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Abstract: This paper investigates three-dimensional printing technology (3DPT) investment strategies promoting low-carbon supply chain development. A theoretical model is built in which either the manufacturer or retailer can lead an investment in 3DPT. The main results are as follows: 1) the manufacturer always benefits from investing in 3DPT and is willing to lead the investment, while the retailer also benefits but is only willing to lead the investment with a large cost coefficient of 3DPT investment; 2) investing in 3DPT always raises consumers' demands and reduces units of carbon emissions. Counterintuitively, implementing 3DPT may decrease the optimal prices and research and development investment (R&D), but increase total carbon emissions; 3) the optimal 3DPT investment is decreasing in terms of cost coefficient (CC); interestingly, CC had positive and negative impacts on wholesale and retail prices.

Keywords: low-carbon product development; 3DPT investment; product variety R&D; Stackelberg game.

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1 Introduction

The booming growth of the manufacturing industry has produced an exponentially increasing amount of carbon dioxide emissions, which contribute to global warming1. Thus, all countries need to promote strategies to reduce carbon emissions. To deal with this challenge and under the framework of the United Nations Framework Convention on climate change, many countries have adopted the Kyoto Protocol and the Paris Agreement in seeking to limit carbon emissions. For example, China would achieve the goals of carbon peaking before 2030 and carbon neutrality by 2060. In addition, other major economies, such as the EU, Germany, and Japan, have presented plans to achieve carbon neutrality by 2050. Therefore, manufacturers in these countries need to invest in advanced green technologies that reduce carbon emissions. Furthermore, manufacturers tend to invest in carbon reduction technology from which they can benefit directly, rather than technology that reduces greenhouse gas emissions alone. Considering this, 3DPT is attractive to manufacturers as it reduces production costs by using fewer raw materials while promoting reduced carbon emissions (Ford and Despeisse, 2016; Rinaldi et al., 2021).

With the proposal of 'Industry 4.0,' 3DPT–also known as *additive manufacturing technology*–has attracted attention from the industry. 3DPT has several advantages when compared with conventional manufacturing processes, such as flexible product variety capability that can respond to dynamic consumer demands (Holmstrom et al. 2010), lower inventory and logistics requirements (Ghadge et al. 2018), less raw material consumption (Westerweel et al. 2018), and improved product quality (Illinda, 2014; Shinde, 2021). Therefore, it has become widely accepted in the manufacturing industry.

3DPT promotes more precise product design/manufacturing, drastically reduces raw material requirements, and has great potential for decreasing carbon emissions (Ford and Despeisse, 2016; Rinaldi et al., 2021). For example, Sakuu used 3DPT to develop solid-state batteries with the same capacity as existing batteries while using only 30–50% of the raw materials[2]. For manufacturers, 3DPT can improve manufacturing processes by decreasing the cost of mould production and help retailers to design products with greater precision, thus enhancing product durability and immediately reducing raw material consumption and carbon emissions. 3DPT can also improve product variety research and development (R&D) processes for retailers. This implies that retailers design horizontally differentiated products to satisfy consumers' endogenous preferences (Rajagopalan and Xia, 2012). For example, retailers can provide differently shaped products through more efficient rapid prototyping with shorter timeframes and more precise product designs. This can indirectly assist manufacturers in reducing raw material consumption. For example, giant bicycle, a famous Taipei bike retailer, used 3DPT to design and print various bicycle saddle moulds, a process that is dramatically cheaper and faster than traditional methods[3].

Manufacturers are increasingly producing original equipment manufacturer (OEM) products designed and developed by downstream retailers. For example, the world's largest sporting retailers, such as Nike, Decathlon, and Vans, and the desktop computer retailer Dell all use OEM[4]. OEMs sell the goods to downstream retailers, and retailers sell them to consumers (Lee et al., 2022). Consequently, manufacturers can–directly and indirectly–reduce raw material usage by investing in 3DPT, and retailers can invest in more affordable product variety R&D. Under governmental sustainability policies and considering business investment revenue, 3DPT will garner increasing attention from retailers and manufacturers. Well-known examples of 3DPT development by manufacturers include B&J Specialty, a metal mould manufacturer, which adopted 3DPT service in their manufacturing process[5]. Decathlon, one of the largest sporting equipment retailers, launched a 3DPT project to diversify its range of sporting equipment[6]. Although some studies (Dong et al., 2019; Shi et al., 2019, 2020; Li et al., 2021) have explored whether a supply chain should invest in low-carbon technology (LCT), they have not discussed responsive 3DPT investment issues considering the differences between 3DPT and traditional LCT. As such, the incentives to invest in 3DPT remain unknown, making it necessary to investigate manufacturer and retailer motivations.

This study focuses on the following research questions to emphasise the strategic decisions related to 3DPT investment and manufacturer/retailer motivations to participate in low-carbon transformation:

1. Who will lead supply chains to invest in 3DPT to achieve low-carbon transformation?
2. What are the effects of the cost coefficient (CC) of 3DPT investment on manufacturers' and retailers' optimal decisions?

3 If a supply chain adopts 3DPT, how might the related investment decisions affect the pricing strategy, the R&D investment decisions, the market demands, and the unit and total carbon emissions?

To answer the research questions mentioned above, this study establishes a Stackelberg game model comprising an upstream manufacturer and a downstream retailer to investigate the 3DPT investment strategies of supply chains. Specifically, it explores three main scenarios in which

1 no one adopts 3DPT

2 the manufacturer invests in 3DPT for low-carbon transformation and helps retailers' product variety R&D

3 the retailer implements 3DPT for significantly cheaper and shorter product variety R&D processes and indirectly reduces manufacturing material consumption.

When a supply chain launches a 3DP project, the manufacturer can save raw materials and lower production costs, thus intuitively reducing the unit and total carbon emissions. A sensitivity analysis is conducted to explore the effects of 3DPT adoption on the equilibrium solution in two cases of 3DPT implementation. Finally, scenarios 2 and 3 are compared to investigate the effects of CC of 3DPT investment.

The major contributions of this paper are threefold. Firstly, two different cases were observed where

1 the manufacturer is the 3DPT investment leader (e.g., B&J Specialty)

2 the retailer (e.g., Decathlon) invests in 3DPT.

This determines which type of firm can best lead a supply chain to invest in 3DPT and achieve low- carbon transformation. Secondly, this study contributes to existing research by considering the key differences between 3DPT and conventional LCT, the economic feasibility of 3DPT, and different supply chain 3DPT investment strategies, further enriching research in the low-carbon field. Thirdly, some interesting analytical findings were made. Both manufacturers and retailers could benefit from investment in 3DPT. This conclusion differs from those of Arbabian and Wagner (2020) and Arbabian (2022), who demonstrated that retailers investing in 3DPT have decreased profits. The different findings are because Arbabian and Wagner (2020) and Arbabian (2022) only considered 3DPT as a mode of flexible manufacturing and ignored its low-carbon characteristics. Hence, manufacturers and retailers are incentivised to lead supply chains in investing in 3DPT. Manufacturers will always be incentivised to lead the supply chain to invest in 3DPT to achieve low-carbon transformation and derive profits. Interestingly, the retailers are willing to lead the low-carbon transformation by investing in 3DPT, but this is true only if the CC of the 3DPT investment is sufficiently high. Further, the optimal 3DPT and variety R&D investment decreases with the CC of 3DPT investment, and CC may have positive impacts on both wholesale and retail prices. Counterintuitively, implementing 3DPT may decrease optimal prices – which differs from the results of Shi et al. (2019) and Dong et al. (2019) – as well as R&D investment, but raises consumers' demands. The unit carbon emission is the lowest under the manufacturer-investment scenario, which agrees with the results of Dong et al. (2019) but differs from those of Shi et al. (2019). However, total carbon emissions are greatest when the CC of the 3DPT investment is high. Further, total carbon emissions are constantly improved under the retailer-investment scenario. The environmental impact of 3DPT is not discussed in previous studies such as Hartl and Kort (2017), Kleer and Piller (2019), Arbabian and Wagner (2020), Arbabian (2022), and Guo et al. (2022).

2 Literature review

This paper relates to the following three relevant issues in the literature:

1 LCT investment

2 3DPT in operations management

3 demand models. These literature streams are reviewed below.

2.1 LCT investment

As the focus of abundant research (Ghosh and Shah, 2012; Raz et al., 2013; Hong and Guo, 2019), LCT investment has become a significant topic in supply chain management. Most of the literature on LCT investment focuses on why and how manufacturers do it. For example, Ghosh and Shah (2012) considered supply chain structures and investigated the impacts of supply chain leadership on LCT investment. They demonstrated that a manufacturer-led structure cannot promote LCT investment. Hong and Guo (2018) considered cost-sharing contracts and implied that they contribute to LCT investment by manufacturers. Ma et al. (2021) focused on the impact of government intervention on LCT investment. They pointed out that carbon emissions reduction subsidies are conducive to such investment, while high carbon emissions reduction standards are not. Jian et al. (2021) established a closed-loop supply chain considering manufacturers' fair concern, which they highlighted as not conducive to LCT investment. Some researchers, such as Chen et al. (2021), have studied LCT investment from the perspective of cap-and-trade mechanisms. Their results showed manufacturers will invest more in LCT when the government implements a cap-and-trade policy.

Retailers also play a critically significant role in LCT investment issues. However, the above research only focused on manufacturer investment. Thus, some scholars, such as Raz et al. (2013), Du et al. (2017), Chen et al. (2020b), Yoon et al. (2020), and Xia et al. (2021), have investigated related issues considering investment by both manufacturers and retailers. Specifically, Raz et al. (2013) created a Newsvendor model to examine manufacturers and retailers' low-carbon efforts. They found that equilibrium LCT investment by manufacturers increases production costs when equilibrium retailers' LCT investment is high. Du et al. (2017) considered consumer environmental awareness and proposed that optimal LCT investment for both manufacturers and retailers increases with consumer low-carbon preference. Some researchers, such as Chen et al. (2020b), have compared optimal LCT investments by manufacturers and retailers, and found that a manufacturer-led structure can encourage investment, which conflicts with the results of Ghosh and Shah (2012). Moreover, Xia et al. (2021) studied how cross-shareholding affects LCT investment by manufacturers and retailers. They demonstrated that both types of equilibrium LCT investment increase with the proportion of cross-shareholding.

Although some of these studies considered the crucial role of retailers in LCT investment issues, they did not focus on the differences between the two types of LCT investments. Accordingly, some researchers have concentrated on scenarios where the retailer and manufacturer invest in LCT and analysed the factors that affect the choices of the supply chain. By comparing the optimal LCT investment decisions of the two models, Chen et al. (2020a) demonstrated that retailers always invest more than manufacturers. In contrast, Li et al. (2021) found that manufacturers always invest more due to the rising costs caused by low-carbon product manufacturing. In addition, Shi et al. (2020) considered that LCT investment provided tax savings per unit product and showed that a retailer would invest more when the CC of 3DPT investment is relatively low. Further, Shi et al. (2019) assumed that there is an extra downstream retail competitor. They highlighted that all manufacturers and retailers have incentives to invest, and that the retailer will invest more when the CC divided by the price sensitivity is sufficiently low.

Currently, under a low-carbon background, several studies have investigated LCT investment. However, there has been limited research on 3DPT as a type of LCT. Thus, this article investigates issues related to 3DPT investment and explores the differences between the two types of 3DPT investments.

2.2 3DPT in operations management

The second literature stream is related to 3DPT in operations management. Some scholars have evaluated the revolution in manufacturing and logistics caused by 3DPT. Simultaneously, some have studied changes in production processes and highlighted that 3DPT could reduce manufacturing costs (Westerweel et al., 2018; Tuck et al., 2007), improve product customisation (Holmstrom et al., 2010; Hartl and Kort, 2017; Kleer and Piller, 2019), and decrease production errors (Boschetto and Bottini, 2016). Others have discussed the revolution in logistics, stating that adopting 3DPT can decrease inventory and delivery costs (Ghadge et al., 2018) and delivery times (Niaki and Nonino, 2017). Unlike this paper, the above papers do not discuss supply chains' 3DPT investment issues against a low-carbon background.

Some scholars have studied supply chain issues in implementing 3DPT and investigated how 3DPT affects issues such as manufacturer and retailer profits and product competition. Hartl and Kort (2017) explored the entry mechanism of 3DPT products and noted that existing enterprises may only produce one product to resist the invasion of 3DPT products. Kleer and Piller (2019) studied competition between conventional and 3DPT products and showed that 3DPT could encourage innovative consumers to purchase 3DPT products and force conventional manufacturers to reduce their product prices. Further, several scholars have focused on retailers investing in 3D printing and explored how retailers benefit from it. Arbabian and Wagner (2020) studied how retailers introducing 3DPT for flexible manufacturing affected profits and found it harmful. Arbabian (2022) considered the impact of supply chain coordination on retailers' profits when investing in 3DPT. This researcher demonstrated that the double marginalisation effect may reduce retailers' profits. Unlike this paper, the above literature ignores environmental issues.

In addition, similar to this paper, some scholars have studied how 3DPT can improve environmental issues from the perspective of sustainable supply chains. Ford and Despeisse (2016) summarised the advantages and challenges of 3DPT in sustainable supply chains. They demonstrated that this technology allows for more responsive supply chains, a potential sustainability benefit. Afshari et al. (2020) evaluated the supply chain operating cost of implementing environmental protection innovation before and after implementing 3DPT. They found that adopting 3DPT can minimise supply chain operating costs. Kunovjanek and Reiner (2020) explored the impacts of 3DPT on the performance of raw material supply chains, pointing out that 3DPT can dramatically reduce the use of raw materials.

Although some of the above studies have considered sustainable supply chain issues related to the adoption of 3DPT, few have concentrated on 3DPT investment under a low-carbon scenario and compared various 3DPT investment strategies. Thus, abundant research gaps remain. The current study will investigate who should invest in 3DPT under a low-carbon background.

2.3 Demand models

Many scholars have studied supply chain issues considering demand models. Some used demand models to solve LCT investment issues. Chen et al. (2020a) and Chen et al. (2021) established the demand functions of renewable energy, considering consumers' sensitivity to renewable energy. Du et al. (2017) and Chen et al. (2020b) determined the impacts of LCT on consumers' demands considering manufacturers and retailers' investments in LCT. Ghosh et al. (2018) explored the pricing of green products under demand models by considering consumers' environmental awareness. Thus, this study investigated the issues with a demand model considering consumers' sensitivity to LCT.

Although many scholars have used demand models to investigate supply chain management issues, few researchers have utilised demand models to solve 3DPT adoption in supply chain management. Most scholars–such as Sun et al. (2020), Kleer and Piller (2019), Hartl and Kort (2017), and Guo et al. (2022)–have used the utility function to study 3DPT adoption issues. Unlike the above studies, this study investigated 3DPT investment issues with a demand model. Meanwhile, considering that 3DPT promotes product variety, we further include consumers' sensitivity to product variety in the demand model, as in the case of Guo et al. (2022).

3 Model description and assumptions

3DPT is widely used in manufacturing processes and can reduce raw material consumption, making it conducive to carbon emissions reduction. Meanwhile, through 3DPT, retailers can achieve more efficient R&D by promoting product variety R&D and decreasing product variety R&D costs, allowing products to more accurately match consumers' specific preferences. Therefore, we consider a situation with a supply chain comprising a manufacturer (M) and a retailer (R) to investigate the impact of 3DPT investment strategies. Based on the characteristics mentioned previously, according to Fudenberg and Tirole (1991), we establish a Stackelberg game model to analyse the situation and evaluate the impact of 3DPT investment. The Stackelberg game model is always adopted in a case where one player (e.g., an upstream M) determines its actions first, and the other player (e.g., a downstream R) observes the actions of the first player and makes its decisions. In our situation, for example, under the manufacturer-investment scenario, R will choose its best strategy (i.e., product variety and retail price strategies) after observing the actions of M (i.e., 3DPT investment and wholesale price strategies). Considering the perfect rationality assumption, the Stackelberg game model is appropriate for solving the issues using the inverse induction methodology.

To better appreciate the model, some assumptions are listed below.

Assumption 1: Assume that consumer product demand not only depends on product prices but also on various R&D and 3DPT investments. Without loss of generality and investment in 3DPT, the product demand is defined as

$$d_B = \alpha - p_B + r_B \tag{1}$$

where the subscript B implies the benchmark scenario, α represents the potential demand for the product, and p is the product's retail price. Without loss of generality, it is assumed that $\alpha = 1$. Essentially, with a higher retail price, there is a lower product demand. According to the above examples of OEMs and retailers' product design, r is the retailers' investment in product variety R&D. When R invests more in product variety R&D, products more accurately fit consumers' preferences, and thus, the product demand rises. This assumption is similar to that of Guo et al. (2022).

Investing in 3DPT makes it easier to use R&D to promote consumer product demand (Hartl and Kort, 2017; Wang et al., 2018). In addition, 'green' consumers can be attracted by the lower raw material usage in manufacturing and fewer carbon emissions via 3DPT (Xu et al., 2017; Shi et al., 2019, 2020; Li et al., 2021). When M implements 3DPT, it directly reduces raw material usage and assists R's product variety R&D through rapid prototyping. Therefore, according to Zhang et al. (2018) and Shi et al. (2019, 2020), the total product demand is assumed to be a linear function of the product price, variety R&D investment, and 3DPT investment as follows:

$$d_M = \alpha - p_M + r_M + be_M \tag{2}$$

where the subscript M reflects the manufacturer-investment scenario; e_M represents 3DPT investment by M; and b is the sensitivity coefficient of 3DPT investment due to the reduction in material consumption reflecting consumers' environmental awareness, meaning that a greater reduction of material consumption or unit carbon emissions can induce increased consumer purchasing. This assumption is similar to Ghosh and Shah (2012), Shi et al. (2019, 2020), and Li et al. (2021), and implies more consumers can be attracted by firms' investment in green technology (3DPT in this paper) which can enhance products' greenness, save on environment-related costs, and reduce carbon emissions. r_M is the investment in product variety R&D by retailers.

Similar to Guo et al. (2022), product demand rises with more product variety R&D.

When R adopts 3DPT, product variety R&D is immediately promoted, and raw material usage is indirectly reduced due to more precise product designs. As such, the total product demand is

$$d_R = \alpha - p_R + \gamma be_R \tag{3}$$

where the subscript R indicates the retailer-investment scenario; e_R represents 3DPT investment by R; b is the sensitivity coefficient of 3DPT investment, implying more consumers can be attracted by firms' investment in 3DPT, which can enhance products' greenness, save on environment-related costs, and reduce carbon emissions (Ghosh and Shah, 2012; Shi et al., 2019; Shi et al., 2020; Li et al., 2021); and r_R is the investment in product variety R&D by R. Also, similar to Guo et al. (2022), product demand rises with greater product variety R&D. Additionally, $\gamma \in (0, 1)$ represents the indirect effects between M and R, implying retailers (e.g., Nike, Decathlon, and Vans) invest in 3DPT that can promote precise product design, allowing M to indirectly save materials. γe_R represents M's material consumption reduction, and $\gamma b e_R$ is the increase in product demand created by R's investment in 3DPT. The assumption of γ is similar to Guo et al. (2020, 2023), where there exists a CC related to green technology investment when R invests in green technology.

Table 1 Meanings of notations

Nomenclature	
Notation	*Meaning*
d	Product demand
a	Potential product demand
b	Sensitivity coefficient of 3DPT investment due to material consumption reduction
c	Unit production cost
k	Cost coefficient (CC) of 3DPT investment
$G(e)$	Total cost of 3DPT investment
$G(r)$	Total cost of product variety R&D investment
π^m	Profit of M
π^r	Profit of R
p	Product retail price
w	Product wholesale price
e	3DPT investment
R	Product variety R&D investment
γ	Indirect effects between M and R
Subscripts	
B	Benchmark scenario
M	Manufacturer-investment scenario
R	Retailer-investment scenario

Assumption 2: Assume that $c \in (0, 1)$ is the unit production cost without 3DPT. Note that adopting 3DPT can reduce production costs due to lower raw material usage; therefore, the costs are denoted as $(c-e_M)$ with manufacturers adopting 3DPT and $(c-\gamma e_R)$ with retailers doing the same, where γ is the indirect effects between M and R and implies retailers (e.g., Decathlon) invest in 3DPT to design and develop more precise products, indirectly reducing raw material consumption (Raz et al., 2013). Investing more in 3DPT can enhance 'printability,' reducing raw material use; hence, greater investment leads to more savings (Weller et al., 2015). Following Li et al. (2021), the investment cost function for 3DPT is denoted as follows:

$$G(e) = ke^2 \tag{4}$$

where k is the CC of 3DPT investment, and high values represent low investment efficiency.

Similarly, it is assumed that product variety R&D investment cost function (Xiao et al., 2014) is denoted by

$$G(r) = hr^2 \tag{5}$$

According to Guo et al. (2020), $h = 1$. Similarly, the effects of 3DPT on unit production cost and the costs of product variety R&D investment are denoted as $G(r_M) = (r_M - \gamma e_M)^2$ with manufacturers adopting 3DPT. In this equation, γ is also the indirect effects between M and R and implies manufacturers (e.g., B&J specialty) invest in 3DPT to provide less lead-time and cheaper moulds to promote R's product variety R&D with lower costs, and $G(r_R) = (r_R - e_R)^2$ with retailers adopting 3DPT. Furthermore, R designing more abundant products means that M suffers more costs per unit product (Xiao et al., 2014), which is r due to the changes in product lines.

Assumption 3: Assume that M sells products to R at a wholesale price w, after which consumers purchase them from R at a retail price p. Moreover, to avoid trivial results and to guarantee the Hessian matrix is negative definite and the optimal solutions are larger than zero, it is considered that k is sufficiently large, that is, $k > \frac{1}{2}$, according to Wang et al. (2016) and Ji et al. (2017). Otherwise, relevant meanings of notations are shown in Table 1.

4 Model equilibrium

Under a 3DPT investment scenario, this article considers a Stackelberg model comprising M and R. The following three models are analysed in this section:

1 benchmark scenario – no 3DPT investment

2 manufacturer-investment scenario

3 retailer-investment scenario.

For simplicity, the subscripts $\{B, M, R\}$ indicate

the optimal decisions of the above investment scenarios (benchmark, manufacturer-investment, and retailer-investment, respectively).

4.1 Benchmark: No 3DPT investment

In this scenario, neither M nor R invests in 3DPT. M and R play a two-stage game. In stage 1, M chooses its wholesale price. In stage 2, R simultaneously determines its product variety R&D investment and retail price. In the absence of 3DPT, the unit production cost and the product variety R&D investment cost remain c and r_B^2, respectively. The product demand function is as per equation (1). Thus, the profit functions of M and R are presented below.

$$\pi_B^m = (w_B - c - r_B)(1 - p_B + r_B) \tag{6}$$

$$\pi_B^r = (p_B - w_B)(1 - p_B + r_B) - r_B^2 \tag{7}$$

The equilibrium results are derived according to backward induction. First, R optimally determines (p_B, r_B) to maximise its profit. From $\frac{\partial \pi_B^r}{\partial p_B} = 0$ and $\frac{\partial \pi_B^r}{\partial r_B} = 0$, the following are derived:

$$p_B(w_B) = \frac{2 + w_B}{3} \tag{8}$$

$$r_B(w_B) = \frac{1 - w_B}{3} \tag{9}$$

Then, using equations (8) and (9) as R's response to retail price and R&D investment function respectively, M sets the optimal value of w_B^* to maximise its profit. Solving $\frac{\partial \pi_B^m(w_B)}{\partial w_B} = 0$ yields

$$w_B^* \frac{5 + 3c}{8} \tag{10}$$

By substituting equation (10) into equations (8) and (9), the following are derived:

$$p_B^* = \frac{7 + c}{8} \tag{11}$$

$$r_B^* = \frac{1 - c}{8} \tag{12}$$

Finally, substituting equations (10), (11), and (12) into equations (1), (6), and (7), respectively, the following are obtained:

$$d_B^* = \frac{1 - c}{4} \tag{13}$$

$$\pi_B^{r*} = \frac{3(1 - c)^2}{64} \tag{14}$$

$$\pi_B^{m*} = \frac{(1 - c)^2}{8} \tag{15}$$

Proposition 1: When neither M nor R invests in 3DPT, the optimal wholesale price w_B^*, retailer price p_B^*, variety R&D investment r_B^*, product demand d_B^*, retailer profit π_B^*, and manufacturer profit π_B^{m*} can be described by equations (10)–(15).

4.2 *Manufacturer investment in 3DPT*

Under the scenario where M invests in 3DPT, M can dramatically reduce raw material usage and assist R's product variety R&D through rapid prototyping. As such, the cost per unit product can be interpreted as ($c-e_M$) due to the reduction in raw materials. The product variety R&D investment cost can be denoted by $G(r_M) = (r_M - \gamma e_M)^2$ because of the more efficient R&D. In this scenario, M and R play a two-stage game as well. First, M simultaneously decides on its 3DPT investment e_M and wholesale price w_M. In stage 2, observing M's decisions, R optimally and simultaneously chooses the product variety R&D investment r_M and retail price p_M. The product demand is represented by equation (2). Therefore, the profit functions of M and R are denoted as follows:

$$\pi_M^m = \left[w_M - (c - e_M) - r_M\right](1 - p_M + r_M + be_M) - ke_M^2 \tag{16}$$

$$\pi_M^r = (p_M - w_M)(1 - p_M + r_M + be_M) - (r_M - \gamma e_M)^2 \tag{17}$$

Backward induction is used to develop the equilibrium solutions. In stage 2, R decides the optimal value of (p_M, r_M) to maximise its profit. From $\frac{\partial \pi_M^r}{\partial p_M} = 0$ and $\frac{\partial \pi_M^r}{\partial r_M} = 0,$ the following are obtained:

$$p_M(w_M, e_M) = \frac{1}{3}(2 + 2be_M + w_M + 2e_M\gamma) \tag{18}$$

$$r_M(w_M, e_M) = \frac{1}{3}(1 + be_M + w_M + 4e_M\gamma) \tag{19}$$

In stage 1, expecting R's response to retail price and R&D investment to be $p_M(w_M, e_M)$ and $r_M(w_M, e_M)$ respectively, M optimally determines w_M^* and e_M^*. By solving $\frac{\partial \pi_M^m(w_M, e_M)}{\partial w_M} = 0$ and $\frac{\partial \pi_M^m(w_M, e_M)}{\partial e_M} = 0,$ we yield.

$$w_M^* = \frac{1 + b^2c - (5 + 3c)k - \gamma + c\gamma + b(1 + c - \gamma + c\gamma)}{1 + 2b + b^2 - 8k} \tag{20}$$

$$e_M^* = \frac{(1 + b)(1 - c)}{1 + 2b + b^2 - 8k} \tag{21}$$

Substituting equations (20) and (21) into equations (2) and (16)–(19), the following are derived:

$$p_M^* = \frac{1 + b^2c - (7 + c)k - \gamma + c\gamma + b(1 + c - \gamma + c\gamma)}{1 + 2b + b^2 - 8k} \tag{22}$$

$$r_M^* = \frac{(-1 + c)(k + \gamma + b\gamma)}{1 + 2b + b^2 - 8k} \tag{23}$$

$$d_M^* = \frac{2(-1 + c)k}{1 + 2b + b^2 - 8k} \tag{24}$$

$$\pi_M^* = \frac{3(-1 + c)^2 k^2}{(1 + 2b + b^2 - 8k)^2} \tag{25}$$

$$\pi_M^* = \frac{(-1 + c)^2 k}{1 + 2b + b^2 - 8k} \tag{26}$$

Proposition 2: When M invests in 3DPT, the optimal wholesale price w_M^*, 3DPT investment e_M^*, retailer price p_M^*, variety R&D investment r_M^*, product demand d_M^*, retailer profit π_M^*, and manufacturer profit $\pi m*$ can be described by equations (20)–(26).

4.3 Retailer investment in 3DPT

When R invests in 3DPT, it can immediately promote product variety R&D and indirectly reduce raw material usage due to more precise product designs. As such, product variety R&D can be determined by $G(r_R) = (r_R - e_R)^2$. The unit production cost will be indirectly affected by 3DPT investment due to more precise product designs with the reduction in raw materials, which is $(c-\gamma e_R)$ (following Shi et al., 2020). In this scenario, M and R play a three-stage game. In stage 1, R simultaneously decides r_R and e_R. In stage 2, M determines w_R. In stage 3, R sets p_R.

Product demand is denoted by equation (3). Thus, the profit functions are as follows:

$$\pi_R^m \left[w_R - (c - \gamma e_R) - r_R\right](1 - p_R + r_R + \gamma b e_R) \tag{27}$$

$$\pi_R^r = \left({}_{rR} - w_R\right)(1 - p_R + r_R + \gamma b e_R) - k e_R^2 \tag{28}$$

Similarly, R decides optimal p_R to maximise its profit. Solving $\frac{\partial \pi_R^r}{\partial p_R} = 0$ yields

$$p_R\left(w_R, r_R, e_R\right) = \frac{1 + r_R + w_R + b e_R \gamma}{2} \tag{29}$$

Then, $\frac{\partial \pi_R^m\left(w_R, r_R, e_R\right)}{\partial w_R} = 0$ is solved to obtain the following:

$$w_R\left(r_R, e_R\right) = \frac{1 + c + 2r_R - e_R\gamma + b e_R \gamma}{2} \tag{30}$$

Substituting equations (29) and (30) into equation (28), $\frac{\partial \pi_R^r}{\partial p_R} = 0$ and $\frac{\partial \pi_R^r\left(r_R, e_R\right)}{\partial e_R} = 0$ are solved to yield the following:

$$e_R^* = \frac{(1+b)(-1+c)\gamma}{-16k + (1+b)^2\gamma^2} \tag{31}$$

$$r_R^* = \frac{(1+b)(-1+c)\gamma}{-16k + (1+b)^2\gamma^2} \tag{32}$$

Consequently, the optimal solutions can be calculated as follows:

$$w_R^* = \frac{-8(1+c)k + (1+b)\gamma(-1+c+\gamma+bc\gamma)}{-16k + (1+b)^2\gamma^2} \tag{33}$$

$$p_R^* = \frac{-4(3+c)k + (1+b)\gamma(-1+c+\gamma+bc\gamma)}{-16k + (1+b)^2\gamma^2} \tag{34}$$

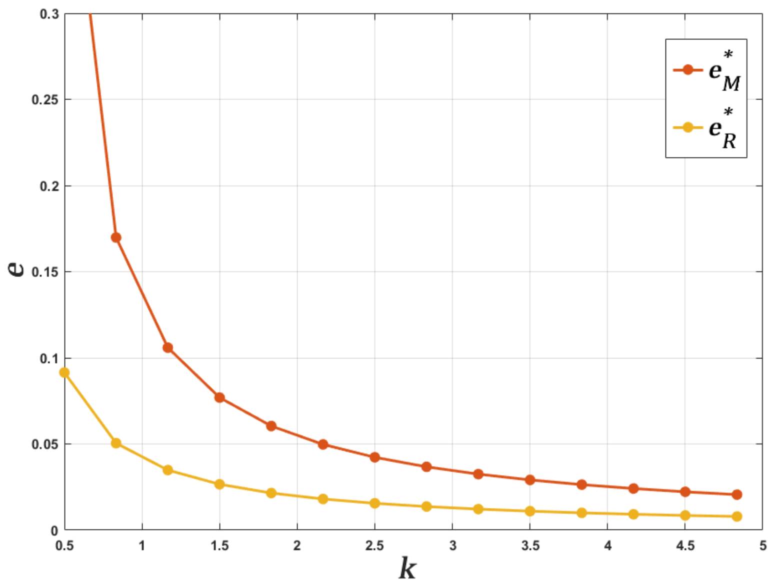
$$d_R^* = \frac{4(1-+c)k}{-16k+(1+b)^2\gamma^2} \tag{35}$$

$$\pi_R^{r*} = \frac{(-1+c)^2 k^2}{\left(-16k+(1+b)^2\gamma^2\right)^2} \tag{36}$$

$$\pi_R^{m*} = \frac{32(-1+c)^2 k^2}{\left(-16k+(1+b)^2\gamma^2\right)^2} \tag{37}$$

Proposition 3: When R invests in 3DPT, the optimal wholesale price w_R^*, 3DPT investment e_R^*, retailer price p_R^*, variety R&D investment r_R^*, product demand d_R^*, retailer profit π_R^*, and manufacturer profit π_R^{m*} can be described by equations (31)–(37).

Figure 1 Impact of k on the optimal 3DPT investment decisions (see online version for colours)



Note: setting default parameter values: $b = 0.5$, $c = 0.5$, $k \in [0.5, 5]$ and $\gamma = 0.8$.

5 Model analysis

5.1 Impact of cost coefficient on optimal decisions

Proposition 4: Under the manufacturer-investment scenario, the impacts of k on the optimal decisions are as follows:

1 $\frac{\partial e_M^*}{\partial k} < 0$

2 $\frac{\partial r_M^*}{\partial k} < 0$

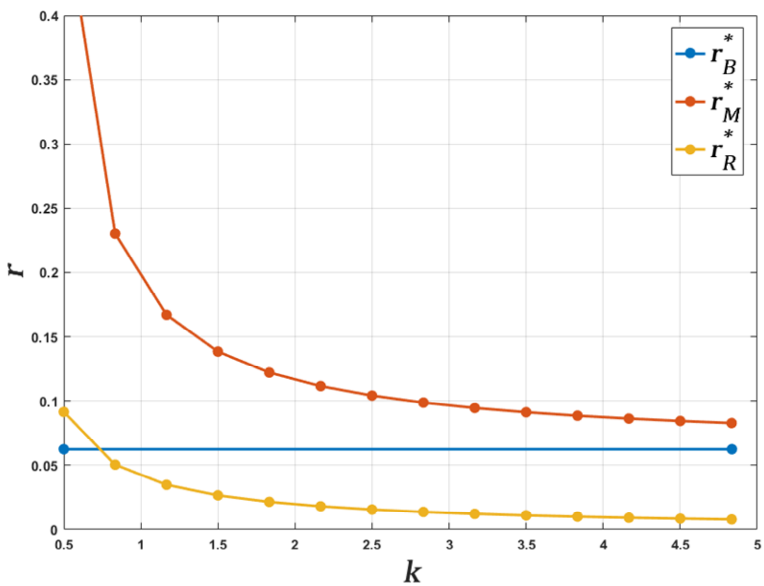
3 If $\max\left\{\frac{1}{8}(3-5b),0\right\} \le \gamma < 1$, then $\partial \frac{\partial w_M^*}{\partial k} \le 0$; otherwise, $\frac{\partial w_M^*}{\partial k} > 0$;

4 If $\max\left\{\frac{1}{8}(1 - 7b),0\right\} \le \gamma < 1$, then $\frac{\partial p_M^*}{\partial k} \le 0$; otherwise, $\frac{\partial p_M^*}{\partial k} > 0$.

Proposition 4 analyses the impacts of k on the optimal decisions under the manufacturer-investment scenario. This is illustrated in Figures 1–4. According to proposition 4(1) and Figure 1, it is suggested that the 3DPT investment motivation decreases with k. This conclusion is similar to those of Shi et al. (2019) and Li et al. (2021) and implies that the impact of CC is the same as that of common LCT, as a higher CC will lead to higher investment costs, which restrains the enthusiasm for investment.

As mentioned in Proposition 4(2) and Figure 2, the product variety R&D investment is decreasing in k. Though investing in 3DPT can reduce retailers' product variety R&D cost (e.g., design cost), the 3DPT investment motivation decreases with k according to proposition 4(1), and a higher k results in lower product variety R&D investment.

Figure 2 Impact of k on the optimal product variety R&D decisions (see online version for colours)

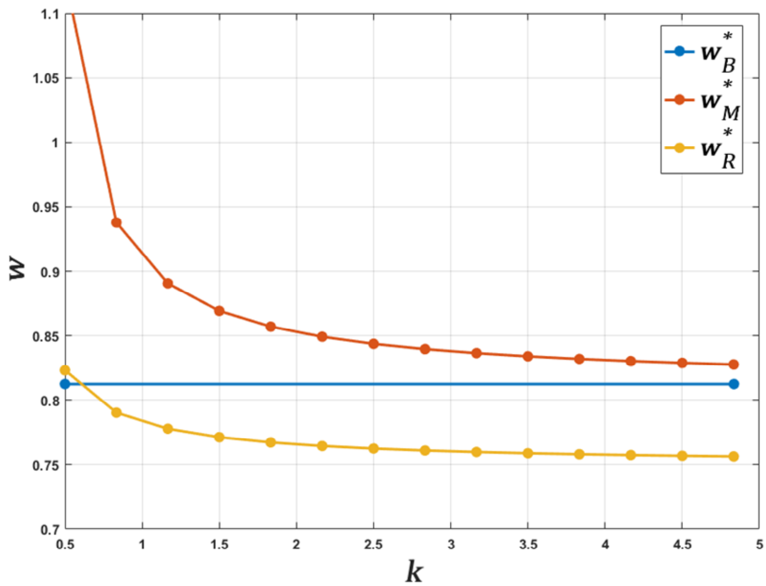


Note: Setting default parameter values: $b = 0.5$, $c = 0.5$, $k \in [0.5, 5]$ and $\gamma = 0.8$.

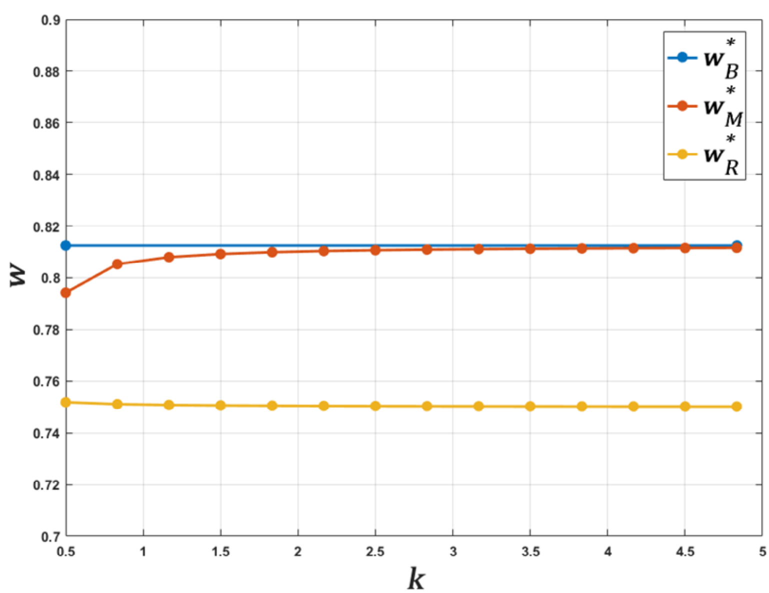
Considering the wholesale and retail prices, Propositions 4(3) and 4(4) show that as the indirect effects γ become significant (e.g., Figs. 3(a) and 4(a)), the prices decrease in k, and when γ becomes sufficiently low (e.g., Figs. 3(b) and 4(b)), the prices increase in k. The results differ from those of Ghosh and Shah (2012) and Shi et al. (2019), who demonstrated that wholesale and retail prices decrease according to k. This is mainly because 3DPT investment can decrease raw material consumption and product variety

R&D cost. This characteristic connects 3DPT investment with the unit production cost, which directly affects the wholesale price decision and links with the retailer product variety R&D cost, which can significantly influence the retail price decision. Facing increases in k, the manufacturer invests less.

Figure 3 Impact of k on the optimal wholesale price decisions (a) setting default parameter values: $b = 0.5$, $c = 0.5$, $k \in [0.5,5]$, and $\gamma = 0.8$ (b) setting default parameter values: $b = 0.5$, $c = 0.5$, $k \in [0.5,5]$, and $\gamma = 0.02$ (see online version for colours)

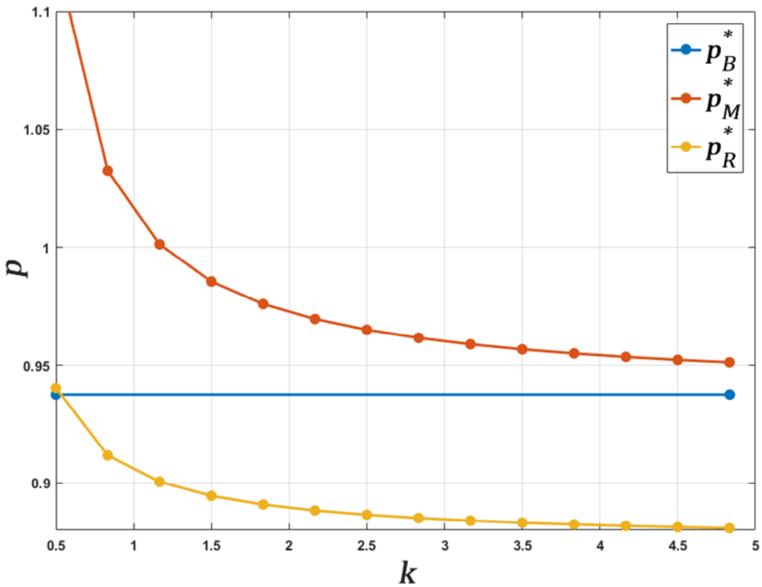


(a)

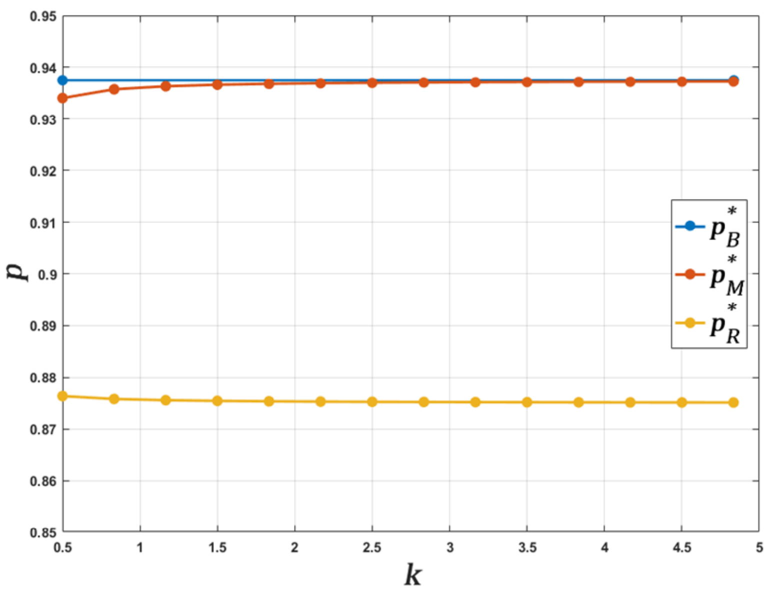


(b)

Figure 4 Impact of k on the optimal retail price decisions (a) setting default parameter values: $b = 0.1$, $c = 0.5$, $k \in [0.5, 5]$, and $\gamma = 0.98$ (b) setting default parameter values: $b = 0.1$, $c = 0.5$, $k \in [0.5, 5]$, and $\gamma = 0.02$ (see online version for colours)



(a)



(b)

When γ is relatively high, the impact of k on γe is strong. A lower k can promote 3DPT investment, markedly decrease the retailer product variety R&D cost, and significantly increase product demand; therefore, the manufacturer and retailer effectively compensate for the revenue lost in 3DPT investment by raising prices.

However, when γ is low, the impact of k on γe is small. It decreases the retailer product variety R&D cost and increases product demands, which are not dramatic. Thus, it is unnecessary to increase the wholesale prices and retail prices to gain more revenue. The above points imply that the characteristics of 3DPT change the impacts of the manufacturer's LCT investment on product prices.

Proposition 5: Under the retailer-investment scenario, the impact of k on the optimal decisions is as follows: $\frac{\partial e_R^*}{\partial k} < 0; \frac{\partial r_R^*}{\partial k} < 0; \frac{\partial w_R^*}{\partial k} < 0; \frac{\partial p_R^*}{\partial k} < 0.$

Proposition 5 concentrates on the impact of k on the optimal decisions when the retailer invests. Similarly, it is straightforward to see that Proposition 5 and Figs. 1 and 2 show that when k becomes small, the retailer will invest more in 3DPT and product variety R&D. These results are not different from Proposition 4(1) and 4(2). Intuitively, k has negative effects on the supply chain's level of LCT investment and reduction of product variety R&D cost. However, Proposition 5 highlights that both wholesale and retail prices rise when k decreases (Figures 3 and 4), and these results differ from Propositions 4(3) and 4(4). This argument is unlike that of Shi et al. (2019), who demonstrated that wholesale prices rise when k increases and properties of retail prices on k depend on the sensitivity coefficient of 3DPT investment.

5.2 Comparison of the three scenarios

Proposition 6: Comparing the optimal wholesale prices among the three scenarios yields the following outcomes:

1 If $\gamma \le \max\left\{\frac{1}{8}(3-5b), 0\right\}$, then $w_M^* \le w_B^*$. Otherwise, $w_M^* > w_B^*$;

2 If $k \le \max\left\{\frac{1}{2}, \breve{k}_R\right\}$, then $w_R^* \le w_B^*$, and if $k > \max\left\{\frac{1}{2}, \breve{k}_R\right\}$, then $w_R^* > w_B^*$;

3 $w_M^* > w_R^*$;

where $\breve{k}_R = \frac{8\gamma + 8b\gamma - 3\gamma^2 + 2b\gamma^2 + 5b^2\gamma^2}{16}$.

Proposition 6 compares the optimal wholesale prices among the three scenarios and indicates that investment in 3DPT may inhibit increases in optimal wholesale prices and result in lower optimal wholesale prices. This is achieved by improving manufacturing and product variety R&D efficiency under the retailer-investment scenario and reducing the indirect effect between retailers and manufacturers under the manufacturer-investment scenario.

Referring to Proposition 6(1), when the indirect effect is sufficiently low (i.e., $\gamma \le \max\left\{\frac{1}{8}(3-5b), 0\right\}$, Figure 3(a)), a higher cost of variety R&D investment $(r_M - \gamma e_M)^2$ decreases the attractiveness of the products and the manufacturer to consumers. Then, the retailer cannot choose higher optimal retail prices, which immediately leads the manufacturer not to choose a higher optimal wholesale price. Therefore, w_M^* is lower than w_B^*. On the contrary, when γ is high, products are more attractive to consumers. Therefore, M can set high wholesale prices.

Similarly, when k is low (i.e., $k \le \max\left\{\frac{1}{2}, \breve{k}_R\right\}$, Figure 3(a)), M and R can benefit more from the high-cost reduction e and cover the 3DPT investment cost. Therefore, w_R^*, is lower than w_B^*. In contrast, when k is high, it is not profitable for e to cover the cost of the 3DPT investment. This result differs from Shi et al. (2019) and Dong et al.'s (2019) findings, demonstrating that the optimal wholesale price is higher in the manufacturer-investment scenario than in the benchmark scenario due to the investment cost in LCT. This difference is caused by the indirect effect of the variety R&D investments on cost.

Furthermore, it is straightforward that w_M^* is higher than w_R^*, as the manufacturer undertakes the investment by itself and needs to increase the wholesale price to compensate for the expenditure.

Proposition 7: Comparing the optimal retail prices among the three scenarios yields the following outcomes:

1 If $\gamma > \max\left\{\frac{1}{8}(1-7b), 0\right\}$, $p_M^* > p_B^*$. Otherwise, $p_M^* \le p_B^*$;

2 If $k \le \max\left\{\frac{1}{2}, \hat{k}_R\right\}$, then $p_R^* \ge p_B^*$; otherwise, $p_R^* < p_B^*$;

3 $p_M^* > p_R^*$;

where $\hat{k}_R = \dfrac{8\gamma + 8b\gamma - \gamma^2 + 6b\gamma^2 + 7b^2\gamma^2}{16}$.16

Proposition 7 shows the relationships between the optimal retail prices among the three scenarios. As suggested by Proposition 7(1), the retailer always increases the retail price when γ is sufficiently high in the manufacturer investing scenario. Combined with Proposition 6(1), a higher γ value brings a larger $w*$ value, leading M to invest more in 3DPT and R to invest more in product variety R&D. This can dramatically increase consumer demand. Further, the demand increase might lead retailers to raise retail prices and cover the decrease in wholesale prices.

Proposition 7(2) implies that R prefers to decrease the retail price in the retailer investing scenario when k is relatively high (refer to Figure 4(a)). Combined with Proposition 6(2), a higher k value leads to a higher wholesale price compared to the benchmark situation (i.e., Figure 3(a)). Counterintuitively, the retailer sets a lower retail price. The retailer chooses to decrease the retail price to compensate for negative effects because higher k results in lower 3DPT and product variety R&D investment, leading to a negative impact on consumer demand. In reality, some products where the manufacturer invests – such as Shapeways' 3D-printed jewelry products – are more expensive than standard products[7]. In contrast, some products where the retailer invests to promote product R&D – such as Instalimb's prosthetic legs – may become more affordable than traditional products[8].

In addition, referring to Proposition 7(3), the optimal retail price in the manufacturer-investment scenario is greater than that in the retailer-investment scenario. This is similar to Dong et al. (2019), but unlike Shi et al. (2019). Considering the results in Proposition 6(3) that w_M^* is higher than w_R^*, and Proposition 7(2) that R has incentives to reduce the retail price under the retailer investing case, it is straightforward that $p_M^* > p_R^*$.

Proposition 8: Comparing the optimal product variety R&D investment decisions among the three scenarios yields the following outcomes:

1 $r_M^* > r_B^*$;

2 If $k \geq \max\left\{\frac{1}{2}, \overline{k}_R\right\}$, then $r_R^* \leq r_B^*$. Otherwise, $r_R^* > r_B^*$;

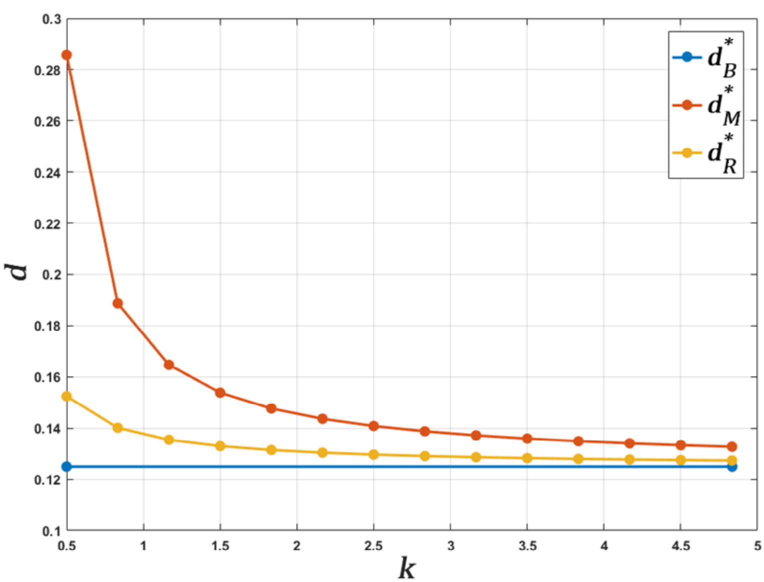
3 $r_M^* > r_R^*$;

where $\overline{k}_R = \dfrac{8\gamma + 8b\gamma + \gamma^2 + 2b\gamma^2 + b^2\gamma^2}{16}$.

Proposition 8 compares the optimal product variety R&D investment decisions among the three scenarios and highlights that retailers will invest more in product variety R&D when manufacturers invest in 3DPT. Further, retailers invest in 3DPT which may not contribute to product variety R&D investment (Figure 2). From retailers' perspectives, it is not affordable for retailers to invest in product variety R&D as well as 3DPT. Moreover, for the retailer investing scenario, the optimal R&D investment is equal to the 3DPT investment, which implies that the R&D investment completely depends on the 3DPT investment.

Proposition 9: Comparing the optimal product demands among the three scenarios yields the following outcome: $d_M^* > d_R^* > d_B^*$.

Figure 5 Comparison of optimal product demands and impacts of *k* (see online version for colours)

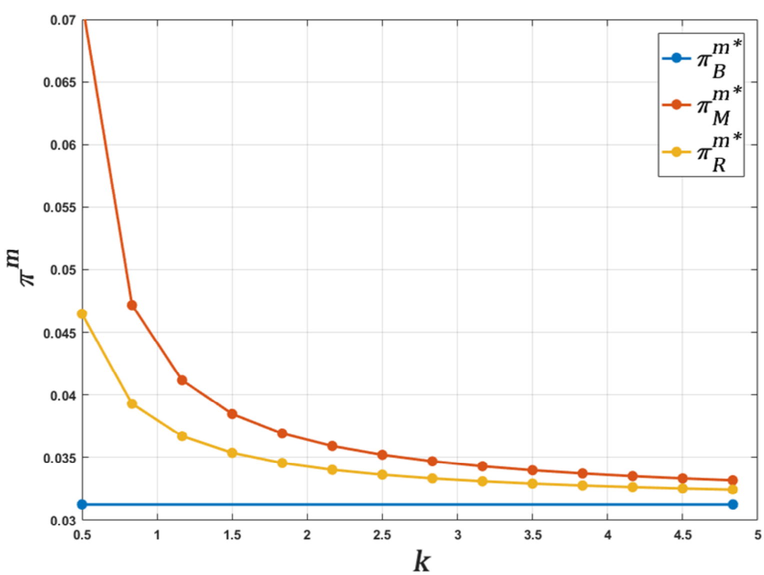


Note: setting default parameter values: $b = 0.5$, $c = 0.5$, $k \in [0.5, 5]$, and $\gamma = 0.8$.

Proposition 9 highlights the relationships between the optimal product demands in the three scenarios. It is clear from Figure 4 that investing in 3DPT promotes consumer willingness to purchase products through a low-carbon manufacturing process. Further, product variety R&D cost reduction means those products will be more abundant and desirable. Thus, investing in 3DPT can increase consumer demand, where $\{d_M^*, d_R^*\} > d_B^*$. Then, the optimal product demand in the retailer-investment scenario is lower than that in the manufacturer-investment scenario. This is because the manufacturer investing in 3DPT can more immediately induce consumer purchasing compared to the retailer-investment case. This finding is similar to the conclusion of Dong et al. (2019) but differs from Shi et al. (2019). Shi et al. (2019) concluded that, in the retailer-investment scenario, the product will always attract more consumers; however, Dong et al. (2019) state the opposite. This is because the retailer's implementation of 3DPT is less affordable than the manufacturer in a Stackelberg model according to Proposition 12 (i.e., $e_M^* > e_R^*$), and the retailer invests more in product variety R&D combined with the conclusion of Proposition 8 (i.e., $r_M^* > r_R^*$). Finally, $r_M^* > r_R^*$ as well as $e_M^* > e_R^*$ can be conducive to $d_M^* > d_R^*$ immediately. Thus, the character of 3DPT as a low-carbon emission approach appears to have a similar effect of savings on the manufacturer's environmental tax, as suggested by Dong et al. (2019).

Proposition 10: Comparing the optimal manufacturer profits among the three scenarios yields the following structure: $\pi_M^* > \pi_R^* > \pi_B^*$.

Figure 6 Comparison of the optimal manufacturer's profits and impacts of *k* (see online version for colours)



Note: setting default parameter values: $b = 0.5$, $c = 0.5$, $k \in [0.5, 5]$, and $\gamma = 0.8$.

Proposition 10 indicates that the manufacturer profits when the supply chain invests in 3DPT. Investing in 3DPT promotes consumer willingness to purchase products due to variety and low-carbon emissions. Compared to traditional technology, 3DPT reduces raw material usage from which the manufacturer can benefit. Further, 3DPT brings a higher profit margin, where $w_M^* - (c - e_M^*) - r_M^* > w_R^*(c - e_R^*) - r_R^* > w_B^* c - r_B^*$, although there may be a decline in the optimal wholesale price according to Proposition 6. Meanwhile, Proposition 9 states that $d_M^* > d_R^* > d_B^*$. Thus, the manufacturer can derive greater revenue from selling products to the retailer, where $\pi_M^{m*} > \pi_R^{m*} > \pi_B^{m*}$. It is implied that manufacturers are always willing to lead supply chains in investing in 3DPT to achieve low-carbon transformation. This conclusion can be drawn from Figure 6.

Proposition 11: Comparing the optimal retailer profits in the three scenarios yields the following structures:

1 $\pi_M^{r*} > \pi_B^{r*}$

2 $\pi_R^{r*} > \pi_B^{r*}$

3 If $k \geq \bar{k}$, then $\pi_M^{r*} \leq \pi_R^{r*}$; otherwise, $\pi_M^{r*} > \pi_R^{r*}$.

where $\bar{k} = \dfrac{(1+b)^2\left(16 - 3\gamma^2 + \sqrt{192 - 96\gamma^2 + 9\gamma^4}\right)}{32}$.

Proposition 11 considers the analysis of the optimal retailer profits among the three scenarios. Further, the results of Proposition 11(1) demonstrate that it is beneficial for R when the supply chain adopts 3DPT. As in the case of Proposition 10, by investing in 3DPT, R could obtain higher margins, where $p_M^* - w_M^* > p_B^* - w_B^*$. Meanwhile, $d_M^* > d_B^*$. Hence, retailers could increase their profits.

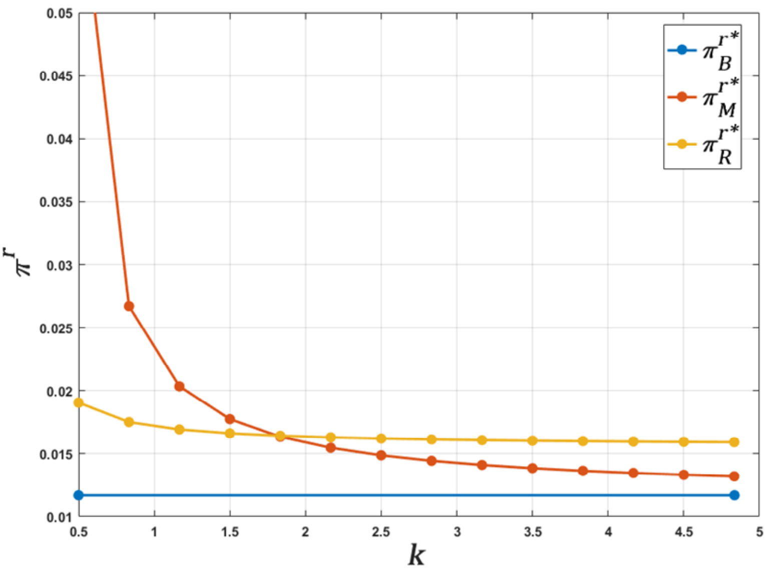
Proposition 11(2) demonstrates that the retailer's investment in 3DPT can increase its profits, where $\pi_R^{r*} > \pi_B^{r*}$. Combined with Proposition 10, it is suggested that both the manufacturer and retailer gain more by implementing 3DPT, as extra-economic returns can cover the expenditure of the investment. 3DPT brings a greater profit margin; where $p_R^* - w_R^* > p_B^{r*} - w_B^*$, and it promotes consumer willingness to purchase. This implies that 3DPT is a more suitable method for firms to conduct industrial low-carbon upgrades compared with conventional LCT.

Except for the above and differing from the optimal manufacturer profits, whether the optimal retailer profit in the retailer-investment scenario is greater than that in the manufacturer-investment scenario depends on *k*. Counterintuitively, when 3DPT is not affordable, where $k \geq k$, the retailer prefers to increase profits by investing in 3DPT. On the contrary, the optimal retailer profit can increase in the manufacturer- investment scenario. The optimal retailer profit in the retailer-investment scenario is higher, which can be concluded from Figure 7. This conclusion differs from the opinions of Shi et al. (2019) and Chen et al. (2021). As such, retailers' willingness to lead supply chains in investing in 3DPT to achieve low-carbon transformation depends on *k* as well, and interestingly, when *k* is high, retailers will display this.

Proposition 12: Comparing the optimal 3DPT investment decisions between the two investing scenarios yields $e_M^* > e_R^*$.

Proposition 12 compares the two 3DPT investment decisions of the two investing scenarios and demonstrates that $e_M^* > e_R^*$. This result is also shown in Figure 1. More specifically, the manufacturer can directly benefit from decreases in the unit production cost. Meanwhile, the manufacturer can transfer their investment expenditure to the retailer via the wholesale price. This means that the manufacturer can bear a larger CC of 3DPT investment. It was mentioned before that investing in 3DPT can increase consumers' willingness to purchase and attract more consumers to do so.

Figure 7 Comparison of optimal retailer profits and impact of *k* (see online version for colours)



Note: Setting default parameter values: $b = 0.5$, $c = 0.5$, $k \in [0.5, 5]$, and $\gamma = 0.8$.

6 Extension

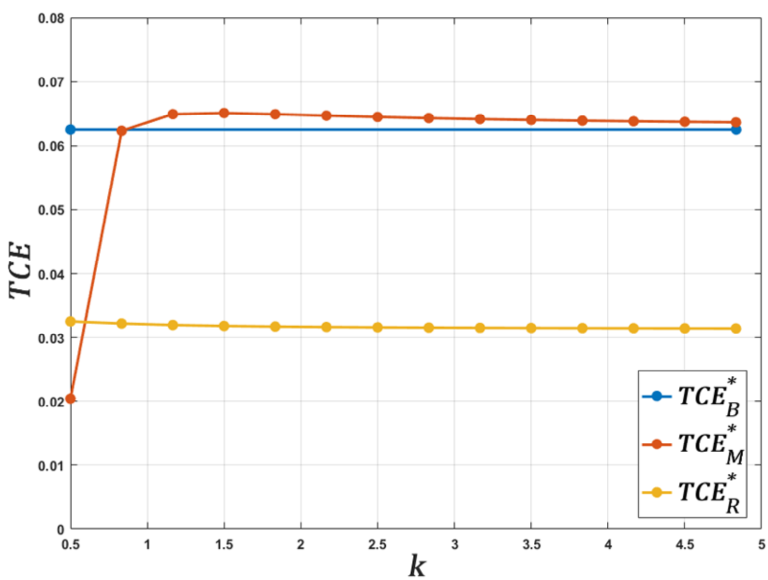
6.1 Environmental impact

This study assumed the unit carbon emission to be E without the adoption of 3DPT to investigate how 3DPT reduces carbon emissions in supply chains. Unit carbon emissions with the adoption of 3DPT are $\frac{(c - e_M^*)}{c}E = \left(1 - \frac{(1+b)(-1+c)}{c(1+2b+b^2-8k)}\right)E$ and $\frac{(c - \gamma e_R^*)}{c}E = 1 - \frac{(1+b)(-1+c)\gamma^2}{c(16k-(1+b)^2\gamma^2)}$. Hence, comparing the three total carbon emissions derives the following proposition.

Proposition 13: Comparing the optimal unit carbon emissions among the three scenarios yields the following: $\frac{(c - e_M^*)}{c}E < \frac{(c - \gamma e_R^*)}{c}E < E$.

Proposition 13 reveals retailers' and manufacturers' implementations of 3DPT can reduce unit carbon emissions. It is implied that 3DPT can increase consumers' willingness to purchase products, as well as attract more consumers and decrease unit carbon emissions due to its environmentally friendly characteristics. Combining the conclusions in Proposition 10 and Proposition 11 for low-carbon manufacturing supply chains demonstrates that 3DPT is a potentially efficient approach to realising enterprises' duty of green transformation while maximising profits. Further, following Proposition 12, the optimal 3DPT investment decisions between the two investing scenarios satisfy $e_M^* > e_R^*$, and considering the indirect effect γ, $e_M^* > \gamma e_R^*$ always holds. This result means that manufacturers can obtain greater savings on unit carbon emissions by investing in 3DPT by themselves. This conclusion is similar to Dong et al. (2019) but different from Shi et al. (2019). To further examine how 3DPT impacts the environment, this study calculated the total carbon emissions (*TCE*) in three scenarios and obtained the following: $TCE_B^* = E * d_B^* = \frac{(-1+c)}{-4}E$, $TCE_M^* \frac{(c - e_M^*)}{c} E * d_M^* = \frac{2(-1+c)k(1+b+bc+b^2c-8ck)}{c(1+2b+b^2-8k)^2}E$, and $TCE_R^* = \frac{(c-\gamma e_R^*)}{c} E * d_R^* =$, $\frac{4(1-c)k\left(16ck-(1+b)\gamma^2-b(1+b)c\gamma^2\right)}{c\left(-16k+(1+b)^2\gamma^2\right)^2}$, respectively. Hence, this study compares these total carbon emissions in Figure 8.

Figure 8 Comparison of the optimal total carbon emissions (see online version for colours)



Note: setting default parameter values: $b = 0.5$, $c = 0.5$, $k \in [0.5, 5]$, $\gamma = 0.8$ and $E = 0.5$.

According to Figure 8, when k is sufficiently low, the optimal total carbon emissions among the three scenarios satisfy $TCE_M^* < TCE_R^* < TCE_B^*$. With increases of k, TCE_M^* rises dramatically, and when k is moderate, $TCE_R^* < TCE_M^* < TCE_B^*$. When k is sufficiently strong, TCE_M^* exceeds TCE_B^*, and thus the optimal total carbon emissions among the three scenarios satisfy $TCE_R^* < TCE_B^* < TCE_M^*$. More specifically, the total carbon emissions in the retailer-investment scenario, TCE_R^*, will always be lower than the emissions under the benchmark scenario. Therefore, retailers investing in 3DPT promote decreased unit carbon emissions and total carbon emission reduction. Further, the total carbon emission in the manufacturer-investment scenario, TCE_M^*, was lowest when *k* was sufficiently small. Therefore, manufacturers' adoption of 3DPT might result in lower total carbon emissions as the investment could immediately reduce unit carbon emissions (Proposition 13). However, with increases in *k*, manufacturers have fewer motivations to invest in 3DPT to reduce unit carbon emissions, causing TCE_M^* to rapidly increase. Notably, the optimal product demand in the manufacturer-investment scenario, d_M^*, is much higher than d_B^* (Proposition 6). Further, it causes TCE_M^* to be slightly larger than TCE_B^* when *k* is sufficiently high, whereas the unit carbon emission in the manufacturer-investment scenario is lower than in the benchmark scenario, namely $\frac{(c-e_M^*)}{c}E < E.$ Counterintuitively, the trend of TCE_M^* with respect to *k* is converse to the trend of d_M^*. This finding may be because e_M^* also decreases along with *k*, leading to increases in $\frac{(c-e_M^*)}{c}E.$ It is suggested that the government needs to offer subsidies or publish policies to support manufacturers' investments in 3DPT to avoid lower e_M^* and less environmental damage, namely $TCE_M^* < TCE_B^*$, when *k* is sufficiently large.

6.2 Different indirect effects

In this section, this study assumes there are two different indirect effects between the manufacturers and retailers (i.e., γ_1), implying the indirect impact of M's 3DPT investment on R's R&D investment cost. Meanwhile, γ_2 reflects the indirect impact of R's 3D technology investment on M's production cost. Some results are comparable to others, such as in Proposition 4 and Proposition 5. However, some dissimilar conclusions arise when the study further assumes that $\gamma_1 \neq \gamma_2$. Specifically, after substituting (γ_1, γ_2) into equation (20), equations (22)–(23), and equations (32)–(34), the following proposition emerges:

Proposition 14: By comparing the optimal solution to two investment scenarios, the following properties are observed:

1 If $k \le \max\left\{\dot{k}(\gamma_1,\gamma_2),\frac{1}{2}\right\}$, $w_M^*(\gamma_1) - w_R^*(\gamma_2) \le 0,$ and otherwise, $w_M^*(\gamma_1) - w_R^*(\gamma_2) > 0$

2 If $k \le \max\left\{\overline{k}(\gamma_1,\gamma_2),\frac{1}{2}\right\}$, $p_M^*(\gamma_1) - p_R^*(\gamma_2) \le 0,$ and otherwise, $p_M^*(\gamma_1) - p_R^*(\gamma_2) > 0$

3 $r_M^*(\gamma_1) > r_R^*(\gamma_2).$

The results of Proposition 14(1) and Proposition 14(2) are not comparable to the results of Proposition 6(3) and Proposition 7(3), respectively. When *k* is low, w^* and p^* under the manufacturer-investment scenario can be lower than those under the retailer-investment scenario when considering the indirect effects (γ_1, γ_2). This is because γ_2 can directly affect consumers' demands (equation (3)), which causes γ_2 to make $\dot{k}(\gamma_1, \gamma_2)$ or $\bar{k}(\gamma_1, \gamma_2)$ higher than $\frac{1}{2}$. Thus, there exists an interval between $\frac{1}{2}$ and $\dot{k}(\gamma_1, \gamma_2)$ or $\bar{k}(\gamma_1, \gamma_2)$, keeping $w_M^*(\gamma_1) \leq w_R^*(\gamma_2)$ and $p_M^*(\gamma_1) \leq p_R^*(\gamma_2)$. Further, $r_M^*(\gamma_1) > r_R^*(\gamma_2)$ always remains the same due to Proposition 8(3). This conclusion confirms that retailers investing in 3DPT may not contribute to product variety R&D investments.

7 Conclusions and managerial insights

This paper studied strategic investments in 3DPT to reduce carbon emissions in a supply chain. It was considered that the manufacturer or retailer could decide to adopt 3DPT. To investigate investing motivations and differences in investment patterns, three cases were discussed:

1 no one adopts 3DPT

2 the manufacturer invests in 3DPT to carry out low-carbon transformation

3 the retailer implements 3DPT to promote carbon emissions reduction.

The optimal solutions of the manufacturer and retailer in the three cases were first derived, followed by exploring the impact of CC of 3DPT investment on the optimal decisions in cases 2) and 3). Furthermore, the optimal decisions in the three cases were compared to discuss how 3DPT investment affects manufacturer and retailer actions. Finally, the optimal profits of the manufacturer and retailer in the three cases were compared to study the differences in investment patterns. From both theoretical and practical perspectives, some managerial insights for enterprises considering investing in 3DPT were gained to achieve low-carbon transformation.

Theoretically, this research introduces some innovations in model setting and analysis. First, the characteristics of investing in 3DPT in terms of low-carbon performance were considered. Specifically, 3DPT can reduce carbon emissions by reducing raw material use manufacturing, and we further focus our research on how 3DPT impacts unit and total carbon emissions. Then, related parameters, such as unit production cost, were combined to analyse the differences from cases using conventional LCT mentioned in previous research. These theoretical managerial insights highlighted crucial points for further research into low-carbon transformation through 3DPT investment.

From a practical perspective, this study provides the following managerial implications for enterprises seeking to achieve low-carbon transformation:

1 Finding 1: As the adoption of 3DPT has advantages in controlling unit production costs and product variety R&D costs, manufacturers and retailers can benefit from investing in 3DPT. However, the manufacturer can benefit more from the investment. Further, when CC is high, the retailer can better increase its profits by investing in 3DPT.

Managerial implication 1 Many firms hesitate to implement 3DPT, and previous studies, such as Arbabian and Wagner (2020) and Arbabian (2022), demonstrate that retailers investing in 3DPT harms their profits. However, this study's findings imply that both manufacturers and retailers can benefit from 3DPT. A lower unit production cost directly contributes to the manufacturer's investment motivation. In other words, a manufacturer, such as B&J Specialty, might be willing to lead an investment in 3DPT if there is a sufficiently low unit production cost. In addition, 3DPT is conducive to the retailer's product variety R&D. Finally, it is also profitable for retailers – as in the cases of Nike, Decathlon, Vans, Giant Bicycle, and Dell – and they are willing to lead an investment in 3DPT even though there is a sufficiently high CC.

2 Finding 2: It is suggested that the optimal investment decreases with the CC of the 3DPT investment. Under the manufacturer-investment scenario, the CC of the 3DPT investment could have positive or negative impacts on wholesale and retail prices. Under the retailer-investment scenario, the CC of the 3DPT investment only decreases the optimal wholesale and retail prices.

Managerial implication 2 Intuitively, increased CC of investment can decrease a firm's motivation. Further, previous studies, such as Ghosh and Shah (2012) and Shi et al. (2019), demonstrated that wholesale and retail prices decrease according to the CCs of 3DPT investments. The findings of this study differ from others and imply that the characteristics of 3DPT allow a direct connection between the investment CC and the unit production cost. A firm with lower indirect effects between the manufacturer and retailer could increase prices to effectively compensate for the investment loss when manufacturers invest in 3DPT.

3 Finding 3: When the manufacturer invests in 3DPT, the optimal wholesale price can be lower than without the investment, with a sufficiently low indirect effect. Manufacturers investing in 3DPT can significantly increase optimal product variety R&D investments and unit carbon emission reduction. Although unit carbon emissions are lower, the total carbon emissions may rise when CC is high, as the investment in 3DPT can attract more consumers to purchase products. Interestingly, when the retailer invests in 3DPT, the optimal wholesale price is only larger than the one without the investment if the CC is sufficiently low. Further, a sufficiently high CC can lower optimal retail prices and product variety R&D investments. Although unit carbon emission reduction under the retailer-investment scenario is lower, the total carbon emissions are always less than those under the benchmark scenario. Finally, investing in 3DPT can increase product demand so that an investing manufacturer can sell more products.

Managerial implication 3 Previous findings, such as those of Shi et al. (2019) and Dong et al. (2019), stated that the optimal wholesale price in the manufacturer-investment scenario is higher than in the benchmark scenario due to the investment cost. However, this study's findings demonstrate that the optimal wholesale price may decline when the manufacturer invests in 3DPT. Therefore, manufacturers should implement 3DPT to achieve low-carbon transformation and derive a higher profit margin. Moreover, some products (such as Shapeways' 3DPT Jewelry products) can attract a higher retail price. Conversely, other products (such as Instalimb's prosthetic legs) could become more affordable with 3DPT. The findings of this study show that charging a higher or lower retail price depends on who invests in 3DPT, the CC, and the indirect effects between manufacturers and retailers. Finally, both the investing scenarios can attract more consumers to purchase products and achieve less unit carbon emissions. Thus, via 3DPT, manufacturers are more motivated to achieve the goals of low-carbon transformation and assist the government's carbon neutrality proposal. Additionally, the results of unit carbon emissions are similar to Dong et al. (2019) but different from Shi et al. (2019).

Finally, the modelling developed in this study has some limitations that prompt further research. First, it did not consider a scenario where the manufacturer and retailer both invest in 3DPT. Future research may consider a model where both invest simultaneously. Furthermore, this paper did not consider the effects of a cost-sharing contract between the manufacturer and retailer. Such a model will be established in the future. Finally, it is assumed that the cost of changes in product lines in the manufacturer investment case do not differ from those in the retailer investment case. Investigating how such differences could affect the optimal solutions will be interesting.

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Appendix

Proof of Proposition 4: Under the scenario where M invests in 3DPT, according to equation (21), we can calculate

$$\frac{\partial e_M^*}{\partial k} = -\frac{8(1+b)(1-c)}{(1+2b+b^2-8k)^2} \tag{A1}$$

Obviously, $\frac{\partial e_M^*}{\partial k} < 0.$ According to equation (23), we can gain

$$\frac{\partial r_M^*}{\partial k} = -\frac{(1+b)(1-c)(1+b+8\gamma)}{(1+2b+b2-8k)^2} \tag{A2}$$

Thus, $\frac{\partial r_M^*}{\partial k} < 0.$ As for the impact of k on w_M^*, we derive

$$\frac{\partial w_M^*}{\partial k} = -\frac{(1+b)(1-c)(3+5b+8\gamma)}{(1+2b+b2-8k)^2} \tag{A3}$$

Due to $\partial\left(\frac{\partial w_M^*}{\partial k}\right)/\partial\gamma = -\frac{8(1+b)(1-c)}{(1+2b+b^2-8k)^2} < 0,$ we can deduce when $\max\left\{\frac{1}{8}(3-5b),0\right\} \le \gamma < 1,$ then $\frac{\partial w_M^*}{\partial k} \le 0,$ otherwise, $\frac{\partial w_M^*}{\partial k} > 0$

Finally, according to equation (22), we can get

$$\frac{\partial p_M^*}{\partial k} = \frac{(1+b)(1-c)(1-7b-8\gamma)}{(1+2b+b^2-8k)^2} \tag{A4}$$

Similar to the proof of $\frac{\partial w_M^*}{\partial k},$ we can deduce when $\max\left\{\frac{1}{8}(1-7b),0\right\} \le \gamma < 1,$ then $\frac{\partial p_M^*}{\partial k} \le 0;$ otherwise, $\frac{\partial p_M^*}{\partial k} > 0.$

Proof of Proposition 5: Under the scenario where R invests in 3DPT, according to equations (31)–(34), we can calculate

$$\frac{\partial e_R^*}{\partial k} = \frac{16(1+b)(1-c)\gamma}{(-16k+(1+b)^2\gamma^2)^2} \tag{A5}$$

$$\frac{\partial r_R^*}{\partial k} = \frac{16(1+b)(1-c)\gamma}{(-16k+(1+b)^2\gamma^2)^2} \tag{A6}$$

$$\frac{\partial w_R^*}{\partial k} = \frac{8(1+b)(1-c)\gamma(2+(1+b)\gamma)}{(-16k+(1+b)^2\gamma^2)^2} \tag{A7}$$

and

$$\frac{\partial p_R^*}{\partial k} = \frac{4(1+b)(1-c)\gamma(4+(1+3b)\gamma)}{(-16k+(1+b)^2\gamma^2)^2} \tag{A8}$$

It is straightforward that $\frac{\partial e_R^*}{\partial k} < 0, \frac{\partial r_R^*}{\partial k} < 0, \frac{\partial w_R^*}{\partial k} < 0,$ and $\frac{\partial p_R^*}{\partial k} < 0.$

Proof of Proposition 6: To compare optimal wholesale prices among three scenarios, we first calculate

$$w_M^* - w_B^* = \frac{(1+b)(-1+c)(-3+5b+8\gamma)}{8((1+b)^2-8k} \tag{A9}$$

$$w_R^* - w_B^* = \frac{(1+c)(16k-(1+b)\gamma(-3+5b)\gamma))}{8(-16k+(1+b)^2\gamma^2)} \tag{A10}$$

and

$$w_M^* - w_R^* = \frac{(1+c)(16k^2-(1+b)^3\gamma(1-\gamma^2)-(1+b)k\left(8-8\gamma-3\gamma^2-b\left(8-5\gamma^2\right)\right)}{(1+2b+b^2-8k)((1+b)^2\gamma^2-16k)} \tag{A11}$$

Obviously, $w_M^* - w_R^* > 0.$ As for $w_M^* - w_B^*,$ similar to the proof of proposition 4, we have $w_M^* - w_B^* \le 0$ when $\gamma \le \max\left\{\frac{1}{8}(3-5b), 0\right\}$ and $w_M^* - w_B^* > 0$ when $\gamma > \max\left\{\frac{1}{8}(3-5b), 0\right\}$. Moreover, we can easily derive $w_R^* \le w_B^*$ with $k \le \max\left\{\frac{1}{2}, \breve{k}_R\right\}$, and $w_R^* > w_B^*$ with $k > \max \ge \left\{\frac{1}{2}, \breve{k}_R\right\}$, where $\breve{k}_R = \frac{8\gamma+8b\gamma-3\gamma^2+2b\gamma^2+5b^2\gamma^2}{16}$.

Proof of Proposition 7: Similar to the proof of proposition 6, we first calculate

$$p_M^* = p_B^* = \frac{(1+b)(1-c)(1-7b-8\gamma)}{8(1+2b+b^2-8k)} \tag{A12}$$

$$p_R^* = p_B^* = \frac{(1-c)(16k-(1+b)\gamma(8+(-1+7b)\gamma))}{8(-16k+(1+b)^2\gamma^2)} \tag{A13}$$

$$p_M^* = p_R^* = \frac{(1-c)(16k^2-(1+b)^3\gamma(1+b)k(4-8\gamma-\gamma^2-b)(12-7\gamma^2)))}{(1+2b+b^2-8\gamma)(-16k+(1+b)^2\gamma^2)} \tag{A14}$$

Obviously, $p_M^* - p_R^* > 0$. Further, $p_M^* - p_B^* > 0$ with $\gamma > \max\left\{\frac{1}{8}(1-7b), 0\right\}$ and $p_M^* - p_B^* \le 0$ with $\gamma \le \max\left\{\frac{1}{8}(1-7b), 0\right\}$. Then, from $p_R^* - p_B^* \ge 0$, we have $k \le \max\left\{\frac{1}{2}, \hat{k}_R\right\}$ because $\frac{\partial\left(p_R^* - p_B^*\right)}{\partial k} = \frac{4(1+b)(-1+c)\gamma(4+(-1+3b)\gamma)}{(-16k+(1+b)^2\gamma^2)^2} < 0$, where $\hat{k}_R = \frac{8\gamma+8b\gamma-\gamma^2+6b\gamma^2-7b^2\gamma^2}{16}$.

Proof of Proposition 8: Similar to the previous proofs, we first calculate

$$r_M^* - r_B^* = \frac{(1+b)(1-c)(1+b+8\gamma)}{8\left(8k-\left(1+2b+b^2\right)\right)} \tag{A14}$$

$$r_R^* - r_B^* = \frac{(1-cb)(16k-(1+b)\gamma(8+\gamma+b\gamma))}{8(16k-\left(1+b\right)^2\gamma^2)} \tag{A15}$$

and

$$r_M^* - r_R^* = \frac{(1-c)\left(16k^2-(1+b)k\gamma(8-\gamma-b\gamma)+(1+b)^3\gamma(1-\gamma^2)\right)}{((1+b)^2-8k)(-16k+\left(1+b\right)^2\gamma^2)} \tag{A16}$$

Obviously, $r_M^* - r_B^* > 0$ and $r_M^* - r_R^* > 0$. Secondly, from $r_R^* - r_B^* \le 0$, we derive $k \ge \max\left\{\frac{1}{2}, \bar{k}_R\right\}$, where $\bar{k}_R = \frac{8\gamma+8b\gamma+\gamma^2+2b\gamma^2+b\gamma^2\gamma^2}{16}$.

Proof of Proposition 9: Similar to the previous proofs, we first calculate

$$d_R^* - d_B^* = \frac{(1+b)^2(1-c)}{4(8k-(1+b)^2)} \tag{A17}$$

and

$$d_M^* - d_R^* = \frac{(1+b)^2(1-c)\gamma^2}{4(16k-(1+b)^2\gamma^2)} \tag{A18}$$

Further, $d_R^* - d_B^* > 0$ and $d_M^* - d_R^* > 0$ obviously.

Proof of Proposition 10: Similar to the previous proofs, we first calculate

$$\pi_R^{m*} - \pi_B^{m*} = \frac{(1+b)^2(1+c)^2}{4(8k-(1+b)^2)} \tag{A19}$$

and

$$\pi_M^{m*} - \pi_R^{m*} = \frac{(1+b)^2(1+c)^2 k\left((1+b)^2\gamma^4+32k(1-\gamma)^2\right)}{(8k-(1+b)^2)\left(16k-(1+b)^2\gamma^2\right)^2} \tag{A20}$$

Further, $\pi_M^{m*} - \pi_B^{m*} > 0$ and $\pi_M^{m*} - \pi_R^{m*} > 0$ obviously.

Proof of Proposition 11: Similar to the previous proofs, we first calculate

$$\pi_M^{r*} - \pi_B^{r*} = \frac{3(1+b)^2(1+c)^2\left(16k-(1+b)^2\right)}{64-((1+b)-8k)^2} \tag{A21}$$

$$\pi_R^{r*} - \pi_B^{r*} = \frac{(-1+c)^2\left(16k+3(1+b)^2\gamma^2\right)}{1024k-64(1+b)^2\gamma^2} \tag{A22}$$

and

$$\pi_R^{r*} - \pi_B^{r*} = (-1+c)^2 k\left(\frac{3k}{((1+b)^2-8k)^2} + \frac{1}{-16k+(1+b)^2\gamma^2}\right) \quad \text{(A23)}$$

Obviously, $\pi_M^{r*} - \pi_B^{r*} > 0$ and $\pi_R^{r*} - \pi_B^{r*} > 0$. Secondly, from $\pi_M^{r*} - \pi_R^{r*} \le 0$, we obtain $k \ge \overline{k}$, where $\overline{k} = \frac{(1+b)^2\left(16-3\gamma^2+\sqrt{192-96\gamma^2+9\gamma^4}\right)}{32}$.

Proof of Proposition 12: Similar to the previous proofs, we first calculate

$$e_M^* - e_R^* = (1+b)(1-c)\left(\frac{1}{8k-(1+2b+b^2)} - \frac{\gamma}{16k-(1+b)^2\gamma^2}\right) \quad \text{(A24)}$$

and it is straightforward that $e_M^* - e_R^* > 0$.

Proof of Proposition 13: Similar to the previous proofs, we first calculate

$$\frac{c\left(\gamma e_R^*\right)}{c}E - E = -\frac{(1+b)(1-c)\gamma^2}{c(16k-(1+b)^2\gamma^2)} \quad \text{(A25)}$$

and

$$\frac{\left(ce_M^*\right)}{c}E - \frac{\left(c-\gamma e_R^*\right)}{c}E = -\frac{8(1+b)(1-c)k(2-\gamma^2)}{c(1+2b+b^2-8k)\left((1+b)^2\gamma^2-16k\right)} \quad \text{(A26)}$$

So, this implies that $\frac{\left(c-\gamma e_R^*\right)}{c}E - E < 0$ and $\frac{\left(c-e_M^*\right)}{c}E - \frac{\left(c-\gamma e_R^*\right)}{c}E < 0$.

Proof of Proposition 14: Similar to the previous proofs, we first calculate

(A27)

(A28)

and

$$w_M^*(\gamma_1) - w_R^*(\gamma_2) = \frac{(1-c)\begin{pmatrix}16k^2+(1+b)^3\gamma_2(1-\gamma_1\gamma_2) \\ -(1+b)k\left(8-16\gamma_1+8\gamma_2-3\gamma_2^2+b\left(-8+5\gamma_2^2\right)\right)\end{pmatrix}}{\left(8k-\left(1+2b+b^2\right)\right)\left(16k-(1+b)^2\gamma_2^2\right)} \quad \text{(A29)}$$

Then, from $w_M^*(\gamma_1) - w_R^*(\gamma_2) \le 0$, we have $k \le \max\left\{\dot{k}(\gamma_1,\gamma_2), \frac{1}{2}\right\}$ and otherwise, $w_M^*(\gamma_1) - w_R^*(\gamma_2) > 0$,

$$\ddot{k}(\gamma_1,\gamma_2) = \frac{1}{32}\left(8-16\gamma_1+8\gamma_2-3\gamma_2^2+b^2\right)\left(-8+5\gamma_2^2\right)+2b\left(-8\gamma_1+\gamma_2(4+\gamma_2)\right)$$

where $\sqrt{\left((1+b)^2\right)\left(64+256\gamma_1^2+64\gamma_2+16\gamma_2^2\right)}-48\gamma_2^3+9\gamma_2^4+b^2(8-5\gamma_2^2)^2+32\gamma_1$
$\left(-8-8\gamma_2+5\gamma_2^2\right)-2b^2\left(64+96\gamma_2-64\gamma_2^2-40\gamma_2^3+15\gamma_2^4+16\gamma_1\left(-8+3\gamma_2^2\right)\right)))\Big)$.

In addition, from $p_M^*(\gamma_1) - p_R^*(\gamma_2) \le 0$, we have $k \le \max\left\{\overline{k}(\gamma_1, \gamma_2), \frac{1}{2}\right\}$, where

$$\overline{k}(\gamma_1, \gamma_2) = \frac{1}{32}\left(4 - 16\gamma_1 + 8\gamma_2 - \gamma_2^2 + b\right) + \left(-8 - 16\gamma_1 + 8\gamma_2 + 6\gamma_2^2\right) + b^2\left(-12 + 7\gamma_2^2\right)$$
$$\sqrt{\left((1+b)^2\right)\left(16 + 256\gamma_1^2 + 56\gamma_2 + 16\gamma_2^2\right)} - \gamma_2^4 + b^2(12 - 7\gamma_2^2)^2 + 32\gamma_1$$
$$\left(-4 - 8\gamma_2 + 3\gamma_2^2\right) - 2b^2\left(48 + 128\gamma_2 - 40\gamma_2^2 - 56\gamma_2^3 + 7\gamma_2^4 + 16\gamma_1\left(-12 + 5\gamma_2^2\right))))\right).$$

Finally, $r_M^*(\gamma_1) - r_R^*(\gamma_2) > 0$ obviously.