European Journal of Operational Research

Implications of Coproduction Technology on Waste Management: Who Can Benefit from the Coproduct Made of Leftover Materials?

--Manuscript Draft--

Manuscript Number:	EJOR-D-21-02246R2
Article Type:	Theory and Methodology Paper
Section/Category:	(T) Supply chain management
Keywords:	Supply chain management; Waste Management; coproduction technology; green consumption; Environmental protection
Corresponding Author:	Yu Zhou Chongqing University Chongqing, CHINA
First Author:	Minyue Jin
Order of Authors:	Minyue Jin
	Baoyong Li
	Yu Xiong
	Ratula Chakraborty
	Yu Zhou
Abstract:	In recent years, coproduction technology has been developed and adopted by many third-party coproduct manufacturers (CMs). Coproducts made of leftover materials from traditional manufacturing are strongly attractive to green consumers who are willing to pay a price premium for environmental protection. However, original equipment manufacturers (OEMs) might hesitate to adopt coproduction technology because the coproduct cannibalizes the sales of their traditional products. In this paper, we develop a game-theoretical model to investigate the economic and environmental implications of coproduction that can be leveraged by one OEM or one CM. We find that from the OEM's perspective, the dominant strategy can be OEM coproduction, CM coproduction, or No coproduction, which is contingent on the demand from green consumers and the supply of raw materials. We also find that the size of green consumers and the unit cost of raw materials have non-monotone impacts on the CM's profit. Interestingly, an enlarging size of green consumers might hurt the CM, while an increasing cost of raw materials might benefit the CM. Although coproduction recovers the value of leftover materials, the adoption of coproduction technology increases the total material consumption and the total material waste when the unit cost of raw materials is sufficiently high, making the environment worse off.
Suggested Reviewers:	
Opposed Reviewers:	

Implications of Coproduction Technology on Waste Management: Who Can Benefit from the Coproduct Made of Leftover Materials?

Minyue Jin[a,b], Baoyong Li[a], Yu Xiong[c], Ratula Chakraborty[d], Yu Zhou[a,b,*]

[a] School of Economics and Business Administration, Chongqing University, Chongqing, China
[b] Chongqing Key Laboratory of Logistics at Chongqing University, Chongqing, China
[c] Surrey Business School, University of Surrey, Surrey, United Kingdom
[d] Norwich Business School, University of East Anglia, Norwich, United Kingdom
[*] Corresponding author. Email: zhouyu@cqu.edu.cn; Postal address: 174 Shazhengjie, Shapingba, Chongqing, 400044, China; Tel: 0086 13883305292.

Abstract

In recent years, coproduction technology has been developed and adopted by many third-party coproduct manufacturers (CMs). Coproducts made of leftover materials from traditional manufacturing are strongly attractive to green consumers who are willing to pay a price premium for environmental protection. However, original equipment manufacturers (OEMs) might hesitate to adopt coproduction technology because the coproduct cannibalizes the sales of their traditional products. In this paper, we develop a game-theoretical model to investigate the economic and environmental implications of coproduction that can be leveraged by one OEM or one CM. We find that, from the OEM's perspective, the dominant strategy can be OEM coproduction, CM coproduction, or No coproduction, which is contingent on the demand from green consumers and the supply of raw materials. We also find that the size of green consumers and the unit cost of raw materials have non-monotone impacts on the CM's profit. Interestingly, an enlarging size of green consumers might hurt the CM, while an increasing cost of raw materials might benefit the CM. Although coproduction recovers the value of leftover materials, the adoption of coproduction technology increases the total material consumption and the total material waste when the unit cost of raw materials is sufficiently high, making the environment worse off.

Key words: supply chain management; waste management; coproduction technology; green consumption; environmental protection

---

1. Introduction

Despite increasing efficiency and resource utilization, raw material wastage is still endemic in much of manufacturing, especially in industries demanding exacting standards from natural resources (such as wood, stone, and leather). Due to specific requirements for raw materials in terms of texture, color, and density, many products only use raw materials whose quality exceeds a certain conventional standard, and the remaining low-quality materials are simply discarded. For example, in the musical instrument industry, black ebony is the best material for making some high-end products, yet most ebony trees are variegated, resulting in only one-tenth of the ebony trees being actually used for production in order to ensure the products possess purity in color. However, the accelerated depletion of natural resources in recent decades is making such practices economically unsustainable as well as environmentally harmful.

With rising public consciousness about environmental protection, more consumers want environmentally friendly products, even if this entails a trade-off between paying a premium price and accepting reduced quality. Accordingly, products made from leftover materials of high-end counterparts, although they are not perfect in terms of look and function, may still be attractive to many consumers because of their green property, i.e., saving raw materials.[1] In fact, a McKinsey report showed that more than 70% of consumers were willing to pay at least 5% extra for environmentally-friendly products (Miremadi et al., 2012). This presents an opportunity for manufacturers to utilize leftover materials for production and capture value from green consumption.

In this study, coproduction technology is defined as an innovative approach for using common raw materials to manufacture products with vertical differentiation in the quality dimension. It allows "a firm to make coproducts out of materials that would otherwise be discarded and, hence, to tap into the green consumer segment of the market" (Lin et al. (2020), Lin et al. (2021), and Hilali et al. (2022)). Taking consumers' environmental awareness into consideration, Lin et al. (2020) optimize the internal coproduction within a single firm. That is, in addition to the production of traditional products, the manufacturer uses its own leftover materials to produce low-quality substitutes that are favored by some green consumers. For instance, Taylor Guitars, as a top acoustic guitar manufacturer, had always selected the best ebony materials to make the fretboards. In 2014, Taylor Guitars abandoned this unsustainable practice and began to use ebony of various colors in the manufacturing process, thereby simultaneously producing guitars at different levels of quality.[2]

But not all original equipment manufacturers (OEMs) are willing to conduct in-house coproduc-

---

[1] See the report from Mintel, http://www.mintel.com/press-centre/social-and-lifestyle/are-americans-willing-to-pay-more-green-to-get-more-green.

[2] See the report from Acoustic Guitar, https://acousticguitar.com/the-ebony-project-taylor-guitars-plants-trees-in-cameroon-to-preserve-this-vulnerable-tonewood/.

tion like Taylor Guitars. In-house co-production carries the risk of harming brand reputation built on the customer promise of only using the very finest raw materials and components while ensuring manufacturing is to the very highest standards. It also carries the risk of increasing production costs, raising manufacturing complexity, and losing economies from specialization when having to adapt production methods to make different product qualities. Accordingly, due to a combination of brand position, process technology, and production costs, many manufacturers would rather discard their leftover materials than making use of them. In such a context, third-party coproduction, undertaken by specialists in using leftover materials, has emerged as an alternative means to develop the potential value of such otherwise wasted materials.

A typical example of third-party coproduction occurs in the luxury goods industry. It is well known that the production of luxury goods will produce a large number of leftover materials. Considering that the production of low-quality products will seriously damage brand reputation, luxury goods producers avoid using inferior leftover materials. To reduce waste and recover the value of these materials, in 2018, a French designer, Virginie Ducatillon, established Adapta, whose main business is to collect leftover materials from luxury brands and resell them at fair prices to low budget designers.[3] Meanwhile, LVMH, a leading luxury brand, also launched an online platform – Nona Source – to sell its leftover materials.[4]

Examples of material saving through third-party coproduction also exist in other industries. For instance, traditional furniture manufacturers produce a large amount of wood chips in the process of making high-quality solid-wood furniture. In the United States alone, hundreds of millions of tons of wood waste are generated every year, and most of these wastes go to landfills. In 2019, Forust, a start-up firm based in San Francisco, developed a 3D-print technology for using wood wastes to make furniture. This technology combines wood chips and a nontoxic binder to create the grain of wood layer by layer.[5] For traditional furniture manufacturers, it is an obviously environmentally-friendly practice to collect the wood chips from their production process and sell them to the 3D-print firm, Forust.

Coproduction technology has been quickly developing in recent years. Nevertheless, it is somewhat unclear whether it is profitable for OEMs to sell their leftover materials to third-party coproduct manufacturers (CMs). Specifically, coproducts made from leftover materials will compete with

---

[3] See the report from Maddyness, https://www.maddyness.com/2020/03/26/maddypitch-adapta/.

[4] See the report from LVMH, https://www.lvmh.com/news-documents/news/lvmh-presents-nona-source-the-first-online-resale-platform-for-materials-from-lvmh-fashion-leather-goods-maisons/.

[5] See the report from FastCompany, https://www.fastcompany.com/90632358/we-can-3d-print-wood-now.

traditional products in the market; so the sales of leftover materials may cannibalize the highly profitable sales of traditional products from the perspective of OEMs. However, if an OEM chooses to coproduce by itself, its brand reputation might be negatively affected. Nevertheless, if the OEM directly discards leftover materials without coproduction, no competition and reputation damage occur, but there may be a missed profit opportunity. Thus, considering the potential damage to brand reputation and the unexploited value of leftover materials, should OEMs be involved in coproduction by themselves? Alternatively, when approached by a third-party CM, such as Adapta or Forust, should OEMs sell their leftover materials? These are the first set of questions we attempt to answer in this paper.

Next, provided that coproduction technology is leveraged by the OEM or the CM, we are interested in optimizing the decisions on coproduction and analyzing its economic performance. Recently, the COVID-19 pandemic has disrupted global markets. Volatile raw material prices have posed distinct challenges for all manufacturers around the world. How are the optimal decisions and profits sensitive to the raw material price in the presence of coproduction? In addition, it is documented that some green consumers are willing to pay a price premium for environmentally-friendly products, such as the coproduct. Thus, how are the optimal decisions and profit shaped by the structure and composition of market demand, i.e., the proportion of green consumers and the magnitude of the price premium willing to be paid? This paper also aims to answer these questions.

Finally, we examine the impact of coproduction on the environment. Coproduction leverages the value of leftover materials, reducing the waste of raw materials, but still might not eliminate all waste as a portion of raw materials might be discarded even in the coproduction process, when quality falls below a necessary minimum threshold. Furthermore, the sales of the coproduct can reduce the production cost of the traditional product from the OEM's perspective, effectively serving as a subsidy, and hence it might encourage the OEM to increase the production quantity of the traditional product, consuming more raw materials. As a consequence, the overall impact of coproduction on the environment is a *priori* unclear.

In this paper, we develop a game-theoretical model to investigate the implications of coproduction technology on waste management. The OEM plays a leading role in the game by firstly choosing the coproduction strategy: No coproduction under which the OEM produces and sells only the traditional product, OEM coproduction under which the OEM produces and sells both the traditional product and the coproduct, and CM coproduction under which the OEM produces and sells the traditional product, and the CM sells the coproduct made of leftover materials from the OEM.

The market consists of traditional consumers and green consumers. Green consumers differ from traditional ones in that they are willing to pay a price premium for the environmentally-friendly property of the coproduct.

We summarize the main results of this paper as follows. First, we identify the conditions where each coproduction strategy is the best choice for the OEM. Specifically, we find that the OEM's optimal coproduction strategy depends greatly on the demand from green consumers. If the fraction of the green consumer segment is small, coproduction is not profitable for the OEM, and then the OEM should choose No coproduction. Otherwise, coproduction is profitable. If the fraction of the green consumer segment is large, the OEM should choose OEM coproduction to monopolize the benefit of coproduction. If the fraction of the green consumer segment is moderate, the OEM should choose CM coproduction to avoid reputation damage. More interestingly, the unit cost of raw materials has a non-monotone impact on the OEM's optimal coproduction strategy. Thus, the OEM should carefully examine the market demand and the material supply to make the right choice on coproduction.

Second, we find that although the market demand and the material supply have straightforward impacts on the OEM's profit, their impacts on the CM's profit can be counterintuitive. With an enhanced demand from green consumers, the CM's profit might discontinuously drop to zero because the OEM's optimal strategy switches from CM coproduction to OEM coproduction. Conventional wisdom might suggest that an increasing unit cost of raw materials raises the CM's production cost and hence hurts the CM. However, the analysis shows that the CM's profit can increase in the material cost because the increasing cost negatively affects the competing OEM to a greater extent. These results highlight the differences between traditional manufacturing and innovative coproducing. More studies in the future are promising for the development of coproduction technology.

Third, we prove that coproduction is not always beneficial to the environment. In particular, when the unit cost of raw materials is sufficiently high, coproduction increases not only the total material consumption but also the total material waste. In this case, the material constraint on coproduction is binding; that is, all leftover materials are used for coproduction. The prospect of making a massive profit from the sales of the coproduct provides a strong incentive for the OEM to boost the output of the traditional product, leading to more material consumption and waste. Moreover, we find that coproduction might become more detrimental to the environment as more consumers are willing to pay the price premium for the coproduct. Therefore, social planners should be cautious when promoting the implementation of coproduction technology to deal with waste management.

The rest of this paper is organized as follows. The next section reviews the relevant literature. Section 3 presents the model for our study. Section 4 provides the subgame prefer equilibria for the OEM's coproduction strategy. Section 5 discusses the economic and environmental implications of coproduction. Section 6 concludes the paper with managerial insights and suggested directions for future research. The online appendices contain all mathematical proofs.

2. Literature review

Our work contributes to two streams of literature: (1) coproduction technology economy and management, and (2) waste management and environmental regulations. In what follows, we delineate the position of this work in the relevant literature and discuss our academic contributions.

2.1. Coproduction technology economy and management

Coproduction technology is an innovative approach to enhancing a firm's profitability and benefiting the environment. Adopting coproduction technology, one firm can produce a low-quality product from leftover materials of a high-quality product. The literature on operations and supply chain management has studied the issue of coproduction technology for decades.

Earlier studies examine the value of coproduction technology, focusing on production flexibility that is valuable in the presence of demand or quality uncertainty; they typically take the product line and the prices as given, and optimize downward substitution whereby the demand for a low-quality product could be satisfied by a high quality product at the low-quality price (Bitran and Leong (1992), Bitran and Gilbert (1994), Gerchak et al. (1996), Hsu and Bassok (1999), and Rao et al. (2004)). Tomlin and Wang (2008) consider a single-period, two-product problem and jointly solve the product pricing and quality allocation problem, finding that demand management is more profitable than supply management in the coproduction system.

Recently, studies on coproduction technology have paid more attention to product line design. For example, Chen et al. (2013) investigate the product line design and process innovation decisions of a monopoly firm that adopts coproduction technology. Bansal and Transchel (2014) analytically study the supply-demand mismatches in the coproduction system, highlighting that the fraction of high-quality products in the line plays a critical role in the optimal strategy. Chen et al. (2017) consider a system in which the coproducts differ vertically or horizontally, and characterize the optimal price and quantity decisions of the system.

Some of the most recent studies have extended the issue of coproduction technology into the setting of supply chain management. For example, Lu et al. (2019) optimize product line design when a manufacturer sells its coproducts through an independent retailer to quality-sensitive consumers. Peng et al. (2020) investigate how to mitigate the mismatch risk in a supply chain with coproduction technology.

The environmental implications of coproduction technology have increasingly attracted researchers' attention. Sunar and Plambeck (2016) consider a market in which the sales of a traditional product incur an emission cost while the sales of a coproduct do not, and examine three candidate rules for the allocation of emissions between the two kinds of products. Lin et al. (2020) optimize a monopoly firm's product line decisions when consumers value the resource conservation enabled by coproduction technology, and find that a greener market may inadvertently result in higher resource consumption and waste.

The existing literature only considers the coproduction technology adopted by the manufacturer of the traditional product. In this paper, motivated by the examples from many industries, we make the first attempt to investigate third-party coproduction, that is, the traditional product and the coproduct are produced by two different manufacturers. One traditional manufacturer sells its leftover material, from which the other manufacturer produces the coproduct. In this sense, the two manufacturers form a supply chain with third-party coproduction technology. Our analysis characterizes the impacts of coproduction technology on the traditional manufacturer's profit and the industry's environmental performance, which, to our knowledge, is novel to the literature on coproduction technology. Moreover, following the assumption of Lin et al. (2020), we take consumers' environmental valuation on the coproduct into consideration. However, unlike Lin et al. (2020), we endogenously examine the market competition between the traditional product and the coproduct, and analytically provide the optimal wholesale price of leftover material in the supply chain with coproduction.

Under CM coproduction, our model shares some similar features with the typical dual-channel model in the literature, e.g., Chiang et al. (2003), Arya et al. (2007), Li et al. (2019), Jiang and He (2021), and Zhang et al. (2022). Specifically, in a sense, the OEM sells the traditional product in a direct channel, and sells its leftover materials in an indirect channel (via the CM). Nevertheless, our model captures the inherent difference for a coproduction system in three aspects. First, the literature on dual-channel design typically assumes that the retailer has a remarkable cost advantage in selling, and investigates whether the manufacturer should establish the direct channel; but in our model, the OEM's principal business is to sell the traditional product, and the sale of leftover materials is a possible strategy under consideration for the enhancement of the OEM's profit. Second, in a dual-channel supply chain, the manufacturer is able to determine the quality levels of two products sold in the two channels; but with CM coproduction, the quality of the coproduct made of leftover materials is exogenously decided by the CM's technology. Finally, the optimal quantities of the two products in the two channels are independent of each other in the dual-channel literature; yet, in our study, the material constraint on coproduction plays a critical role in shaping the equilibrium outcome. Therefore, our work differs significantly from the existing literature with the dual-channel model.

2.2. Waste management and environmental regulations

In the research field of waste management, many studies consider the competition between green manufacturers whose products are environmentally friendly, e.g., Yalabik and Fairchild (2011), Li et al. (2012), Yu et al. (2016), Bi et al. (2017), and Yang et al. (2021). They assume a symmetrically competitive industry in which manufacturers are equally capable of developing green products. Moreover, some other papers, e.g., Galbreth and Ghosh (2013), Zhou (2018), and Kleber et al. (2020), investigate the asymmetric competition between manufacturers who have different capabilities to develop a green product; in their models, not all consumers are willing to pay for the environmental attribute of the green product. Our work extends this stream of literature by considering the competition between one OEM and one CM, and attempts to reveal the implications of coproduction technology on waste reduction.

Waste management can also be a new approach for profit enhancement. For example, Liu et al. (2019), Esenduran et al. (2020), and Yang et al. (2022) investigate how to optimize the waste recycling system, including recycling standards, recycling capacities, and information management. To divert waste from landfills, He et al. (2019), Wang et al. (2020), and Zhang et al. (2021) develop game theoretical models to improve the operating efficiency of reverse logistics.

Furthermore, OEMs in many countries are required by environmental regulations to manage their waste. Atasu and Subramanian (2012) investigate the economic and environmental implications of collective and individual producer responsibility. Jacobs and Subramanian (2012) examine responsibility sharing within a supply chain under product recovery mandates. Atasu et al. (2013) study E-waste take-back legislation from the perspectives of different stakeholders, including manufacturers, consumers, and the environment, and identify each stakeholder's preference. Wen et al. (2019) develop a multi-agent simulation model and examine the impact of quality regulation on the performance of a closed-loop supply chain with remanufacturing. Mazahir et al. (2019) analyze different forms of E-waste legislation and compare their economic and environmental implications.

The classical literature on economics routinely shows that the new competition from a third party enlarges the total production quantity, which is detrimental to the incumbent's profit as well as to the environmental performance. However, in this study, third party coproduction, by leveraging the residual value of leftover materials wasted by the OEM, can be beneficial to not only the OEM's profit but also the environmental performance. In this stream of literature, the study of third-party remanufacturing is probably the closest to this paper. Third-party remanufacturing refers to that an independent remanufacturer collects used products produced by OEMs to produce remanufactured products. The remanufactured product is typically a low-quality substitute to the new product. The relevant literature argues that third-party remanufacturing cannibalizes the sales of the new product, and hence OEMs should deter the entry of third-party remanufacturing, e.g., Majumder and Groenevelt (2001), Debo et al. (2005), Ferguson and Toktay (2006), Ferrer and Swaminathan (2010), and Örsdemir et al. (2014). However, in recent years, some studies have demonstrated that third-party remanufacturing might be beneficial to OEMs. Wu and Zhou (2016) find that for competing OEMs, the entry of third-party remanufacturers can mitigate the intensity of market competition and then increase their profits. Jin et al. (2017) show that third-party remanufacturing can reduce the negative impact of double marginalization within the forward supply chain. Wu and Zhou (2019) consider a closed-loop supply chain in which one supplier sells a key component that cannot be remanufactured, and demonstrate that regardless of the wholesale pricing policy, third-party remanufacturing can lead to a triple win for all firms in their model.

In this paper, we focus on the economic and environmental implications of third-party coproduction that shares many common characteristics with third-party remanufacturing. However, from the perspective of theoretical modeling, we find that they are significantly different. Remanufacturing recovers the residual value of end-of-use products, and hence the quantity of the remanufactured product is constrained by the output of the original product, in other words, how many materials are used in original manufacturing. Coproduction technology makes use of leftover material of the original product; that is, the quantity of the coproduct is constrained by the materials that are not used in original manufacturing.

This critical difference induces us to reconsider the optimal management strategy for third-party coproduction. We find that the OEM can benefit from third-party coproduction. Moreover, surprisingly, the CM's profit might be increasing in the unit cost of raw materials. We also consider consumers' environmental awareness, and find that consumers' higher willingness-to-pay for the coproduct can lower the CM's profit and worsen the industry's environmental performance. These findings reveal the interesting implications of third-party coproduction for the first time and enrich our understanding of waste management and environmental regulations.

3. Model description

In this paper, we develop a game-theoretic model to investigate the interaction between one OEM and one CM. The OEM uses raw materials in production. The quality of raw material is measured by its physical attribute, which can be vertically differentiable (Lin et al. (2020)). In preserving its brand reputation and its production specialization, the OEM only uses a portion of the raw material whose quality exceeds a conventional standard to produce a guaranteed high-quality traditional product. Therefore, the leftover material is a waste of the production process of the traditional product.

The development of coproduction technology enables the utilization of the leftover material to produce a lower-quality but perceived environmentally-friendly coproduct (Chen et al. (2013), Chen et al. (2017), and Lu et al. (2019)). The coproduct has a quality level that is below the conventional standard and uses the raw material with quality between the lowest acceptable-minimum level and the conventional standard (which is the minimum level for the traditional product). We assume the quality of the raw material x is uniformly distributed over the interval $[0, 1]$.[6] Let x_t denote the conventional standard for the production of the traditional product, and x_c the lowest quality level for the production of the coproduct. Thus, for one unit of the raw material, the high-end part with quality $[x_t, 1]$ will be used in the traditional product, the middle part with quality $[x_c, x_t]$ will be used in the coproduct, and the low-end part with quality $[0, x_c]$ will be wasted. Without loss of generality, we assume that the residual value of unused material is 0. Figure 1 graphically illustrates the industry structure and raw material utilization.

Coproduction technology can be leveraged by either the OEM or the CM. However, it is the OEM who fully controls leftover materials. Thus, we assume that the OEM plays a leading role in deciding the coproduction strategy. Consistent with the practical examples, the OEM has three possible choices. First, the OEM can make the coproduct by itself and sells both the traditional product and the coproduct, which we refer to as the strategy of OEM coproduction. For example,

---

[6] Following the assumption of Lin et al. (2020), we examine an extension based on a general distribution of quality. We find that the main results of this paper are qualitatively preserved. Please see Appendix C for details.

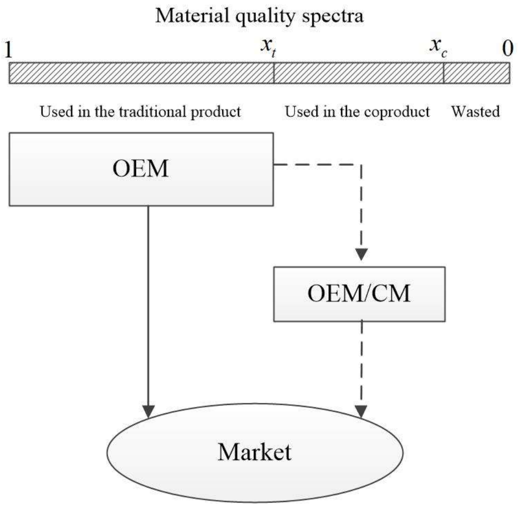


Figure 1: The industry structure and raw material utilization

the top acoustic guitar manufacturer, Taylor Guitars, is involved in coproduction. Second, the OEM can allow the CM to make the coproduct by selling leftover materials to the CM, which we refer to as the strategy of CM coproduction. For example, the leading luxury brand, LVMH, sell its leftover materials to independent designers. Third, the OEM can prevent coproduction by wasting leftover materials, which we refer to as the strategy of No coproduction.

Following the relevant literature on green consumption, e.g., Kotchen (2006), Yenipazarli and Vakharia (2015), Zhou et al. (2021), and Jin et al. (2022), we assume that the market is heterogeneous and consists of two segments: traditional consumers who are willing to pay only for private-good quality of a product, and green consumers who are willing to pay additional for public-good quality of a product to protect the environment. Without loss of generality, we normalize the market size to 1. Let ϕ denote the fraction of the green consumer segment, and hence the fraction of the traditional consumer segment is $1-\phi$. The firms know the distribution of two segments, but do not know the type of one individual consumer. Each consumer buys at most one unit of the product to maximize her/his net utility.

Let $p_t(p_c)$ and $q_t(q_c)$ be the selling price and the selling quantity of the traditional (co-) product, respectively. Consistent with the literature on quality management, e.g., Yalcin et al. (2013), Reimann et al. (2019), and Yu et al. (2021), we assume that the marginal consumer valuation of quality v is distributed uniformly over $[0,1]$. All consumers obtain a net utility of $\Delta x_t v - p_t$ from the consumption of one traditional product. Considering the possibility that the extension of the product line with a low-quality coproduct damages the OEM's reputation (Randall et al. (1998), Amaldoss and Jain (2015), and Song et al. (2022)), we assume that $\Delta = \delta$ in the presence of OEM coproduction, and $\Delta = 1$ in the absence of OEM coproduction. Here, $\delta \in (0, 1)$ captures the magnitude of reputation damage. From the consumption of coproduct, traditional consumers can obtain a net utility of $x_c v - p_c$ and green consumers can obtain a net utility of $x_c v + (x_t - x_c)\,\theta - p_c$. The utility functions of traditional and green consumers for the coproduct have been developed in the literature (Lin et al. (2020)). The quality differential $x_t - x_c$ captures the magnitude of environment protection, that is, the greater the quality difference is, the less materials are wasted. The parameter θ indicates the price premium that green consumers are willing to pay for environment protection. However, it is worth noting that the traditional product always has a higher quality than the coproduct, i.e., $x_t > x_c$. Thus, green consumers may still obtain a higher net utility from the consumption of traditional products, i.e., $x_t v - p_t > x_c v + (x_t - x_c)\,\theta - p_c$.

From the optimization of the consumption utility, we derive the following linear inverse demand functions (see Appendix B for the derivation):

$$p_t(q_t, q_c) = \Delta x_t(1 - q_t) - x_c q_c, \tag{1}$$

$$p_c(q_t, q_c) = x_c(1 - q_t - q_c) + (x_t - x_c)\phi\theta. \tag{2}$$

We assume the following sequence of events in the game between the OEM and the CM, as shown in Figure 2. First, the OEM makes a choice on the coproduction strategy: No coproduction, OEM coproduction, or CM coproduction.[7] Second, contingent on the OEM's coproduction strategy, we have three subgames. In the subgame under No coproduction, we have the production quantity of the coproduct always equal to zero, and the OEM decides on the production quantity of the traditional product. In the subgame under OEM coproduction, the OEM decides on the production quantities of the two products. In the subgame under CM coproduction, the OEM decides on the production quantity of the traditional product and the wholesale price, w, of the leftover material to the CM, and then the CM decides on the production quantity of the coproduct. Finally, consumers make their purchase decisions, and firms obtain their profits. The sequence of events implies that the OEM plays the role of a Stackelberg leader in the interaction with the CM. This is consistent with practice because the wholesale price of the OEM's leftover material is one of the most critical determinants of whether third-party CM will produce the coproduct. The Stackelberg

---

[7] We also consider a mixed strategy under which the OEM and the CM make the coproduct simultaneously. A casual analysis shows that such a strategy is always suboptimal for the OEM because both reputation damage and new competition will occur.

leader position of the OEM also reflects its gatekeeper role, in that the CM can only operate if the OEM is willing to supply leftover materials (e.g., due to the OEM having exclusive access to the critical raw material arising from unique knowhow or contractual monopsony control).

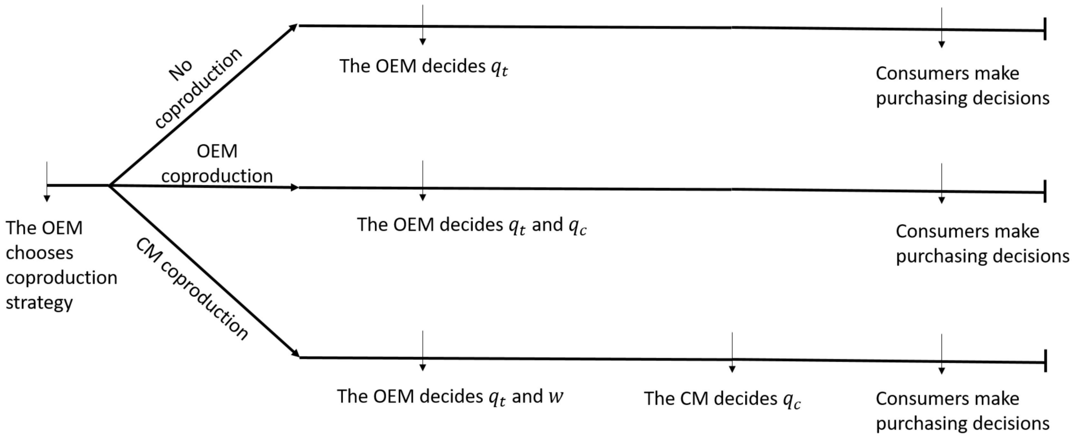


Figure 2: The sequence of events

Following most literature on operations and supply chain management (Wu et al. (2013), Arya and Mittendorf (2015), and Nie et al. (2021)), we assume that all firms are risk-neutral and aim to maximize their own profits. Thus, under No coproduction, the OEM's profit function is

$$\Pi_{OEM}^{N} = (p_t - d)\, q_t - c\frac{q_t}{1-x_t}. \tag{3}$$

Under OEM coproduction, the OEM's profit function is

$$\Pi_{OEM}^{O} = (p_t - d)\, q_t + (p_c - d)\, q_c - c\frac{q_t}{1-x_t}, s.t. \frac{q_c}{x_t - x_c} \leq \frac{q_t}{1-x_t}. \tag{4}$$

Under CM coproduction, the OEM's profit function is

$$\Pi_{OEM}^{C} = (p_t - d)\, q_t - c\frac{q_t}{1-x_t} + w\frac{q_c}{x_t - x_c}, \tag{5}$$

and the CM's profit function is

$$\Pi_{CM}^{C} = (p_c - d)\, q_c - w\frac{q_c}{x_t - x_c}, s.t. \frac{q_c}{x_t - x_c} \leq \frac{q_t}{1-x_t}. \tag{6}$$

Note that the superscript $i \in \{N, O, C\}$ indicates No coproduction, OEM coproduction, and CM coproduction, respectively, the parameter c denotes the unit cost of the raw material, and the parameter d denotes the unit production cost. The raw material used in the traditional product is $\frac{q_t}{1-x_t}$, and the raw material used in the coproduct is $\frac{q_c}{x_t - x_c}$. The raw material that can be used in the coproduct is constrained by the traditional manufacturer's leftover material (Chen et al.

(2013), Peng et al. (2020), and Lin et al. (2020)). Therefore, when engaging in coproduction, the firm must consider the constraint that $\frac{q_c}{x_t - x_c} \leq \frac{q_t}{1-x_t}$.

4. Analysis

In this section, provided that the OEM selects a certain coproduction strategy, we derive the subgame perfect equilibrium. The sensitivity analysis reveals that the key parameters of our model can have non-monotone impacts on the optimal decisions.

4.1. No coproduction

Under No coproduction, the CM does not enter the market, and the OEM is a monopolist that sells only the traditional product. Substituting $q_c^N = 0$ into Equation 1, we obtain the inverse demand function for the traditional product in this subgame.

It is clear that the OEM's profit function is concave in the quantity of the traditional product. From the first-order condition, the optimal quantity decision of the OEM is $q_t^{N*} = \frac{x_t(1+d-x_t)-c-d}{2x_t(1-x_t)}$. Based on the optimal quantity decision, we can obtain the OEM's profit under No coproduction as $\prod_{OEM}^{N*} = \frac{(x_t(1+d-x_t)-c-d)^2}{4x_t(1-x_t)^2}$.

4.2. OEM coproduction

Under OEM coproduction, the CM does not enter the market, and the OEM is a monopolist that sells not only the traditional product but also the coproduct. The following proposition characterizes the optimal quantity decision of the OEM in the subgame. Define

$\phi_1^O = \frac{d(1-x_t)(\delta x_t - x_c) - c x_c}{\delta\theta(x_t - x_c)(1-x_t)x_t}$,

$\phi_2^O = \frac{c(1-x_c)x_c + (1-x_t)(\delta x_t - x_c)\left(x_c^2 - d(1-x_t) - x_c x_t\right)}{\theta(x_t - x_c)(1-x_t)\left(x_c^2 - (\delta + x_c)x_t + \delta x_t^2\right)}$;

c_j^O is the solution of c for the equation $\phi = \phi_j^O$, $j \in \{1, 2\}$.

Proposition 1. *Under OEM coproduction, the OEM's optimal decisions are*

(i) $q_t^{O*} = \frac{1}{2}\left(1 - \frac{c+d-dx_t}{\delta(1-x_t)x_t}\right)$, *and* $q_c^{O*} = 0$ *if* $\phi \leq \phi_1^O$;

(ii) $q_t^{O*} = \frac{c+(1-x_t)((1-\theta\phi)x_c + (\theta\phi - \delta)x_t)}{2(1-x_t)(x_c - \delta x_t)}$, *and* $q_c^{O*} = \frac{c x_c + (1-x_t)\left(d x_c - \delta(d + \theta\phi x_c)x_t + \delta\theta\phi x_t^2\right)}{2x_c(1-x_t)(\delta x_t - x_c)}$ *if* $\phi_1^O < \phi \leq \phi_2^O$;

(iii) $q_t^{O*} = \frac{(1-x_t)\left(\delta x_t - (\delta - \theta\phi)x_t^2 + x_c(d + (1-2\theta\phi)x_t) - c - d - (1-\theta\phi)x_c^2\right)}{2\delta(1-x_t)^2 x_t + 2x_c(x_t - x_c)(2 - x_c - x_t)}$,

and $q_c^{O*} = \frac{(x_t - x_c)\left(\delta x_t - (\delta - \theta\phi)x_t^2 - (1-\theta\phi)x_c^2 + x_c(d + (1-2\theta\phi)x_t) - c - d\right)}{2\delta(1-x_t)^2 x_t + 2x_c(x_t - x_c)(2 - x_c - x_t)}$ *if* $\phi > \phi_2^O$.

Proposition 1 is illustrated in Figure 3. Note that, ϕ_1^O can be lower than ϕ_2^O under certain condition and then item (ii) of Proposition 1 does not exist. Proposition 1 reveals that if the fraction of the green consumer segment is sufficiently small, the OEM with coproduction capability does not produce the coproduct. Otherwise, the coproduct will be provided by the OEM. If the fraction of the green consumer segment is sufficiently large, all leftover materials are used for coproduction, i.e., we have $q_c = \frac{q_t(x_t - x_c)}{1 - x_t}$ from the item (iii) of Proposition 1. If the fraction is intermediate, a portion of leftover materials are used, i.e., we have $q_c < \frac{q_t(x_t - x_c)}{1 - x_t}$ from the item (ii) of Proposition 1.

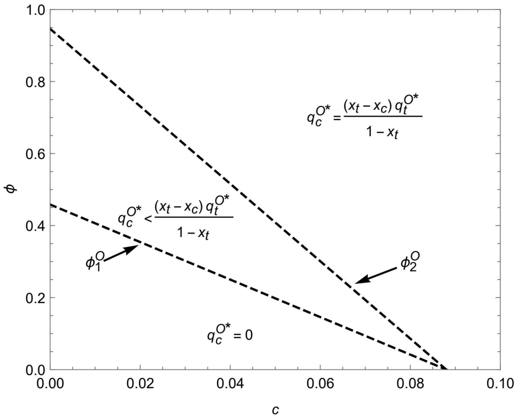


Figure 3: The optimal quantity decision under OEM coproduction ($x_t = 0.8, x_c = 0.2, \theta = 0.5, d = 0.2, \delta = 0.8$)

However, the accurate impacts of the fraction of the green consumer segment and other parameters of our model are still unclear. Therefore, we conduct the sensitivity analysis on parameters ϕ and c.[8]

Corollary 1. *Under OEM coproduction,*

(i) q_t^{O*} *can be increasing in* ϕ *if* $\phi > \phi_2^O$, *and* q_c^{O*} *is always increasing in* ϕ*;*
(ii) q_t^{O*} *is always decreasing in* c, *and* q_c^{O*} *can be increasing in* c *if* $c < c_2^O$.

As the fraction of the green consumer segment, ϕ, enlarges, the demand for the coproduct is enhanced and intuitively, the OEM increases the production quantity of the coproduct. Because of the cannibalization effect of coproduction on the sales of the traditional product, as ϕ enlarges, the OEM reduces the production quantity of the traditional product. But, if $\phi > \phi_2^O$, the material constraint on coproduction is binding, and then the OEM strategically increases the quantity of the traditional product to generate more leftover materials for the coproduct. That is the reason why the optimal production of the traditional product can be increasing in ϕ.

---

[8] The parameters ϕ and θ jointly shape the market structure, and they have the similar impact. The parameters c and d jointly shape the cost structure, and they also have the similar impact. For the sake of brevity, we omit the analysis on θ and d.

As the unit cost of the raw material, c, increases, the OEM reduces the production quantity of the traditional product. However, it is interesting that the OEM raises the production quantity of the coproduct if $c < c_2^O$ (which is equivalent to $\phi < \phi_2^O$). This is because that for $c < c_2^O$, the material constraint on coproduction is not binding, i.e., a portion of leftover materials are available for coproduction. Thus, the OEM can incur no additional cost to make more coproducts to satisfy the market demand.

4.3. CM coproduction

Under CM coproduction, the OEM sells its leftover material to the CM. The OEM and the CM sell the traditional product and the coproduct, respectively. To analyze the interaction between the two firms, we use backward induction to ensure subgame perfection. Taking the OEM's wholesale price and its quantity decision as given, we derive the best-response function of the CM, as follows. Define

$$w_1^C = \frac{(x_t-x_c)\left(2q_tx_t^2-(1-x_t)(d-\theta\phi x_t)+x_c((1-\theta\phi)(1-x_t)-q_t(1+x_t))\right)}{1-x_t};$$

$$w_2^C = (x_t - x_c)\left((1-\theta\phi-q_t)\,x_c - d + \theta\phi x_t\right).$$

Lemma 1. *Under CM coproduction, given w^C and q_t^C, the CM's optimal quantity response is*

(i) $q_c^C(q_t^C, w^C) = \frac{q_t(x_t-x_c)}{1-x_t}$ *if* $w^C \leq w_1^C$;

(ii) $q_c^C(q_t^C, w^C) = \frac{(1-\theta\phi-q_t)x_c-d+\frac{w}{x_c-x_t}+\theta\phi x_t}{2x_c}$ *if* $w_1^C < w^C \leq w_2^C$;

(ii) $q_c^C(q_t^C, w^C) = 0$ *if* $w^C > w_2^C$.

Lemma 1 indicates that the CM has a kinked quantity response curve contingent on the value of w^C. In line with intuition, the CM's unit cost for the coproduct is increasing in w^C, and then the CM's optimal quantity response is always weakly decreasing in w^C. However, revisiting the CM's profit function, from Equation 6, the CM's raw material is constrained by the OEM's leftover material, i.e., $\frac{q_c}{x_t-x_c} \leq \frac{q_t}{1-x_t}$. For a low w^C, the CM is willing to provide the coproduct as many units as possible; in other words, the CM will purchase all leftover materials to produce the coproduct. As a result, the material constraint on the coproduct is binding, i.e., $q_c^C\left(q_t^C, w^C\right) = \frac{q_t^C(x_t-x_c)}{1-x_t}$. From item (i) of Lemma 1, the traditional product and the coproduct exhibit the relationship of complements because $q_c^C\left(q_t^C, w^C\right)$ is increasing in q_t. In contrast, for a high w^C, the material constraint on the coproduct is not binding, i.e., $q_c^C\left(q_t^C, w^C\right) < \frac{q_t^C(x_t-x_c)}{1-x_t}$. From item (ii) of Lemma 1, the traditional product and the coproduct are substitutes because $q_c^C\left(q_t^C, w^C\right)$ is decreasing in q_t.

The OEM anticipates the CM's kinked quantity response curve when making its own price and quantity decisions. The derivation of the OEM's optimal decisions contains two steps: (1) To find out the local optimality in each of the three scenarios of Lemma 1; (2) to compare the OEM's profits in the three scenarios and identify the global optimal solutions, as follows. Define

$\phi_1^C = \frac{cx_c+d(x_c-x_t)(1-x_t)}{\theta(x_c-x_t)(1-x_t)x_t}$,
$\phi_2^C = \frac{\left(x_c^2+x_c(d-2x_t)-d(1-x_t)\right)(x_t-x_c)(1-x_t)+cx_c(1-2x_c+x_t)}{\theta(x_t-x_c)(1-x_t)\left(x_c^2-(1+x_c)x_t+x_t^2\right)}$;
c_j^C is the solution of c for the equation $\phi = \phi_j^C$, $j \in \{1, 2\}$.

Proposition 2. *Under CM coproduction, the OEM and CM's optimal decisions are*

(i) $q_t^{C*} = \frac{(1+d)x_t-x_t^2-c-d}{2(1-x_t)x_t}$, *and* $q_c^{C*} = 0$ *if* $\phi \le \phi_1^C$;

(ii) $q_t^{C*} = \frac{(1-x_t)((2-\theta\phi)x_t-d-(1-\theta\phi)x_c)-2c}{2(2x_t-x_c)(1-x_t)}$, $w^{C*} = \frac{1}{2}(x_t-x_c)(\theta\phi x_t - d + (1-\theta\phi)x_c)$ *and* $q_c^{C*} = \frac{cx_c+(x_c-x_t)(1-x_t)(d-\theta\phi x_t)}{2x_c(2x_t-x_c)(1-x_t)}$ *if* $\phi_1^C < \phi \le \phi_2^C$;

(iii) $q_t^{C*} = \frac{(1-x_t)\left(\theta\phi(x_t-x_c)^2-x_c^2+dx_c+x_t(1+x_c-x_t)-c-d\right)}{2\left(2x_c^3+2x_cx_t+(1-x_t)^2x_t-2x_c^2(1+x_t)\right)}$,

$$\begin{aligned} w_t^{C*} = &\Big((x_c-x_t)\Big(cx_c(2x_c-1-x_t)+\theta\phi(x_c-x_t)\Big(2x_c^3+x_c(3-x_t)x_t-2(1-x_t)^2x_t-x_c^2(3+x_t)\Big) \\ &+d\Big(2x_c^3+2(1-x_t)^2x_t-x_c(1-3x_t)-x_c^2(1+3x_t)\Big) \\ &+x_c\left(x_c^2(3+x_t)-2x_c^3-x_cx_t(5-3x_t)+x_t((4-3x_t)x_t-1)\right)\Big)\Big) / \\ &\Big(2\Big(2x_c^3+2x_cx_t+(1-x_t)^2x_t-2x_c^2(1+x_t)\Big)\Big), \end{aligned}$$

and $q_c^{C*} = \frac{(x_c-x_t)\left(c+d-dx_c+x_c^2-\theta\phi(x_c-x_t)^2-x_t-x_cx_t+x_t^2\right)}{2\left(2x_c^3+2x_cx_t+(1-x_t)^2x_t-2x_c^2(1+x_t)\right)}$ *if* $\phi > \phi_2^C$.

Proposition 2 is graphically illustrated in Figure 4. Substituting the OEM's optimal decisions w^{C*} and q_t^{C*} back into the CM's optimal response function, we can obtain the optimal quantity of the coproduct, q_c^{C*}. In line with intuition, if the fraction of the green consumer segment is sufficiently small, the CM's optimal production quantity of the coproduct is zero, and then the OEM does not need to set a wholesale price for its leftover material. That is the reason why w^{C*} is not applicable in item (i) of Proposition 2. Otherwise, similar to the outcome under OEM coproduction, the material constraint on coproduction is binding if and only if the fraction of the green consumer segment is sufficiently large.

The impacts of parameters on the OEM's optimal wholesale price are straightforward. As ϕ increases, the demand for the coproduct is enhanced, and then w^{C*} always weakly increases. As c increases, the supply for the leftover material is shrunk, and then w^{C*} weakly increases as well. The following corollary characterizes the impacts of paramters on the two firms' optimal quantities.

Corollary 2. *Under CM coproduction,*

(i) q_t^{C*} *can be increasing in* ϕ *if* $\phi > \phi_2^C$, *and* q_c^{C*} *is always increasing in* ϕ;

(ii) q_t^{C*} *is always decreasing in* c, *and* q_c^{C*} *can be increasing in* c *if* $c < c_2^C$.

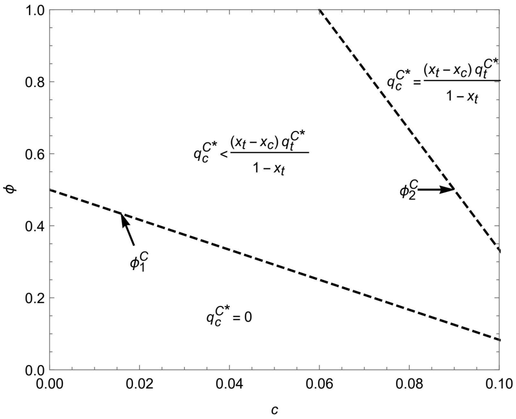


Figure 4: The optimal quantity decision under CM coproduction
($x_t = 0.8, x_c = 0.2, \theta = 0.5, d = 0.2$)

From Corollaries 1 and 2, we find that the impacts of parameters ϕ and c on the optimal quantities share the identical structure under OEM coproduction and CM coproduction. Specifically, the demand-enhanced impact of an enlarging ϕ on the coproduct has a spillover effect on the demand for the traditional product if the material constraint on coproduction is binding; the negative impact of an increasing c on the traditional product can stimulate coproduction if the material constraint is not binding.

5. Discussion

In this section, we discuss the impacts of coproduction technology on industry profit, social welfare, and environmental performance.

5.1. Industry profit

Based on the optimal decisions in Section 4, we can obtain the profits of the OEM and the CM in each subgame, as shown in the Appendix. Under No coproduction and OEM coproduction, the CM does not enter the market and obtains a profit of zero. Thus, the strategy of CM coproduction is intuitively beneficial to the CM. For the OEM, the optimal coproduction strategy is characterized by the following proposition. The expressions of thresholds are given in the Appendix because they are long and complex.

Proposition 3. *The OEM's optimal coproduction strategy is,*
(i) No coproduction if and only if $\phi \leq t_1$*;*
(ii) OEM coproduction if and only if $\phi > t_2$*;*
(iii) CM coproduction, otherwise.

Proposition 3 is graphically illustrated in Figure 5.[9] It clearly shows that each of the three strategies can be the OEM's dominant choice under certain conditions. We interpret the underlying tradeoff for the OEM's optimal coproduction strategy as follows. In line with intuition, coproduction has two opposing effects on the OEM's profit. On the one hand, the OEM can sell the coproduct to final consumers or sell leftover materials to the CM, positively affecting the OEM's profit. On the other hand, coproduction cannibalizes the sales of the traditional product and may damage the OEM's quality reputation, negatively affecting the OEM's profit. If the fraction of the green consumer segment is sufficiently small, the positive effect of coproduction on the OEM's profit is insignificant. Thus, to avoid the negative cannibalization effect, the OEM should forgo any form of coproduction; that is, No coproduction is the OEM's dominate strategy in this case.

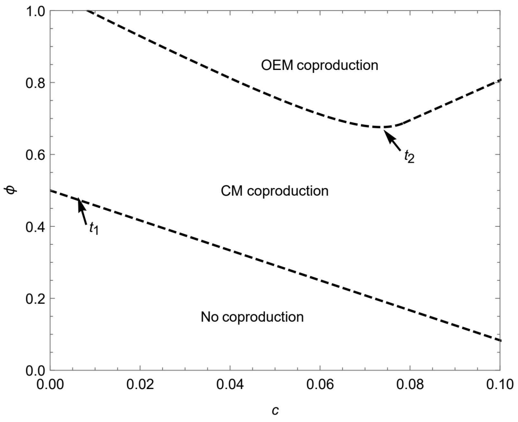


Figure 5: The OEM's optimal coproduction strategy
$(x_t = 0.8, x_c = 0.2, \theta = 0.5, d = 0.2, \delta = 0.8)$

Otherwise, the positive effect dominates, i.e., coproduction is profitable. Proposition 3 reveals that the OEM prefers coproduction by itself if the fraction of the green consumer segment is sufficiently large. Under OEM corproduction, the OEM can reap the profit of coproduction monopolistically, but will incur a loss due to reputation damage. As ϕ increases, the coproduct is more attractive in the market and hence the profit of coproduction increases. For a sufficiently large ϕ, the profit of coproduction naturally outweighs the loss due to reputation damage, and then the OEM prefers coproduction by itself. However, for an intermediate ϕ, the modest profit of coproduction cannot recoup the OEM's loss due to reputation damage. In this case, the OEM is willing to accommodate an independent CM to provide the coproduct.

---

[9] We test the model for profit maximization numerically in Appendix D. The numerical results show how the profits in equilibrium changes with two key parameters, c and ϕ , which are perfectly consistent with our analytical results in this paper.

Figure 5 graphically shows an interesting impact of an increasing c on the OEM's optimal coproduction strategy. That is, when c is low, an increasing c may induce the OEM to switch its strategy from CM coproduction to OEM coproduction. However, when c is high, an increasing c may reverse the switch from OEM coproduction to CM coproduction. We interpret the intuition behind this result as follows. When c is sufficiently low, the OEM's optimal quantity of the traditional product is high, and then there is a significant loss due to reputation damage under OEM coproduction. Therefore, in this case, the OEM has to give up in-house coproduction and may allow CM coproduction. As c increases, the optimal quantity of the traditional product decreases, implying the loss due to reputation damage decreases as well, and then the OEM can be better off with coproduction by itself. When c is sufficiently high, the optimal quantity of the traditional product is so low that the material constraint on coproduction is binding. In this case, the OEM is willing to make more leftover materials available for coproduction by increasing the quantity of the traditional product. To stimulate the demand for the traditional product, the OEM must prevent reputation damage by changing its strategy from OEM coproduction to CM coproduction.

We are also interested in the impacts of the parameters on the profits of the two firms, which are characterized in the following corollary.

Corollary 3. *In equilibrium,*

(i) the OEM's profit always weakly increases in ϕ, and the CM's profit decreases in ϕ if and only if the OEM's optimal strategy switches from CM coproduction to OEM coproduction;

(ii) the OEM's profit always strictly decreases in c, and the CM's profit increases in c if and only if (a) the OEM's optimal strategy switches from No coproduction to CM coproduction, or (b) $c < c_2^C$ under CM coproduction.

The OEM has the advantage of choosing the optimal coproduction strategy. Corollary 3 reveals that the impacts of parameters ϕ and c on the OEM's profit are in line with intuition. Note that, when the OEM's optimal choice is No coproduction, its profit is independent of the fraction of the green consumer segment. Thus, the OEM's profit does not always strictly increase in ϕ.

The impacts of parameters ϕ and c on the CM's profit depend greatly on the OEM's optimal coproduction strategy. An increasing ϕ enhances the demand for the coproduct, which is beneficial to the CM. However, as ϕ increases, the OEM's optimal strategy can switch from CM coproduction to OEM coproduction, and then the CM's profit discontinuously drops to 0. Similarly, as c increases, the OEM's optimal strategy can switch from OEM coproduction to CM coproduction, and then the CM's profit discontinuously jumps from 0.

More interestingly, under CM coproduction, the CM's profit still may increase in c. Conventional wisdom might suggest that the increasing unit cost of raw materials hurts the OEM's profit as well as the CM's profit because the OEM can shift the effect of an increasing cost to the CM through an increasing wholesale price. However, we find that the CM can actually benefit from the increase in the unit cost of raw materials. The counter-intuitive result is driven by the nature of the optimal wholesale price of leftover materials. It can be seen from Proposition 2, if $c < c_2^C$, the material constraint on coproduction is not binding, and then the optimal wholesale price is not affected by the unit cost of raw materials. In other words, when the leftover material is redundant, the OEM cannot shift the effect of an increasing cost to the CM. Meanwhile, the increasing unit cost of raw materials forces the OEM to reduce the quantity of the traditional product. Thus, the CM is able to sell more coproducts even at a higher market-clearing price. That is the reason why the CM can benefit from the increase in the unit cost of raw materials when the cost is sufficiently low.

5.2. Social welfare

In this subsection, we adopt a social planner's perspective and investigate how the OEM's choice of coproduction strategy influences social welfare. Social welfare can be defined as:

$$SW = PS + CS, \tag{7}$$

where $PS = \Pi_{OEM} + \Pi_{CM}$ is the total producer surplus, and CS is the total consumer surplus. In our model, the total consumer surplus is the sum of the surplus of traditional product buyers and the surplus of the coproduct buyers, equating to

$$CS = (1-\phi)\int_v \max\left\{\Delta x_t v - p_t, x_c v - p_c, 0\right\} dv \tag{8}$$

$$+\phi \int_v \max\{\Delta x_t v - p_t, x_c v + (x_t - x_c)\theta - p_c, 0\} dv. \tag{9}$$

The following proposition shows the impact of coproduction on social welfare.

Proposition 4. *The existence of OEM coproduction decreases the social welfare if and only if $c < T^{OW}$, though the existence of CM coproduction always increases the social welfare.*

Proposition 4 firstly demonstrates that CM coproduction is always beneficial to the society. In fact, compared with No coproduction, the adoption of CM coproduction can benefit not only producer surplus but also consumer surplus. The supply of coproducts can utilize the potential of green consumers who are willing to pay more for environmental protection, and segment the market so that the total producer surplus increases. For consumers, the benefit lies in the additional choice of buying a coproduct or the possibility of buying a traditional product at a lower price.

However, the adoption of OEM coproduction cannot always improve social welfare. Recall that under in-house coproduction, the OEM's reputation will be damaged and the consumer's valuation on the traditional product decreases, which negatively affects producer surplus and consumer surplus. The negative effect becomes even stronger when more traditional products are sold. Thus, in line with intuition, when c is low, the optimal supply of traditional products is large, and hence the negative effect of OEM coproduction on the society dominates. That is the reason why the existence of OEM coproduction may decrease social welfare.

As more consumers are aware of environmental protection, the consumer valuation on the coproduct, on average, improves. However, the improvement of consumer valuation does not necessarily increase social welfare, as demonstrated by the following corollary.

Corollary 4. *In the presence of OEM (CM) corproduction, social welfare decreases in* ϕ *if and only if* $\phi > \Psi^O$ $(\phi > \Psi^C)$*.*

In the presence of coproduction by either the OEM or the CM, we find that the fraction of the green consumer segment has a non-monotonic impact on social welfare. Specifically, as ϕ increases, social welfare increases at first, but finally decreases once if ϕ becomes sufficiently large. Social welfare consists of producer surplus and consumer surplus. To better understand the insight, we decompose the impacts of ϕ on the two manufacturers and the consumers in the following analysis. In line with intuition, the total producer surplus always increases in ϕ. However, the total consumer surplus can decrease in ϕ. Moreover, we find that the reasons behind the decrease of consumer surplus are different under the two coproduction strategies.

Under CM coproduction, the relationship between the OEM and the CM is co-operative. That is, the two manufacturers compete with each other in the market, yet they also cooperate to form a supply chain for coproduction. Intuitively, competition generally benefits consumers. As ϕ increases, the OEM strategically increases the wholesale price of leftover materials, and hence the OEM relies more on the cooperation with the CM to share the profit of coproduction. In other words, the increase of ϕ moderates the market competition between the two manufacturers, making all consumers worse off.

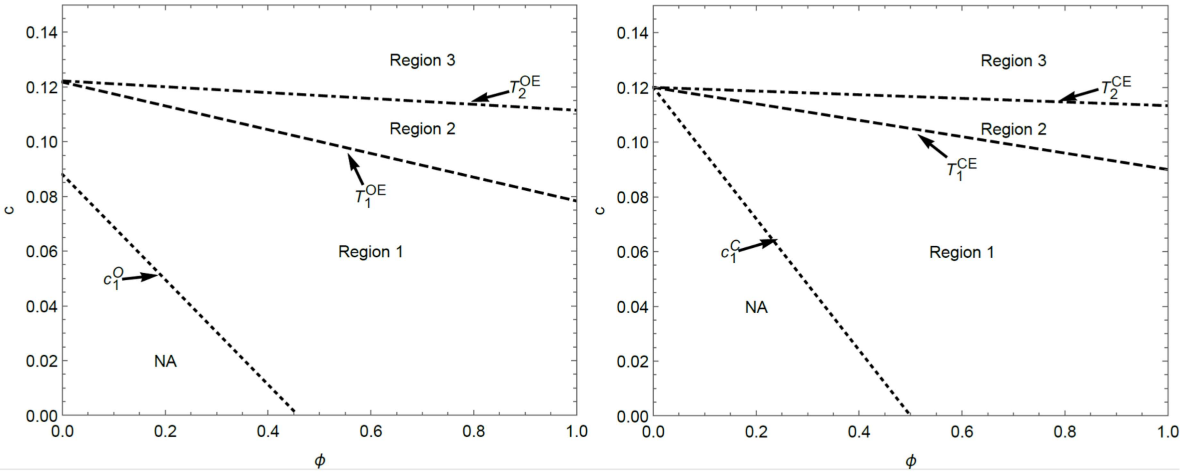
Under OEM coproduction, the OEM monopolizes the market, and then the increase of ϕ influences consumer surplus in a different way. As ϕ increases, some consumers who were likely to buy the traditional product become more willing to buy the coproduct. For a sufficiently large ϕ, the demand for the coproduct is so high that the material constraint on coproduction is binding. Thus, the short supply of the coproduct makes the additional valuation of most green consumers for environmental protection unrealized. Moreover, the increase of ϕ continually drives up the market clearing price of the coproduct. As a consequence, consumer surplus decreases sharply in ϕ, which eventually leads to a decrease in social welfare.

5.3. Environmental performance

Coproduction has been heralded as an environmentally-friendly technology because it uses the leftover material of traditional manufacturing to satisfy market demand. In this subsection, we examine the impacts of coproduction on the environment. Following the relevant literature, e.g., Agrawal et al. (2012), Wang et al. (2017), and Jin et al. (2021), we use two metrics to measure the environmental impact, namely the changes of the total material consumption, i.e., $\frac{q_t}{1-x_t}$, and the total material waste, i.e., $\frac{x_k q_t}{1-x_t}$, $k \in \{t, c\}$. Note that if $c \leq c_1^i$, $i \in \{O, C\}$, the optimal quantity of the coproduct is 0, and hence coproduction has no impact on the environment. The following proposition summarizes the environmental impact of coproduction for $c > c_1^i$.

Proposition 5. *The existence of OEM (CM) coproduction increases the total material consumption if and only if $c > T_1^{OE}$ ($c > T_1^{CE}$), and increases the total material waste if and only if $c > T_2^{OE}$ ($c > T_2^{CE}$).*

Counterintuitively, Proposition 5 demonstrates that coproduction might be detrimental to the environment, especially, it can increase not only the total material consumption but also the total material waste. The two thresholds in Proposition 5 divide the parameter space into three regions, as shown in Figure 6.



(a) OEM coproduction

(b) CM coproduction

Figure 6: Impacts of coproduction on the environment
($x_t = 0.8, x_c = 0.2, \theta = 0.5, d = 0.2, \delta = 0.8$)

If $c < T_1^{iE}$, i.e., Region 1 of Figure 6, in this scenario, coproduction can reduce the material consumption and material waste, simultaneously. The low unit cost of raw materials implies that it is highly profitable for the OEM to produce the traditional product. Thus, a high quantity of leftover materials will be available. In the presence of coproduction, a portion of leftover materials will be used to produce the coproduct, and hence the total material waste is reduced. Meanwhile, the supply of the coproduct will cannibalize the sales of the traditional product. As a consequence, the total consumption is also reduced.

In contrast, i.e., Regions 2 and 3 of Figure 6, coproduction might hurt the environment. Note that if the unit cost of raw materials is sufficiently high, the material constraint on coproduction is binding, and then the OEM has an incentive to increase the quantity of the traditional product for more leftover materials available for coproduction. This explains why the total material consumption is higher in these two regions. In this sense, coproduction has two opposing effects on the environment: the negative effect of the increasing material consumption and the positive effect of the use of leftover materials. The net effect depends on the relative change for the traditional product, i.e., the effect on material consumption. If $c > T_2^{iE}$, i.e., Region 3 of Figure 6 applies, then in the absence of coproduction, the optimal quantity of the traditional product is sufficiently low because of the sufficiently high unit cost. However, in the presence coproduction, the optimal quantity of the traditional product will be significantly improved. As a consequence, the negative effect dominates, and hence material consumption and material waste both increase.

Our study considers the existence of green consumers who are willing to pay a premium for the coproduct that is made of leftover materials. The following corollary characterizes the impact of an enlarging fraction of the green consumer segment on the environment.

Corollary 5. *In the presence of OEM (CM) coproduction, the total material consumption and the total material waste both increase in ϕ if and only if $\phi > \phi_2^O$ ($\phi > \phi_2^C$).*

The intuition behind Corollary 5 is similar to that behind Proposition 5. As ϕ increases, more consumers are willing to buy the coproduct, and then the material constraint on the coproduct is binding. The increasing demand for the coproduct also increases the optimal quantity of the traditional product, making material consumption and material waste increased. In practice, to protect the environment, stakeholders, e.g., government agencies and environmental groups, encourage consumers to buy green products such as the coproduct made of leftover materials. Corollary 5 demonstrates that such a strategy might backfire. Over-stimulated demand for the coproduct will push up the overall output of the traditional product, increasing material waste and hurting the environment.

6. Conclusions

Coproduction technology has been developed and adopted by OEMs and CMs in recent years. However, the economic and environmental implications of third-party coproduction are not immediately clear. OEMs might boycott coproduction technology because they fear that coproducts damage their quality reputation or cannibalize the sales of their traditional products. Moreover, while environmental protection organizations may embrace and encourage coproduction technology that generates coproducts made of leftover materials from traditional manufacturing, the availability of production by this means might reduce the proportion of waste but not necessarily the total amount of waste or the total amount of resources used if coproduction enhances the overall market demand.

To provide a better understanding of the implications of coproduction technology on waste management, we develop a game-theoretical model in which the coproduct can be made of leftover materials by one OEM or one CM. We find that the interaction between the OEM and the CM generates some interesting results that have nontrivial implications for theory and for practice.

First, it is not necessary for the OEM to deter the entry of third-party coproduction. The OEM's optimal coproduction strategy depends greatly on the demand from green consumers and the supply of raw materials. Under certain conditions, allowing the CM to make the coproduct is the dominant strategy for the OEM.

Second, the size of green consumers and the unit cost of raw materials have non-monotone impacts on the CM's profit. A positive change in material cost or consumer preference that improve the competitiveness of the coproduct might induce the OEM to raise the wholesale price of leftover materials, which negatively affects the CM's profit. Thus, the CM whose profit relies on the sales of the coproduct should not always encourage green consumers to pay a price premium for the coproduct.

Third, an enlarging size of green consumers may reduce the total consumer surplus. As more consumers are aware of environmental protection, the enhanced demand for the coproduct drives up its market clearing price. However, due to the material constraint on coproduction, the short supply of the coproduct dissatisfies most green consumers, which leads to the decrease in consumer surplus. Fortunately, we find that the existence of coproduction can usually increase social welfare. Thus, the social planner can use redistribution (e.g., levying a carbon tax on the traditional product so as to subsidize consumers of the coproduct) to achieve Pareto improvement.

Finally, we discuss some limitations of this study that might inspire interesting future research. Our theoretical model focuses on the vertical interaction between the OEM and the CM, in the sense that these two manufacturers form a supply chain even if competing in the same final market. One natural extension for our model would be to consider horizontal interaction with other competing manufacturers. For example, if there were multiple OEMs, then the bargaining power for a specialist CM might shift in its favor when purchasing leftover materials. How competition plays out in this scenario might be essential to understand the value of coproduction when developing specific expertise in using leftover materials as well as providing increased understanding of competitive incentives alongside straight profit motives for OEMs to supply a third-party CM. In addition, we could also envisage interesting empirical work on this subject. Our analysis in this paper yields many testable predictions, and it might be an exciting avenue for empirical work to explore these analytical results to ascertain the economic and environmental impact of coproduction technology.

Acknowledgement

The authors thank the editor and three anonymous referees for their constructive comments. This research work was supported by the National Natural Science Foundation of China [grant numbers 71971033 and 72071020] and the Fundamental Research Funds for the Central Universities [grant number 2021CDJSKJC09].

Appendix

The appendix is provided as an online companion.

References

Agrawal, V.V., Ferguson, M., Toktay, L.B., Thomas, V.M., 2012. Is leasing greener than selling? Management Science 58, 523–533.

Amaldoss, W., Jain, S., 2015. Branding conspicuous goods: An analysis of the effects of social influence and competition. Management Science 61, 2064–2079.

Arya, A., Mittendorf, B., 2015. Supply chain consequences of subsidies for corporate social responsibility. Production and Operations Management 24, 1346–1357.

Arya, A., Mittendorf, B., Sappington, D.E., 2007. The bright side of supplier encroachment. Marketing Science 26, 651–659.

Atasu, A., Özdemir, Ö., Van Wassenhove, L.N., 2013. Stakeholder perspectives on e-waste take-back legislation. Production and Operations Management 22, 382–396.

Atasu, A., Subramanian, R., 2012. Extended producer responsibility for e-waste: Individual or collective producer responsibility? Production and Operations Management 21, 1042–1059.

Bansal, S., Transchel, S., 2014. Managing supply risk for vertically differentiated co-products. Production and Operations Management 23, 1577–1598.

Bi, G., Jin, M., Ling, L., Yang, F., 2017. Environmental subsidy and the choice of green technology in the presence of green consumers. Annals of Operations Research 255, 547–568.

Bitran, G.R., Gilbert, S.M., 1994. Co-production processes with random yields in the semiconductor industry. Operations Research 42, 476–491.

Bitran, G.R., Leong, T.Y., 1992. Deterministic approximations to co-production problems with service constraints and random yields. Management Science 38, 724–742.

Chen, Y.J., Tomlin, B., Wang, Y., 2013. Coproduct technologies: Product line design and process innovation. Management Science 59, 2772–2789.

Chen, Y.J., Tomlin, B., Wang, Y., 2017. Dual coproduct technologies: Implications for process development and adoption. Manufacturing & Service Operations Management 19, 692–712.

Chiang, W.y.K., Chhajed, D., Hess, J.D., 2003. Direct marketing, indirect profits: A strategic analysis of dual-channel supply-chain design. Management Science 49, 1–20.

Debo, L.G., Toktay, L.B., Van Wassenhove, L.N., 2005. Market segmentation and product technology selection for remanufacturable products. Management Science 51, 1193–1205.

Esenduran, G., Lin, Y.T., Xiao, W., Jin, M., 2020. Choice of electronic waste recycling standard under recovery channel competition. Manufacturing & Service Operations Management 22, 495–512.

Ferguson, M.E., Toktay, L.B., 2006. The effect of competition on recovery strategies. Production and Operations Management 15, 351–368.

Ferrer, G., Swaminathan, J.M., 2010. Managing new and differentiated remanufactured products. European Journal of Operational Research 203, 370–379.

Galbreth, M.R., Ghosh, B., 2013. Competition and sustainability: The impact of consumer awareness. Decision Sciences 44, 127–159.

Gerchak, Y., Tripathy, A., Wang, K., 1996. Co-production models with random functionality yields. IIE Transactions 28, 391–403.

He, Q., Wang, N., Yang, Z., He, Z., Jiang, B., 2019. Competitive collection under channel inconvenience in closed-loop supply chain. European Journal of Operational Research 275, 155–166.

Hilali, H., Hovelaque, V., Giard, V., 2022. Integrated scheduling of a multi-site mining supply chain with blending, alternative routings and co-production. International Journal of Production Research , 1–20.

Hsu, A., Bassok, Y., 1999. Random yield and random demand in a production system with downward substitution. Operations Research 47, 277–290.

Jacobs, B.W., Subramanian, R., 2012. Sharing responsibility for product recovery across the supply chain. Production and Operations Management 21, 85–100.

Jiang, J., He, C., 2021. Low-price guarantees in a dual channel of distribution. Marketing Science 40, 765–782.

Jin, M., Li, G., Reimann, M., 2022. Team of rivals: How should original equipment manufacturers cooperate with independent remanufacturers via authorisation? European Journal of Operational Research 296, 837–845.

Jin, M., Nie, J., Yang, F., Zhou, Y., 2017. The impact of third-party remanufacturing on the forward supply chain: a blessing or a curse? International Journal of Production Research 55, 6871–6882.

Jin, M., Zhang, X., Xiong, Y., Zhou, Y., 2021. Implications of green optimism upon sustainable supply chain management. European Journal of Operational Research 295, 131–139.

Kleber, R., Reimann, M., Souza, G.C., Zhang, W., 2020. Two-sided competition with vertical differentiation in both acquisition and sales in remanufacturing. European Journal of Operational Research 284, 572–587.

Kotchen, M.J., 2006. Green markets and private provision of public goods. Journal of Political Economy 114, 816–834.

Li, G., Li, L., Sethi, S.P., Guan, X., 2019. Return strategy and pricing in a dual-channel supply chain. International Journal of Production Economics 215, 153–164.

Li, L., Jiang, L., Liu, L., 2012. Service and price competition when customers are naive. Production and Operations Management 21, 747–760.

Lin, Y.T., Sun, H., Wang, S., 2020. Designing sustainable products under coproduction technology. Manufacturing & Service Operations Management 22, 1181–1198.

Lin, Y.T., Sun, H., Wang, S., 2021. Socially responsible co-product design, in: Responsible Business Operations. Springer, pp. 137–161.

Liu, J., Nie, J., Yuan, H., 2019. To expand or not to expand: A strategic analysis of the recycler's waste treatment capacity. Computers & Industrial Engineering 130, 731–744.

Lu, T., Chen, Y.J., Tomlin, B., Wang, Y., 2019. Selling co-products through a distributor: The impact on product line design. Production and Operations Management 28, 1010–1032.

Majumder, P., Groenevelt, H., 2001. Competition in remanufacturing. Production and Operations Management 10, 125–141.

Mazahir, S., Verter, V., Boyaci, T., Van Wassenhove, L.N., 2019. Did europe move in the right direction on e-waste legislation? Production and Operations Management 28, 121–139.

Miremadi, M., Musso, C., Weihe, U., et al., 2012. How much will consumers pay to go green? McKinsey Quarterly 4, 14–14.

Nie, J., Wang, Q., Shi, C., Zhou, Y., 2021. The dark side of bilateral encroachment within a supply chain. Journal of the Operational Research Society , 1–11.

Örsdemir, A., Kemahlıoğlu-Ziya, E., Parlaktürk, A.K., 2014. Competitive quality choice and remanufacturing. Production and Operations Management 23, 48–64.

Peng, Y., Xu, X., Liang, X., Xue, W., 2020. Mismatch risk allocation in a coproduct supply chain. Annals of Operations Research 291, 707–730.

Randall, T., Ulrich, K., Reibstein, D., 1998. Brand equity and vertical product line extent. Marketing Science 17, 356–379.

Rao, U.S., Swaminathan, J.M., Zhang, J., 2004. Multi-product inventory planning with downward substitution, stochastic demand and setup costs. IIE Transactions 36, 59–71.

Reimann, M., Xiong, Y., Zhou, Y., 2019. Managing a closed-loop supply chain with process innovation for remanufacturing. European Journal of Operational Research 276, 510–518.

Song, H., Duan, H., Deng, S., Xu, J., 2022. Brand extension and channel structure: An analysis of the effects of social influence. Omega 110, 102626.

Sunar, N., Plambeck, E., 2016. Allocating emissions among co-products: Implications for procurement and climate policy. Manufacturing & Service Operations Management 18, 414–428.

Tomlin, B., Wang, Y., 2008. Pricing and operational recourse in coproduction systems. Management Science 54, 522–537.

Wang, L., Cai, G., Tsay, A.A., Vakharia, A.J., 2017. Design of the reverse channel for remanufacturing: must profit-maximization harm the environment? Production and Operations Management 26, 1585–1603.

Wang, N., Song, Y., He, Q., Jia, T., 2020. Competitive dual-collecting regarding consumer behavior and coordination in closed-loop supply chain. Computers & Industrial Engineering 144, 106481.

Wen, D., Li, J., Xiao, T., 2019. Impact of quality regulation policy on performance of a remanufacturing supply chain with non-waste returns. International Journal of Production Research 57, 3678–3694.

Wu, X., Kouvelis, P., Matsuo, H., 2013. Horizontal capacity coordination for risk management and flexibility: Pay ex ante or commit a fraction of ex post demand? Manufacturing & Service Operations Management 15, 458–472.

Wu, X., Zhou, Y., 2016. Does the entry of third-party remanufacturers always hurt original equipment manufacturers? Decision Sciences 47, 762–780.

Wu, X., Zhou, Y., 2019. Buyer-specific versus uniform pricing in a closed-loop supply chain with third-party remanufacturing. European Journal of Operational Research 273, 548–560.

Yalabik, B., Fairchild, R.J., 2011. Customer, regulatory, and competitive pressure as drivers of environmental innovation. International Journal of Production Economics 131, 519–527.

Yalcin, T., Ofek, E., Koenigsberg, O., Biyalogorsky, E., 2013. Complementary goods: creating, capturing, and competing for value. Marketing Science 32, 554–569.

Yang, R., Tang, W., Zhang, J., 2021. Technology improvement strategy for green products under competition: The role of government subsidy. European Journal of Operational Research 289, 553–568.

Yang, R., Tang, W., Zhang, J., 2022. Optimal subsidy and recycling mode of waste cooking oil under asymmetric information. Journal of the Operational Research Society 73, 674–691.

Yenipazarli, A., Vakharia, A., 2015. Pricing, market coverage and capacity: Can green and brown products co-exist? European Journal of Operational Research 242, 304–315.

Yu, Y., Han, X., Hu, G., 2016. Optimal production for manufacturers considering consumer environmental awareness and green subsidies. International Journal of Production Economics 182, 397–408.

Yu, Y., Wang, Y., Liu, Y., 2021. Product quality and quantity with responsive pricing. International Journal of Production Research 59, 7160–7178.

Zhang, F., Chen, H., Xiong, Y., Yan, W., Liu, M., 2021. Managing collecting or remarketing channels: Different choice for cannibalisation in remanufacturing outsourcing. International Journal of Production Research 59, 5944–5959.

Zhang, S., Wei, L., Zhang, J., 2022. Demand forecast sharing for a dominant retailer with supplier encroachment and quality decisions. European Journal of Operational Research 301, 39–50.

Zhou, Y., 2018. The role of green customers under competition: A mixed blessing? Journal of Cleaner Production 170, 857–866.

Zhou, Y., Xiong, Y., Jin, M., 2021. Less is more: Consumer education in a closed-loop supply chain with remanufacturing. Omega 101, 102259.