: $\theta = 0.4; \alpha = 1.5; \beta = 6.5; \tau = 20; \varphi = 0.2; c_{m1} = 7; c_{m2} = 2; c_r = 4$ (Bian et al., 2017; Wang and He, 2022).

Fig. 7 shows the impact of potential market size a on the optimal customization degree among four different models. As shown in Fig. 7, within a certain threshold range, the optimal customization degree increases with a. When the potential market size exceeds a certain threshold, the optimal customization degree will no longer be affected by a and always remain at 1.

Under Model MA, the manufacturer offers partially customized products when $66.82 < a < 72.18$, the manufacturer offers fully customized products when $a \geq 72.18$; under Model RA, the retailer offers partially customized products when $60 < a < 64.33$, the retailer offers fully customized products when $a \geq 64.33$ (Fig. 7a). The optimal customization degree in Model RA is always no less than that in Model MA, i.e., $e^{A*}_R \geq e^{A*}_M$.

Under Model MB, the manufacturer offers partially customized products when $66.82 < a < 160.18$, the manufacturer offers fully customized products when $a \geq 160.18$; under Model RB, the retailer offers partially customized products when $60 < a < 166.5$, the retailer offers fully customized products when $a \geq 166.5$ (Fig. 7b). In addition, if $60 < a < 115.28$, the optimal customization degree in Model RB is higher than that in Model MB, i.e., $e^{B*}_R > e^{B*}_M$; if $115.28 \leq a < 166.5$, the optimal customization degree in Model MB is higher than that in Model

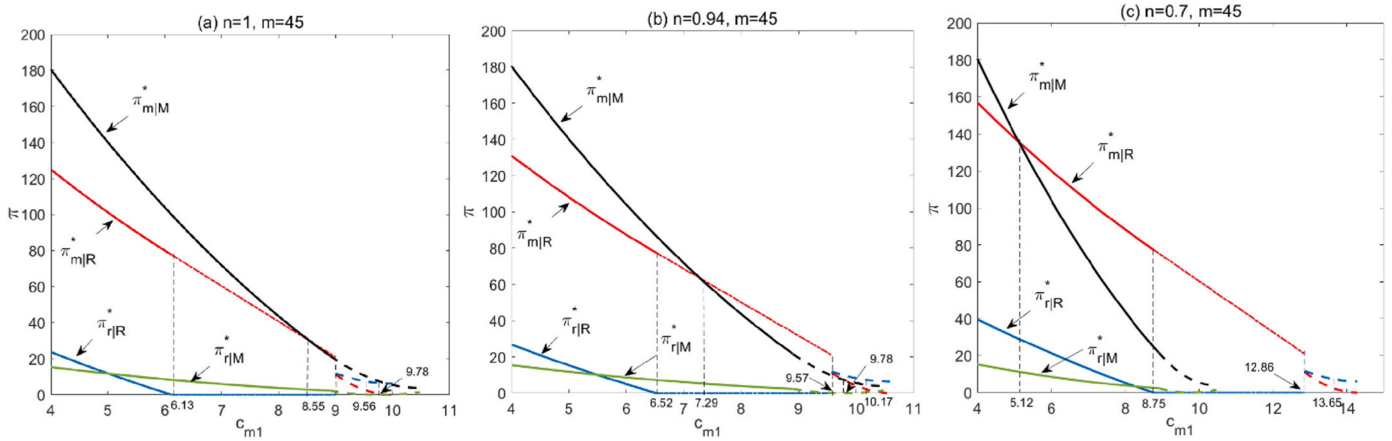
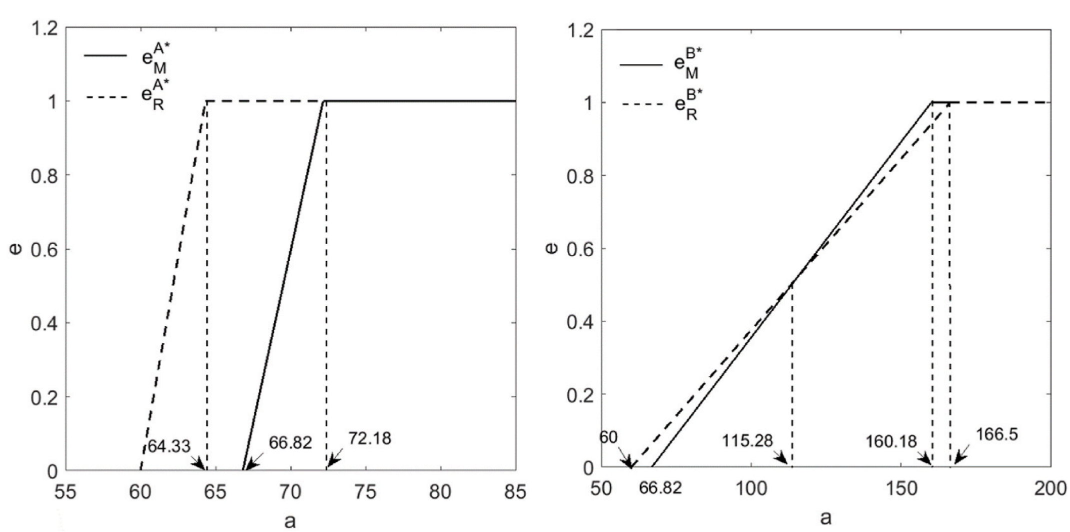


Fig. 6. Comparison of optimal customized strategy in Model M and Model R ($m = 45$).

(i) In Fig. 6a, if $n = 1$ and $m = 45$, the manufacturer should choose the fully customized strategy under Model M when $0 < c_{m1} \leq 8.55$; the manufacturer should choose the fully customized strategy under Model R when $8.55 < c_{m1} \leq 9$; the manufacturer should choose the partially customized strategy under Model M when $9 < c_{m1} \leq 9.56$.

(ii) In Fig. 6b, if $n = 0.94$ and $m = 45$, the manufacturer should choose the fully customized strategy under Model M when $0 < c_{m1} \leq 7.29$; the manufacturer should choose the fully customized strategy under Model R when $7.29 < c_{m1} \leq 9.57$; the manufacturer should choose the partially customized strategy under Model R when $9.57 < c_{m1} \leq 10.17$.

(iii) In Fig. 6c, if $n = 0.7$ and $m = 45$, the manufacturer should choose the fully customized strategy under Model M when $0 < c_{m1} \leq 5.12$; the manufacturer should choose the partially customized strategy under Model R when $5.12 < c_{m1} \leq 12.86$. the manufacturer should choose the partially customized strategy under Model R when $12.86 < c_{m1} \leq 13.65$.



(a) Model MA and RA **(b) Model MB and RB**

Fig. 7. Optimal degree of customization.

RB, i.e., $e_M^{B*} > e_R^{B*}$; if $a \geq 166.5$, The optimal customization degree in Model MB and Model RB is always equal to 1, i.e., $e_M^{B*} = e_R^{B*}$.

Combining Fig. 7a and b, it is found that when the unit production cost decreases with the increase of customization degree, within a certain threshold range, the optimal customization degree is relatively sensitive to the change of potential market size. However, when the unit production cost increases with the customization degree, the optimal customization degree is relatively insensitive to potential market size changes. Thus, for products whose production costs can be reduced with more usage of 3DP, company should pay more attention to the potential market size.

Fig. 8 shows the impact of potential market size a on the optimal profit for the manufacturer and the retailer among the four models. It can be seen from Fig. 8 that the profits of the manufacturer and the retailer both increase with the potential market size.

In Fig. 8a, the manufacturer should choose the partially customized strategy under Model RA when $60 < a < 64.33$; the manufacturer should choose the fully customized strategy under Model RA when $a \geq 64.33$. In Fig. 8b, the manufacturer should choose the partially customized strategy under Model RB when $60 < a < 66.82$ and $a_x < a < a_y$; the manufacturer should choose the partially customized strategy under Model MB when $66.82 < a < a_x$ and $a_y < a < 160.18$; the manufacturer should choose the fully customized strategy under Model MB when $a \geq 160.18$.

Combining Fig. 8a and b, it is found that in the scenario that the unit production cost decreases when the customization degree increases,

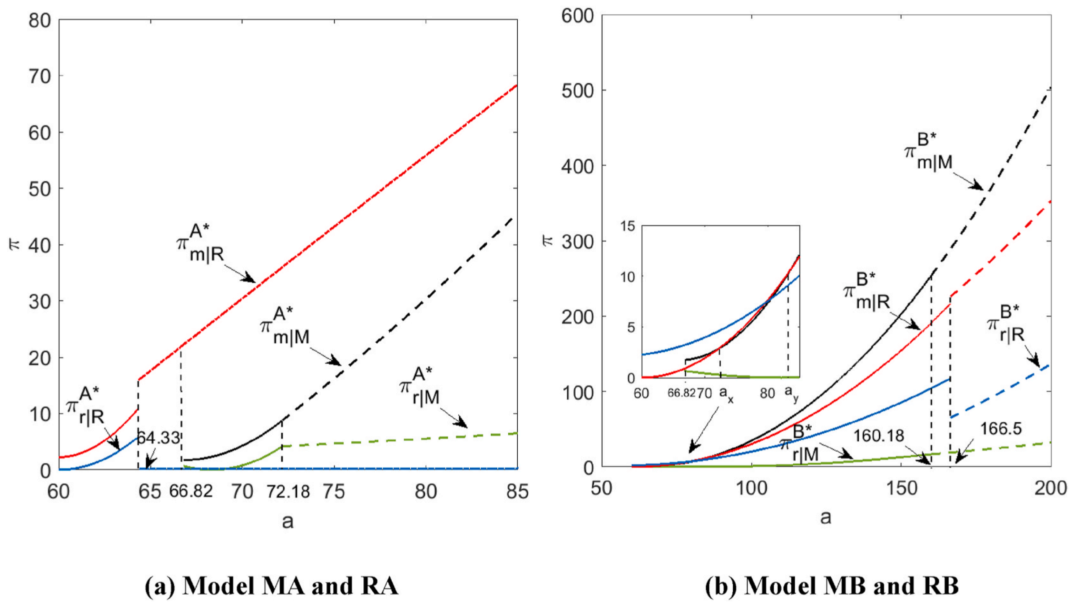


Fig. 8. Comparison of optimal customized strategy.

manufacturers as the leader will always choose the retailer to adopt 3DP for customization (retailer-customized model) due to the higher profit he/she can obtain. However, the retailer's optimal profit can only be achieved in Manufacturer-customized model (Model MA). It is also found that in the scenario that the unit production cost increases when the customization degree increases, when the market's potential size is relatively small, the manufacturer will also choose the retailer to adopt 3D printing for customization. Retailer can also achieve optimal profit (when $60 < a < 66.82$ and $a_x < a < a_y$); When the potential market size is relatively large, the manufacturer will conduct 3DP at its own facilities. However, retailer cannot achieve its optimal profits. Thus, it is found that under certain conditions there is a conflict of interests between the manufacturer and the retailer. The manufacturer and the retailer cannot always obtain the highest profits in the same customization model. So, in order to achieve optimal profits for both the manufacturer and the retailer, there is a need of better coordination among stakeholders.

7. Conclusion

3DP technology allows an unparalleled degree of customization. As a result, 3DP has been adopted in sectors that predominantly produce customized products (Rogers et al., 2016). A pertinent research question is: considering the high production costs associated with 3DP, what is the extent to which 3DP can complement or entirely substitute traditional customized manufacturing processes when middle-level production volumes are considered?

This paper explores innovative business models for a two-echelon 3DP manufacturing supply chain, consisting of manufacturer and retailer, producing customized products in a hybrid customization manufacturing method (3DP combined with traditional manufacturing). Specifically, we implement a *Stackelberg Game* model to study decision-making in a non-cooperative game mode between the two supply chain players – the manufacturer (the leader) and the retailer (the follower). The game-theoretic model explores a manufacturer's decision to decentralize customized production to a retailer and distribute the customized product through online and offline channels based on customers' channel preferences. By analyzing the games based on different customized models (the centralized manufacturer-customized model and the decentralized retailer-customized model), we derive the conditions under which the manufacturer and retailer may conduct customized 3DP production. Through analytical results and numerical analysis, we present insights into how 3DP manufacturers can make supply chain configuration decisions considering 3DP costs and obtain optimal profits based on the degree of customization offered. More specifically, the key findings of our study are as follows: Firstly, when the unit production cost is relatively small, it is optimal for the manufacturer/retailer to offer consumers fully 3DP customized products. Secondly, with both the manufacturer-customized and the retailer-customized model, an increase in consumers' offline channel preference, although this increases the profits obtained through the channel, will reduce overall profits. Thirdly, in the case of the retailer-customized model, the optimal selling price and profits are not affected by the ratio of the manufacturer's unit production cost and the total unit production cost. Our models reveal the conflict between the two heterogeneous channels (online and offline) and demonstrate the price and profit implication of both channels affected by consumers' channel preferences. Our findings have practical relevance for firms seeking to gain competitiveness by deciding on the customization degree and supply chain configuration strategies.

7.1. Contributions

Our work makes the following contribution. Firstly, we are the first study which explore and define the customization degrees in the 3DP manufacturing context from a process view, which has hitherto not been addressed in the literature. We complement the work of Lampel and Mintzberg (1996) and Duray et al. (2000) by showing that the optimal customization degree for the manufacturer/retailer is not only affected by consumers' involvement cost, but also by channel heterogeneity and production models. Our results show that the manufacturer/retailer decides on the customization degree based on the cost structure of 3DP products. Under certain conditions, it is optimal for the manufacturer/retailer to offer consumers fully 3DP customized products rather than products manufactured using traditional customization production technology. The manufacturer/retailer will use 3DP technology to fully customize products when the (total) unit production cost is relatively low; otherwise, the manufacturer/retailer will combine 3DP with traditional manufacturing technology to partially customize the products. In the latter case, the optimal customization degree of products decreases with the increase of (total) unit production cost, which implies that the proportion of production using 3DP decreases. Thus, we show that under specific considerations of production costs, it may be more economical to manufacture fully customized products using 3DP. When the production cost is high, 3DP will continue to be used to facilitate traditional customization production *(Proposition 1 and 4)*. In the model, we also relax the assumptions on firms' cost of 3DP adoption from fixed costs to flexible costs; this reflects the cost efficiency of investment in 3DP adoption. We show that the manufacturer may compare the difference in customization degree in the centralized manufacturer-customized model and decentralized retailer-customized model, considering the cost efficiency of investment in 3DP adoption m, the unit cost variation coefficient $n = \frac{c_T}{c_{m1}}$ and total unit production cost in the centralized manufacturer-customized model. Our work has direct practical relevance for firms that want to promote 3DP technology and maximize customization degree to encourage higher consumer utility; however, optimal profits may not be achieved in this case *(Proposition 1, 4 and 7)*.

Secondly, we examine the customization choices of the manufacturer under two heterogeneous channels (online/offline) that account for customers' channel preferences. In the centralized manufacturer-customized model, we show that if the unit production cost of products is low, the manufacturer will choose to fully customize the products without reducing its profitability and the retailer will need to adopt a high offline price strategy to obtain the maximum profit. Also, the increase in customers' offline channel preference will not affect the optimal customization degree. This is the only scenario where the retailer will adopt a high offline price strategy. If the unit production cost is high, the customization degree will be reduced. Under the decentralized retailer-customized model, the customization degree will not be affected by customers' channel preferences. Furthermore, irrespective of whether it is the manufacturer or the retailer-customized model, an increase in consumers' offline channel preference increases the competition between the two channels. The competition will lead to a drop in overall profits for the manufacturer/retailer, even though the profits from the offline channel will increase. Thus, the manufacturer/retailer would have strong incentives to encourage the online channel. Therefore, companies that heavily promote online channels will increasingly become the norm. *(Proposition 2, 3, 5 and 6)*.

Thirdly, we find that under the decentralized retailer-customized model, the retailer should not only pay attention to the cost of its customized parts and assembly, but also consider the manufacturer's cost towards purchasing 3D printers, 3DP raw materials, and standard parts. Therefore, they have incentives to collaborate with the manufacturer to carry out R&D with 3DP; the manufacturer should equally consider ways of collaborating with the retailer. *(Proposition 8)*.

Fourthly, our numerical investigation identifies the entity (manufacturer or retailer) that should carry out 3DP customized production. We show that if the 3D adoption cost coefficient is relatively large, the manufacturer lets the retailer conduct customized production only when (a) the cost variation coefficient is relatively small and (b) the unit production cost is relatively high. On the other hand, the manufacturer will choose centralized production if the unit production cost is relatively small, regardless of the 3D investment cost coefficient and the cost variation coefficient.

Finally, our extended models reveal that the industry that can reduce unit production costs through 3DP customization should pay more attention to the potential market size of their products. In addition, the manufacturer and the retailer cannot always obtain the highest profits in the same customization model.

7.2. Limitations and future research directions

It is acknowledged that, as one of the first studies of 3D printing in the context of hybrid manufacturing process, this research has several limitations, and which are pointers for future research. First, this paper only discusses the impact of potential market size on customization strategies in the extended model. Future research could further explore the impact path of costs on customization strategies when unit production costs change with the degree of customization. Secondly, our research method relies on models and numerical analysis to reveal relevant theoretical and practical significance. Future empirical studies such as case study and simulations (Jia et al., 2016) can be conducted to test the hypothesis and our model using empirical evidence. Thirdly, we consider our models in a monopoly market and do not consider competition from other manufacturers. Also, we consider only one retailer in the market. The duopoly market or competition scenarios have been explored in other supply chain settings (Almehdawe and Mantin, 2010; Liu et al., 2021) not in the context of 3DP supply chain. Future research could explore the robustness of our results in a duopoly market or competition between multi-retailers in the same market boundary. Fourthly, our model does not consider the inventory costs of standard parts and 3DP raw materials. It is worth noting that inventory costs in different channels may vary. This will affect the sales price and sales volume of products in the individual channels, indirectly impacting the customization degree. By referring to Zhao et al. (2016) and Moon et al. (2018), One of the future studies could take inventory costs into consideration. Fifthly, we assume that the manufacturer is the supply chain leader. With the maturity of 3DP technology and decreasing costs of 3D printers and raw materials, a retailer may, in future, also serve as the supply chain leader due to their relatively shorter distance to customers. Hence, the scenario of the retailer as the leader of the 3DP supply chain deserves further study. Finally, based on the findings that retailers have the incentive to collaborate with the manufacturer to reduce 3DP production cost, this research can be extended by investigating how different collaborative mechanisms affect 3DP mass customization production planning decisions. One element of collaboration could be cooperative (co-op) advertising, and which could potentially boost the revenues generated by the supply chain constituents, including the manufacturer and retailers (Sarkar et al., 2020). As 3DP becomes increasingly mainstream, investigation of collaborative policies for co-op advertising is a pertinent area for future research.

Data availability

No data was used for the research described in the article.

Acknowledgments

This study was partially supported by National Natural Science Foundation of China (71971078); Natural Science Foundation of Hunan Province (2022JJ30013).

Appendix A

Proof of Lemma 1.

We solve the game by backward induction. Under Model M, the profit function of the retailer is given by:

$$\pi_{r|M} = \left(p_{t|M} - w_M\right) D_{t|M}$$

Where $D_{t|M} = \theta a - \beta p_{t|M} + \alpha p_{o|M} + \tau e_M$. Taking the first derivative of $\pi_{r|M}$ with respect to $p_{t|M}$, we have

$$\frac{\partial \pi_{r|M}}{\partial p_{t|M}} = a\theta - 2\beta p_{t|M} + \tau e_M + \beta w_m + \alpha p_{o|M}$$

which yields

$$p_{t|M}\left(w_m, p_{o|M}, e_M\right) = \frac{a\theta + e_M\tau + \beta w_M + \alpha p_{o|M}}{2\beta}$$

The profit function of the manufacturer is given by:

$$\pi_{m|M} = (w_M - c_{m1})D_{t|M} + \left(p_{o|M} - c_{m1}\right)D_{o|M} - m{e_M}^2$$

Where $D_{o|M} = (1-\theta)a - \beta p_{o|M} + \alpha p_{t|M} + \tau e_M$. Substituting $p_{t|M}(w_m, p_{o|M}, e_M)$ into $\pi_{m|M}$ and then taking the first derivative of $\pi_{m|M}$ with respect to w_M, $p_{o|M}$ and e_M, we have

$$\frac{\partial \pi_{m|M}}{\partial w_M} = \frac{a\theta + e_M\tau + c_{m1}(\beta-\alpha) - 2\beta w_M + 2\alpha p_{o|M}}{2}$$

$$\frac{\partial \pi_{m|M}}{\partial p_{o|M}} = \frac{2\left(e_M\tau - \beta p_{o|M}\right) - \alpha(c_{m1} - w_m) + 2a(1-\theta)}{2} + \frac{\left(2\beta^2 - \alpha^2\right)\left(c_{m1} - p_{o|M}\right)}{2\beta} + \frac{\alpha\left(a\theta + e_M\tau + \beta w_m + \alpha p_{o|M}\right)}{2\beta}$$

$$\frac{\partial \pi_{m|M}}{\partial e_M} = -2me_M - \frac{\tau(c_{m1} - w_m)}{2} - \frac{\tau\left(c_{m1} - p_{o|M}\right)(2\beta+\alpha)}{2\beta}$$

which yields

$$w_M = \frac{L_4 - 2c_{m1}L_2(\tau^2 L_3 - 4\beta m L_1)}{2L_2L_{10}}$$

$$p_{o|M} = \frac{L_5 - 2c_{m1}L_2(\tau^2 L_3 - 4\beta m L_1)}{2L_2L_{10}}$$

$$e_M = \frac{\tau(a(2\beta - \theta L_1) - c_{m1}L_1L_3)}{L_{10}}$$

Substituting w_M, $p_{o|M}$ and e_M into $p_{t|M}(w_m, p_{o|M})$, we have

$$p_{t|M} = \frac{L_6 - 2c_{m1}L_2(\tau^2 L_3 - 2mL_1L_2)}{2L_2L_{10}}$$

Substituting offline demand $D_{t|M}$ and online demand $D_{o|M}$ into the manufacturer's profit function $\pi_{m|M}$ and retailer's profit function $\pi_{r|M}$. The second-order derivative of $\pi_{r|M}$ with respect to $p_{t|M}$ is $\frac{\partial^2 \pi_{r|M}}{\partial {p_{t|M}}^2} = -2\beta < 0$, and thus $\pi_{r|M}$ is concave in $p_{t|M}$. Subsequently, taking the second-order partial derivatives of $\pi_{m|M}$ with respect to w_M, $p_{o|M}$ and e_M, we have:

$$\frac{\partial^2 \pi_{m|M}}{\partial {w_M}^2} = -\beta < 0, \frac{\partial^2 \pi_{m|M}}{\partial {p_{o|M}}^2} = \frac{\alpha^2 - 2\beta^2}{\beta} < 0, \frac{\partial^2 \pi_{m|M}}{\partial {e_M}^2} = -2m < 0$$

$$\begin{vmatrix} \frac{\partial^2 \pi_{m|M}}{\partial {w_M}^2} & \frac{\partial^2 \pi_{m|M}}{\partial w_M p_{o|M}} \\ \frac{\partial^2 \pi_{m|M}}{\partial p_{o|M} w_M} & \frac{\partial^2 \pi_{m|M}}{\partial {p_{o|M}}^2} \end{vmatrix} = \begin{vmatrix} -\beta & \alpha \\ \alpha & \frac{\alpha^2 - 2\beta^2}{\beta} \end{vmatrix} = 2\left(\beta^2 - \alpha^2\right) > 0$$

$$\begin{vmatrix} \frac{\partial^2 \pi_{m|M}}{\partial {w_M}^2} & \frac{\partial^2 \pi_{m|M}}{\partial w_M p_{o|M}} & \frac{\partial^2 \pi_{m|M}}{\partial w_M e_M} \\ \frac{\partial^2 \pi_{m|M}}{\partial p_{o|M} w_M} & \frac{\partial^2 \pi_{m|M}}{\partial {p_{o|M}}^2} & \frac{\partial^2 \pi_{m|M}}{\partial p_{o|M} e_M} \\ \frac{\partial^2 \pi_{m|M}}{\partial e_M w_M} & \frac{\partial^2 \pi_{m|M}}{\partial e_M p_{o|M}} & \frac{\partial^2 \pi_{m|M}}{\partial {e_M}^2} \end{vmatrix} = \begin{vmatrix} -\beta & \alpha & \frac{\tau}{2} \\ \alpha & \frac{\alpha^2 - 2\beta^2}{\beta} & \frac{2\beta\tau + \alpha\tau}{2\beta} \\ \frac{\tau}{2} & \frac{2\beta\tau + \alpha\tau}{2\beta} & -2m \end{vmatrix} = \frac{-8\beta m\left(\beta^2 - \alpha^2\right) + \tau^2\left(3\beta^2 + 4\beta\alpha + \alpha^2\right)}{2\beta}$$

Thus, we know that if $-8\beta m(\beta^2 - \alpha^2) + \tau^2(3\beta^2 + 4\beta\alpha + \alpha^2) < 0$, i.e., the three order principal minors of the Hessian matrix is negative, the manufacturer's profit function $\pi_{m|M}$ is jointly concave in (w_M, $p_{o|M}$, e_M), thus $m > m_b = \frac{\tau^2 L_3}{8\beta L_1}$.

According to $e_M = \frac{\tau(a(2\beta - \theta L_1) - c_{m1}L_1L_3)}{L_{10}}$, we know that c_{m1} has a negative effect on e_M, and $e_M = 0$ when $c_{m1} = \frac{a(2\beta - \theta L_1)}{L_1L_3}$. With c_{m1} continues to increase, e_M remains unchanged at 0; $e_M = 1$ when $c_{m1} = \frac{\tau a(2\beta - \theta L_1) + L_3\tau^2 - 8\beta m L_1}{\tau L_1 L_3}$, with c_{m1} continues to decrease, e_M remains unchanged at 1.

Let $c_a = \frac{a(2\beta - \theta L_1)}{L_1L_3}$, $c_b = \frac{\tau a(2\beta - \theta L_1) + L_3\tau^2 - 8\beta m L_1}{\tau L_1 L_3}$, when $m < m_a = \frac{L_3\tau^2 + a\tau(2\beta - \theta L_1)}{8\beta L_1}$, $c_b > 0$. $c_a - c_b = \frac{8\beta m L_1 - \tau^2 L_3}{\tau L_3 L_1} > 0$. $m_a - m_b = \frac{a\tau(\beta(2-\theta) + \alpha\theta)}{8\beta(\beta - \alpha)} > 0 \Rightarrow m_a > m_b$, thus $m_b < m < m_a$

The degree of customization can be rewritten as:

$$e_M = \begin{cases} 1 & 0 < c_{m1} \le c_b \\ \dfrac{\tau(a(2\beta - \theta L_1) - c_{m1}L_1L_3)}{L_{10}} & c_b < c_{m1} < c_a \end{cases}$$

then, the online and offline demand functions can be rewritten as:

$$D_{t|M} = \begin{cases} \theta a - \beta p_{t|M} + \alpha p_{o|M} + \tau & 0 < c_{m1} \le c_b \\ \theta a - \beta p_{t|M} + \alpha p_{o|M} + \tau e_M & c_b < c_{m1} < c_a \end{cases}$$

$$D_{o|M} = \begin{cases} (1-\theta)a - \beta p_{o|M} + \alpha p_{t|M} + \tau & 0 < c_{m1} \le c_b \\ (1-\theta)a - \beta p_{o|M} + \alpha p_{t|M} + \tau e_M & c_b < c_{m1} < c_a \end{cases}$$

Therefore, in Model M, the manufacturer's optimal degree of customization, optimal pricing and profit are e_M^*, w_M^* , $p_{o|M}^*$ and $\pi_{m|M}^*$, the customized product sales volume of offline channel and online channel are $D_{t|M}^*$ and $D_{o|M}^*$, the retailer' s optimal pricing and profit are $p_{t|M}^*$ and $\pi_{r|M}^*$:

$$e_M^* = \begin{cases} 1 & 0 < c_{m1} \le c_b \\ \dfrac{\tau(a(2\beta - \theta L_1) - c_{m1}L_1L_3)}{L_{10}} & c_b < c_{m1} < c_a \end{cases}$$

$$w_M^* = \begin{cases} \dfrac{a(\alpha + \theta L_1) + \tau L_2 + c_{m1}L_1L_2}{2L_1L_2} & 0 < c_{m1} \le c_b \\ \dfrac{L_4 - 2c_{m1}L_2\left(\tau^2 L_3 - 4\beta m L_1\right)}{2L_2L_{10}} & c_b < c_{m1} < c_a \end{cases}$$

$$p_{o|M}^* = \begin{cases} \dfrac{a(\beta - \theta L_1) + tL_2 + c_{m1}L_1L_2}{2L_1L_2} & 0 < c_{m1} \le c_b \\ \dfrac{L_5 - 2c_{m1}L_2\left(\tau^2 L_3 - 4\beta m L_1\right)}{2L_2L_{10}} & c_b < c_{m1} < c_a \end{cases}$$

$$p_{t|M}^* = \begin{cases} \dfrac{a(2\beta\alpha + \theta L_1L_3) + tL_2(3\beta - \alpha) + c_{m1}{L_2}^2L_1}{4\beta L_1L_2} & 0 < c_{m1} \le c_b \\ \dfrac{L_6 - 2c_{m1}L_2\left(\tau^2 L_3 - 2mL_1L_2\right)}{2L_2L_{10}} & c_b < c_{m1} < c_a \end{cases}$$

$$D_{t|M}^* = \begin{cases} \dfrac{a\theta + \tau - c_{m1}L_1}{4} & 0 < c_{m1} \le c_b \\ \dfrac{\beta\left(4am\theta L_1 - a\tau^2(2\theta - 1) - 4c_{m1}m{L_1}^2\right)}{2L_{10}} & c_b < c_{m1} < c_a \end{cases}$$

$$D_{o|M}^* = \begin{cases} \dfrac{a(\beta(2-\theta) - \theta L_1) + (2\beta + \alpha)(\tau - c_{m1}L_1)}{4\beta} & 0 < c_{m1} \le c_b \\ \dfrac{L_7 - 4c_{m1}m{L_1}^2(2\beta + \alpha)}{2L_{10}} & c_b < c_{m1} < c_a \end{cases}$$

$$\pi_{m|M}^* = \begin{cases} \dfrac{L_9 - c_{m1}L_1L_2L_3(2\tau - c_{m1}L_1)}{8\beta L_1L_2} & 0 < c_{m1} \le c_b \\ \dfrac{L_8 - 4c_{m1}mL_1L_2(2a(2\beta - \theta L_1) + c_{m1}L_1L_3)}{4L_2L_{10}} & c_b < c_{m1} < c_a \end{cases}$$

$$\pi_{r|M}^* = \begin{cases} \dfrac{(a\theta + \tau - c_{m1}L_1)^2}{16\beta} & 0 < c_{m1} \le c_b \\ \dfrac{\beta\left(4c_{m1}m{L_1}^2 + a\tau^2(2\theta - 1) - 4am\theta L_1\right)^2}{4{L_{10}}^2} & c_b < c_{m1} < c_a \end{cases}$$

In Model M, we can directly judge that $\pi_{r|M}^* > 0$.

If $\pi_{m|M}^* > 0$, that is $\frac{L_9 - c_{m1}L_1L_2L_3(2\tau - c_{m1}L_1)}{8\beta L_1L_2} > 0$ and $\frac{L_8 - 4c_{m1}mL_1L_2(2a(2\beta - \theta L_1) + c_{m1}L_1L_3)}{4L_2L_{10}} > 0$, by solving the equation $L_9 - c_{m1}L_1L_2L_3(2\tau - c_{m1}L_1) = 0$ and $L_8 - 4c_{m1}mL_1L_2(2a(2\beta - \theta L_1) + c_{m1}L_1L_3) = 0$, we derive a threshold m_1 and m_2 respectively.

Combining with $m_b < m < m_a$, we can obtain that $\pi_{m|M}^* > 0$ when $m_b < m < min\{m_a, m_1, m_2\}$.

Where $m_1 = \frac{a^2\beta\tau^2(2\theta - 1)^2}{4a^2(2\beta^2 + \theta^2L_1(3\beta - \alpha) - 4\beta v\theta L_1) - 8ac_{m1}L_1L_2(2\beta - \theta L_1) + 4{c_{m1}}^2L_2{L_1}^2L_3}$,

$$m_2 = \frac{a^2\left(2\beta^2 + \theta^2L_1(3\beta - \alpha) - 4\beta\theta L_1\right) + \tau^2L_2L_3 - c_{m1}L_1L_2(2\tau - c_{m1}L_1)L_3 + 2a(\tau - c_{m1}L_1)L_2(2\beta - \theta L_1)}{8\beta L_1L_2}$$

The proof is completed.

Proof of Lemma 2.

We solve the game by backward induction. under Model R, the profit function of the retailer is given by:

$$\pi_{r|R} = \left(p_{t|R} - w_R - c_r\right)D_{t|R} + \left(p_{o|R} - w_R - c_r\right)D_{o|R} - me_R{}^2$$

where $D_{t|R} = \theta a - \beta p_{t|R} + \alpha p_{o|R} + \tau e_R$ and $D_{o|R} = (1-\theta)a - \beta p_{o|R} + \alpha p_{t|R} + \tau e_R$.

Taking the first derivative of $\pi_{r|R}$ with respect to $p_{t|R}$, $p_{o|R}$ and e_R, we have

$$\frac{\partial \pi_{r|R}}{\partial p_{t|R}} = a\theta - \theta p_{t|R} + e_R\tau + p_{o|R}\alpha + \beta\left(c_r - p_{t|R} + w_R\right) - \alpha\left(c_r - p_{o|R} + w_R\right)$$

$$\frac{\partial \pi_{r|R}}{\partial p_{o|R}} = e_R\tau - \beta p_{o|R} + \alpha p_{t|R} - a(\theta - 1) + \beta\left(c_r - p_{o|R} + w_R\right) - \alpha\left(c_r - p_{t|R} + w_R\right)$$

$$\frac{\partial \pi_{r|R}}{\partial e_R} = -2e_R m - \tau\left(c_r - p_{o|R} + w_R\right) - \tau\left(c_r - p_{t|R} + w_R\right)$$

which yields

$$p_{t|R}(w_R) = \frac{4(\beta+\alpha)(c_r + w_R)(\tau^2 - \beta m + m\alpha) - 4am(\alpha + \theta(\beta - \alpha)) + a\tau^2(2\theta - 1)}{4(\beta+\alpha)(\tau^2 - 2\beta m + 2m\alpha)}$$

$$p_{o|R}(w_R) = \frac{4(\beta+\alpha)(c_r + w_R)(\tau^2 - \beta m + m\alpha) - a\tau^2(2\theta - 1) - 4am(\beta - \beta\theta + \alpha\theta)}{4(\beta+\alpha)(\tau^2 - 2\beta m + 2m\alpha)}$$

$$e_R(w_R) = -\frac{\tau(a - 2(c_r + w_R)(\beta - \alpha))}{2(\tau^2 - 2\beta m + 2m\alpha)}$$

The profit function of the manufacturer is given by:

$$\pi_{m|R} = (w_R - c_{m2})\left(D_{t|R} + D_{o|R}\right)$$

Substituting $p_{t|R}(w_R)$, $p_{o|R}(w_R)$ and $e_R(w_R)$ into $\pi_{m|R}$ and then taking the first derivative of $\pi_{m|R}$ with respect to w_R, we have

$$\frac{\partial \pi_{m|R}}{\partial w_R} = -\frac{m(\beta - \alpha)(a + 2(c_{m2} - c_r)(\beta - \alpha) - 4w_R(\beta - \alpha))}{\tau^2 - 2\beta m + 2m\alpha}$$

which yields

$$w_R = \frac{a + 2L_1(c_{m2} - c_r)}{4L_1}$$

Substituting w_R into $p_{t|R}(w_R)$, $p_{o|R}(w_R)$ and $e_R(w_R)$, we have

$$p_{t|R} = \frac{L_{12} - 2c_T(\tau^2 - mL_1)L_1L_2}{4L_2L_1L_{14}}$$

$$p_{o|R} = \frac{L_{11} - 2c_T(\tau^2 - mL_1)L_1L_2}{4L_1L_2L_{14}}$$

$$e_R = \frac{\tau(a - 2L_1c_T)}{4L_{14}}$$

Substituting offline demand $D_{t|R}$ and online demand $D_{o|R}$ into the manufacturer's profit function $\pi_{m|R}$ and retailer's profit function $\pi_{r|R}$. The second-order derivative of $\pi_{r|R}$ with respect to $p_{t|R}$, $p_{o|R}$ and e_R is

$$\frac{\partial^2 \pi_{r|R}}{\partial p_{t|R}{}^2} = -2\beta < 0, \frac{\partial^2 \pi_{r|R}}{\partial p_{o|R}{}^2} = -2\beta < 0, \ \frac{\partial^2 \pi_{r|R}}{\partial e_R{}^2} = -2m < 0$$

$$\begin{vmatrix} \dfrac{\partial^2 \pi_{r|R}}{\partial p_{t|R}{}^2} & \dfrac{\partial^2 \pi_{r|R}}{\partial p_{t|R}p_{o|R}} \\ \dfrac{\partial^2 \pi_{r|R}}{\partial p_{o|R}p_{t|R}} & \dfrac{\partial^2 \pi_{r|R}}{\partial p_{o|R}{}^2} \end{vmatrix} = \begin{vmatrix} -2\beta & 2\alpha \\ 2\alpha & -2\beta \end{vmatrix} = 2\left(\beta^2 - \alpha^2\right) > 0$$

$$\begin{vmatrix} \frac{\partial^2 \pi_{r|R}}{\partial p_{t|R}{}^2} & \frac{\partial^2 \pi_{r|R}}{\partial p_{t|R} p_{o|R}} & \frac{\partial^2 \pi_{r|R}}{\partial p_{t|R} e_R} \\ \frac{\partial^2 \pi_{r|R}}{\partial p_{o|R} p_{t|R}} & \frac{\partial^2 \pi_{r|R}}{\partial p_{o|R}{}^2} & \frac{\partial^2 \pi_{r|R}}{\partial p_{o|R} e_R} \\ \frac{\partial^2 \pi_{r|R}}{\partial e_R p_{t|R}} & \frac{\partial^2 \pi_{r|R}}{\partial e_R p_{o|R}} & \frac{\partial^2 \pi_{r|R}}{\partial e_R{}^2} \end{vmatrix} = \begin{vmatrix} -2\beta & 2\alpha & \tau \\ 2\alpha & -2\beta & \tau \\ \tau & \tau & -2m \end{vmatrix} = 4(\beta+\alpha)\left(\tau^2 - 2\beta m + 2\alpha m\right)$$

Thus, we know that if $\tau^2 - 2\beta m + 2\alpha m < 0$, i.e., the three order principal minors of the Hessian matrix are negative, the manufacturer's profit function $\pi_{r|R}$ is jointly concave in ($p_{t|R}$, $p_{o|R}$, e_R). Subsequently, taking the second-order partial derivatives of $\pi_{m|R}$ with respect to w_R, we have, $\frac{\partial^2 \pi_{m|R}}{\partial w_R{}^2} = \frac{4m(\beta - \alpha)^2}{\tau^2 - 2\beta m + 2\alpha m} < 0$ if $\tau^2 - 2\beta m + 2\alpha m$, thus $m > m_d = \frac{\tau^2}{2L_1}$.

According to $e_R = \frac{\tau(a - 2L_1 c_T)}{4L_{14}}$, we know that c_T has a negative effect on e_R , and $e_R = 0$ when $c_T = \frac{a}{2L_1}$. With c_T continues to increase, e_R remains unchanged at 0; $e_R = 1$ when $c_T = \frac{a\tau + 4\tau^2 - 8mL_1}{2n\tau L_1}$, with c_T continues to decrease, e_R remains unchanged at 1.

Let $c_c = \frac{a}{2L_1}$, $c_d = \frac{a\tau + 4\tau^2 - 8mL_1}{2n\tau L_1}$, when $m < m_c = \frac{4\tau^2 + a\tau}{8L_1}$, $c_d > 0$, and $c_c - c_d = \frac{2(2mL_1 - \tau^2)}{\tau L_1} > 0$. $m_c - m_d = \frac{\tau(a\beta + \tau(\beta - \alpha))}{8\beta(\beta - \alpha)} > 0 \Rightarrow m_c > m_d$, thus $m_d < m < m_c$

The degree of customization can be rewritten as:

$$e_R = \begin{cases} 1 \quad 0 < c_T \le c_d \\ \frac{\tau(a - 2L_1 c_T)}{4L_{14}} c_d < c_T < c_c \end{cases}$$

then, the online and offline demand functions can be rewritten as:

$$D_{t|R} = \begin{cases} \theta a - \beta p_{t|R} + \alpha p_{o|R} + \tau 0 < c_T \le c_d \\ \theta a - \beta p_{t|R} + \alpha p_{o|R} + \tau e_R c_d < c_T < c_c \end{cases}$$

$$D_{o|R} = \begin{cases} (1-\theta)a - \beta p_{o|R} + \alpha p_{t|R} + \tau 0 < c_T \le c_d \\ (1-\theta)a - \beta p_{o|R} + \alpha p_{t|R} + \tau e_R c_d < c_T < c_c \end{cases}$$

Therefore, in Model R, the optimal pricing and profit of the manufacturer are w_R^* and $\pi_{m|R}^*$, the demand for customized products in offline channels and online channels are $D_{t|R}^*$ and $D_{o|R}^*$, the optimal degree of customization, price and profit for retailers are e_R^*, $p_{o|R}^*$, $p_{t|R}^*$ and $\pi_{r|R}^*$:

$$e_R^* = \begin{cases} 1 \quad 0 < c_T \le c_d \\ \frac{\tau(a - 2L_1 c_T)}{4L_{14}} c_d < c_T < c_c \end{cases}$$

$$w_R^* = \begin{cases} \frac{a + 2\tau + 2L_1(c_{m2} - c_r)}{4L_1} 0 < c_T \le c_d \\ \frac{a + 2L_1(c_{m2} - c_r)}{4L_1} c_d < c_T < c_c \end{cases}$$

$$p_{o|R}^* = \begin{cases} \frac{a(5\beta + \alpha) + 4a\theta L_1 + 6\tau L_2 + 2L_1 L_2(c_{m2} + c_r)}{8L_1 L_2} 0 < c_T \le c_d \\ \frac{L_{11} - 2(c_{m2} + c_r)\left(\tau^2 - mL_1\right)}{4L_1 L_2 L_{14}} c_d < c_T < c_c \end{cases}$$

$$p_{t|R}^* = \begin{cases} \frac{a(\beta + 5\alpha) + 4a\theta L_1 + 6\tau L_2 + 2L_1 L_2 c_T}{8L_1 L_2} 0 < c_T \le c_d \\ \frac{L_{12} - 2c_T\left(\tau^2 - mL_1\right)L_1 L_2}{4L_2 L_1 L_{14}} c_d < c_T < c_c \end{cases}$$

$$D_{t|R}^* = \begin{cases} \frac{a(4\theta - 1) + 2\tau - 2L_1 c_T)}{8} 0 < c_T \le c_d \\ \frac{amL_1(4\theta - 1) - a\tau^2(2\theta - 1) - 2mc_T L_1{}^2}{4L_{14}} c_d < c_T < c_c \end{cases}$$

$$D_{o|R}^* = \begin{cases} \frac{a(3 - 4\theta) + 2\tau - 2L_1 c_T}{8} 0 < c_T \le c_d \\ \frac{a\tau^2(2\theta - 1) - amL_1(4\theta - 3) - 2mc_T L_1{}^2}{4L_{14}} c_d < c_T < c_c \end{cases}$$

$$\pi_{m|R}^* = \begin{cases} \frac{(a + 2\tau - 2L_1 c_T)^2}{16L_1} 0 < c_T \le c_d \\ \frac{m(a - 2L_1 c_T)^2}{8L_{14}} c_d < c_T < c_c \end{cases}$$

$$\pi^*_{r|R} = \begin{cases} \dfrac{L_{13} - 4L_1L_2c_T(a + 2\tau - c_TL_1)}{32L_1L_2} & 0 < c_T \le c_d \\ \dfrac{L_{12} - 4mL_1L_2c_T(a - L_1c_T)}{16L_2L_{14}} & c_d < c_T < c_c \end{cases}$$

In Model R, we can directly judge that $\pi^*_{m|R} > 0$.

If $\pi^*_{r|R} > 0$, that is $\frac{L_{13} - 4L_1L_2c_T(a+2\tau - c_TL_1)}{32L_1L_2} > 0$ and $\frac{L_{12} - 4mL_1L_2c_T(a - L_1c_T)}{16L_2L_{14}} > 0$, by solving the equation $L_{13} - 4L_1L_2c_T(a+2\tau - c_TL_1) = 0$ and $L_{12} - 4mL_1L_2c_T(a - L_1c_T) = 0$, we derive a threshold m_3 and m_4 respectively. Combining with $m_d < m < m_c$, we can obtain that $\pi^*_{r|R} > 0$ when $m_d < m < min\{m_c, m_3, m_4\}$.

Where $m_3 = \frac{2a^2\tau^2(2\theta - 1)^2}{a^2(5\beta - 3\alpha + 16\theta L_1(\theta - 1)) + 4c_T{}^2L_2L_1{}^2 - 4ac_TL_1L_2}$,

$$m_4 = \frac{a^2(5\beta - 3\alpha + 16\theta L_1(\theta - 1)) + 4\tau^2L_2 - 4L_1L_2c_T(a + 2\tau - c_TL_1) + 4a\tau L_2}{32L_1L_2}$$

The proof is completed.

Proof of Proposition 1.

$e^*_M = 1$ when $0 < c_{m1} \le c_b$, and $\frac{\partial e^*_M}{\partial c_{m1}} = 0$;

$0 < e^*_M < 1$ when $c_b < c_{m1} < c_a$, and $\frac{\partial e^*_M}{\partial c_{m1}} = -\frac{\tau L_1L_3}{8\beta mL_1 - L_3\tau^2} < 0$

The proof is completed.

Proof of Proposition2.

When $0 < c_{m1} \le c_b$, $\frac{\partial e^*_M}{\partial \theta} = 0$; $\frac{\partial w^*_M}{\partial \theta} = \frac{a}{2L_2} > 0$; $\frac{\partial p^*_{o|M}}{\partial \theta} = -\frac{a}{2L_2} < 0$; $\frac{\partial p^*_{t|M}}{\partial \theta} = \frac{aL_3}{4\beta L_2} > 0$; $\frac{\partial D^*_{o|M}}{\partial \theta} = -\frac{a(2\beta - \alpha)}{4\beta} < 0$; $\frac{\partial D^*_{t|M}}{\partial \theta} = \frac{a}{4} > 0$; $\frac{\partial \pi^*_{m|M}}{\partial \theta} = -\frac{a(2a\beta + \tau L_2 - c_{m1}L_1L_2 - a\theta(3\beta - \alpha))}{4\beta L_2}$, by solving the equation $-a(2a\beta + \tau L_2 - c_{m1}L_1L_2 - a\theta(3\beta - \alpha)) = 0$, we derive a threshold c_1, and $c_b - c_1 = -\frac{4\beta(2mL_1L_2 + a\beta\tau(1-2\theta))}{\tau L_3L_1L_2} < 0 \Longrightarrow c_{m1} \le c_1$, where $c_1 = \frac{2a\beta + \tau L_2 - a\theta(3\beta - \alpha)}{L_1L_2}$, thus $\frac{\partial \pi^*_{m|M}}{\partial \theta} < 0$; $\frac{\partial \pi^*_{r|M}}{\partial \theta} = \frac{a(a\theta + \tau - c_{m1}L_1)}{8\beta} > 0$.

When $c_b < c_{m1} < c_a$, $\frac{\partial e^*_M}{\partial \theta} = -\frac{a\tau L_1}{8\beta mL_1 - \tau^2L_3} < 0$; $\frac{\partial w^*_M}{\partial \theta} = \frac{4a\beta mL_1 - a\tau^2(2\beta + \alpha)}{(8\beta mL_1 - L_3\tau^2)L_2}$, and $\frac{\partial w^*_M}{\partial \theta} > 0$ or $\frac{\partial w^*_M}{\partial \theta} < 0$; $\frac{\partial p^*_{o|M}}{\partial \theta} = -\frac{a\beta(4mL_1 - \tau^2)}{(8\beta mL_1 - \tau^2L_3)L_2} < 0$; $\frac{\partial p^*_{t|M}}{\partial \theta} = \frac{2amL_1L_3 - a\tau^2(3\beta + 2\alpha)}{(8\beta mL_1 - L_3\tau^2)L_2}$, and $\frac{\partial p^*_{t|M}}{\partial \theta} > 0$ or $\frac{\partial p^*_{t|M}}{\partial \theta} < 0$; $\frac{\partial D^*_{o|M}}{\partial \theta} = \frac{a(\beta\tau^2 - 2mL_1(2\beta - \alpha))}{8\beta mL_1 - \tau^2L_3} < 0$; $\frac{\partial D^*_{t|M}}{\partial \theta} = \frac{a\beta(2mL_1 - \tau^2)}{8\beta mL_1 - \tau^2L_3} > 0$; $\frac{\partial \pi^*_{m|M}}{\partial \theta} = \frac{\beta a^2\tau^2(1-2\theta) - 2ma^2L_1(2\beta - \theta(3\beta - \alpha)) + 2ac_{m1}mL_1{}^2L_2}{(8\beta mL_1 - L_3\tau^2)L_2}$, by solving the equation $\beta a^2\tau^2(1 - 2\theta) - 2ma^2L_1(2\beta - \theta(3\beta - \alpha)) + 2ac_{m1}mL_1{}^2L_2 = 0$, we derive a threshold c_2, and $c_2 - c_a = \frac{a\beta(1-2\theta)(8\beta mL_1 - L_3\tau^2)}{2mL_1{}^2(3\beta^2 + 4\beta\alpha + \alpha^2)} > 0 \Rightarrow c_{m1} < c_2$, where $c_2 = \frac{\beta a^2\tau^2(2\theta - 1) + 2ma^2L_1(2\beta - \theta(3\beta - \alpha))}{2amL_1{}^2L_2}$, thus $\frac{\partial \pi^*_{m|M}}{\partial \theta} < 0$; $\frac{\partial \pi^*_{r|M}}{\partial \theta} = \frac{\beta(a\tau^2 - 2amL_1)(4c_{m1}mL_1{}^2 + a\tau^2(2\theta - 1) - 4am\theta L_1)}{(\tau^2L_3 - 8\beta mL_1)^2}$, and $\frac{\partial \pi^*_{r|M}}{\partial \theta} > 0$ or $\frac{\partial \pi^*_{r|M}}{\partial \theta} < 0$.

The proof is completed.

Proofof Proposition 3.

When $0 < c_{m1} \le c_b$,

$\Delta D_{M1} = D^*_{t|M} - D^*_{o|M} = -\frac{2a\beta + \tau L_2 - c_{m1}L_1L_2 - a\theta(3\beta - \alpha)}{4\beta}$, by solving the equation $-(2a\beta + \tau L_2 - c_{m1}L_1L_2 - a\theta(3\beta - \alpha)) = 0$, we derive a threshold c_4, $c_4 - c_b = \frac{4\beta(2mL_1L_2 + a\beta\tau(1-2\theta))}{\tau L_3(\beta^2 - \alpha^2)} > 0 \Rightarrow c_{m1} < c_4$, where $c_4 = \frac{a(\alpha\theta - \beta(3\theta - 2)) + \tau L_2}{L_1L_2}$, thus $D^*_{t|M} < D^*_{o|M}$, and $\frac{\partial \Delta D_{M1}}{\partial c_{m1}} = \frac{L_1L_2}{4\beta} > 0$;

$\Delta p_{M1} = p^*_{t|M} - p^*_{o|M} = \frac{\tau L_2 + a(5\beta\theta - 2\beta + \alpha\theta) - c_{m1}L_1L_2}{4\beta L_2}$, by solving the equation $\tau L_2 + a(5\beta\theta - 2\beta + \alpha\theta) - c_{m1}L_1L_2 = 0$, we derive a threshold c_5, $p^*_{t|M} > p^*_{o|M}$ if $c_{m1} < c_5$, $p^*_{t|M} < p^*_{o|M}$ if $c_{m1} > c_5$, and $\frac{\partial \Delta p_{M1}}{\partial c_{m1}} = \frac{L_1}{4\beta} > 0$ where $c_5 = \frac{\tau L_2 + a(5\beta\theta - 2\beta + \alpha\theta)}{L_1L_2}$

When $c_b < c_{m1} < c_a$,

$\Delta D_{M2} = D^*_{t|M} - D^*_{o|M} = \frac{\beta(4am\theta L_1 - 4c_{m1}mL_1{}^2 - a\tau^2(2\theta - 1)) - 4amL_1(\alpha\theta - 2\beta(\theta - 1)) + 4c_{m1}mL_1{}^2(2\beta + \alpha) + a\beta\tau^2(1-2\theta)}{2L_{10}}$, by solving the equation $\beta(4am\theta L_1 - 4c_{m1}mL_1{}^2 - a\tau^2(2\theta - 1)) - 4amL_1(\alpha\theta - 2\beta(\theta - 1)) + 4c_{m1}mL_1{}^2(2\beta + \alpha) + a\beta\tau^2(1 - 2\theta) = 0$, we derive a threshold c_6, $c_6 - c_a = \frac{a\beta(1-2\theta)(8\beta mL_1 - \tau^2L_3)}{2mL_1{}^2(3\beta^2 + 4\beta\alpha + \alpha^2)} > 0 \Rightarrow c_{m1} < c_6$ where $c_6 = \frac{a(\beta\tau^2(2\theta - 1) + 2mL_1(2\beta - 3\beta\theta + \alpha\theta))}{2mL_2L_1{}^2}$, thus $D^*_{t|M} < D^*_{o|M}$, and $\frac{\partial \Delta D_{M2}}{\partial c_{m1}} = \frac{2mL_2L_1{}^2}{8\beta mL_1 - \tau^2L_3} > 0$;

$\Delta p_{M2} = p^*_{t|M} - p^*_{o|M} = \frac{2mL_1(a(5\beta\theta - 2\beta + \alpha\theta) - c_{m1}L_1L_2) - a\tau^2(2\theta - 1)(2\beta + \alpha)}{L_2(8\beta mL_1 - \tau^2L_3)}$, by solving the equation $2mL_1(a(5\beta\theta - 2\beta + \alpha\theta) - c_{m1}L_1L_2) - a\tau^2(2\theta - 1)(2\beta + \alpha) = 0$, we derive a threshold c_7, $p^*_{t|M} > p^*_{o|M}$ if $c_{m1} < c_7$, $p^*_{t|M} < p^*_{o|M}$ if $c_{m1} > c_7$, where $c_7 = \frac{a\tau^2(1-2\theta)(2\beta + \alpha) + 2amL_1(5\beta\theta - 2\beta + \alpha\theta)}{2mL_1{}^2L_2}$, and $\frac{\partial \Delta p_{M2}}{\partial c_{m1}} = \frac{2mL_1{}^2L_2}{L_2(8\beta mL_1 - \tau^2L_3)} > 0$.

The proof is completed.

Proof of Proposition 4.

$e^*_R = 1$ when $0 < c_T \le c_d$, and $\frac{\partial e^*_R}{\partial c_T} = 0$;

$0 < e^*_R < 1$ when $c_d < c_T \le c_c$, and $\frac{\partial e^*_R}{\partial c_T} = -\frac{\tau(\beta - \alpha)}{4(2m(\beta - \alpha) - \tau^2)} < 0$

The proof is completed.

Proof of Proposition 5.

When $0 < c_T \le c_d$, $\frac{\partial e^*_R}{\partial \theta} = 0$; $\frac{\partial w^*_R}{\partial \theta} = 0$; $\frac{\partial p^*_{o|R}}{\partial \theta} = -\frac{a}{2L_2} < 0$; $\frac{\partial p^*_{t|R}}{\partial \theta} = \frac{a}{2L_2} > 0$; $\frac{\partial D^*_{o|R}}{\partial \theta} = -\frac{a}{2} < 0$; $\frac{\partial D^*_{t|R}}{\partial \theta} = \frac{a}{2} > 0$; $\frac{\partial \pi^*_{m|R}}{\partial \theta} = 0$; $\frac{\partial \pi^*_{r|R}}{\partial \theta} = -\frac{a^2(1-2\theta)}{2L_2} < 0$.

When $c_d < c_T \le c_c$, $\frac{\partial e^*_R}{\partial \theta} = 0$; $\frac{\partial w^*_R}{\partial \theta} = 0$; $\frac{\partial p^*_{o|R}}{\partial \theta} = -\frac{a}{2L_2} < 0$; $\frac{\partial p^*_{t|R}}{\partial \theta} = \frac{a}{2L_2} > 0$; $\frac{\partial D^*_{o|R}}{\partial \theta} = -\frac{a}{2} < 0$; $\frac{\partial D^*_{t|R}}{\partial \theta} = \frac{a}{2} > 0$; $\frac{\partial \pi^*_{m|R}}{\partial \theta} = 0$; $\frac{\partial \pi^*_{r|R}}{\partial \theta} = -\frac{a^2(1-2\theta)}{2L_2} < 0$.

The proof is completed.

Proof of Proposition 6.

When $0 < c_T \le c_d$, $\Delta D_{R1} = D^*_{t|R} - D^*_{o|R} = -\frac{a(1-2\theta)}{2} < 0$, and $\frac{\partial \Delta D_{R1}}{\partial c_T} = 0$;

$\Delta p_{R1} = p^*_{t|R} - p^*_{o|R} = -\frac{a(1-2\theta)}{2(\beta + \alpha)} < 0$, and $\frac{\partial \Delta p_{R1}}{\partial c_T} = 0$.When $c_d < c_T \le c_c$, $\Delta D_{R2} = D^*_{t|R} - D^*_{o|R} = -\frac{a(1-2\theta)}{2} < 0$, and $\frac{\partial \Delta D_{R2}}{\partial c_T} = 0$;

$\Delta p_{R2} = p^*_{t|R} - p^*_{o|R} = -\frac{a(1-2\theta)}{2(\beta + \alpha)} < 0$, and $\frac{\partial \Delta p_{R2}}{\partial c_T} =$.

The proof is completed.

Proof of Tables 9 and 10.

It can be known from Lemma 1 and 2,

$$e_M^* = \begin{cases} 1 & 0 < c_{m1} \le c_b \\ \dfrac{\tau(a(2\beta - \theta L_1) - c_{m1} L_1 L_3)}{L_{10}} & c_b < c_{m1} < c_a \end{cases}$$

$$e_R^* = \begin{cases} 1 & 0 < c_T \le c_d \\ \dfrac{\tau(a - 2L_1 c_T)}{4L_{14}} & c_d < c_T < c_c \end{cases}$$

We define $n = \frac{c_T}{c_{m1}}$ as the cost variation coefficient, that is $c_T = nc_{m1}$. Thus, we have

$$e_R^* = \begin{cases} 1 & 0 < c_{m1} \le c_f \\ \dfrac{\tau(a - 2L_1 n c_{m1})}{4L_{14}} & c_f < c_{m1} < c_e \end{cases}$$

, where $c_e = \frac{a}{2nL_1}$ and $c_f = \frac{a\tau + 4\tau^2 - 8mL_1}{2n\tau L_1}$ $m_b - m_d = -\frac{\tau^2}{8\beta} < 0$; $m_a - m_c = \frac{\tau(a(\beta(1-\theta)+\alpha\theta) - \tau L_1)}{8\beta L_1} = 0$, by solving the equation $m_a - m_c = 0$, we obtain that $m_a > m_c$ when $a > \frac{\tau L_1}{\beta(1-\theta)+\alpha\theta}$, and $m_a \le m_c$ when $0 < a \le \frac{\tau L_1}{\beta(1-\theta)+\alpha\theta}$. To simplify the analysis, we only consider the situation of relatively large market scale (i.e., $a > \frac{\tau L_1}{\beta(1-\theta)+\alpha\theta}$).

Hence, we have

$$s.t \begin{cases} m_b < m < m_a \\ m_d < m < m_c \end{cases} \Rightarrow m_d < m < m_c$$

Scenario 1. . $c_f - c_b = \frac{a\tau + 4\tau^2 - 8mL_1}{2n\tau L_1} - \frac{\tau a(2\beta - \theta L_1) + L_3\tau^2 - 8\beta m L_1}{\tau L_1 L_3} = 0$, by solving the equation $c_f - c_b = 0$, we derive a threshold n_1.

When $n \ge n_1$, $c_f \le c_b$, where $n_1 = \frac{L_3(4\tau^2 + a\tau - 8mL_1)}{2\tau^2 L_3 + 2a\tau(2\beta - \theta L_1) - 16\beta m L_1}$. $c_a - c_e = \frac{a(2\beta - \theta L_1)}{L_1 L_3} - \frac{a}{2nL_1} = 0$, by solving the equation $c_a - c_e = 0$, we derive a threshold n_2.

When $n \le n_2$, $c_a \le c_e$, where $n_2 = \frac{L_3}{4\beta - 2\theta L_1}$. $n_1 - n_2 = \frac{L_3(4\tau^2 + a\tau - 8mL_1)}{2\tau^2 L_3 + 2a\tau(2\beta - \theta L_1) - 16\beta m L_1} - \frac{L_3}{4\beta - 2\theta L_1} = 0$, by solving the equation $n_1 - n_2 = 0$, we derive a threshold $m_e = \frac{\tau^2(4(\beta - \theta L_1) + L_1)}{8L_1(\beta - \theta L_1)}$. $m_e - m_d = \frac{\tau^2}{8(\beta(1-\theta)+\alpha\theta)} > 0$; $m_a - m_e = \frac{\tau(\beta(2-\theta)+\alpha\theta)(a(\beta(1-\theta)+\alpha\theta) - \tau L_1)}{8\beta L_1(\beta(1-\theta)+\alpha\theta)}$, $m_c - m_e = \frac{\tau(a(\beta(1-\theta)+\alpha\theta) - \tau L_1)}{8L_1(\beta(1-\theta)+\alpha\theta)}$. $m_a > m_e$, $m_c > m_e$ and $m_a > m_c$ when $a > \frac{\tau L_1}{\beta(1-\theta)+\alpha\theta} \Rightarrow m_d < m_e < m_c$. If $m \ge m_e$, $n_1 \le n_2$. Hence, when $m_e \le m < m_c$ and $n_1 \le n \le n_2$, $0 < c_f \le c_b < c_a \le c_e$.

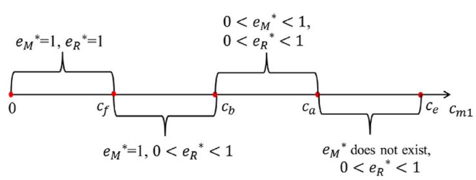


Fig. A1. $m_e \le m < m_c$ **and** $n_1 \le n \le n_2$

Scenario 2. . $c_e - c_b = \frac{a}{2nL_1} - \frac{\tau a(2\beta - \theta L_1) + L_3\tau^2 - 8\beta m L_1}{\tau L_1 L_3} = 0$. By solving the equation $c_e - c_b = 0$, we derive a threshold n_3.

When $n \le n_3$, $c_b \le c_e$, where $n_3 = \frac{a\tau L_3}{2\tau^2 L_3 + 2a\tau(2\beta - \theta L_1) - 16\beta m L_1}$. It can be obtained from the Scenario 1, $c_b \ge c_f$ if $n \ge n_1$, $c_a > c_e$ if $n > n_2$, and $n_1 \le n_2$ if $m \le m_e$. Hence, when $m_e \le m < m_c$ and $n_2 < n \le n_3$, $0 < c_f \le c_b \le c_e < c_a$.

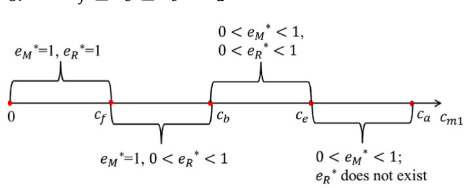


Fig. A2. $m_e \le m < m_c$ **and** $n_2 < n \le n_3$

Scenario 3. . It can be obtained from the Scenario 2, $c_b > c_e$ if $n > n_3$. Hence, when $n > n_3$, $0 < c_f < c_e < c_b < c_a$. We analyze Scenario 3 under the condition of $m_e \le m < m_c$.

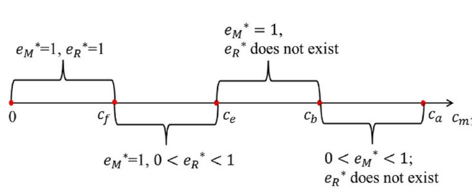


Fig. A3. $m_e \le m < m_c$ **and** $n > n_3$

Scenario 4. . Based on Scenario 1, we can obtain when $m_d < m < m_e$ and $n_2 < n \le n_1$, $0 < c_b \le c_f < c_e < c_a$.

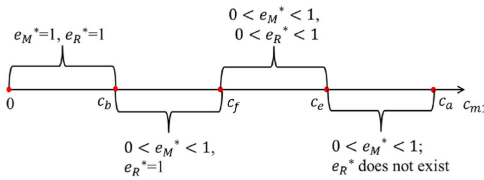


Fig. A4. $m_d < m < m_e$ and $n_2 < n < n_1$

Scenario 5. **.** $c_a - c_f = \frac{a(2\beta-\theta L_1)}{L_1L_3} - \frac{a\tau+4\tau^2- 8mL_1}{2n\tau L_1}$. Therefore, when $> n_4,\ c_a > c_f$, where $n_4 = \frac{L_3(4\tau^2+a\tau -8mL_1)}{2a\tau(2\beta-\theta L_1)}$. Based on Scenario 4, we can obtain when $m_d < m < m_e$ and $n_4 < n \leq n_2$, $0 < c_b < c_f < c_a < c_e$.

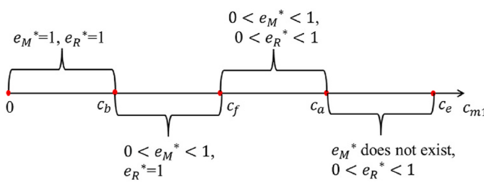


Fig. A5. $m_d < m < m_e$ **and** $n_4 < n \leq n_2$

Scenario 6. **.** It can be obtained from the Scenario 5, $c_a \leq c_f$ if $n \leq n_4$. Hence, when $n < n_4$, $0 < c_b < c_a \leq c_f < c_e$. We analyze Scenario 6 under the condition of $m_d < m < m_e$.

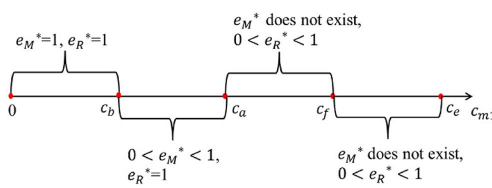


Fig. A6. $m_d < m < m_e$ and $n \leq n_4$.

The proof is completed.

Proof of Proposition 7.

$e_M^* - e_R^* = \frac{4L_{14}\tau(a(2\beta - \theta L_1) - c_{m1}L_1L_3) - L_{10}\tau(a-2L_1(c_{m2}+c_r))}{4L_{14}L_{10}}$, by solving the equation $4L_{14}\tau(a(2\beta - \theta L_1) - c_{m1}L_1L_3) - L_{10}\tau(a - 2L_1nc_{m1}) = 0$, we derive a threshold $c_g = \frac{4a\tau L_{14}(2\beta - \theta L_1) - L_{10}a\tau}{4\tau L_1L_3L_{14} - 2n\tau L_1L_{10}}$. We can get $e_R^* \geq e_M^*$ if $c_{m1} \geq c_g$, $e_R^* < e_M^*$ if $c_{m1} < c_g$.

(1) When $m_e \leq m < m_c$ and $n_1 \leq n \leq n_2$, $c_b < c_g < c_a$, under this constraint, we get $0 < e_R^* < e_M^* < 1$ if $c_b \leq c_{m1} < c_g$, $0 < e_M^* \leq e_R^* < 1$ if $c_g \leq c_{m1} < c_a$.
(2) When $m_e \leq m < m_c$ and $n_2 < n \leq n_3$, $c_e < c_g$, under this constraint, we get $0 < e_R^* < e_M^* < 1$ if $c_b \leq c_{m1} < c_e$.
(3) When $m_d < m < m_e$ and $n_4 < n \leq n_2$, $c_a < c_g$, under this constraint, we get $0 < e_M^* < e_R^* < 1$ if $c_f \leq c_{m1} < c_a$.
(4) When $m_d < m < m_e$ and $n_2 < n \leq n_1$, $c_f < c_g < c_e$, under this constraint, we get $0 < e_M^* < e_R^* < 1$ if $c_f \leq c_{m1} < c_g$, $0 < e_R^* \leq e_M^* < 1$ if $c_g \leq c_{m1} < c_e$

The proof is completed.

Proof of Proposition 8.

(1) $q = \frac{c_{m2}}{c_T}$ $(0 < q < 1)$ is defined as the cost composition ratio, where $c_T = c_{m2} + c_r$. We can further obtain $c_{m2} = qc_T$ and $c_r = (1-q)c_T$. $c_{m2} + c_r = qc_T + (1-q)c_T = c_T$, thus $\frac{\partial p_{t|R}^*}{\partial q} = \frac{\partial p_{o|R}^*}{\partial q} = \frac{\partial \pi_{m|R}^*}{\partial q} = \frac{\partial \pi_{r|R}^*}{\partial q} = 0$.

(2) When $0 < c_{m1} \leq c_f$, $\frac{\partial p_{t|R}^*}{\partial n} = \frac{\partial p_{o|R}^*}{\partial n} = \frac{c_{m1}}{4} > 0$; $\frac{\partial \pi_{m|R}^*}{\partial n} = -\frac{c_{m1}(a+2\tau-2c_{m1}nL_1)}{4} < 0$, $\frac{\partial \pi_{r|R}^*}{\partial n} = -\frac{c_{m1}(a+2\tau-2c_{m1}nL_1)}{8} < 0$

When $c_f < c_{m1} \leq c_e$, $\frac{\partial p_{t|R}^*}{\partial n} = \frac{\partial p_{o|R}^*}{\partial n} = \frac{c_{m1}(mL_1-\tau^2)}{2L_{14}}$, by solving the equation $c_{m1}(\tau^2 - mL_1) = 0$, we derive a threshold m_5, $\frac{\partial p_{t|R}^*}{\partial \theta} = \frac{\partial p_{o|R}^*}{\partial n} > 0$ if $m_5 \leq m < m_c$; $\frac{\partial p_{t|R}^*}{\partial \theta} = \frac{\partial p_{o|R}^*}{\partial n} < 0$ if $m_d < m < m_5$, where $m_5 = \frac{\tau^2}{L_1}$; $\frac{\partial \pi_{m|R}^*}{\partial n} = -\frac{c_{m1}mL_1(a-2c_{m1}nL_1)}{2L_{14}} < 0$, $\frac{\partial \pi_{r|R}^*}{\partial n} = -\frac{c_{m1}mL_1(a-2c_{m1}nL_1)}{4L_{14}} < 0$.

The proof is completed.

Proof of Theorem 3.

Because the proof process of *Theorem* 3 is similar to that of Lemma 1 and Lemma 2, we omit them.

Appendix B

$L_1 = \beta - \alpha$; $L_2 = \beta + \alpha$; $L_3 = 3\beta + \alpha$

$L_4 = 8a\beta m(\alpha+\theta L_1) - a\tau^2(2\theta-1)(2\beta+\alpha)$

$L_4 = L_5 = 8a\beta m(\beta-\theta L_1) + a\beta\tau^2(2\theta-1)$

$L_6 = 4am(2\beta\alpha+\theta L_1 L_3) - a\tau^2(2\theta-1)(3\beta+2\alpha)$

$L_7 = 4amL_1(\alpha\theta-2\beta(\theta-1)) + a\beta\tau^2(2\theta-1)$

$L_8 = 4a^2m\left(\theta^2L_1(3\beta-\alpha)+2\beta(\beta-2\theta L_1)\right) - a^2\beta\tau^2(2\theta-1)^2$

$L_9 = a^2\left(\theta^2(3\beta-\alpha)L_1+2\beta^2-4\beta\theta L_1\right) + 2aL_2(2\beta-\theta L_1)(\tau-c_{m1}L_1) - 8\beta mL_1L_2 + \tau^2L_3L_2$

$L_{10} = 8\beta mL_1 - \tau^2L_3$

$L_{11} = amL_1(5\beta+\alpha-4\theta L_1) - 2a\tau^2(\beta-\theta L_1)$

$L_{12} = amL_1(\beta+5\alpha+4\theta L_1) - 2at\tau^2(\alpha+\theta L_1)$

$L_{12} = a^2m(5\beta-3\alpha+16\theta L_1(\theta-1)) - 2a^2\tau^2(2\theta-1)^2$

$L_{13} = a^2(5\beta-3\alpha+16\theta L_1(\theta-1)) + 4a\theta L_2 + 4L_2\left(\tau^2-8mL_1\right)$

$L_{14} = 2mL_1 - \tau^2$

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