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Interactions of traceability and reliability optimization in a competitive supply chain with product recall

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ABSTRACT

Traceability which is a tracking capability used to identify the sources of many quality problems, such as product recalls, has become an important feature of supply chains. In this paper, we develop a game-theoretical model to study the interactions of supply chain traceability and product reliability optimization in a competitive supply chain with product recall. Specifically, we consider two competing manufacturers that may choose to invest in traceability on the basis of product reliability optimization, by using the Non-track, Mono-track, and Duo-track models, and then sell products through two competing retailers to customers who are concerned with the differentiation of the product, the channel, and the traceability. We derive the optimal traceability and product reliability strategies under the three tracking models with endogenous pricing, and demonstrate the equilibrium tracking strategies for two competing manufacturers. The results show that traceability can fully substitute product reliability when the traceability investment cost coefficient is low but it may improve product reliability when the cost coefficient is high and the reliability investment cost coefficient is low. Investing in traceability will always benefit the manufacturer itself, and may benefit the competitor who does not track when the traceability investment cost coefficient is large enough. Interestingly, we find that the profit of the manufacturer who invests in traceability is increasing in the traceability competition intensity.

1. Introduction

Product recall, which is becoming a fairly challenging issue in supply chain management, refers to a request that products should be returned after the discovery of safety problems or product defects. In general, the number of recalls has been increasing along with the increase in the complexity and globalization of supply chains, and product recalls occur in various industries, such as food, pharmaceuticals, automobiles (CNNMoney, 2016), toys and furniture. For example, in 1997, 25 million pounds of beef products were recalled by Hudson Foods due to bacterial contamination, which was the largest ground beef recall in the US history (Loader & Hobbs, 1999). Similarly, salmonella-contaminated food recalls have been observed in the milk, beef, peanut turkey, etc. industries (Karimi & Goldschmidt, 2018). In 2017, a drug manufacturer, Merck, lost nearly $2.5 billions because of the arthritis medication Vioxx recall (Bala, Bhardwaj, & Chintagunta, 2017). More recently, according to Christensen (2018), a recall of a list of medications contaminated with a substance that may cause cancer in 23 countries was announced by the U.S. Food and Drug Administration (FDA). Additionally, since the product's introduction in 2012, five infant fatalities have occurred in the Kids II rocking sleepers. Similar to Fisher-Price, Kids II responded by recalling all rocking sleepers on April 26, 2019 (Farber, 2019).

Product recalls not only induce considerable financial losses due to the costs of collecting and replacing defective products, but they also damage a company's image and reputation, and they even pose safety risk issues to the public. Academic research also highlights the negative impacts of product recalls documented in the business press. For example, these negative impacts include financial and market losses (Shah, Ball, & Netessine, 2017); the reduction of shareholder wealth (Jarrell & Peltzman, 1985); and poor future product safety, a higher injury rate and an increase in future recall frequency (Kalaignanam, Kushwaha, & Eilert, 2013). The essential of a product recall is to responsively recognize the origins of the risk and then recall products that cannot be identified as safe (Dai, Fan, Lee, & Jianbin, 2017). The consequence of a product recall not only depends on the occurrence probability of prod-

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uct recall events (namely product reliability) but also the product recall scale, which is determined by the number of sold products that can be identified as safe. Thus far, most firms are focusing on improving the product reliability by improving the quality of the materials, products and production processes, such as supplier audits or certification (Chen & Lee., 2017), and updating production equipments and design standards. Even though the product recall issue can be mitigated by quality improvement (Chao, Seyed, Iravani, & Canan, 2009), product recall events are still not infrequent to witness. Therefore, besides improving product reliability, academics and practitioners are considering other methods of managing product recalls, such as the product category design (Bala et al., 2017) and the introduction of a supply chain traceability system (Dai, Tseng, & Zipkin, 2015). In all the aforementioned recall events, a common feature is that it is difficult to trace defective products back to the origin and to identify the safety products from the very start of the supply chain through to end-use, particularly in the agri-food and pharmaceutical industries. Even if the supplier at the source of a product recall can be identified, firms still face the challenges of holding suppliers accountable and attributing the responsibility to suppliers. However, the recent technological developments such as GS1, RFID and the Blockchain are promising methods to facilitate manufacturers establishing the traceability of supply chains (Provenance, 2015). For example, BSR is leveraging the Blockchain and GS1 to trace the ingredients from smallholder farmers to global brands.

Compared to the traditional product reliability, supply chain traceability could benefit the management of product recall issues in different ways. First, it enables a firm to trace defective products back to their risky origins and to identify the contaminated batch of materials or the failure-causing supplier or process. Second, unlike the traditional product reliability that cuts the probability of product recall events, traceability enables the tracking of the journey of products from the source of the contamination to their end-use. Consequently, it can be used to limit the number of recalled products by filtering products from the product pool that cannot be identified as safe. In other words, traceability is also called the tracking capability. Third, it exposes consumers to the story-telling of the provenance and journey of products. For example, it provides an opportunity for a firm to credibly make and verify safety or sustainability claims, or even to meet the some regulatory requirements. However, from the perspective of the investment costs, unlike the product reliability that mainly requires a fixed investment cost, the traceability system induces a unit device cost per product and a setup cost which depends on the production volume, therefore, the investment costs for traceability are mainly variable costs.

Actually, traceability has attracted considerable attention in many economies, e.g., the US consumer product safety law (Public law No. 110–314) and the online food traceability system SEICA in Japan. These regulations or standards for traceability urge increasingly more companies in multiple industries to establish traceability systems to improve their supply chain traceability. Furthermore, the Blockchain-enabled traceability system provides credible claims of quality, safety, sustainability and etc for consumers. When making purchasing decisions, an increasing number of consumers take product traceability into account in addition to the product price. Pouliot (2008) finds that there exists a positive impact of the tracking capability on a consumer's willingness to pay in farming industry. Similarly, consumers in Nanjing, China, are willing to pay a significant positive price premium for food traceability despite variations across products (Zhang, Bai, & Wahl, 2012). Driven by the regulations and the motivation to raise the consumers' willingness to pay, increasingly more firms are establishing their traceability systems, such as the Amazon Chain in Amazon, GS1 in P&G, and the Blockchain based BaaS in JD. The competition of traceability is thus increasingly becoming more significant in supply chain risk management. As the supply chain traceability has become an important feature of supply chains, some studies have investigated the optimization of the traceability, e.g., the design of the traceability level in product recall by Dai et al. (2015), and the joint optimization of traceability and pricing by Dai et al. (2017). However, to the best of our knowledge, the optimization of the traceability under competitive supply chains with product recalls is still an open research question. In addition to the supply chain traceability, the product recall issue is linked with other supply chain operations. Some other studies are attempting to investigate the interactions of traceability and the recall cost in a perishable food supply network (Piramuthu, Farahani, & Grunow, 2013), a contingent payment scheme under information asymmetry (Resende-Filho & Hurley, 2012), sourcing decisions (Sun & Wang, 2019), and quality contracting (Cui, Hu, & Liu, 2019). Therefore, there is still a demand for a deeper understanding of how to manage such product recall risk by investigating the interactions of traceability and traditional supply chain operations. Particularly, how to jointly optimize the traceability and product reliability in a competitive supply chain captured by product differentiation, channel differentiation, and traceability differentiation with endogenous pricing still remains an open question. Additionally, it is of great interest to investigate the interactions of traceability and reliability optimization and the equilibrium tracking strategies for competitive manufacturers.

To answer these research questions, a three-stage recalling supply chain consisting of two manufacturers, two retailers and consumers is considered. Each manufacturer, who determines the product recall efforts characterized by the product reliability only or both product reliability and traceability, sells its products to downstream retailers. We investigate each manufacturer's optimal product recall efforts strategies and further examine the equilibrium tracking decisions for these two competing manufacturers. Based on the analytical results, managerial implications are discussed and insights are provided to corporate executives to be used as references to make strategic decisions on investing in traceability in supply chain risk management. This study contributes to both theory and practice in the following three ways.

(a) Both the optimal product reliability and traceability in a competitive supply chain with product recall are identified, which enriches the literature on supply chain risk management. We find that for manufacturers who both conduct tracking, the tracking capability is always a necessity. Particularly, traceability will fully substitute the product reliability using unit tracking when the traceability investment cost coefficient is sufficiently low. When it is sufficiently high and the product reliability investment cost coefficient is relatively low, full product reliability with an economic tracking will be optimal. Otherwise, economic product reliability and economic tracking capability will be preferred.

(b) We demonstrate how the introduction of traceability interacts with the traditional product reliability and the two competing manufacturers' equilibrium tracking decisions. We find that when the traceability investment cost coefficient is low, the tracking capability fully substitutes the product reliability effort but it improves the product reliability effort when it is high with a low product reliability investment cost coefficient. Additionally, the manufacturer will always be better off by investing in its tracking capability. Interestingly, for the manufacturer whose competitor takes product reliability effort only, we find that the investment in tracking capability may benefit his competitor when the tracking effort investment cost coefficient is large enough.

(c) In addition to the price competition of product differentiation and channel differentiation, the competition of traceability differentiation is considered in the competitive supply chain, and we show that such competition will not influence the structure of two competing manufacturers' optimal effort decisions. However, the competition of tracking capability reduces the upper thresholds for the strategy of no reliability effort with unit tracking and the strategy of full reliability effort with an economic tracking. Particularly, we find the optimal profit of a manufacturer who invests in traceability is monotone increasing in the tracking capability competition intensity while that of the manufacturer who does not track decreases in it.

The rest of this paper is organized as follows. In Section 2, we review the related literature. In Section 3, we describe the model. The traceability and product reliability effort optimization results and the equilibrium tracking decisions are demonstrated in Sections 4 and 5, respectively. We examine the impacts of key parameters in Section 6 and conclude the paper in Section 7.

2. Literature review

Focusing on the interactions of traceability and product reliability optimization in the supply chain risk management of product recalls, our paper is related to the following three streams of research: (i) supply chain risk management, (ii) traceability or the tracking capability, and (iii) the impact of competition in supply chain systems.

Supply chain risk management is a fairly important research topic, which has drawn significant interests from practitioners and researchers in recent years (Sodhi, Son, & Tang, 2012). The literature in this stream can be categorized in terms of whether the involved effort is an audit, inspection or quality improvement. Plambeck and Taylor (2015) explore the interactions between one buyer's audit level and one supplier's compliance and their levels of deception using a game-theoretic model. Inspired by Mattel's lead tainted toys event in 2007, Babich and Tang (2012) and Rui and Lai (2015) examine the extent to which various mechanisms characterized by the inspection effort and deferred payments deter suppliers from product adulteration. Zhu, Zhang, and Tsung (2007) focus on contrasting supplier- and buyer-initiated quality improvement efforts in the setting of a single supplier and buyer with deterministic demand. Bray, Serpa, and Colak (2019) find that product quality is related to supply chain proximity. Lee and Li (2018) investigate three ways to manage the supplier quality. Chao et al. (2009) also study the quality improvement efforts exerted by both the supplier and the buyer but in the recalling supply chain context. They consider two types of cost sharing contracts using selective root cause analysis to coordinate the quality improvement efforts of supply chain members. Apart from the three forms of effort mentioned above, some papers consider multiple efforts exerted by different supply chain members. For instance, models in which the supplier selects its effort at controlling product quality and the buyer determines whether or not to inspect were proposed by Reyniers and Tapiero (1995a,b). Starbird (2001) also proposes a model in which the buyer decides its inspection effort and further examines how the inspection effort affects the supplier's quality level under contracts involving certain rewards and penalties. Our work complements the literature on supply chain risk management in two ways. First, the reliability effort, aimed at reducing the product failure rate and thus controlling the probability of a product recall, differs from the product quality mentioned above. Second, traceability acts as a new form of effort in supply chain risk management. In addition, we examine how such traceability interacts with the traditional product reliability and the impact of these efforts on the product recall issue.

The second stream is on traceability or the tracking capability, which is defined as improving the capability to trace the history, application or location of a traceable objective through recorded identifications across the supply chain (Nguyen, 2004). Thus far, the literature of this stream related to our work includes the impacts of traceability systems and the optimization of the tracking capability. A traceability system has many potential benefits in alleviating the product recall issue, such as limiting the size of recalls (Pouliot, 2008), obtaining the order progress information using RFID (Gaukler, Ozer, & Hausman, 2008, Huang, Tu, Zhang, & Yang, 2012), etc. Economic analysis in evaluating the impacts of traceability systems varies in terms of whether it assesses the benefits and costs of different tracking systems (Dessureault, 2001, Fritz & Schiefer, 2009), the relationship between traceability and profits (Pouliot, 2008), the marginal effect of traceability on recall costs (Piramuthu et al., 2013), the impacts on supply chain decisions (Saak, 2016, Fan, Tao, Deng, & Li, 2015), or the impacts on the optimal inspection policies (Yao & Zhu, 2020). These aforementioned studies analyze the impacts of traceability, but they do not deal with the optimization of the tracking capability. To fill this research gap, Aiello, Enea, and Muriana (2015) carry out a numerical analysis to identify the economical traceability unit size that optimizes the supply chain profits based on the expected value of the traceability system implemented for perishable products. Dai et al. (2015) design the optimal tracking effort in terms of the item level, batch level and barcode level in a two-stage supply chain consisting of a manufacturer and two suppliers. Dai et al. (2017) also examine the optimization of the tracking capability but their focus is on the joint optimization of the tracking capability in terms of the traceable unit size and price considering the tracking cost and recall cost in a supply chain with endogenous pricing. In contrast to the existing tracking capability optimization literature, our work has a different intent: we are interested in the interactions of traceability and product reliability optimization in the context of a competitive supply chain and further investigate competing manufacturers' equilibrium tracking decisions.

The third stream of related literature is the impact of competition on the operational decisions in supply chain systems, which can be categorized in terms of whether there exists upstream competition, downstream competition or a mixed supply chain model with both upstream and downstream competition. Banker, Khosla, and Sinha (1988) explore the impact of the competitive intensity of upstream manufacturers with asymmetry demand and cost structure on the quality level. Qi, Shi, and Xu (2015) examine the impact of an upstream supplier's pricing and reliability competition and find that the supplier should pursue a high wholesale price and reliability. Ingene and Parry (1995) study the case of a manufacturer selling to independent retailers in the downstream that directly compete for customers and they show that coordination is not always in the manufacturer's interest when the downstream competition exists. Tang and Kouvelis (2011) model the downstream competition among retailers in the face of suppliers with varying yield uncertainty and they find that the value of dual sourcing will not be affected by downstream competition. Kumar, Basu, and Avittathur (2018) study how a retailer can use pricing decisions along with sourcing strategies under disruption risk when competing against another retailer with a more reliable supply chain. All the work mentioned above mainly discusses either upstream or downstream competition. Both upstream and downstream competition were first proposed by Choi (1996), and he extends the traditional channel model in which each manufacturer distributes its product through exclusive dealers who do not sell competing brands in the multiple-manufacturer-multiple-retailer channel with intra- and interchannel price competition. The question of how the traceability effort in supply chain risk management is influenced by both upstream and downstream competition, however, has not received much attention so far. Therefore, our work contributes to the existing literature by setting up in a competitive recalling supply chain where both the upstream tracking capability competition and downstream price competition in terms of product differentiation and channel differentiation are considered. Furthermore, we particularly discuss the specific impacts of the tracking capability competition on the supply chain decisions.

3. Model formulation

Considering a supply chain in which two competitive manufacturers sell products to consumers through two competitive retailers, manufacturers will recall the defective products from consumers when a product recall event occurs. The product recall costs are mainly determined by two factors: the probability of recall events and the proportion of recalled products. The manufacturer can reduce the recalling probability by strategic decisions through product reliability effort, such as supplier selection quality improvement and retooling. Additionally, the manufacturer can invest in traceability system, such as the application of GS1, RFID and Blockchain technology to enable the tracking of the journey of products from the contaminated source to the end-use through product batches, to decrease the proportion of recalled products, which is defined as the tracking capability (or tracking effort). Let ρ and θ denote the manufacturer's product reliability effort and tracking capability, respectively, where $0 \le \rho \le 1$ and $0 \le \theta \le 1$.

First, under the given product reliability level ρ, referring to Chao et al. (2009), the manufacturer can reduce the occurrence probability of recalling events from the initial value $1-e^{-\lambda}$ to $1-e^{-\lambda(1-\rho)}$. Note that in practice, λ is usually very small and thus $1-e^{-\lambda(1-\rho)}$ is approximately equal to $\lambda(1-\rho)$ according to Taylor's formula. Second, we model the recall proportion as a function of the tracking capability. Let $f(\theta)$ denote the recall proportion, with $f(0)=1, f(1)=0, f'(\theta)<0$, and $f''(\theta)\le 0$. Note that $\theta=0$ implies that no product is equipped with a tracking device and thus all products sold cannot be identified as safe, and need to be recalled once the product recall event occurs (i.e., a defective product is reported). As to $\theta=1$, meaning that each product is equipped with a tracking device, and the defective product can be exactly identified to be recalled, therefore, the recall proportion is nearly zero. $f'(\theta)<0$ means that a higher tracking capability indicates a lower the recall proportion which is reasonable in practice. Note that $f(\theta)=1-(1-f(\theta))$ and there is one-on-one mapping between θ and $1-f(\theta)$. For simplicity, we assume that $f(\theta)=1-\theta$ where $\theta\in[0,1]$. We have three reasons for this assumption. First, θ has practical implications that a higher θ corresponds to a smaller batch size and thus a lower recall proportion. For example, when θ is 0.75, meaning that products sold are divided into four $(\frac{1}{1-\theta})$ sub-batches which are equipped with a tracking device. Once a defective product occurs, this product along with the rest products within the same batch, that is, a proportion of 0.25 of all products sold should be recalled, which corresponds to the recall proportion of (1–0.75). Second, similar simplifications are common in the existing literature on quality (Guo, 2009). Third, considering the concavity of $f(\theta)$, and the one-on-one mapping property of θ and $f(\theta)$, the specific form of $f(\theta)$ does not affect the explanations of our model and our focus is on the tracking capability rather than the recall proportion. Analytical results in Sections 4 and 5 are derived on the basis of this assumption. Three competitive supply chain structures characterized by tracking or not are shown in Fig. 1. Subscripts 1 and 2 are used to distinguish competing manufacturers or retailers, and superscripts $\widetilde{\square}$ and $\hat{\square}$ mark Mono-track model and Duo-track model, respectively.

Table 1 summarizes parameters and variables denoted in this paper, other notations will be defined as needed.

3.1. Common demand functions

Considering the product differentiation, the channel differentiation, and the tracking capability differentiation, the problem can be formulated using a three-dimensional competition model. Referring to Tirole (1988), the demand for manufacturer *i's* product sold by retailer *j* in each model is given by the following:

$$D_{ij}=1-p_{ij}+\theta_i+\alpha(p_{3-i,j}-p_{ij})+\beta(p_{i,3-j}-p_{ij})+\gamma(\theta_i-\theta_{3-i}), \quad (1)$$

$$\widetilde{D}_{ij}=1-\widetilde{p}_{ij}+\widetilde{\theta}_i+\alpha(\widetilde{p}_{3-i,j}-\widetilde{p}_{ij})+\beta(\widetilde{p}_{i,3-j}-\widetilde{p}_{ij})+\gamma(\widetilde{\theta}_i-\widetilde{\theta}_{3-i}), \quad (2)$$

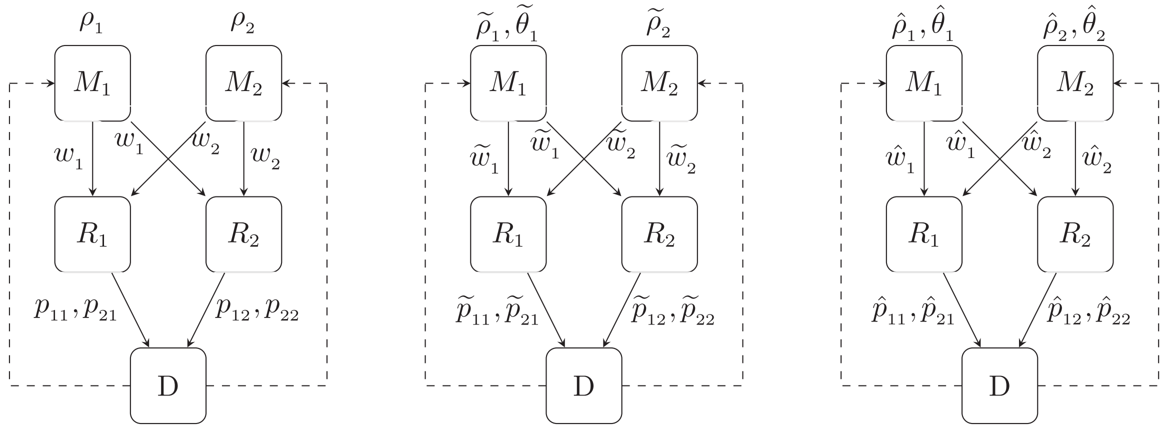
$$\hat{D}_{ij}=1-\hat{p}_{ij}+\hat{\theta}_i+\alpha(\hat{p}_{3-i,j}-\hat{p}_{ij})+\beta(\hat{p}_{i,3-j}-\hat{p}_{ij})+\gamma(\hat{\theta}_i-\hat{\theta}_{3-i}), \quad (3)$$

where $\theta_1=\theta_2=\widetilde{\theta}_2=0$, meaning that the product has no tracking capability under the Non-track model and the Mono-track model.

Note that i is the index for the manufacturer, where $i\in\{1, 2\}$, and j is the index for the retailer, where $j\in\{1, 2\}$. p_{ij} is the price of manufacturer *i*'s products sold by retailer *j*. Parameter α is the competition intensity of the product differentiation, where $\alpha\ge 0$; β is the competition intensity of the channel differentiation where $\beta\ge 0$, and γ is the competition intensity of the tracking capability differentiation, where $\gamma\ge 0$. Note that the tracking capability is usually transparent to consumers and manufacturers can clearly signal the tracking capabilities of their products to consumers in a credible way. Furthermore, Pouliot (2008) has pointed out that a consumer's willingness to pay will be positively affected by the tracking capability. Thus, tracking capability differentiation is also considered in this common demand function. This way of modeling demand functions is inspired by Choi (1996) and Zhu and He (2017). In addition, according to the recent research on demand function modeling by Huang, Leng, and Parlar (2013), such a linear demand model has been widely adopted in the economic modeling literature (see Banker et al., 1988; Chen, 2001; Yan, Zhao, & Tang, 2015). Here, the product reliability differentiation is not characterized in the demand function, and the underlying reasons are as follows. First, in this paper we aim to investigate the impact of competition on the optimization of the tracking effort (which has been rarely studied in the existing literature) in addition to the decisions on reliability and price. The optimization of product reliability (e.g., quality) has been intensively investigated in the existing literature, such as Li (2013), Zhu et al. (2007) and etc. Second, the product reliability differentiation could be characterized by the product differentiation (at the manufacturer's level) to some extent, which is already considered in the price differentiation. It is difficult for customers to distinguish the product reliability differentiation from the price differentiation in practice. Third, considering reliability effort in the demand functions could be treated as a special case of the asymmetric market potential which will be investigated in Section 5.2.

3.2. Sequence of events

Based on our investigation in product recalls, manufacturers which recall products usually are branded firms, such as General Motors (GM) in the automobile industry, Merck in the pharmaceutical industry, and Mattel in the toys manufacturing industry. Meaning that manufacturers tend to be more powerful than retailers. Therefore, We formulate the interactions of manufacturers and retailers as a Stackelberg game where manufacturers are the leader and retailers are the follower. The sequence of events for the recalling supply chain members is shown in Fig. 2. We divide the decision process into three stages. (i) In the designing stage, two manufacturers as leaders first decide their optimal product reliability effort simultaneously. Note that they can observe their competitors' reliability before deciding tracking effort. In practice, a manufacturer's product reliability investment can be



Model I: Non-track Model II: Mono-track Model III: Duo-track

Fig. 1. Model structures under various tracking strategies.

Table 1
Notations.

Decision variables	
$p_{ij}(\widetilde{p}_{ij}, \hat{p}_{ij})$	Retailer *j's* price for manufacturer *i's* product, $i, j \in \{1, 2\}$
$w_i(\widetilde{w}_i, \hat{w}_i)$	Manufacturer *i's* wholesale price
$\theta_i(\widetilde{\theta}_i, \hat{\theta}_i)$	Manufacturer *i's* tracking capability
$\rho_i(\widetilde{\rho}_i, \hat{\rho}_i)$	Manufacturer *i's* product reliability effort
Model parameters	
C_r	Unit recall cost
c	Unit production cost
K_θ	Tracking capability investment cost coefficient
K_ρ	Product reliability effort investment cost coefficient
λ	Initial product recall probability
α	Competition intensity of product differentiation, $\alpha \geq 0$
β	Competition intensity of channel differentiation, $\beta \geq 0$
γ	Competition intensity of tracking capability differentiation, $\gamma \geq 0$
Other notations	
$D_{ij}(\widetilde{D}_{ij}, \hat{D}_{ij})$	Demand function for manufacturer *i's* product sold by retailer *j*
$\Pi_{Mi}(\widetilde{\Pi}_{Mi}, \hat{\Pi}_{Mi})$	Manufacturer *i's* profit function
$\Pi_{Rj}(\widetilde{\Pi}_{Rj}, \hat{\Pi}_{Rj})$	Retailer *j's* profit function

accessed via its supplier selection, product design, news on investing in advanced production machines or polishing up production techniques. Therefore, referring to Li (2013) and Zhu et al. (2007), the product reliability effort is long-term and strategic, and therefore is decided prior to the wholesale price. For example, Apple and Samsung, as competitors in the electronic & smart appliance industry, tend to unfold their product design as well as collaboration with reliable suppliers to the public before a new generation hits the market, for warm-up or other strategic purposes. Furthermore, observable product reliability effort to reduce product recall cost is also witnessed in the existing literature, for example, Chao et al. (2009). (ii) In the production stage, manufacturers set the wholesale price and tracking capability (if necessary) simultaneously. In practice, product tracking (labeling process in the production stage) is short-term tactic decisions, which are determined in the production stage before distribution. Based on the optimal principle in dynamic programming, deciding the tracking effort and wholesale price simultaneously is preferred to deciding them sequentially, the tracking effort and wholesale price are set to be simultaneously determined, which is also consistent with Dai et al. (2017) which jointly optimizes the tracking capability and price. (iii) In the distribution stage, two retailers as followers, simultaneously decide their retailing prices for end consumers.

3.3. *Manufacturers' optimization problems*

Note that manufacturer *i*'s recall probability in such case is $\lambda(1-\rho_i)$. His expected revenue is given by $(1-\lambda(1-\rho_i))w_i(D_{i1} + D_{i2}) + \lambda(1-\rho_i)w_i(D_{i1} + D_{i2})$ and his costs consist of three parts: production cost, recall cost as well as investment cost on product recall efforts. Let c and C_r denote the unit production cost and unit recall cost, respectively. A fixed cost $\frac{1}{2}K_\rho\rho_i^2$ of updating, retooling production machines will be incurred to reduce the recall probability by improving the product reliability ρ_i, where K_ρ corresponds with the product reliability investment cost coefficient. Similar cost functions have been widely used in economics and operations literature to model the diminishing impact of investment effort (Moothy, 1998, Heese & Swaminathan, 2006, Tang, Gurnani, & Gupta, 2014). Furthermore, the quadratic cost function is a common assumption for model tractability (Li, 2013) and has no bearing on complex results. Since we only consider a one-period problem, by assuming the product savage value of zero, obviously the retailer should wholesale enough quantity from the manufacturer to satisfy all demands. We start from the benchmarking model I of Non-track where two competitive manufacturers take product reliability effort only. Problems for the two competitive retailers and

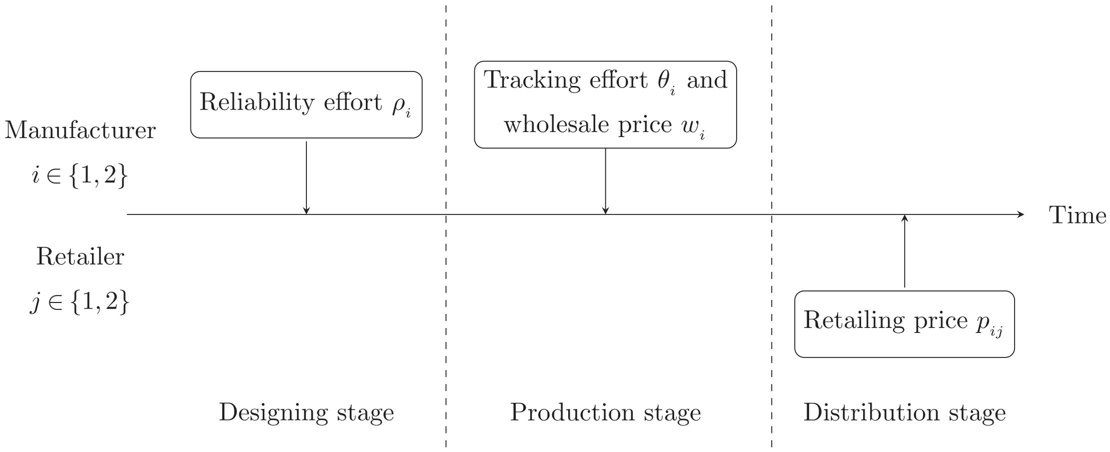


Fig. 2. Sequence of events.

two competitive manufacturers can be written as:

$$\max_{\substack{p_{ij}\geq 0,\\ D_{ij}\geq 0,\\ i,j\in\{1,2\}}} : \Pi_{Rj}(p_{ij}) = \sum_{i=1}^{2}(p_{ij}-w_i)D_{ij}, \tag{4}$$

$$\max_{\substack{w_i\geq 0,\\ 0\leq\rho_i\leq 1,\\ i\in\{1,2\}}} : \Pi_{Mi}(w_i,\rho_i)=\sum_{j=1}^{2}(w_i-c-\lambda C_r(1-\rho_i))D_{ij}-\frac{1}{2}K_\rho\rho_i^2. \tag{5}$$

Next, we come to model II of Mono-track where the first manufacturer M_1 exerts both product reliability effort and tracking capability while the second manufacturer M_2 exerts product reliability effort only. Note that M_1's costs consist of three parts: production cost, recall cost as well as investment cost. Apart from the fixed investment cost on product reliability effort, a variable cost $\frac{1}{2}K_\theta\widetilde{\theta}_1^2$ of equipping every product batch with tracking technology will also be induced, where K_θ corresponds to the tracking capability investment cost coefficient. Thus, problems for the competitive supply chain of two retailers and two manufacturers can be written as:

$$\max_{\substack{\widetilde{p}_{ij}\geq 0,\\ \widetilde{D}_{ij}\geq 0,\\ i,j\in\{1,2\}}} : \widetilde{\Pi}_{Rj}(\widetilde{p}_{ij}) = \sum_{i=1}^{2}(\widetilde{p}_{ij}-\widetilde{w}_i)\widetilde{D}_{ij}, \tag{6}$$

$$\max_{\substack{\widetilde{w}_1\geq 0,\\ 0\leq\widetilde{\rho}_1\leq 1,\\ 0\leq\widetilde{\theta}_1\leq 1}} : \widetilde{\Pi}_{M1}(\widetilde{w}_1,\widetilde{\rho}_1,\widetilde{\theta}_1) = \sum_{j=1}^{2}(\widetilde{w}_1-c-\lambda C_r(1-\widetilde{\rho}_1)f(\widetilde{\theta}_1) - \frac{1}{2}K_\theta\widetilde{\theta}_1^2)\widetilde{D}_{1j}-\frac{1}{2}K_\rho\widetilde{\rho}_1^2, \tag{7}$$

$$\max_{\substack{\widetilde{w}_2\geq 0,\\ 0\leq\widetilde{\rho}_2\leq 1}} : \widetilde{\Pi}_{M2}(\widetilde{w}_2,\widetilde{\rho}_2) = \sum_{j=1}^{2}(\widetilde{w}_2-c-\lambda C_r(1-\widetilde{\rho}_2))\widetilde{D}_{2j}-\frac{1}{2}K_\rho\widetilde{\rho}_2^2. \tag{8}$$

We continue to discuss the optimization problems for supply chain members under model III of Duo-track where both competitive manufacturers exert product reliability effort and tracking capability, whose problems can be written as:

$$\max_{\substack{\hat{p}_{ij}\geq 0,\\ \hat{D}_{ij}\geq 0,\\ i,j\in\{1,2\}}} : \hat{\Pi}_{Rj}(\hat{p}_{ij}) = \sum_{i=1}^{2}(\hat{p}_{ij}-\hat{w}_i)\hat{D}_{ij}, \tag{9}$$

$$\max_{\substack{\hat{w}_i\geq 0,\\ 0\leq\hat{\rho}_i\leq 1,\\ 0\leq\hat{\theta}_i\leq 1,\\ i\in\{1,2\}}} : \hat{\Pi}_{Mi}(\hat{w}_i,\hat{\rho}_i,\hat{\theta}_i) = \sum_{j=1}^{2}(\hat{w}_i-c-\lambda C_r(1-\hat{\rho}_i)f(\hat{\theta}_i) - \frac{1}{2}K_\theta\hat{\theta}_i^2)\hat{D}_{ij}-\frac{1}{2}K_\rho\hat{\rho}_i^2. \tag{10}$$

4. Optimization results of product reliability effort and tracking capability

In this section, we present the optimal product recall effort strategies under both upstream and downstream competition by solving the competing manufacturers' and the retailers' problems stated in Section 3. Let $\rho_i^*, \widetilde{\rho}_i^*, \hat{\rho}_i^*$ be the manufacturer i's optimal reliability effort under models I, II and III, respectively. Let $\theta_i^*, \widetilde{\theta}_i^*, \hat{\theta}_i^*$ be the manufacturer i's optimal tracking effort under model I, II and III, respectively. Below is a theorem that states the optimal product recall effort strategies under model I where two manufacturers only take product reliability effort. Let i be the product recall effort strategies for two manufacturers (symmetric in this case), where $i\in\{N, E, F\}$ with N denoting *no reliability effort*, E denoting *economic reliability effort*, and F denoting *full reliability effort*. Additionally, for expositional succinctness, we define $\rho_I=\frac{8(1+\beta)^2(4\alpha+\beta+2)((2\alpha+\beta+1)(2+\beta)(2\alpha+1)+(1+\beta)(4\alpha+\beta+2))\lambda C_r(1-c-\lambda C_r)}{(2+\beta)((2\alpha+\beta+1)(2+1\beta)(2\alpha+1)+13(1+\beta)(4\alpha+\beta+2))^2K_\rho-16(1+\beta)^2((2\alpha+\beta+1)(2+\beta)(2\alpha+1)+(1+\beta)(4\alpha+\beta+2))\lambda^2C_r^2}$, and threshold $K_\rho^I(c)=\frac{8(1+\beta)^2(4\alpha+\beta+2)((2\alpha+\beta+1)(2+\beta)(2\alpha+1)+(1+\beta)(4\alpha+\beta+2))\lambda C_r(1-c)}{(2+\beta)((2\alpha+\beta+1)(2+\beta)(2\alpha+1)+3(1+\beta)(4\alpha+\beta+2))^2}$ where $1-c-\lambda C_r\geq 0$. Noting that this can be explained by the marginal profit of the manufacturer is non-negative even when the manufacturer exerts no product reliability effort. Thus, the following theorem states two competitive manufacturers' product recall effort strategies under the Non-track setting.

Theorem 1. *Under the case of Non-track: (i) when $K_\rho\in(0,K_\rho^I(c)]$, both manufacturers take a full reliability effort. (ii) otherwise, both take an economic effort.*

Theorem 1 presents closed-form expressions for the competing manufacturers' optimal product recall effort strategies in terms of

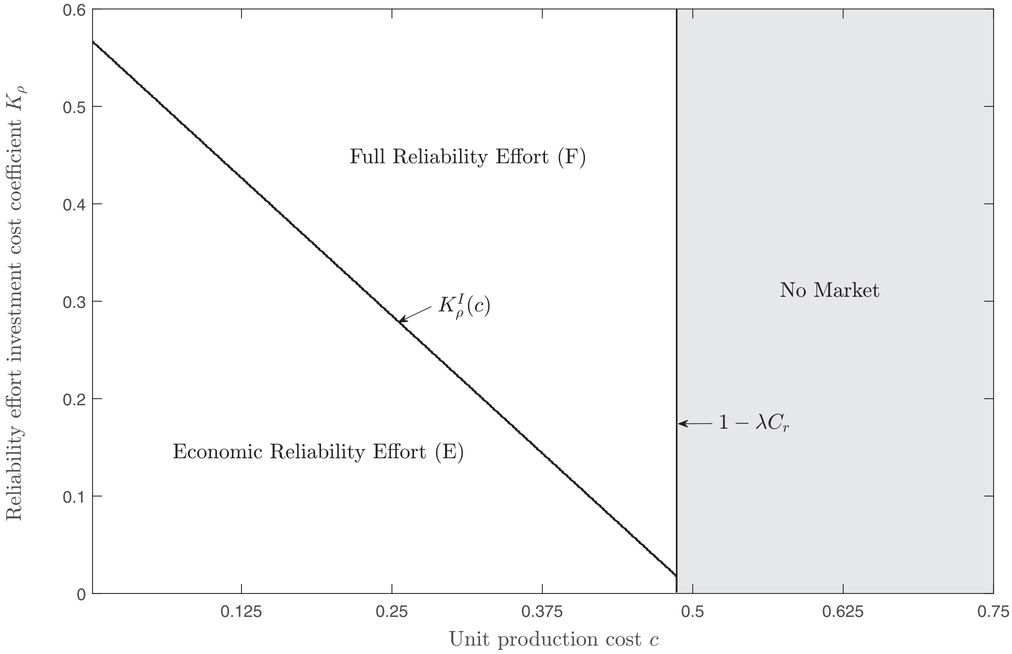


Fig. 3. Optimal product reliability efforts and tracking capability under the model of Non-track ($\lambda = 0.05, C_r = 0.6, \alpha = 0.8, \beta = 1$).

the problem parameters under the Non-track model, and a threshold policy is obtained. When the product reliability investment cost coefficient is low, meaning that it is lower than a threshold which increases in the unit recall cost and the initial recall probability, the optimal product recall efforts strategy is to take a full reliability effort (*F*). In such a case, the optimal product reliability is fixed and will not be affected by the price competition among manufacturers or retailers. As the unit production cost increases, the threshold of the product reliability investment cost coefficient decreases, implying that manufacturers are less likely to take a full product reliability effort for high-cost products. When the product reliability investment cost coefficient is high, the optimal strategy is to take an economic reliability effort (*E*), which is jointly determined by the price competition intensity parameters and the cost parameters. Fig. 3 shows the optimal product recall effort strategies under Non-track model. Note that when the unit production cost is sufficiently high, there is no profit margin for manufacturers and therefore no market for the right region (filled by gray).

Next is a theorem that states the optimal product recall efforts strategies for two competing manufacturers under the Mono-track model where M_1 exerts both product reliability effort and tracking capability while M_2 exerts product reliability effort only. Let (*i*, *j*, *k*) be the product recall effort strategies for two manufacturers (asymmetric in this case), where (*i*, *j*) denotes the product reliability effort and tracking effort strategies for M_1 while *k* denotes the product reliability effort strategy for M_2. Note that $i \in \{N, E, F\}$ where *N* denotes *no reliability effort*, *E* denotes *economic reliability effort*, *F* denotes *full reliability effort*; and $j \in \{E, U\}$, where *E* denotes *economic tracking* and *U* denotes *unit tracking*.

For expositional succinctness, we redefine the competition intensity related parameters (α, β, γ) as follows: $m(\alpha,\beta,\gamma) = \frac{(2+\beta)(4\alpha+\beta+2)[(2\alpha+1)(2\alpha+\beta+1)(2+\beta)-(1+\beta)(4\alpha+\beta+2)]}{2(2+\beta)(4\alpha+\beta+2)[(1+\beta)(4\alpha+\beta+2)+(2+\beta)(2\alpha+1)(2\alpha+\beta+1)]}$, $g(\alpha,\beta,\gamma) = \frac{2(1+\gamma)(2+\beta)(4\alpha+\beta+2)-(4\alpha+\beta+2)-(2+\beta)(2\alpha+1)(2\gamma+1)}{(1+\beta)(4\alpha+\beta+2)+(2+\beta)(2\alpha+1)(2\alpha+\beta+1)}$, $x(\alpha,\beta,\gamma) = \frac{(1+\beta)(4\alpha+\beta+2)+(2\alpha+\beta+1)(2\alpha+1)(2+\beta)}{(2+\beta)(4\alpha+\beta+2)}$, and $\bar{g}(\alpha,\beta,\gamma) = \frac{1}{2[1-m^2(\alpha,\beta,\gamma)]-1}[g(\alpha,\beta,\gamma) + \frac{m(\alpha,\beta,\gamma)}{x(\alpha,\beta,\gamma)}(\frac{(2\alpha+1)(2\gamma+1)}{(4\alpha+\beta+2)} - \frac{4\gamma+2\gamma\beta+1}{(2+\beta)})]$. Considering the expositional complexity, three other thresholds of the reliability effort investment cost coefficient $(\overline{K}_{II}(K_\theta), \hat{K}_{II}(K_\theta), \widetilde{K}_{II}(K_\theta))$ and one threshold of the tracking effort investment cost coefficient (K_θ^u) and the manufacturers' optimal product recall efforts (which are in either closed forms or implicit forms) are demonstrated in details in the Appendix. Given $c \le \frac{2(1+\beta)(4\alpha+\beta+2)}{(1+\beta)(4\alpha+\beta+2)+(2+\beta)(2\alpha+1)(2\alpha+\beta+1)} - (\frac{1}{2} + \frac{(2+\beta)(2\alpha+1)(2\alpha+\beta+1)(1-m)}{2(1+\beta)(4\alpha+\beta+2)(1+m)})\lambda C_r$, we obtain the following theorem on the two manufacturers' product recall effort strategies (*i*, *j*, *k*).

Theorem 2. *Assume* $K_\rho \in (\overline{K}_{II}(K_\theta), +\infty)$ *where* $K_\theta \in (\bar{g}(\alpha,\beta,\gamma) + \lambda C_r, K_\theta^u)$ *under the case of Mono-track.* M_2 *takes a full reliability effort if* $K_\rho \in (0, \hat{K}_{II}(K_\theta)]$ *and an economic reliability effort otherwise. However,*

(i) when $K_\theta \in (0, g(\alpha,\beta,\gamma) + \lambda C_r]$, M_1 *takes no reliability effort and unit tracking.*

(ii) when $K_\theta \in (g(\alpha,\beta,\gamma) + \lambda C_r, \bar{g}(\alpha,\beta,\gamma) + \lambda C_r]$, M_1 *takes no reliability effort and an economic tracking.*

(iii) when $K_\theta \in (\bar{g}(\alpha,\beta,\gamma) + \lambda C_r, K_\theta^u)$ *and* $K_\rho \in (0, \widetilde{K}_{II}(K_\theta)]$, M_1 *takes a full reliability effort and an economic tracking.*

(iv) when $K_\theta \in (\bar{g}(\alpha,\beta,\gamma) + \lambda C_r, K_\theta^u)$ *and* $K_\rho \in (\widetilde{K}_{II}(K_\theta), +\infty)$, M_1 *takes an economic reliability effort and an economic tracking.*

Theorem 2 presents the optimal product recall effort strategies for M_1 and M_2 in terms of the problem parameters under the Mono-track model, which are shown in Fig. 4 as (*i*, *j*, *k*)'s. A threshold policy is also observed. First, we look at M_1's side. When the tracking effort investment cost coefficient is sufficiently low, meaning that it is lower than a threshold which increases in the unit recall cost and the initial recall probability, the optimal product recall effort strategy is to take no reliability effort and implement unit tracking (*N*, *U*), meaning that the first manufacturer should not invest in the product reliability effort, and should equip every product with tracking technologies such as barcodes and RFID instead. In such a case, it does not make any difference to lower the recall probability since the recall range, in the form of the recall probability multiply recall probability $\lambda(1-\widetilde{\rho}_1^*)(1-\widetilde{\theta}_1^*)$, has been reduced to zero via unit tracking. The tracking effort fully substitutes the product reliability effort. As the tracking effort investment cost coefficient increases, M_1's optimal

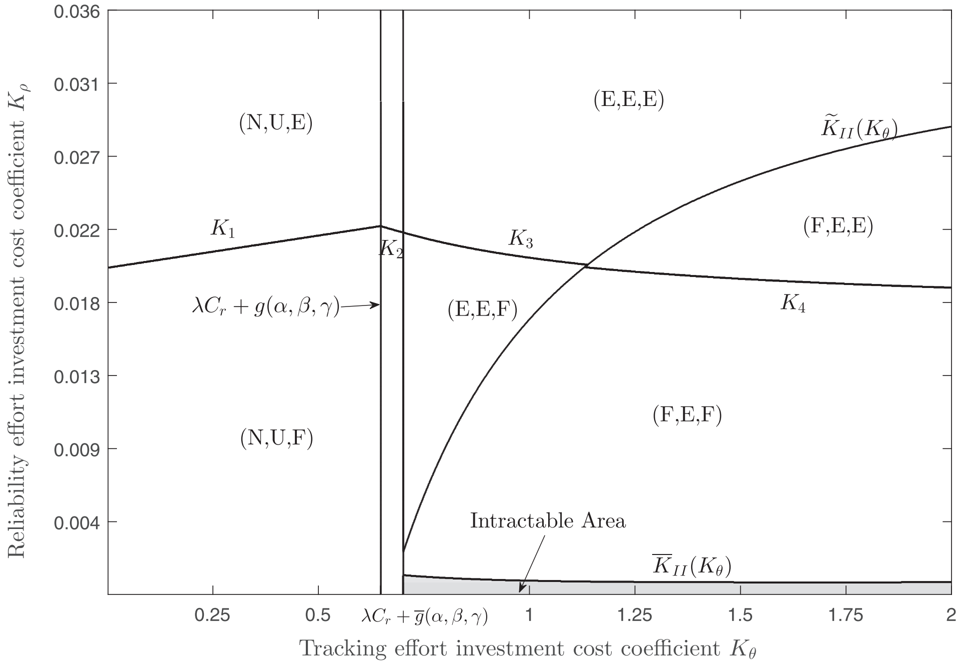


Fig. 4. Optimal product reliability efforts and tracking capability under the Mono-track model ($\lambda = 0.05, C_r = 0.6, c = 0.3, \alpha = 1, \beta = 1, \gamma = 0.2$).

product reliability effort stays zero but the optimal tracking effort decreases to the economic tracking (*N*, *E*).

When the tracking effort investment cost coefficient is high enough but the product reliability investment cost coefficient is low, the optimal product recall effort strategy is full product reliability effort with economic tracking (*F*, *E*). This corresponds with the fact that firms usually have no incentive to improve their tracking capabilities to a high level at the early stage of tracking technology development (costly usually). Instead, they prefer to reduce the recall probability to zero by taking full product reliability effort (relatively cheap). Take $\widetilde{\theta}_1 = 0.8$ as an example, it implies that M_1 should divide the newly produced products into five batches and it only needs to recall the batch within which the product is reported to have some defects. Note that in such a case, in spite of the fact that M_1 can decrease the recall range to zero by taking full product reliability effort, it is still necessary to make a low investment in tracking technology for the sake of retaining the market share (since consumers' willingness to pay increases in the product tracking capability). When both the tracking effort and the product reliability investment cost coefficients are high, the optimal product recall effort strategy is an economic reliability effort with an economic tracking capability (*E*, *E*), meaning that the manufacturer should control the recall costs by simultaneously reducing the recall probability and the recall proportion. Based on the above theorem, we find that the manufacturer who tracks under the Mono-track model, e.g, M_1 in our model, should always make a trade-off between the tracking effort and the reliability effort. Particularly, we show that the traditional product reliability effort can be perfectly replaced by the emerging tracking capability when the tracking effort investment cost coefficient is very low, and it is partially replaced otherwise. For M_2, the optimal product recall effort strategies are much simpler. We find that when the product reliability investment cost coefficient is low, the optimal strategy is full product reliability effort (*F*). In such a case, even though the product reliability effort is fixed and will not be affected by competition, the investment cost coefficient threshold $\hat{K}_{II}$ still depends on the competition intensity parameters and the cost parameters. When the product reliability investment cost coefficient is high, the optimal product recall effort strategy is an economic reliability effort (*E*) but the specific value varies with the range of the tracking effort investment cost coefficient K_θ because M_2's optimal product recall effort strategies interact with his competitor's.

Below is a theorem that states the optimal product recall efforts strategies for manufacturers under the Duo-track model where both manufacturers track. Let (*i*, *j*) be the product recall effort strategy for each manufacturer (symmetric in this case), where $i \in \{N, E, F\}$ with *N* denotes *no reliability effort*, *E* denotes *economic reliability effort*, *F* denotes*full reliability effort*, and $j \in \{E, U\}$ with *E* denotes *economic tracking*, *U* denotes *unit tracking*.

For simplicity, thresholds of the investment cost coefficients are defined as $\overline{K}_{III}(K_\theta) = 2x(\lambda C_r(1 - \frac{1}{2(1-m^2)}) - \frac{\lambda C_r}{2x(1-m^2)K_\theta}(2(1+\gamma) - \frac{1}{2+\beta} - \frac{(2\alpha+1)(2\gamma+1)}{4\alpha+\beta+2}) - \frac{m\lambda C_r}{2x(1-m^2)K_\theta}(-2\gamma - \frac{1}{2+\beta} + \frac{(2\gamma+1)(2\alpha+1)}{4\alpha+\beta+2}))^2 + \frac{2(1+\beta)\lambda^2 C_r^2}{(2+\beta)(1-m)K_\theta}(1 - c + \frac{g(2-g)}{2K_\theta})(1 - \frac{1}{2(1-m^2)})$, and $\widetilde{K}_{III}(K_\theta) = \frac{2(1+\beta)}{(2+\beta)(1-m)}(1 - c + \frac{g(2-g)}{2K_\theta})(\lambda C_r(1 - \frac{1}{2(1-m^2)}) - \frac{\lambda C_r}{2x(1-m^2)K_\theta}(2(1+\gamma) - \frac{1}{2+\beta} - \frac{(2\alpha+1)(2\gamma+1)}{4\alpha+\beta+2}) - \frac{m\lambda C_r}{2x(1-m^2)K_\theta}(-2\gamma - \frac{1}{2+\beta} + \frac{(2\gamma+1)(2\alpha+1)}{4\alpha+\beta+2}))$. Given $c \leq 1 - \lambda C_r$, we obtain the following theorem on the two manufacturers' product recall effort strategies (*i*, *j*).

Theorem 3. *Assume* $K_\rho \in (\overline{K}_{III}(K_\theta), +\infty)$ *where* $K_\theta \in (\bar{g}(\alpha,\beta,\gamma) + \lambda C_r, 4 - 2c)$ *under Duo-track.*

(i) when $K_\theta \in (0, g(\alpha,\beta,\gamma) + \lambda C_r]$, *both* M_1 *and* M_2 *take no reliability effort and unit tracking.*

(ii) when $K_\theta \in (g(\alpha,\beta,\gamma) + \lambda C_r, \bar{g}(\alpha,\beta,\gamma) + \lambda C_r]$, *both* M_1 *and* M_2 *take no reliability effort and an economic tracking.*

(iii) when $K_\theta \in (\bar{g}(\alpha,\beta,\gamma) + \lambda C_r, +\infty)$, $K_\rho \in (0, \widetilde{K}_{III}(K_\theta)]$, *both* M_1 *and* M_2 *take a full reliability effort and an economic tracking.*

(iv) otherwise, both M_1 *and* M_2 *take an economic reliability effort and an economic tracking.*

Theorem 3 presents the optimal product recall effort strategies for symmetric M_1 and M_2 in terms of problem parameters under the Duo-track model, which are shown in Fig. 5 as (*i*, *j*). Similar to the structure of Mono-track, both manufacturers will exert no product reliability effort with unit tracking when the tracking effort investment cost coefficient is sufficiently low (*N*, *U*), or

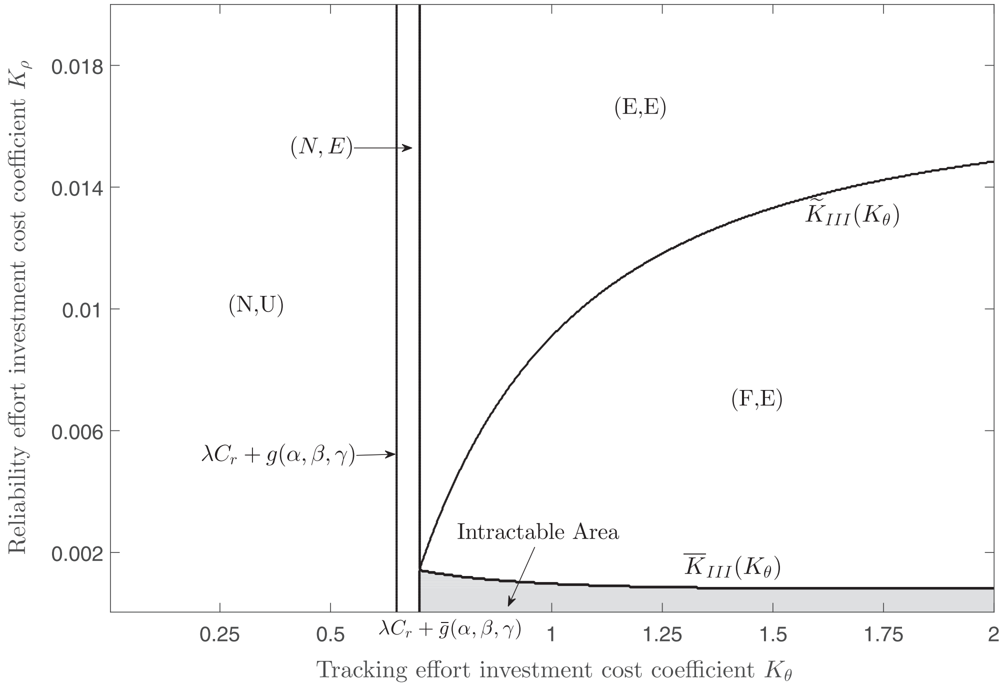


Fig. 5. Optimal product reliability efforts and tracking capability under Duo-track Model ($\lambda = 0.05, C_r = 0.6, c = 0.3, \alpha = 1, \beta = 1, \gamma = 0.2$).

full product reliability effort with an economic tracking capability when it is high but the product reliability investment cost coefficient is low. Otherwise, they both take an economic product reliability and tracking effort. Even though the thresholds of the tracking effort investment cost coefficient stay the same as before, the difference mainly lies in the thresholds of the product reliability investment cost coefficient, for example, $\widetilde{K}_{III}(K_\theta)$ shown in Fig. 5, which divides strategy (F, E) and strategy (E, E).

5. To track or not

In this section, we investigate the equilibrium tracking decisions for two competing manufacturers by comparing Non-track, Mono-track and Duo-track models. Let $\Pi^*_{M_i}, \widetilde{\Pi}^*_{M_i}, \widehat{\Pi}^*_{M_i}$ be the manufacturer i's optimal profit under Non-track, Mono-track and Duo-track, respectively.

5.1. Two competing manufacturers' equilibrium tracking decisions

First, we provide a comparison of the optimal results under Mono-track and Non-track.

Proposition 1. *By comparison, (i)* $\widetilde{\Pi}^*_{M_1} > \Pi^*_{M_1}$ *always holds while the relation of* $\widetilde{\Pi}^*_{M_2}$ *and* $\Pi^*_{M_2}$ *depends on* K_θ *and* K_ρ*. Only when* $K_\theta > K^l_\theta(K_\rho)$*, then* $\widetilde{\Pi}^*_{M_2} > \Pi^*_{M_2}$*, meaning that* M_1*'s investing in tracking may have a free-rider effect on his competitor. (ii) Given a relatively low* γ*,* $\widetilde{\rho}^*_2 \geq \rho^*_2$ *holds when* $K_\theta > K^l_\theta(K_\rho)$*.*

Proposition 1 shows the comparison of the optimal outcomes under Non-track and Mono-track. For a manufacturer whose competitor does not exert tracking effort (e.g., M_1), it is always better off by investing in product traceability because he has an alternative decision of traceability to manage the recall cost, leading to $\Pi^*_{M_1} < \widetilde{\Pi}^*_{M_1}$. For a manufacturer whose competitor tracks (e.g., M_2), When K_θ is low, M_2's optimal profit under Mono-track is lower than that under Non-track as his market size is increased by exerting cost-effective tracking effort. However, as M_1's market size increases, the wholesale price and retailing price of his products will increase as well, which may benefit M_2 when the tracking effort investment coefficient K_θ is sufficiently high. M$_2$ will also be better off even without tracking, when the market enhancement of M_1 is limited. We call this effect as a free-rider effect from M_1's tracking investment. Additionally in this case, M_2's optimal reliability effort under Mono-track is higher than that under Non-track. In terms of the product recall scale, i.e., in the form of $\lambda(1 - \widetilde{\rho}^*_2)$, it can be narrowed by higher reliability effort, e.g., when K_θ is sufficiently high. This is another indication of the free-rider effect caused by M_1's investing in tracking.

According to the numerical findings, M_1's optimal product reliability effort under Mono-track, however, is not always higher than that under Non-track, depending on the size of K_θ and K_ρ. Particularly, as is shown in Fig. 6, when K_θ is very low, M_1's tracking will perfectly substitute its reliability effort, i.e., $1 \geq \rho^*_1 > \widetilde{\rho}^*_1 = 0$. When K_θ is high, M_1's tracking leads to a higher reliability effort, i.e., $\widetilde{\rho}^*_1 \geq \rho^*_1 > 0$. Two kinds of effects behind can account for the above results. Intuitively, a higher K_ρ (K_θ) will lead to lower product reliability effort (tracking effort), which can be defined as the *investment cost effect*. Furthermore, investment in tracking will result in lower product reliability, which can be defined as the *efforts interaction effect*. Interestingly, when K_θ is relatively low, the tracking effort is relatively high and thus the reliability effort is low by efforts interaction effect. In this case, given K_θ, the reliability effort will be even lower as K_ρ increases because of the investment cost effect, which accounts for $\rho^*_1 > \widetilde{\rho}^*_1$ in Fig. 6. When K_θ is high enough, the tracking effort is relatively low and thus the reliability effort is high, which mitigates the investment cost effect as K_ρ increases. This explains why $\rho^*_1 \leq \widetilde{\rho}^*_1$ can hold in Fig. 6.

Proposition 2. *By comparison, (i) both* $\widehat{\Pi}^*_{M_1} > \Pi^*_{M_1}$ *and* $\widehat{\Pi}^*_{M_2} > \Pi^*_{M_2}$ *always hold, meaning that Duo-track dominates Non-track. (ii) Both* $\rho^*_1 \geq \hat{\rho}^*_1$ *and* $\rho^*_2 \geq \hat{\rho}^*_2$ *also hold.*

Proposition 2 presents a comparison of the optimal results under Duo-track and Non-track. We find that both $\widehat{\Pi}^*_{M_1} > \Pi^*_{M_1}$ and $\widehat{\Pi}^*_{M_2} > \Pi^*_{M_2}$ hold, indicating that both manufacturers can be better off by simultaneously exerting tracking efforts. From this

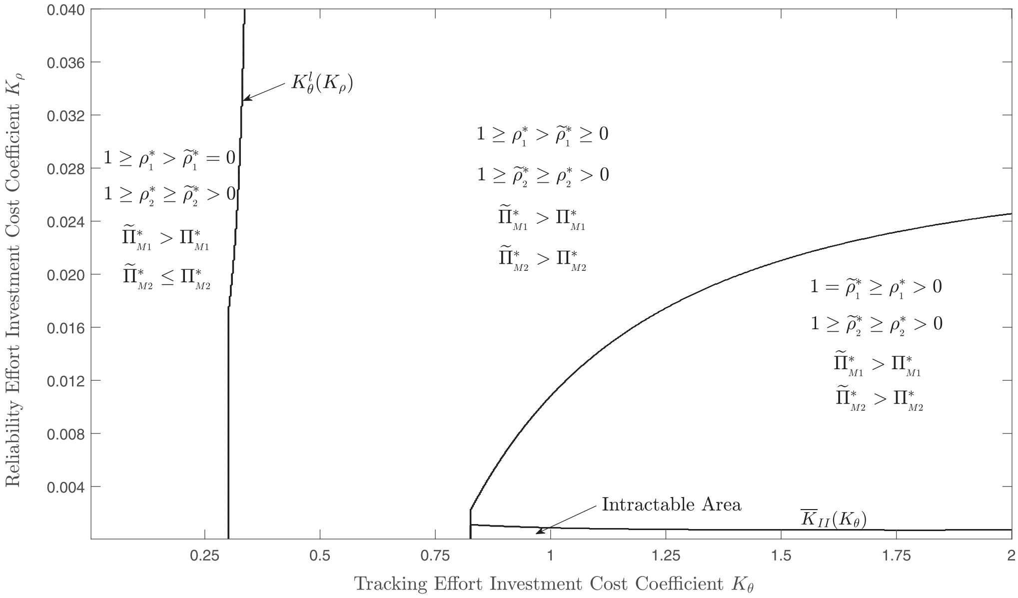


Fig. 6. Comparison of the optimal outcomes under Non-track and Mono-track for two competing manufacturers ($\alpha = 1, \beta = 1, \gamma = 0.5, \lambda = 0.05, C_r = 0.6, c = 0.3$).

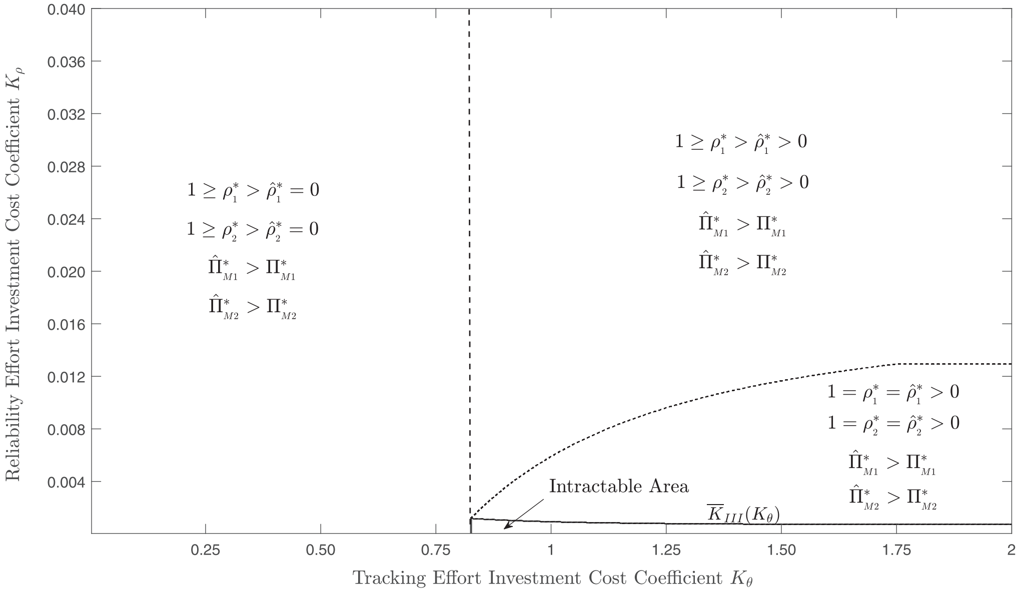


Fig. 7. Comparison of the optimal outcomes under Non-track and Duo-track for two competing manufacturers ($\alpha = 1, \beta = 1, \gamma = 0.5, \lambda = 0.05, C_r = 0.6, c = 0.3$).

perspective, the introduction along with the wide use of new tracking technologies, such as Blockchain and RFID can be socially economical. If we set the tracking efforts under Duo-track as zero, then Duo-track model reduces to Non-track model, which explains why Duo-track outperforms Non-track. Also, as is shown in Fig. 7, we find that M_1's and M_2's optimal reliability efforts under Duo-track are no higher than those under Non-track, which indicates that the tracking effort is a substitute for the conventional reliability effort if both manufacturers track. According to Proposition 1, given that M_2 does not track, M_1 prefers to track. In order to obtain the equilibrium tracking strategies for the two competing manufacturers by analyzing their mutual responses, a comparison of M_2's optimal profit under Mono-track and Duo-track is provided below.

Proposition 3. *$\widetilde{\Pi}^*_{M_2} < \hat{\Pi}^*_{M_2}$ always holds, meaning that (T, T) is the unique Nash equilibrium strategy for two competing manufacturers.*

Proposition 3 shows that M_2 is willing to track, given that its competitor M_1 already tracks. Let $\{N, T\}$ denote each manufacturer's strategy set, where N denotes *not to track* and T denotes *to track*. Combining with the conclusion from Proposition 1 that M_1 prefers to track given its competitor M_2 does not track, we find that (T, T) is the unique Nash equilibrium strategy for the two competing manufacturers. This can be explained in the following way. Under Mono-track, M_2's tracking effort $\widetilde{\theta}_2$ is zero, as a special case of that under Duo-track $\hat{\theta}_2 \in [0, 1]$. When K_θ is sufficiently low, e.g., $K_\theta \leq g(\alpha, \beta, \gamma) + \lambda C_r$, $\hat{\theta}^*_2{=}1$ is independent of $\hat{\rho}^*_2$. As K_θ increases, $\hat{\theta}^*_2 = \frac{\lambda C_r(1-\hat{\rho}^*_2)+g(\alpha,\beta,\gamma)}{K_\theta}$ is negatively related to $\hat{\rho}^*_2$. In either case, $\hat{\theta}_2$ is endogenous in the optimization for Duo-track while $\widetilde{\theta}_2$ is exogenous in the optimization for Mono-track as it is fixed at 0, which implies why M_2 is better off by tracking if M_1 already tracks and thus (T, T) is the unique Nash equilibrium.

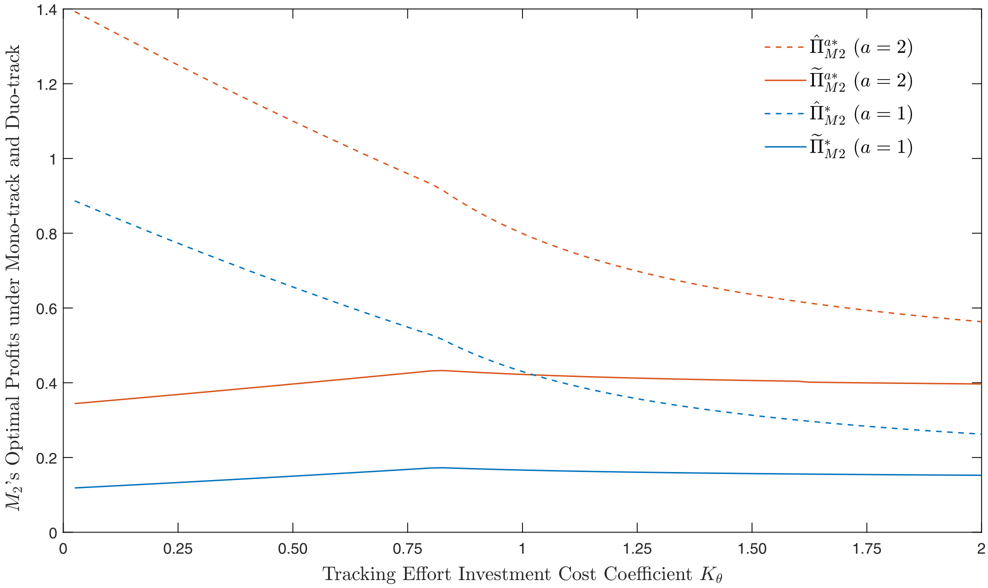


Fig. 8. M_2's optimal profits under Mono-track and Duo-track ($K_\rho = 0.032, \alpha = 1, \beta = 1, \gamma = 0.5, \lambda = 0.05, C_r = 0.6, c = 0.3$). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

5.2. The impact of asymmetry

A key assumption of the model discussed above is that the supply chain is symmetric. In reality, manufacturers may be heterogeneous. Thus, in this subsection, we explore whether the main results still hold for an asymmetric supply chain with heterogeneous market potential. We distinguish the two manufacturers by redefining the demand functions, i.e., the demands for manufacturer 1's and 2's products sold by retailer $j \in \{1, 2\}$ are respectively given by

$$D^a_{1j} = a - p_{1j} + \theta_1 + \alpha(p_{2,j} - p_{1j}) + \beta(p_{1,3-j} - p_{1j}) + \gamma(\theta_1 - \theta_2),$$
$$D^a_{2j} = 1 - p_{2j} + \theta_2 + \alpha(p_{1,j} - p_{2j}) + \beta(p_{2,3-j} - p_{2j}) + \gamma(\theta_2 - \theta_1),$$

where $a \geq 1$ and $a = 1$ reduces to the symmetric case.

Let Π^{a*}_{Mi}, $\tilde{\Pi}^{a*}_{Mi}$ and $\hat{\Pi}^{a*}_{Mi}$ denote M_i's optimal profit under asymmetric Non-track, Mono-track and Duo-track, respectively. We find that even under the asymmetric setting, the structures of the optimal product recall efforts strategies under Non-track, Mono-track and Duo-track models still preserve, which are shown in the following Theorems 4, 5 and 6, respectively. Particularly, for asymmetric Non-track case, the threshold $K^{al}_\rho(c)$ is defined as $K^{al}_\rho(c) = 2x\lambda C_r(1 - \frac{1}{2(1-m^2)})(\frac{(2m-1)c}{2(1-m)} + \frac{m}{2x(1-m^2)}(2a - \frac{1+a}{2+\beta} + \frac{(2\alpha+1)(1-a)}{4\alpha+\beta+2}) + \frac{1}{2x(1-m^2)}(2 - \frac{2}{2+\beta} + \frac{(2\alpha+1)(a-1)}{4\alpha+\beta+2}))$.

Theorem 4. *Under the asymmetric Non-track model, (i) when $K_\rho \in (0, K^{al}_\rho(c)]$, both manufacturers take the full reliability effort. (ii) otherwise, both take an economic reliability effort.*

As to asymmetric Mono-track case, considering the thresholds $\overline{K}^a_{II}(K_\theta)$, $\tilde{K}^a_{II}(K_\theta)$ and $\hat{K}^a_{II}(K_\theta)$ are complicated, the definition details are left out here (refer to the Appendix).

Theorem 5. *Assume $K_\rho \in (\overline{K}^a_{II}(K_\theta), +\infty)$ where $K_\theta \in (\bar{g}(\alpha, \beta, \gamma) + \lambda C_r, +\infty)$ under the asymmetric Mono-track model.*

(i) when $K_\theta \in (0, g(\alpha, \beta, \gamma) + \lambda C_r]$, M_1 takes no reliability effort and unit tracking.

(ii) when $K_\theta \in (g(\alpha, \beta, \gamma) + \lambda C_r, \bar{g}(\alpha, \beta, \gamma) + \lambda C_r]$, M_1 takes no reliability effort and economic tracking.

(iii) when $K_\theta \in (\bar{g}(\alpha, \beta, \gamma) + \lambda C_r, +\infty)$ and $K_\rho \in (0, \tilde{K}^a_{II}(K_\theta)]$, M_1 takes full reliability effort and an economic tracking.

(iv) when $K_\theta \in (\bar{g}(\alpha, \beta, \gamma) + \lambda C_r, +\infty)$ and $K_\rho \in (\tilde{K}^a_{II}(K_\theta), +\infty)$, M_1 takes an economic reliability effort and economic tracking.

In any of above four cases, M_2 takes full reliability effort if $K_\rho \in (0, \hat{K}^a_{II}(K_\theta)]$ and an economic reliability effort otherwise.

As to the asymmetric Duo-track model, two thresholds are defined for simplicity: $\overline{K}^a_{III}(K_\theta) = 2x(1 - \frac{1}{2(1-m^2)})\frac{\lambda^2 C_r^2}{K_\theta}(\frac{(2m-1)}{2(1-m)}(c + \frac{g^2}{2K_\theta}) + \frac{1}{2x(1-m^2)}(2(a + \frac{(1+\gamma)g}{K_\theta}) - \frac{1+a+g/K_\theta}{2+\beta} + \frac{(2\alpha+1)(-(2\gamma+1)g/K_\theta+1-a)}{4\alpha+\beta+2}) + \frac{m}{2x(1-m^2)}(2(1 - \frac{\gamma g}{K_\theta}) - \frac{2+g/K_\theta}{2+\beta} + \frac{(2\alpha+1)((2\gamma+1)g/K_\theta+a-1)}{4\alpha+\beta+2})) + 2x(\lambda C_r(1 - \frac{1}{2(1-m^2)}) - \frac{\lambda C_r g}{2(1-m^2)K_\theta} - \frac{m\lambda C_r}{2x(1-m^2)K_\theta}(-2\gamma - \frac{1}{2+\beta} + \frac{(2\alpha+1)(2\gamma+1)}{4\alpha+\beta+2}))^2$, and $\tilde{K}^a_{III}(K_\theta) = 2x(\frac{(2m-1)}{2(1-m)}(c + \frac{g^2}{2K_\theta}) + \frac{1}{2x(1-m^2)}(2(a + \frac{(1+\gamma)g}{K_\theta}) - \frac{1+a+g/K_\theta}{2+\beta} + \frac{(2\alpha+1)(-(2\gamma+1)g/K_\theta+1-a)}{4\alpha+\beta+2}) + \frac{m}{2x(1-m^2)}(2(1 - \frac{\gamma g}{K_\theta}) - \frac{2+g/K_\theta}{2+\beta} + \frac{(2\alpha+1)((2\gamma+1)g/K_\theta+a-1)}{4\alpha+\beta+2}))[\lambda C_r(1 - \frac{1}{2(1-m^2)}) - \frac{\lambda C_r g}{2(1-m^2)K_\theta} - \frac{m\lambda C_r}{2x(1-m^2)K_\theta}(-2\gamma - \frac{1}{2+\beta} + \frac{(2\alpha+1)(2\gamma+1)}{4\alpha+\beta+2})]$.

Theorem 6. *Assume $K_\rho \in (\overline{K}^a_{III}(K_\theta), +\infty)$ where $K_\theta \in (\bar{g}(\alpha, \beta, \gamma) + \lambda C_r, +\infty)$ under the Duo-track model.*

(i) when $K_\theta \in (0, g(\alpha, \beta, \gamma) + \lambda C_r]$, both M_1 and M_2 take no reliability effort and unit tracking.

(ii) when $K_\theta \in (g(\alpha, \beta, \gamma) + \lambda C_r, \bar{g}(\alpha, \beta, \gamma) + \lambda C_r]$, both M_1 and M_2 take no reliability effort and economic tracking.

(iii) when $K_\theta \in (\bar{g}(\alpha, \beta, \gamma) + \lambda C_r, +\infty)$, $K_\rho \in (0, \tilde{K}^a_{III}(K_\theta)]$, both M_1 and M_2 take full reliability effort and an economic tracking.

(iv) otherwise, both M_1 and M_2 take an economic reliability effort and economic tracking.

The main difference is the impact of market potential (parameter a) on the boundaries of the optimal product recall efforts strategies. Interestingly, we find under Duo-track model when either the traceability investment cost coefficient K_θ or the product reliability investment cost coefficient K_ρ is low, two competitive manufacturers take the same product recall efforts strategies even if they are asymmetric in their market potential. Only when both investment cost coefficients are high, their product recall efforts differ and will be affected by such asymmetry. However, the equilibrium tracking decisions for the two competing manufacturers are still (T, T) where both of them track.

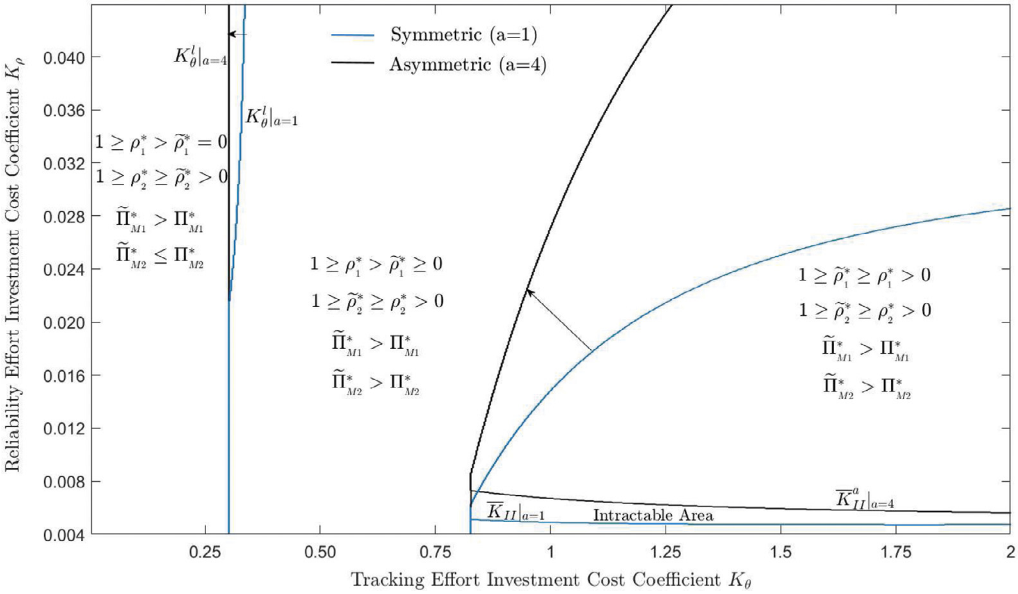


Fig. 9. Comparison of the optimal outcomes under Non-track and Duo-track for two competitive asymmetric manufacturers ($\alpha = 1, \beta = 1, \gamma = 0.5, \lambda = 0.05, C_r = 0.6, c = 0.3$). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

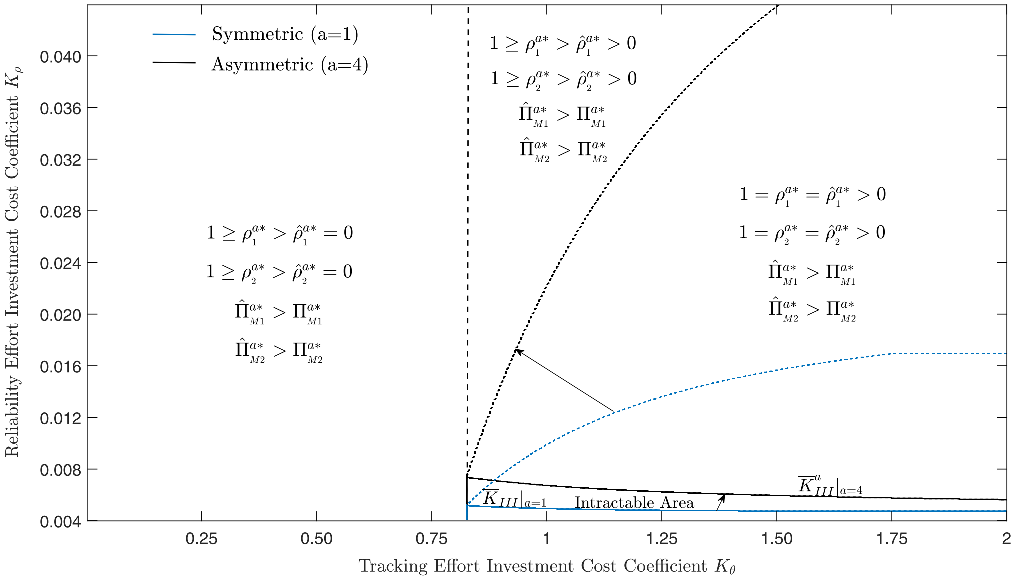


Fig. 10. Comparison of the optimal outcomes under Non-track and Duo-track for two competitive asymmetric manufacturers ($\alpha = 1, \beta = 1, \gamma = 0.5, \lambda = 0.05, C_r = 0.6, c = 0.3$). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

For example, as is shown in Fig. 8, given $K_\rho = 0.032$, even if M_2's optimal profits under Mono-track and Duo-track are both higher with a larger a, its optimal profit under asymmetric Duo-track $\hat{\Pi}_{M2}^{a*}$ is still higher than that under the asymmetric Mono-track $\widetilde{\Pi}_{M2}^{a*}$, which implies that (T, T) is the Nash equilibrium strategy. And under this equilibrium, both $\hat{\Pi}_{M1}^{a*} > \Pi_{M1}^{a*}$ and $\hat{\Pi}_{M2}^{a*} > \Pi_{M2}^{a*}$ hold, regardless of $a \geq 1$. Thus, the original conclusion that Duo-track Pareto improves Non-track preserves in an asymmetric supply chain with a large-size manufacturer and a small-size one. Also, numerical results show that the comparisons of the manufacturers' optimal profits under Non-track, Mono-track, and Duo-track preserve but the thresholds are adjusted by a, e.g., parameter a is set from 1 (blue lines) to 4 (black lines) in Figs. 9 and 10.

6. The impact of traceability competition

In this section, we first give sensitivity analysis on the dividing boundaries of the optimal product recall efforts strategies under each model. Then we focus on examining how the traceability competition intensity parameter influences the competing manufacturers' product reliability efforts as well as their optimal profits.

6.1. Sensitivity analysis on the dividing boundaries

Below is a proposition that presents the sensitivity of the key dividing boundaries to the traceability competition intensity γ.

Proposition 4. *$\hat{K}_{II}(K_\theta)$, $\widetilde{K}_{II}(K_\theta)$, and $\widetilde{K}_{III}(K_\theta)$ are all monotone decreasing in γ.*

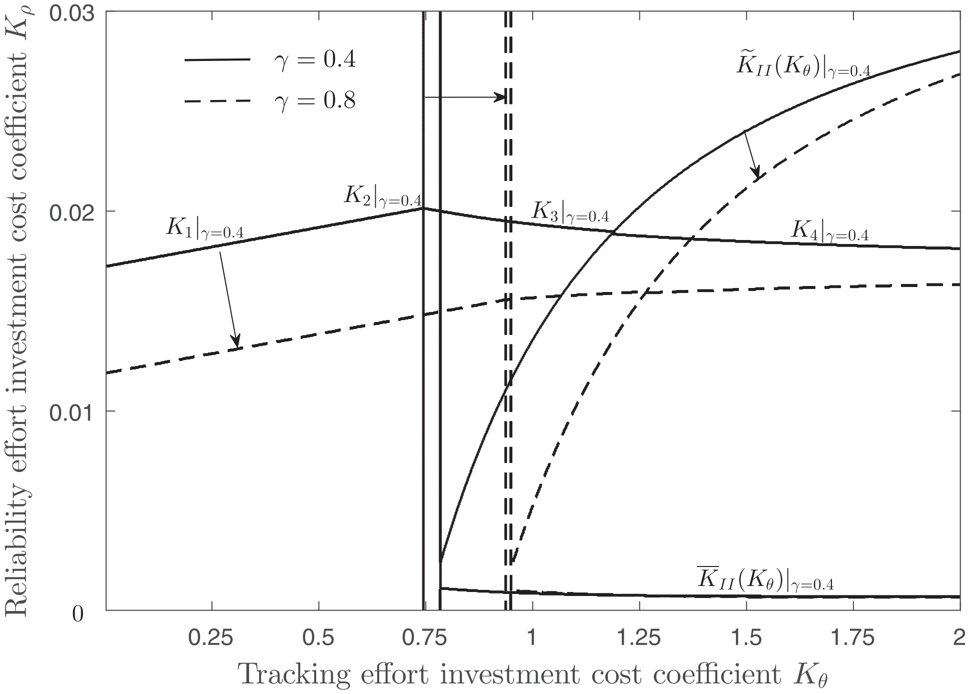


Fig. 11. The impact of tracking capability competition on the dividing boundaries under the model of Mono-track ($\lambda = 0.05, C_r = 0.6, c = 0.3, \alpha = 1, \beta = 1$).

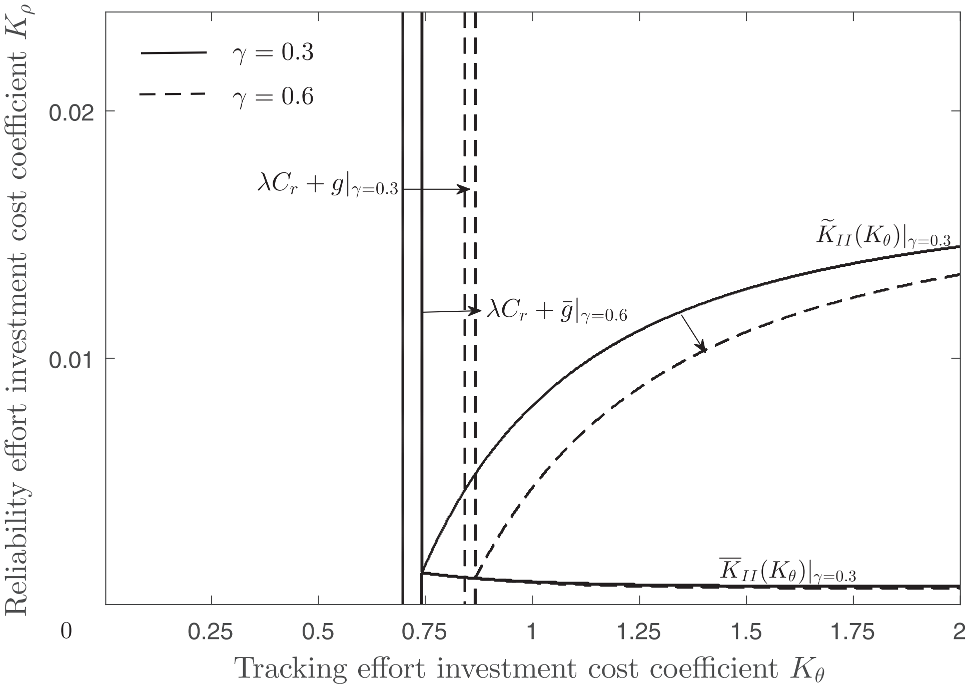


Fig. 12. The impact of tracking capability competition on the dividing boundaries under model of Duo-track ($\lambda = 0.05, C_r = 0.6, c = 0.3, \alpha = 1, \beta = 1$).

As to model of Mono-track where only M_1 exerts tracking effort, the boundary dividing M_1's full or economic product reliability effort strategy and that dividing M_2's both decrease in the traceability competition intensity. This indicates that a higher traceability competition intensity, or a greater consumer's willingness to pay for traceability, will discourage manufacturers from exerting full product reliability effort. Similar results can be derived from the model of Duo-track. Take Figs. 11 and 12 for example, the full line and the dashed line represent the dividing boundaries under a lower (e.g., $\gamma = 0.4$) and a higher (e.g., $\gamma = 0.8$) tracking capability competition intensity, respectively. We find that when γ increases, the real lines will move towards the dashed line. Furthermore, in either Mono-track or Duo-track model, the boundary dividing M_1's strategy of unit tracking and economic tracking strategy, i.e., $\lambda C_r + g(\alpha, \beta, \gamma)$, is monotone increasing in γ. This also implies that fierce product traceability

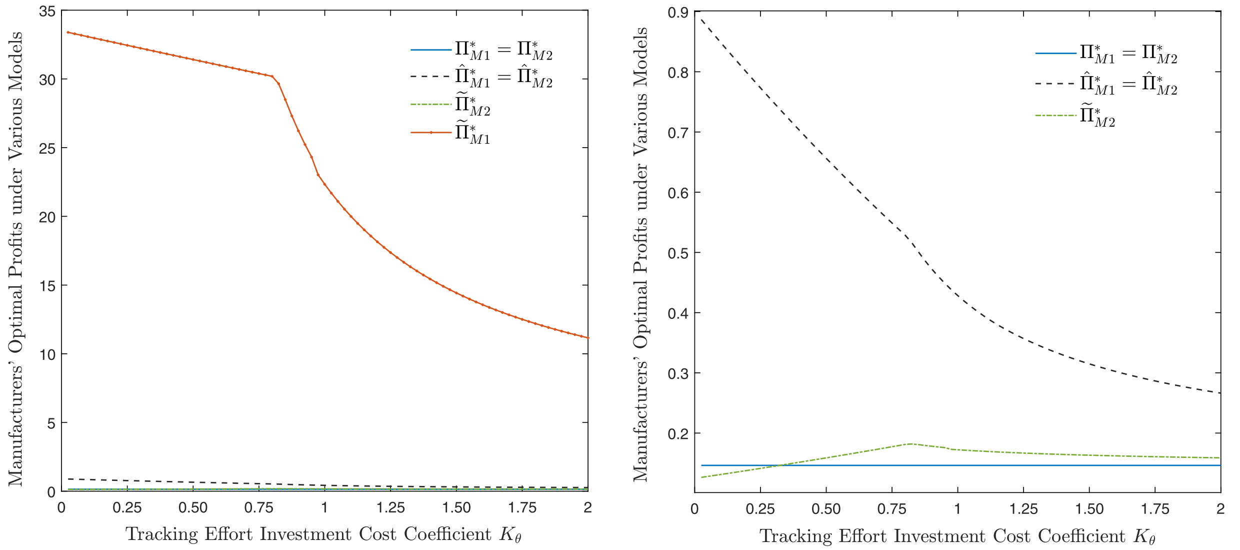


Fig. 13. The impact of tracking capability investment cost on the manufacturers' optimal profits ($\lambda = 0.05, C_r = 0.6, c = 0.3, K_\rho = 0.008, \alpha = 1, \beta = 1, \gamma = 0.5$). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

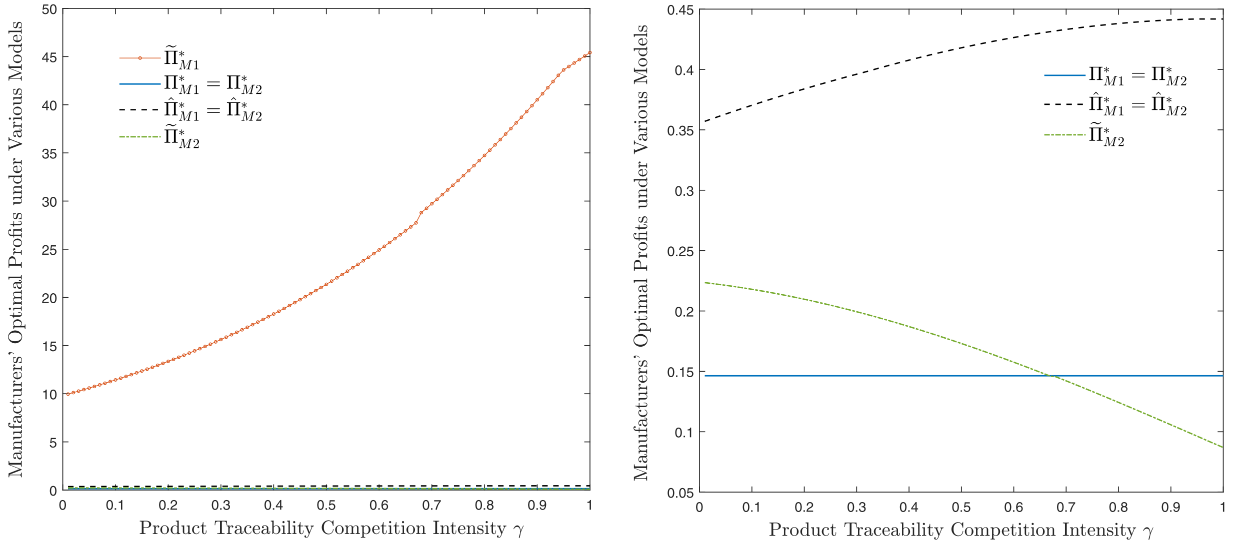


Fig. 14. The impact of tracking capability competition on the manufacturers' optimal profits ($\lambda = 0.05, C_r = 0.6, c = 0.3, K_\rho = 0.008, K_\theta = 1, \alpha = 1, \beta = 1$). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

competition will motivate manufacturers to use unit tracking strategy, equipping every product with advanced tracking devices.

6.2. Sensitivity analysis on the manufacturer's optimal profits

Below is a proposition that states the sensitivity of the manufacturers' optimal profits to key parameters. In order to show the impact of introducing the new tracking technologies, we concentrate on analyzing how their profits change with the tracking effort investment cost coefficient as well as the traceability competition intensity.

Proposition 5. *(i)* $\tilde{\Pi}^*_{M_1}$, $\hat{\Pi}^*_{M_1}$ *and* $\hat{\Pi}^*_{M_2}$ *are all monotone decreasing in* K_θ *except* $\tilde{\Pi}^*_{M_2}$. *When* $K_\theta \le \lambda C_r + g(\alpha, \beta, \gamma)$, $\tilde{\Pi}^*_{M_2}$ *is increasing in* K_θ, *and otherwise,* $\tilde{\Pi}^*_{M_2}$ *is decreasing in* K_θ.

(ii) $\tilde{\Pi}^*_{M_1}$, $\hat{\Pi}^*_{M_1}$ *and* $\hat{\Pi}^*_{M_2}$ *are all monotone increasing in* γ *while* $\tilde{\Pi}^*_{M_2}$ *is monotone decreasing in* γ.

Proposition 5 states the monotonicity of the manufacturer's profit to the tracking capability investment cost coefficient K_θ and the tracking capability competition intensity γ, as is demonstrated by Figs. 13 and 14. It is intuitive that $\tilde{\Pi}^*_{M_1}$, $\hat{\Pi}^*_{M_1}$ and $\hat{\Pi}^*_{M_1}$ are all monotone decreasing in K_θ. But interestingly, we find that $\tilde{\Pi}^*_{M_2}$ first increases and then decreases in K_θ, for example, the green line in Fig. 13. As to γ, $\tilde{\Pi}^*_{M_1}$, $\hat{\Pi}^*_{M_1}$ and $\hat{\Pi}^*_{M_1}$ are all monotone increasing in γ, implying that tracking capability competition intensity will benefit those firms who invest in product traceability. For those who do not track, for example, M_2 under Mono-track, the optimal profit will decrease in γ, which is shown as the green line in Fig. 14. This indicates the free-rider effect from M_1's investment in tracking will disappear when the product traceability competition intensity is very high, i.e, when consumers' willingness to pay for product traceability is very strong. The gap of M_2's optimal profits under Mono-track and Duo-track will be larger as the traceability competition intensifies, and thus the unique tracking equilibrium (T, T) will not be affected. These results provide more insights into comparisons of the optimal outcomes under various models summarized in Propositions 1 and 2.

7. Conclusions

With the advancement of blockchain and RFID technology, the traceability system has been an important supply chain feature aiming to resolve the product recall issue. Unlike traditional quality improvement initiatives such as efforts to improve the product reliability, which can help reduce the probability of product recall events, supply chain traceability can help reduce the proportion of recalled products that cannot be identified as safe given a product recall event. Furthermore, the traceability system investment costs in practice are the variable costs to equip a device on each product, while the product reliability investment cost is usually a fixed setup cost. As such, the efficiency of managing a recalling supply chain is jointly determined by the interactions of the traceability and product reliability optimization. In this paper, using a game theoretical model that captures the interactions of two manufacturers, two retailers and consumers, we study the interactions of the product reliability effort and tracking capability optimization in the recalling supply chain considering both upstream traceability competition and downstream channel competition. We find the optimal product reliability effort and tracking capability under various tracking models of Non-track, Mono-track and Duo-track. Then, we investigate two competing manufacturers' equilibrium tracking strategies under various traceability investment cost coefficient. Lastly, we discuss the impact of competition and asymmetry on the manufacturers' tracking strategies.

Three major findings and implications are concluded in three aspects. First, for competitive manufacturers who both consider tracking capability, there exists a unique optimal product reliability effort, tracking capability and wholesale price with closed-form expressions. We find that tracking capability is always of necessity, however, no product reliability effort will be exerted when the tracking capability investment cost coefficient is low enough. Additionally, when it is sufficiently high but the product reliability investment cost coefficient is relatively low, full product reliability effort is suggested. Otherwise, the manufacturer will exert an economic product reliability effort and economic tracking capability. Second, the interactions of traceability optimization and product reliability optimization depends on the investment cost coefficient of traceability and product reliability. When the tracking capability investment cost coefficient is low, tracking capability can fully substitute the product reliability effort but may improve the product reliability when it is high and the product reliability investment cost coefficient is low. Furthermore, we find that for the manufacturer whose competitor takes product reliability effort only, it prefers to track. Interestingly, we find the investment in the tracking capability may benefit his competitor when the tracking effort investment cost coefficient is large enough. Third, the competition of tracking capability reduces the upper thresholds for the strategy of no reliability effort with unit tracking and the strategy of full reliability effort with an economic tracking. The profit of the manufacturer who invests on tracking capability is increasing in the competition intensity of tracking capability. Lastly, we find the structures of optimal product reliability and tracking efforts for both competitive manufacturers still hold even when they are asymmetric, and the Duo-track pareto improves Non-track as well.

As the first attempt at understanding the interactions of traceability and reliability optimization under both upstream and downstream competition, with realization of works in this paper, our research can be further extended in the following aspects: (1) optimize the supply chain product recall efforts and price under shared recall costs; (2) instead of the wholesale price contract, optimize the supply chain product recall efforts and price under other supply chain contracts or the game sequence of a leading retailer; (3) consider the involvement of upstream suppliers on designing the supply chain tracking capability.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ejor.2020.08.003.

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