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Decision analysis and coordination in green supply chains with stochastic demand

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Abstract

Consumer goods supply chains are intensifying their efforts to develop and offer green products, in order to seize new business opportunities and improve profitability. A specific type of green products concerns marginal and development cost-intensive green products (MDIGPs), like electric vehicles. As greening these products affects both marginal and development costs, their design presents special challenges, especially within the context of uncertain demand. This paper formulates the joint product pricing-ordering-greening decision problem in the supply chains of MDIGPs and examines the impact of demand uncertainty. A sequential game-theoretic framework is developed, providing analytical expressions of the optimal solutions for the stochastic model. A bargaining game on the wholesale price between supply chain members is proposed to coordinate decisions. We compare the optimal decisions numerically in the stochastic and deterministic cases and find that, although demand uncertainty creates inefficiency in the green supply chain, it might positively impact product greenness and prices. Given the impact of the unit-variable greening costs of MDIGPs, we are able to identify cases where – contrary to common belief – demand uncertainty does not always lead firms to reduce greenness or increase prices.

Keywords: Supply chain management; Green product development; Marginal and development cost-intensive green product (MDIGP); Stochastic demand; Game theory

1 Introduction

The consistent growth of markets for green products has been widely recognised by both practitioners and academicians. This rapid development has also presented challenges to the operations of supply chain firms, one of the major challenges being demand uncertainty (Abdi et al., 2021; Chuang et al., 2019). We address this phenomenon of uncertainty in the context of production, sourcing, and pricing decisions for products where greening implies changes in both development costs and marginal costs. Even though the demand as a whole is increasing, there are still uncertainties when marketing green products (Chemama et al., 2018; C. Chen, 2001; Day & Schoemaker, 2011). For instance, in the case of electric vehicles (EVs), uncertainty arises from unfamiliarity to many consumers (de Rubens et al., 2018) or regulations and financial incentives by governments, considerably affecting production and pricing decisions (Chevalier-Roignant et al., 2019). An important challenge faced by managers is to 'learn how to embrace uncertainty and benefit from it' (Day & Schoemaker, 2011). Given the potential effect of demand uncertainty on decisions involving production, pricing, and greening investment, it is necessary for operations management research to include it in the decision-making processes of green supply chains. Motivated by that observation, in this paper, we examine how uncertain demand for green products affects the decisions made in supply chains.

The second motivation for our research has to do with the specific nature of the green product type. The greenness of products is usually associated with the improvement of manufacturing technology, the utilisation of sustainable materials, resource efficiency, and emissions savings relative to ordinary products. It is a quantifiable, measurable product attribute, even though different standards can be used (Guo et al., 2020; Nouira et al., 2014). Green products usually incur additional costs, and the greenness improvement level selected by a firm can affect fixed production costs and/or variable production costs (Benjaafar et al., 2013; Z. G. Liu et al., 2012; Qian, 2011). W. G. Zhu and He (2017) use the factor costs to divide green products into development-intensive green products (DIGPs) and marginal cost-intensive green products (MIGPs), i.e., products of which the driving force of greenness improvement mainly affects either the fixed costs or the variable manufacturing costs. The increase in fixed costs is primarily due to the investment in green product design and manufacturing system development. While fixed costs are volume-independent, they are not totally 'fixed' with respect to a certain planning period because they correlate with the greenness of the product (Krishnan & Zhu, 2006). Furthermore, similar to the marginal and development cost-intensive products studied by Lacourbe et al. (2009) and Qian (2011), there are green products that are both marginal cost-intensive and development cost-intensive, in that they are a mixture of MIGP and DIGP, i.e., MDIGPs. In this context, it is meaningful to incorporate the impact of greenness improvement on both fixed *and* variable production costs in the decision-making of supply chain firms.

In this paper, we investigate the profit-optimal decisions of each member firm and how they affect the greenness and profits in the supply chains of MDIGPs with stochastic demand by addressing the following research questions:

(1) How does the demand uncertainty affect supply chain members' decisions and profits?

(2) How are supply chain members' decisions and profits affected if greening products implies changes in both development costs and marginal costs?

(3) How should the focal firm structure contracts to coordinate the decisions and increase profitability in the supply chain?

To answer these questions, we apply and generalise the newsvendor model to the supply chain of MDIGPs. By employing a sequential game-theoretic framework, we derive profit-optimal pricing and ordering decisions as well as greening decisions, for decentralised and centralised supply chains. The impact of demand uncertainty is analysed by comparing the solutions of deterministic demand and stochastic demand cases. We show that findings obtained in deterministic demand and traditional newsvendor settings do not necessarily carry over to MDIGP supply chains with stochastic demand. Also, we explore the impact of the variable greening cost on the decisions and the firm's product type choice and find that for MDIGPs, a reduction of the variable greening costs can often be more attractive than incurring additional manufacturing costs to improve product greenness and firm profitability. Finally, the supply chain is coordinated through a bargaining wholesale price contract.

The main contribution of this paper is the integration of green product development with the traditional newsvendor model, to support decision-making with regard to pricing, ordering, and greening in supply chains of MDIGPs with stochastic demand. As such, this research explores how demand uncertainty and cost structures of green products together influence the decisions and performance of green supply chains. Although earlier studies address components of our model, none have offered the combined perspective where different elements interact. It contributes to the debate about the potential for firms to offer greener products at a lower price while also keeping profitable, and when facing an uncertain consumer market. Contrary to common perception, results suggest that if the retailer sets an appropriate service level, consumers can benefit from demand uncertainty through cheaper greener products, especially when greening creates a production cost reduction. It is also shown that demand uncertainty plays a vital role in the profit allocation of supply chain firms and should therefore not be ignored. Although the presence of demand uncertainty reinforces the focal firm's profit allocation advantage, a bargaining wholesale price scheme can coordinate joint decisions and achieve a win-win situation. It is noteworthy that the model we develop is generic. Although we use the case of electric vehicles to apply our model, it is also suitable for other industries which produce MDIGPs, e.g., green home appliances.

The remainder of this paper is structured as follows. Section 2 reviews related literature. Section 3 explains the model development, including assumptions, notations, and profit functions. We derive analytical solutions and study full coordination under a Nash bargaining scheme in Section 4. The sequential solution procedure is illustrated by numerical experiments in Section 5. Here, we also compare the results of stochastic versus deterministic demand cases and present sensitivity analyses on the variable cost coefficient and greenness demand coefficient. Finally, overall conclusions, managerial insights, related discussions, and directions for future research are presented in Section 6. Some proofs of the analytical results are deferred to the appendix.

2 Literature review

This paper examines how demand uncertainty and cost structures of green products together influence the decisions and profitability of green supply chains. We review and discuss three main streams of related literature: research in green supply chain models with stochastic demand, green product development, and bargaining contracts in supply chain coordination. Table 1 shows a comparison with the papers that are most relevant to this study.

2.1 Green supply chain models with stochastic demand

Recent literature reviews of green or sustainable supply chains indicate that few papers address uncertainty issues. Even though most papers recognise them as important factors in the decision-making of supply chains, models that reflect uncertainty or stochasticity are insufficiently presented in the literature (Agi et al., 2020; de Oliveira et al., 2018). In their review of a significantly large set of 220 papers, Barbosa-Póvoa et al. (2018) find that only 15% of the papers include uncertainty-related aspects. The authors conclude that uncertainty is basically related to product demand. Stochastic approaches should be developed to solve decision-making problems in sustainable supply chains operating in uncertain environments. Nevertheless, researchers have not yet clearly ascertained how customers' green preference affects product demand. Lack of relevant information is one of the primary sources for demand uncertainty. Chauhan and Singh (2018) point to similar conclusions that, although stochastic demand represents a more realistic decision-making environment, very few studies use stochastic models, possibly because of the high complexity and difficulty in solving them (Abdi et al., 2021; Rezaee et al., 2017).

In the traditional pricing literature, the effect of a demand shock on stochastic demand is mainly modelled either in an additive or multiplicative form (Huang et al., 2013; Petruzzi & Dada, 1999; J. C. Wang et al., 2019). Most papers are predicated on the newsvendor framework with price effects, in which a profit-maximising decision-maker makes joint pricing and inventory decisions prior to observing uncertain demand (Choi, 2012). Several researchers have extended the model by introducing attributes like greenness, sustainability, and corporate social responsibility. Considering both additive and multiplicative demand in the interaction between a government and a supplier, Cohen et al. (2015) analyse how demand uncertainty influences the optimal consumer subsidy for green technology adoption, prices, and production quantities. They conclude that demand uncertainty results in higher production quantities and lower prices. However, their model is not concerned with greening. Assuming that the product's

Table 1: Literature comparison

Literature	Green product	Green-sensitive demand	Demand uncertainty	Decisions			Coordination mechanisms
				Price	Order	Green	
Swami and Shah (2013)	DIGP	✓		✓		✓	two-part tariff contract
Ghosh and Shah (2012, 2015)	DIGP	✓		✓		✓	two-part tariff contract; cost-sharing contract through bargaining
W. G. Zhu and He (2017)	MIGP; DIGP	✓		✓		✓	cost-sharing contract
Dey et al. (2019)	MIGP; DIGP	✓		✓	✓	✓	
Cohen et al. (2015)	MIGP		✓	✓	✓		consumer subsidies
Raza (2018); Raza and Govindaluri (2019); Raza et al. (2018)*	DIGP	✓	✓		✓		revenue-sharing contract through bargaining
C. Liu and Chen (2019)	DIGP	✓	✓		✓	✓	
W. Wang et al. (2021)	DIGP	✓	✓	✓		✓	reward contract with/without target green degree
This paper	MDIGP	✓	✓	✓	✓	✓	wholesale price contract through bargaining

Notes: Sustainability issues are also included in 'green';

'*': Given that the pricing and greening decisions are exogenous, the authors use a two-phase solution approach to solve the stochastic demand model.

market and wholesale prices are exogenous, Dong et al. (2016) derive optimal order quantities and sustainability levels for sustainable products with an additive demand model within the cap-and-trade context. Similarly, treating the retail price in an additive stochastic demand model as being exogenous, C. Liu and Chen (2019) examine ordering and greening decisions in green supply chains under the effect of external reference points. Raza (2018), Raza et al. (2018), and Raza and Govindaluri (2019) developed additive demand models that are sensitive to both prices and greening to investigate pricing, inventory, and greening decisions. Their main focus is revenue-sharing contracts and market segmentation caused by price differentiation between green and regular products. When deriving analytical results of stochastic demand models, they regard the pricing and greening effort as exogenous decisions. W. Wang et al. (2021) assume that firms in a retailer-led supply chain are risk-averse towards demand uncertainty and examine a couple of incentive mechanisms, finding that the reward contract with a target green degree is desirable to improve product green degree.

As Barbosa-Póvoa et al. (2018) and Chauhan and Singh (2018) observed, few papers have featured demand uncertainty in the model and determined joint decisions on pricing, ordering (production), and greening in the supply chain. Jiang and Chen (2016) investigate a two-echelon supply chain facing stochastic demands and derive optimal production, pricing, and green technology investment strategies under the cap-and-trade regulation. Their study suggests that finding optimal joint decisions towards the achievement of sustainability goals is not a trivial task. In this paper, we look at whether considering demand uncertainty in the decisions of green supply chains is essential. We are particularly interested in learning how these decisions adjust when firms consider a stochastic demand, compared to when demand is deterministic. For this purpose, we extend the price-setting newsvendor model by including the product greenness while regarding product price, production quantity, and greenness itself as decision variables.

2.2 Green product development

Green product development is considered as one of the fundamental elements to encourage economic growth and environmental sustainability through product design and innovation (C. Chen, 2001; W. G. Zhu & He, 2017). It has received significant attention in the economics and operations management literature. The development of green products is often costly and as summarised in W. G. Zhu and He (2017), products are classified as MIGPs, DIGPs, and MDIGPs based on the greening cost structure.

Most papers that discuss the issue of green product design or green supply chain study DIGPs modelling fixed costs as a constant or as a function of product greenness (see X. Chen et al., 2017; Dong et al., 2016; Ghosh & Shah, 2012, 2015; Ghosh et al., 2020; Hong & Guo, 2019; Jiang & Chen, 2016; Murali et al., 2018; Swami & Shah, 2013; Yalabik & Fairchild, 2011; Q. H. Zhu et al., 2018). A handful of research papers focus on green products with only unit-variable greening costs or consider two types of MIGPs and DIGPs (Dey et al., 2019; Gao et al., 2020; Q. Y. Li et al., 2020; Z. G. Liu et al., 2012; C. T. Zhang & Liu, 2013; C. T. Zhang et al., 2014). Different cost functions can produce different decision-making results, including the level of greenness improvement (Chambers et al., 2006; Krishnan & Zhu, 2006; Qian, 2011). Dey et al. (2019); Gao et al. (2020); Krishnan and Zhu (2006); Q. Y. Li et al. (2020); W. G. Zhu and He (2017) compared MIGPs and DIGPs in a specific context and confirmed that the two types of products had unique characteristics and led to different decisions and performance for supply chain members. The difference between the two types of green products is attracting attention from the industry and academia. However, few researchers focus on the MDIGPs. Only Banker et al. (1998), C. Chen (2001), and Q. Zhang et al. (2017) include both fixed and unit-variable costs in their deterministic models. Therefore, this paper contributes to this field by developing an integrated model that supports decision-making with regard to pricing, greening, and ordering in the supply chains of MDIGPs with stochastic demand. The model extends the cost structure to describe the impact of greenness improvement on fixed as well as variable production costs, including the effect of variable cost reduction.

2.3 Bargaining contracts in supply chain coordination

Coordination is key to the achievement of green supply chains and the optimisation of their overall performance. A supply chain, typically employing decentralised decision-making due to separate ownership, is coordinated if the members make decisions that are optimal for the whole supply chain. Coordination through contracts is predominantly used in both practice and literature. Various contracts have been developed to coordinate supply chains with different configurations. Cachon (2003) and Govindan et al. (2013) provide comprehensive reviews on coordination contracts, where a number of contracts have been identified and analysed. Revenue-sharing contracts, cost-sharing contracts, and two-part tariff contracts are widely applied in the green supply chain context (Chauhan & Singh, 2018). It is noteworthy that there is no universal contract for supply chain coordination. The application and study of coordination contracts are context-dependent and are affected by diverse factors, e.g., demand uncertainty, information structure, and power structure.

The majority of the literature design the contract in a take-it-or-leave-it scheme, i.e., a supply chain member with relatively more power is assigned to make the contract offer. The partner can only choose to accept or reject the contract, which is implausible in most business environments. To this end, there is a trend in green supply chain management literature that considers the application of bargaining contracts to expand the view of coordination (Chinchuluun et al., 2008). In a Nash bargaining structure, players cooperatively decide how to divide their coordination surplus; see Chinchuluun et al. (2008) and Nagarajan and Sošić (2008) for a detailed explanation of the bargaining framework. Song and Gao (2018) and Raza (2018) explore the revenue-sharing contract through bargaining for the green supply chain with deterministic demand and stochastic demand, respectively. They conclude that bargaining contracts promote the greenness level and make all supply chain members profitable. Similar conclusions are also drawn by other researchers with different bargaining models or negotiated contract parameters (e.g., Adhikari & Bisi, 2020; Bhaskaran & Krishnan, 2009; Ghosh & Shah, 2015; Heydaryan & Taleizadeh, 2017). In this paper, we develop a bargaining wholesale price contract to coordinate the supply chain of MDIGPs with stochastic demand.

3 Model development

We investigate a single-period green supply chain, including a manufacturer and a retailer, in a full information setting, i.e., each firm knows all the information that the other firm has at every point in the proceedings. Both actors are risk-neutral. They make rational decisions to maximise their expected profits based on perfect information about their partners in the supply chain. For ease of reference, we assume that the manufacturer is female (she) and the retailer is male (he) in later sections.

Figure 1 presents the proposed supply chain structure. With costly investment, the manufacturer in the supply chain initiates green practices, such as adopting environmentally friendly materials, green technologies, eco-design, and green information systems to green her operations and to produce green products. The retailer orders Q units of green products from the manufacturer at price w and then resells S units to the consumer at price p. The green product demand is stochastic. Therefore, the retailer solves a price-setting newsvendor problem. It is assumed that the retailer only focuses on distributing the green product and does not engage in green practices like green advertising.

This situation is common in supply chains with powerful upstream manufacturers, e.g., electric vehicle supply chains led by manufacturers like BYD and Ford, laptop supply chains led by Lenovo and Hewlett-Packard, and home appliance supply chains led by Haier and TCL. Greening those supply chains often involves close cooperation between members, and the manufacturers usually take the initiative to go green and organise the supply chain business. Therefore, when developing the model, it is quite realistic to set the manufacturer as the focal firm with relatively more bargaining power and assume a perfect information condition (Dong et al., 2016; Hong & Guo, 2019; Q. Y. Li et al., 2020). The manufacturer

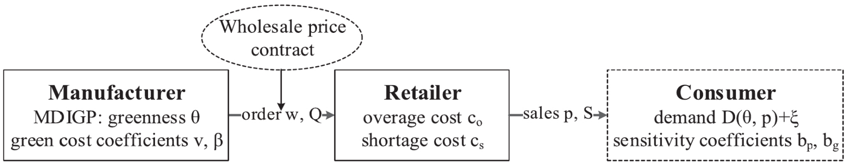


Figure 1: The proposed supply chain

is in the position of making the contract offer and coordinating the supply chain.

Another important consideration associated with the practicality of supply chain models is decision-making in single or multiple periods. It is pointed out that the single-period model is generic and applicable for cases with a short planning time frame. Take the EV supply chains in China as an example. CAAM[1] and the leading carmakers usually set a sales target for EVs at the beginning of the year and then check the realisation at the end of the year. In the course of achieving the target, they look at the demand uncertainty created by various factors like fast-changing policies. Therefore, we can regard one year as one single planning period for analysis. One can consider a longer time frame and extend the model for multiple periods to examine how the decisions change over time. Nevertheless, we aim to explore the effect of demand uncertainty on the decision-making process in the supply chains of MDIGPs. As Cohen et al. (2015) pointed out, it is sufficient to achieve this purpose without the added complexity of time dynamics.

To construct a sound game-theoretic optimisation model, we consider some assumptions. Some are applied to make the model closer to reality, while others are for simplification to model the phenomena in question analytically tractable and facilitate the characterisation of analytic solutions. Nevertheless, we notice that all assumptions are consistent with related studies in the literature and will elaborate further on these assumptions in later subsections. Table 2 provides a summary of relevant notations. For brevity, we sometimes only use the function name without including variables in later sections.

3.1 Demand and cost functions of MDIGPs

Demand For ease of modelling and analysis, we adopt a tractable linear additive demand function that captures the 'demand expansion effect of greening efforts' (Swami & Shah, 2013) and the market risk: $D(p, \theta) + \xi$, which incorporates two parts: a deterministic demand and an additive shock.

More specifically, we assume that the deterministic demand is influenced by the retail price p as well as the greenness improvement level θ, which is linearly decreasing in the price but increasing in greenness. Consistent with related studies (e.g., Ghosh et al., 2020; W. G. Zhu & He, 2017), it is given as $D(p, \theta) = a - b_p p + b_g \theta$, where a denotes the potential deterministic market size ($a > b_p p$), b_p and b_g represent market sensitivity coefficients to price and greenness respectively ($b_p > 0, b_g > 0$).

The linear demand function regarding price and non-price variable greenness is widely used in marketing and operations management literature because it is relatively easy to derive explicit analytical results and parameter estimations in empirical studies (Huang et al., 2013). Although the linearity and resulting requirements of finite ranges on some parameters often fail to correspond to reality precisely, this approach is sufficient to reflect the demand responsiveness to the product price and greenness (Ghosh & Shah, 2012, 2015).

In the function, ξ is a price-independent and green-independent random variable with a continuous and strictly increasing distribution $F(\xi)$ and a density function $f(\xi)$ defined on the range $[A, B]$ with a

[1]China Association of Automobile Manufacturers (CAAM) is a national industrial organisation consisting of 2,700 members, including major car parts suppliers, manufacturers, retailers, and research institutes in China. It is a prominent information provider in Chinese automobile industry.

Table 2: Notations

Decision-makers	Decision variables	Non-decision variables
Manufacturer Π_M: manufacturer's expected profit	w: wholesale price θ: greenness improvement ($\theta \geq 0$)	C: manufacturer's total cost $(c + v\theta)Q + \beta\theta^2$ c: per-unit production cost not including green-related costs v: unit-variable cost coefficient β: fixed investment cost coefficient ($\beta > 0$)
Retailer Π_R: retailer's expected profit	p: retail price Q: order quantity ($p > w > c + v\theta > 0$)	a: potential deterministic market size ($a > 0$) b_p and b_g: demand sensitivity to retail price and greenness, respectively ($b_p > 0$,$b_g > 0$) D: riskless demand for green products $a - b_p p + b_g\theta$ ξ: demand shock, a price-independent and green-independent random variable with a continuous and strictly increasing distribution $F(\xi)$ and a density function $f(\xi)$ defined on the support $[A, B]$ with a mean μ and a standard deviation σ S: expected sales $E[\min(Q, D + \xi)]$ transformed expected sales $S = D + z - I(z)$ with leftovers $I(z) = \int_A^z F(\xi)d\xi$ c_o and c_s: per-unit holding cost and goodwill penalty cost, respectively
Centralised supply chain Π_{SC}: expected profit of the supply chain	θ: greenness improvement p: retail price z: service level	Superscripts: 'gs': green products with stochastic demand 'gd': green products with deterministic demand Subscripts: 'c': centralised decision-making 'm': decentralised decision-making 'b': Nash bargaining setting

mean μ and a standard deviation σ. Let $h(\xi)$ represent the failure rate of the distribution; then, we have $h(\xi) = \frac{f(\xi)}{1-F(\xi)}$. To ensure a unique solution by the first-order optimality condition, the distribution is restricted to those with an increasing failure rate (IFR), i.e., $\frac{dh(\xi)}{d\xi} > 0$ for all ξ. The IFR assumption is a 'very mild restriction on the demand distribution' (Cachon, 2003; Choi, 2012). Many commonly applied distributions, including the uniform, normal, exponential, and lognormal distributions, satisfy the IFR property. To avoid a negative demand, we assume that $D(p,\theta) + A \geq 0$.

Expected sales are $S(p,\theta,Q) = E[\min(Q, D(p,\theta)+\xi)]$, where Q is the retailer's order quantity defined in the range of $[D(p,\theta)+A, D(p,\theta)+B]$. Then, it can be derived that $S(p,\theta,Q) = Q - \int_A^{Q-D(p,\theta)} F(\xi)d\xi$. Overstock occurs if the demand during the selling season does not exceed the order quantity, and then the retailer has leftovers $I(p,\theta,Q)$, which can be expressed as $I(p,\theta,Q) = \max\{0, Q-(D(p,\theta)+\xi)\} = Q - S(p,\theta,Q) = \int_A^{Q-D(p,\theta)} F(\xi)d\xi$. Alternatively, understock occurs if demand exceeds order quantity and the expected shortages are $\max\{0,(D(p,\theta)+\xi)-Q\} = D(p,\theta)+\mu-Q+I(z) = \mu+I(z)-z$.

Consistent with Q. Li and Atkins (2002), we define $z = Q-D(p,\theta)$ as the service level, i.e., an indicator describing the probability of not stocking out, because this transformation indicates that $\Pr\{D(p,\theta)+\xi \leq Q\} = \Pr\{\xi \leq z\} = F(z)$. It also allows the problem in the rest of the paper to switch from finding a profit-optimal Q to finding a z. Then sales can be rewritten as $S(p,\theta,z) = D(p,\theta)+z-I(z)$, where $I(z) = \int_A^z F(\xi)d\xi$ and it is nonnegative. In this case, z is supposed to be bounded in the range of $[A,B]$.

Cost The cost of the manufacturer is given as $C(\theta,Q) = (c+v\theta)Q + \beta\theta^2$, incorporating a volume-dependent variable cost and a volume-independent fixed cost. Recall that $Q = D(p,\theta)+z$, and then the cost function can be rewritten as $C(\theta,z) = (c+v\theta)(D(p,\theta)+z) + \beta\theta^2$.

Consistent with studies on innovative investment (Banker et al., 1998; D'Aspremont & Jacquemin, 1988; Ghosh & Shah, 2012), the fixed investment cost is assumed to be $\beta\theta^2$, where $\beta > 0$ is the investment coefficient. It is increasing and convex in the greenness improvement level θ. The quadratic cost function is commonly adopted to describe the increasing marginal cost investment for greenness improvement, i.e., initial greenness improvement is easier to achieve, but each additional subsequent improvement is more difficult with diminishing returns from R&D expenditures. While $c > 0$ denotes basic production cost per unit in the absence of greenness improvement, $v\theta$ represents the unit-variable cost, which depends on the greenness improvement. The total variable cost cannot be negative, i.e., $c+v\theta > 0$. Most green supply chain literature assumes that greening initiatives do not affect the manufacturer's marginal costs (see Chauhan & Singh, 2018 for details), i.e., $v = 0$ always holds. In the current paper, we relax this assumption and let the real number v be possibly less than, greater than, or equal to zero, i.e., it is possible for the marginal costs to decrease or increase by $|v\theta|$ or be unaffected by the greenness improvements. For instance, to green a product, such as a car, the manufacturer may install additional devices in the car to deal with carbon emissions, which incurs an additional unit cost; however, if she simplifies extra components, uses recycled material, or enhances the production efficiency by investing in advanced equipment and processes, marginal costs may actually fall (Baik et al., 2019). A survey by the European Commission (2018) shows that 41% of the SMEs involved in greening activities claim that production costs have fallen as a result. Cost reduction is also an important enabler of green manufacturing apart from the demand expansion effect (Dubey et al., 2015).

As the retailer confronts a newsvendor problem, apart from the transfer payment to the manufacturer, he also incurs a per-unit goodwill penalty cost c_s due to understock and a per-unit holding cost (or salvage value with a negative value) c_o ($c_o < c$) due to overstock. It is noted that since the consideration of costs for shortages and overages does not qualitatively affect the analysis of results, but only changes the quantile of the service level, we can assume that $c_s = 0$ and $c_o = 0$ for further simplicity (see Cohen et al., 2015; Y. Wang et al., 2004 for similar assumptions).

In the subsequent analysis, we confine our attention to the situation where the greenness improvement and demand are positive and both the supply chain and its members are profitable; thus, we impose additional conditions on the price and cost coefficients, namely, $p > w > c + v\theta > 0$, $-\frac{b_g}{b_p} < v < \frac{b_g}{b_p}$, $\beta > \frac{(b_g - vb_p)^2}{4b_p}$, and $a - b_1 c + A > 0$.

3.2 Expected profit functions

Considering the assumptions outlined above, we formulate the expected profit of the green supply chain as follows:

$$\begin{aligned}\Pi_{SC}^{gs}(p,\theta,z) &= pS(p,\theta,z) - C(\theta,z) - c_o I(z) - c_s(\mu + I(z) - z) \\ &= (p - (c+v\theta))\,D(p,\theta) - \beta\theta^2 + (p - (c+v\theta) + c_s)\,z - (p + c_o + c_s)I(z) - c_s\mu \end{aligned} \quad (1)$$

Note that the order quantity equals the demand in the deterministic demand setting. Therefore, it is observed that Eq. (1) is made up of two parts, the riskless profit in the absence of uncertainty, i.e., $\Pi_{SC}^{gd}(p,\theta) = (p - (c+v\theta))\,D(p,\theta) - \beta\theta^2$, and the expected profit loss caused by the presence of uncertainty, i.e., $Z_{SC}^{gs}(p,\theta,z) = (p - (c+v\theta) + c_s)\,z - (p + c_o + c_s)I(z) - c_s\mu$.

The commonly used wholesale price contract is applied between the supply chain members, i.e., the manufacturer charges the retailer w per unit ordered. Then, their profits are respectively given as:

$$\begin{aligned}\Pi_{M}^{gs}(w,\theta) &= wQ - C(\theta,z) \\ &= (w - (c+v\theta))\,D(p,\theta) - \beta\theta^2 + (w - (c+v\theta))\,z \end{aligned} \quad (2)$$

$$\begin{aligned}\Pi_{R}^{gs}(p,z) &= pS(p,\theta,z) - wQ - c_o I(z) - c_s(\mu + I(z) - z) \\ &= (p - w)D(p,\theta) + (p - w + c_s)z - (p + c_o + c_s)I(z) - c_s\mu \end{aligned} \quad (3)$$

The profit functions for the manufacturer and the retailer in the absence of uncertainty, i.e., when demand is deterministic, are $\Pi_{M}^{gd}(w,\theta) = (w - (c+v\theta))\,D(p,\theta) - \beta\theta^2$ and $\Pi_{R}^{gd}(p) = (p - w)D(p,\theta)$, respectively.

Here, the superscripts '^{gs}' and '^{gd}' denote cases of green products with stochastic demand and deterministic demand, respectively, and the subscripts '$_{SC}$', '$_{M}$' and '$_{R}$', represent the supply chain, the manufacturer and the retailer, respectively.

4 Model analysis

We start our analysis by solving the model concerning the decision-making variables for decentralised and centralised decision-making structures. Two policies under deterministic demand and stochastic demand are considered and compared.

4.1 Optimal decisions in decentralised supply chains

In decentralised supply chains, members make decisions individually, intending to maximise their own profits. The backward induction approach (Cachon & Netessine, 2006) is adopted to find the equilibrium solutions of the sequential game-theoretic model. Let the subscript '$_{m}$' denote this case. The profits of the retailer and the manufacturer in the deterministic case are represented as Π_{R}^{gd} and Π_{M}^{gd}, respectively. Solving the model, we obtain the following results.

Lemma 1. *In a decentralised supply chain with deterministic demand, the optimal decision of the manufacturer on the greenness improvement and the wholesale price, and the optimal retail price of the retailer are* $\theta_m^{gd} = \frac{(b_g - vb_p)(a - b_p c)}{8\beta b_p - (b_g - vb_p)^2}$, $w_m^{gd} = \frac{(4\beta + v(b_g - vb_p))(a - b_p c)}{8\beta b_p - (b_g - vb_p)^2} + c$, *and* $p_m^{gd} = \frac{(6\beta + v(b_g - vb_p))(a - b_p c)}{8\beta b_p - (b_g - vb_p)^2} + c$, *respectively.*

Proof. See Appendix A. □

Correspondingly, the demand and profits at equilibrium greenness improvement and prices are $D_m^{gd} = \frac{2\beta b_p(a-b_p c)}{8\beta b_p-(b_g-vb_p)^2}$, $\Pi_R^{gd} = \frac{4\beta^2 b_p(a-b_p c)^2}{(8\beta b_p-(b_g-vb_p)^2)^2}$, $\Pi_M^{gd} = \frac{\beta(a-b_p c)^2}{8\beta b_p-(b_g-vb_p)^2}$, and $\Pi_{SCm}^{gd} = \frac{\beta\left(12\beta b_p-(b_g-vb_p)^2\right)(a-b_p c)^2}{(8\beta b_p-(b_g-vb_p)^2)^2}$, respectively.

To stimulate the engagement in the development and production of MDIGPs, the manufacturer seeks to collect market demand information from the retailer at the start of the selling season, which can take the form of an early commitment to a service level from the retailer as he is in charge of product distribution. This behaviour can be observed in automobile and home appliances industry practices (Arrunada et al., 2005; Wei et al., 2021). Therefore, the interaction between the two supply chain firms takes place in the following sequence in time:

(1) The retailer determines a service level z before the realisation of the demand.

(2) The manufacturer makes her decisions on the greenness θ and the wholesale price w.

(3) The retailer determines his retail price after observing the manufacturer's behaviour.

The profits of the manufacturer and the retailer are shown in Eqs. (2) and (3), respectively. Similarly to the deterministic demand model analysis, we can derive the following solutions for the stochastic demand model, and details are omitted.

Lemma 2. *The equilibrium greenness improvement and prices in the decentralised supply chain with stochastic demand are, respectively:*

$$\theta_m^{gs}(z) = \theta_m^{gd} + \frac{(b_g - vb_p)\,(z + I(z))}{8\beta b_p - (b_g - vb_p)^2}$$

$$w_m^{gs}(z) = w_m^{gd} + \frac{(4\beta + v(b_g - vb_p))\,(z + I(z))}{8\beta b_p - (b_g - vb_p)^2}$$

$$p_m^{gs}(z) = p_m^{gd} + \frac{(6\beta + v(b_g - vb_p))\,b_p z - (2\beta b_p - b_g(b_g - vb_p))\,I(z)}{b_p\,(8\beta b_p - (b_g - vb_p)^2)}$$

We can observe that whether the equilibrium greenness improvement and prices under stochastic demand are lower or higher than the corresponding equilibrium decisions under deterministic demand depends on $\frac{z}{I(z)}$, the ratio of service level to leftovers. It is a relative index to characterise the relationship between the service level and leftovers. We call this ratio a relative service level. Corollary 1 and Corollary 2 can be directly obtained from Lemma 2.

Corollary 1. *The higher the retailer's service level is, the greener the product and the higher the manufacturer's profit will be.*

Corollary 2. *In a decentralised supply chain, the relation of optimal decisions under stochastic demand to those under deterministic demand depends on the range of the relative service level. Specifically, it has the following properties:*

(1) For the manufacturer, if the relative service level satisfies $\frac{z}{I(z)} \geq -1$ at the equilibrium value, the greenness and the wholesale price decisions made by the manufacturer under stochastic demand are no less than the relevant deterministic decisions, which increases her profit, i.e., $\theta_m^{gs} \geq \theta_m^{gd}$, $w_m^{gs} \geq w_m^{gd}$, and $\Pi_M^{gs} \geq \Pi_M^{gd}$; if $\frac{z}{I(z)} < -1$, the equilibrium outcomes for the manufacturer are smaller than the deterministic solutions.

(2) For the retailer, if $\frac{z}{I(z)} < \frac{2\beta b_p - b_g(b_g - v b_p)}{(6\beta + v(b_g - v b_p))b_p}$*, then* $p_m^{gs} < p_m^{gd}$*; if* $\frac{z}{I(z)} \geq \frac{2\beta b_p - b_g(b_g - v b_p)}{(6\beta + v(b_g - v b_p))b_p}$*, then* $p_m^{gs} \geq p_m^{gd}$*.*

Proof. See Appendix B. □

Noticeably, we have $\frac{2\beta b_p - b_g(b_g - v b_p)}{(6\beta + v(b_g - v b_p))b_p} > -1$ according to the condition $\beta > \frac{(b_g - v b_p)^2}{4 b_p}$. Therefore, by Corollary 2, we can see that when $-1 \leq \frac{z}{I(z)} < \frac{2\beta b_p - b_g(b_g - v b_p)}{(6\beta + v(b_g - v b_p))b_p}$, the inequalities $\theta_m^{gs} \geq \theta_m^{gd}$ and $p_m^{gs} < p_m^{gd}$ hold simultaneously, which implies that consumers can purchase greener products at a lower price in the stochastic demand setting than they can in a deterministic demand setting.

It is noteworthy that the service level z is a decision variable on the part of the retailer and that the leftover $I(z)$ is also information held by the retailer that depends on his order quantity and sales. The service level and its ratio to leftovers significantly influence the manufacturer's decisions and profit. As such, the retailer's ordering decision plays a crucial role in the economic performance (profits) and the environmental performance (greenness) of supply chains with stochastic demand. Remarkably, the demarcation value for greenness and wholesale price is constant. The independence of the relative service level allows the retailer to achieve desired outcomes by intentionally making it fall into a favourable range.

We now analyse the service level equilibrium. Substituting θ_m^{gs}, w_m^{gs} and p_m^{gs} into the profit function of the retailer gives us the problem $\max_z \Pi_R^{gs}(z|p_m^{gs}, w_m^{gs}, \theta_m^{gs})$. Proposition 1 provides the optimal solution for z.

Proposition 1. *The unique optimal service level* z_m^{gs} $(A \leq z_m^{gs} < B)$ *that maximises the expected profit of the retailer in a decentralised supply chain with stochastic demand is implicitly determined by* $F(z) = 1 - \frac{w_m^{gs}(z) + c_o + 2V(z)}{p_m^{gs}(z) + c_s + c_o + V(z)}$*, where* $V(z) = \frac{2\beta b_p\left(4\beta b_p - (b_g - v b_p)^2\right)(a - b_p c + z + I(z)) + b_g(b_g - v b_p)\left(8\beta b_p - (b_g - v b_p)^2\right)I(z)}{b_p(8\beta b_p - (b_g - v b_p)^2)^2}$*.*

Proof. See Appendix C. □

4.2 Optimal decisions in centralised supply chains

In this section, decisions are centralised in one firm that seeks to maximise the supply chain's total profit with full access to all information, which subsequently provides benchmarks for the performance measure and coordination of the decentralised supply chain. The model is denoted by the subscript '$_c$'.

In a similar sequential procedure with the analysis of the decentralised model, we first derive solutions for the deterministic demand case. The central decision-maker chooses the greenness improvement θ and the retail price p to maximise the supply chain's profit $\Pi_{SC}^{gd}(p, \theta)$. Details of the solution procedure are not presented for brevity but note that to guarantee the joint concavity of the profit in the retail price and the greenness, and to ensure that the price is higher than the costs and the greenness improvement is positive, we require the following assumptions on the cost coefficients: $-\frac{b_g}{b_p} < v < \frac{b_g}{b_p}$ and $\beta > \frac{(b_g - v b_p)^2}{4 b_p}$.

Lemma 3. *The profit-optimal greenness improvement and retail price in the centralised supply chain with deterministic demand are* $\theta_c^{gd} = \frac{(b_g - v b_p)(a - b_p c)}{4\beta b_p - (b_g - v b_p)^2}$ *and* $p_c^{gd} = \frac{(2\beta + v(b_g - v b_p))(a - b_p c)}{4\beta b_p - (b_g - v b_p)^2} + c$*, respectively.*

The corresponding deterministic demand and profit at the equilibrium greenness improvement and retail price are $D_c^{gd} = \frac{2\beta b_p(a - b_p c)}{4\beta b_p - (b_g - v b_p)^2}$ and $\Pi_{SCc}^{gd} = \frac{\beta(a - b_p c)^2}{4\beta b_p - (b_g - v b_p)^2}$, respectively.

In the stochastic demand setting, the introduction of stochasticity makes the order quantity deviate from the deterministic demand, increasing complexity and making it more difficult to solve the model. To solve this stochastic model, the service level z is selected first, as the subsequent decisions on greenness improvement θ and sales price p are determined based on its information. Since it is easiest to change the price, that decision is the last one made. As such, the decision sequence is $z \to \theta \to p$, and we can find the equilibrium solutions by solving backward. Similarly, details are omitted. To ensure that the selling price is higher than the unit-variable production cost, we require a positive base demand assumption, i.e., $a - b_p c + A > 0$.

Lemma 4. *The profit-maximising greenness improvement and retail price in the centralised supply chain with stochastic demand are* $\theta_c^{gs}(z) = \theta_c^{gd} + \frac{(b_g - vb_p)z - (b_g + vb_p)I(z)}{4\beta b_p - (b_g - vb_p)^2}$ *and* $p_c^{gs}(z) = p_c^{gd} + \frac{(2\beta + v(b_g - vb_p))z - 2(\beta + vb_g)I(z)}{4\beta b_p - (b_g - vb_p)^2}$, *respectively.*

According to the equations in Lemma 4, we can obtain Corollary 3.

Corollary 3. *In a centralised supply chain, the relation of optimal decisions under stochastic demand to those under deterministic demand depends on the range of the relative service level. Specifically, it has the following properties:*

(1) For the greenness, if $\frac{z}{I(z)} \geq \frac{b_g + vb_p}{b_g - vb_p}$ *at the optimal value of* z*, we have* $\theta_c^{gs} \geq \theta_c^{gd}$*, i.e., the optimal greenness improvement under stochastic demand is higher than the optimal greenness improvement under deterministic demand; if* $\frac{z}{I(z)} < \frac{b_g + vb_p}{b_g - vb_p}$*, then* $\theta_c^{gs} < \theta_c^{gd}$*.*

(2) For the retail price, if $\frac{z}{I(z)} < \frac{2(\beta + vb_g)}{2\beta + v(b_g - vb_p)}$*, then* $p_c^{gs} < p_c^{gd}$*; if* $\frac{z}{I(z)} \geq \frac{2(\beta + vb_g)}{2\beta + v(b_g - vb_p)}$*, then* $p_c^{gs} \geq p_c^{gd}$*.*

Noticeably, the inequality $\frac{b_g + vb_p}{b_g - vb_p} < \frac{2(\beta + vb_g)}{2\beta + v(b_g - vb_p)}$ follows when $v < 0$, and we can see that when the conditions $v < 0$ and $\frac{b_g + vb_p}{b_g - vb_p} \leq \frac{z}{I(z)} < \frac{2(\beta + vb_g)}{2\beta + v(b_g - vb_p)}$ are satisfied, from which $\theta_c^{gs} \geq \theta_c^{gd}$ and $p_c^{gs} < p_c^{gd}$ follow, consumers can purchase greener products at a lower price in the stochastic demand setting than they can in the deterministic demand setting.

From Corollary 2 and Corollary 3, we formulate:

Remark 1. Suppose the manufacturer undertakes variable cost-reduction green initiatives, and the retailer maintains a reasonable service level. In this case, the supply chain can provide greener products for consumers at lower prices in the stochastic demand setting than they can in the deterministic demand setting.

As manufacturing productivity increases due to greening efforts, unit costs decline, and then green products are passed on to consumers through retailers with lower prices (UNIDO, 2018). The practices of BYD Auto Company[2], one of the largest EV producers in the world, corroborate this possibility. Reductions in battery costs due to technological advancements and increasing sales by working more closely with dealerships bring down overall EV manufacturing costs and selling prices. For example, the newly-launched Tang EV model updates vehicle configurations but is 50 thousand RMB (about eight thousand USD) cheaper than the old model[3]. As we can see, even though the overall market demand for EVs is growing steadily, there is currently a great deal of uncertainty due to the ongoing changes in the framework conditions and the major technological upheavals. However, embracing uncertainty with a stochastic demand setting is not always bad for marketing greener products when supply chain firms can trade off greening costs against service level. Especially when greening creates production cost reduction, incorporating demand uncertainty in the operational decision-making is important because the reduction could be passed on to the consumers via an appropriate service level setting in terms of cheaper green products. It is beneficial to break up the stereotype of green products being perceived as expensive and achieve greater market penetration (Peattie & Crane, 2005).

Next, we derive the service level equilibrium. Substituting p_c^{gs} and θ_c^{gs} into the profit function of the supply chain produces $\Pi_{SCc}^{gs}(z|p_c^{gs}, \theta_c^{gs})$. Then the problem comes to $\max_z \Pi_{SCc}^{gs}(z|p_c^{gs}, \theta_c^{gs})$. If we find the optimal z, the optimal solutions for θ and p are also obtained. Proposition 2 provides the optimal solution for z.

[2] https://www.byd.com/en/index.html

[3] Source: http://www.bydauto.com.cn/auto/news/2020-08-16/1514437244227

Proposition 2. *Assume the condition* $\frac{v}{c+v\theta_c^{gs}+c_o}\frac{d\theta_c^{gs}}{dz} > -\frac{1}{3h(z)}\left(2h^2(z)+\frac{dh(z)}{dz}\right)$ *is satisfied. Then there is a unique optimal service level* z_c^{gs} $(A \leq z_c^{gs} < B)$ *that maximises the expected profit of the centralised supply chain with a stochastic demand, which is implicitly determined by* $F(z) = 1 - \frac{c+v\theta_c^{gs}(z)+c_o}{p_c^{gs}(z)+c_s+c_o}$.

Proof. See Appendix D. □

4.3 Comparison

Compared with the traditional price-setting newsvendor model, the newsvendor model with greening effects primarily has different implications for two aspects: prices and service levels. Concerning pricing, in traditional newsvendor studies like Petruzzi and Dada (1999), Q. Li and Atkins (2002), and Y. Wang et al. (2004), the optimal price derived from the stochastic demand model is always lower than that from the deterministic demand model. We relax this relationship as explained in Corollary 2 and Corollary 3. Concerning the service level, we show that the introduction of greening complicates the optimal solution for z by imposing additional requirements on the variable greening cost and obtain the result of Corollary 4.

Corollary 4. *Comparing* z_m^{gs} *and* z_c^{gs} *yields the relation of* $z_m^{gs} < z_c^{gs}$*, i.e., the optimal service level of decentralised supply chains is lower than that of centralised supply chains, the decentralised optimal decisions deviate from the centralised optimal decisions.*

Proof. See Appendix E. □

As observed, there are two types of green practices that affect the marginal cost of MDIGPs: incurring additional manufacturing cost activities and cost-reduction ones. We relax the general assumption that the unit-variable cost coefficient satisfies $v \geq 0$. A negative variable cost coefficient deserves to be considered in the model to investigate how it affects the decisions and profits. We analyse the impact of v on product greenness and retail price in the decentralised supply chain by first-order derivatives of the equilibrium solutions for v.

Corollary 5. *When* $-\frac{b_g}{b_p} < v < \left(\frac{1-F(z)}{1+F(z)} - \frac{2I(z)}{a-b_pc+z+I(z)}\right)\frac{b_g}{b_p}$*, the service level, the greenness improvement, and the retail price are decreasing in* v *for stochastic demand cases.*

Proof. See Appendix F. □

In the deterministic demand setting, the greenness and order quantity decrease with v, while the retail price increases with v in the interval of $-\frac{b_g}{b_p} < v < \frac{-(2\beta b_p - {b_g}^2)+2\sqrt{\beta b_p(\beta b_p - 2{b_g}^2)}}{b_p b_g} < 0$. We can see that within a certain negative interval, the impact of v on the retail price in the stochastic demand setting versus the deterministic demand setting is different.

In addition, the sign of the variable cost coefficient plays a vital role in the choice of the manufacturer's product strategy, i.e., being DIGPs or MDIGPs. We rewrite the expressions of the manufacturer's optimal greenness and profit for DIGPs by letting $v = 0$, i.e., the variable cost is negligible. Table 3 presents the results. By comparison, we find that v determines the relation between manufacturer's performance of being DIGPs and being MDIGPs under both deterministic and stochastic demand cases. For the manufacturer, when $-\frac{b_g}{b_p} < v < 0$, i.e., green practices are cost-reduction, the greenness and profit for MDIGPs are higher than those for DIGPs, while being DIGPs performs better than being MDIGPs when the variable cost coefficient is positive, i.e., green practices incur additional manufacturing cost.

Table 3: Manufacturer's optimal greenness and profit for DIGPs and MDIGPs

Indicators	DIGPs ($v=0$)	MDIGPs
θ_m^{gd}	$\frac{b_g(a-b_pc)}{8\beta b_p-b_g{}^2}$	$\frac{(b_g-vb_p)(a-b_pc)}{8\beta b_p-(b_g-vb_p)^2}$
Π_M^{gd}	$\frac{\beta(a-b_pc)^2}{8\beta b_p-b_g{}^2}$	$\frac{\beta(a-b_pc)^2}{8\beta b_p-(b_g-vb_p)^2}$
θ_m^{gs}	$\theta_m^{gd}+\frac{b_g(z+I(z))}{8\beta b_p-b_g{}^2}$	$\theta_m^{gd}+\frac{(b_g-vb_p)(z+I(z))}{8\beta b_p-(b_g-vb_p)^2}$
Π_M^{gs}	$\frac{\beta\left(a-b_pc+z+I(z)\right)^2}{8\beta b_p-b_g{}^2}$	$\frac{\beta\left(a-b_pc+z+I(z)\right)^2}{8\beta b_p-(b_g-vb_p)^2}$

4.4 Supply chain coordination

We first analyse the profit share of the decentralised supply chain with a wholesale price contract and then devise a bargaining scheme to coordinate the green supply chain with stochastic demand. Since the manufacturer is the focal firm in the supply chain, the analysis focuses on the most commonly investigated performance measure for two-echelon supply chains, namely, the manufacturer's profit share ($r=\Pi_M/\Pi_{SC}$). The following corollary is obtained.

Corollary 6. *Comparing the results of deterministic demand and stochastic demand models, the relation of the manufacturer's profit share satisfies* $r^{gs}>r^{gd}>50\%$.

Proof. See Appendix G. □

Intuitively, the dominant manufacturer always has a profit allocation advantage, i.e., her profit is greater than that of the retailer. The presence of stochasticity reinforces the leader's advantage, i.e., the manufacturer retains a larger profit share in the stochastic setting.

In addition, the manufacturer was assumed to have a complete say in negotiating the wholesale price by offering a take-it-or-leave-it contract. If the optimal decisions in decentralised supply chains are the same as those in centralised supply chains, i.e., the wholesale price contract achieves perfect coordination, we need to set $\theta_m^{gs}(z_m^{gs})=\theta_c^{gs}(z_c^{gs})$, $p_m^{gs}(z_m^{gs})=p_c^{gs}(z_c^{gs})$, and then $z_m^{gs}=z_c^{gs}$. To satisfy those equations, it is required that $w_m^{gs}(z_m^{gs})=c+v\theta_m^{gs}(z_m^{gs})-(1+F(z_m^{gs}))\,V(z_m^{gs})$, where $V(z_m^{gs})>0$. Therefore, $w_m^{gs}(z_m^{gs})<c+v\theta_m^{gs}(z_m^{gs})$, the wholesale price is lower than the unit manufacturing cost. Accordingly, the manufacturer's expected profit will be negative, which is unacceptable to her. The contract cannot coordinate the supply chain in this case.

To incentivise firms to participate in the coordination, we now relax the assumption and assume that the manufacturer and the retailer cooperatively determine the wholesale price through bargaining. The bargaining model is formulated as a Nash Bargaining game (Nagarajan & Sošić, 2008; Nash, 1950), which is denoted by the subscript 'b':

$$\max_w \Pi_b(w)=\max_w \left(\Pi_{Mb}^{gs}(w|\theta_c^{gs},p_c^{gs})\right)^{\tau}\left(\Pi_{Rb}^{gs}(w|\theta_c^{gs},p_c^{gs})\right)^{1-\tau} \tag{4}$$

where τ ($0\le\tau\le 1$) represents the bargaining power of the manufacturer relative to the retailer. Initially, we assume that the disagreement points of both players are the same and are normalised to zero (Bhaskaran & Krishnan, 2009; Yenipazarli, 2017), i.e., conditions $\Pi_{Mb}^{gs}\ge 0$ and $\Pi_{Rb}^{gs}\ge 0$ must hold. The condition can be understood as the participation constraint to ensure nonnegative profits for both players while maximising the supply chain's total profit. Given that supply chain members agree on the bargaining process, the total profit of the supply chain is maximised. Proposition 3 shows the wholesale price through bargaining between firms. For notational convenience, let $J>0$, $K>0$, and $L>0$ denote $a-b_pc+z+I(z)$, $8\beta b_p-(b_g-vb_p)^2$ and b_g-vb_p, respectively.

Proposition 3. *The profit is divided between the two players by determining the wholesale price cooperatively as*

$$w_b = c + v\theta_c^{gs} + \frac{(2b_g I(z) - JL)^2 \beta}{(K - 4\beta b_p)(2\beta b_p J - b_g L I(z))} + \frac{J^2\beta - ((4\beta + vL)(a+z) - b_g(vI(z) + cL))\, I(z) - (K - 4\beta b_p)\,(c_o I(z) + (\mu + I(z) - z)c_s)}{2\beta b_p J - b_g L I(z)}\tau$$

Proof. See Appendix H. □

From Proposition 3, the manufacturer obtains a profit of $\Pi_{Mb}^{gs} = \tau\Pi_{SCc}^{gs}$ and the retailer obtains $\Pi_{Mb}^{gs} = (1-\tau)\Pi_{SCc}^{gs}$, i.e., in this Nash bargaining game, the profit shares of the two players depend on their bargaining power. The coordinated wholesale price is made up of two parts: the power-independent part and the power-dependent part. The power-independent part is fixed and constitutes the base for the final decision of the wholesale price. The power-dependent part is negotiable and can help the manufacturer to analyse and solve the coordination problems with the retailer. Further, conditions $\Pi_{Mb}^{gs} \geq \Pi_{M}^{gs}$ and $\Pi_{Rb}^{gs} \geq \Pi_{R}^{gs}$ are put in as constraints to determine the final wholesale price. The constraints ensure that both players could benefit from coordination, i.e., the coordination contract achieves Pareto improvement. Then, we obtain $\frac{\Pi_M^{gs}}{\Pi_{SCc}^{gs}} \leq \tau \leq 1 - \frac{\Pi_R^{gs}}{\Pi_{SCc}^{gs}}$, which indicates that the manufacturer can induce supply chain members to Pareto improvement by intentionally making her profit share fall into a favourable range when bargaining on the wholesale price. Expressions of Π_M^{gs}, Π_R^{gs}, and Π_{SCc}^{gs} are summarised in Table 6.

5 Numerical analysis

5.1 Solution procedure

We perform numerical analyses to illustrate the results derived in Section 4 and show how the analytical solution procedure can be applied to determine the optimal solutions. The analysis is performed by using Maple software version 2020.0. We propose a solution procedure for solving the model numerically, which includes the following main steps:

Step 0: Assign values to relevant parameters, namely a, b_p, b_g, c, c_s, c_o, v and β according to the assumptions.

Step 1: Specify the probability distribution function and compute the equilibrium greenness improvement ($\theta_c^{gs}(z)$, $\theta_m^{gs}(z)$) and prices ($p_c^{gs}(z)$, $w_m^{gs}(z)$) through the corresponding equations. Here, the results reduce to functions of only one variable z.

Step 2: Compute the optimal service level (z_c^{gs}, z_m^{gs}) using the corresponding propositions with the solutions obtained in Step 1.

Step 3: Set $z = z_c^{gs}$ (or $z = z_m^{gs}$) and substitute it in the functions we derived in Step 1. Then optimal values of the greenness improvement and prices can be obtained.

5.2 Setup of the numerical experiment

We first assume that $c_s = 0$ and $c_o = 0$ for simplicity. Then, we use estimates from the Chinese electric vehicle market to generate values for the baseline parameters, with all monetary parameters being in Chinese Yuan (¥) – for interpretation purposes, roughly, exchange rates apply of CNY 8 per EUR and CNY 7 per USD. Other main values are obtained as follows:

Table 4: Baseline parameters

Parameter	c_s	c_o	a	b_p	b_g	c	β	v	A	B
Value	0	0	2×10^6	10	2×10^5	10^5	10^{10}	10^3	-2.5×10^5	2.5×10^5

(1) Since the Chinese government[4] has officially set a goal in its development plans that annual production and sales of EVs must reach two million units by 2020, we consider $a = 2 \times 10^6$.

(2) Several empirical studies have estimated demand, cost, and related parameters for the Chinese automobile market (e.g., Deng & Ma, 2010; Wu et al., 2019). Based on this research, we set the average annual price elasticity $b_p = 10$ and the marginal cost of production$c = 10^5$. Checking the R&D expenditure indicators of the listed EV companies like BYD, Geely, and GWM through their annual financial statements, in conjunction with the average of the car manufacturing industry published in the China Science and Technology Statistics Yearbook 2019[5], we consider $\beta = 10^{10}$.

(3) Information provided by CAAM shows that EV sales targets were 0.7, 0.7, 1 and 1.6 million units for the years 2016-2019, respectively. Realised sales are reported as 0.5, 0.8, 1.3 million and 1.2 million units for these years, respectively. Consequently, we consider $A = -2.5 \times 10^5$ and $B = 2.5 \times 10^5$.

(4) In the absence of detailed data on the greening variable cost and demand elasticities in public reports and the academic literature, we assume $v = 10^3$ and $b_g = 2 \times 10^5$ according to assumptions and analytical results discussed above. In Section 5.5, we conduct sensitivity analyses by varying v and b_g in corresponding intervals to illustrate their impacts on the optimal solutions.

Table 4 summarises the parameter values. Although the numbers are crude estimates, we argue that they are representative of firm-level practice and allow us to provide plausible insights into the empirical properties of our model.

5.3 Computational results

The probability distribution of the stochastic demand needs to be specified as an input for the model. A uniform distribution is widely used to derive tractable closed-form solutions for stochastic demand models (e.g., in papers of C. Liu & Chen, 2019; Tsao & Lee, 2020). Perakis and Roels (2008) adopt the minimax regret approach to examine the newsvendor model with partial demand distribution information and to suggest some guidelines for which distribution needs to be considered as an input to the newsvendor model. Based on their suggestions, normal and exponential distributions are also adopted apart from the uniform distribution.

Note that the exponential distribution ensures a positive z, i.e., the order quantity is not less than the deterministic demand. In contrast, the value of z in the uniform and normal distributions is not necessarily positive. Accordingly, we also study a truncated uniform distribution and a truncated normal distribution with a nonnegative lower bound to investigate the differences. To keep the exposition simple, we let the mean of the normal and exponential distributions be identical to the uniform distribution. The range $[A, B] = [-2.5 \times 10^5, 2.5 \times 10^5]$ discussed before can be used for the uniform and normal distributions. We truncate the range to $[A, B] = [0, 2.5 \times 10^5]$ for an exponential distribution. Corresponding to a 99.73% confidence interval with the three-sigma rule, we define $[A, B] = [\mu - 3\sigma, \mu + 3\sigma]$ for the normal distribution.

[4]Source: Energy saving and new energy vehicles industry development plan (2012-2020) issued by the State Council of PRC, http://www.gov.cn/zhengce/content/2012-07/09/content_3635.htm

[5]Source: https://www.chinayearbooks.com/tags/china-statistical-yearbook-on-science-and-technology

Table 5: Optimal solutions under different demand settings

Demand	Deterministic		Stochastic case 1 $U(-2.5\times 10^5, 2.5\times 10^5)$		Stochastic case 2 $N(0, 8.33\times 10^4)$		Stochastic case 3 $Exp(1.25\times 10^5)$		Stochastic case 4 $U(0, 2.5\times 10^5)$		Stochastic case 5 $N(1.25\times 10^5, 4.17\times 10^4)$	
Decisions	gdc	gdm	gsc	gsm	gsc	gsm	gsc	gsm	gsc	gsm	gsc	gsm
z			-86721	-218999	-34109	-125869	56497	9322	92536	18010	111791	64545
θ	0.5221	0.2487	0.4615	0.1945	0.4934	0.2180	0.5453	0.2510	0.5605	0.2533	0.5742	0.2651
w		152612		141140		146113		153120		153593		156078
p	155482	178793	149176	161517	152530	168826	157998	179520	159656	180198	161078	183850
D	549600	261810	600529	423728	573380	355345	529072	255022	515547	248689	504073	214521
Q			513808	204729	539271	229476	585569	264344	608083	266699	615864	279066
S			487148	203768	520366	227123	574526	264005	590957	266050	605033	277718
$I(z)$			26660	961	18905	2353	11043	339	17126	649	10831	1348
$z/I(z)$			-3.253	-227.9	-1.804	-53.49	5.116	27.50	5.403	27.75	10.32	47.88
$R(\times 10^9)$		6.854		4.012		4.811		6.929		6.977		7.502
$M(\times 10^9)$		13.09		8.002		10.04		13.36		13.59		14.88
$SC(\times 10^{10})$	2.748	1.994	1.892	1.202	2.275	1.486	2.893	2.028	3.006	2.056	3.221	2.239
$e(\%)$		72.56		63.53		65.32		70.10		68.40		69.51
$r(\%)$		65.65		66.57		67.56		65.88		66.10		66.46
$d_R(\%)$				-41.46		-29.81		1.09		1.79		9.45
$d_M(\%)$				-38.87		-23.30		2.06		3.82		13.67
$d_{SC}(\%)$			-31.15	-39.72	-17.21	-25.48	5.28	1.71	9.39	3.11	17.21	12.29
$d_\theta(\%)$			-11.61	-21.79	-5.50	-12.34	4.44	0.92	7.35	1.85	9.98	6.59
$d_p(\%)$			-4.06	-9.66	-1.90	-5.57	1.62	0.41	2.68	0.79	3.60	2.83
$d_Q(\%)$			-6.51	-21.80	-1.88	-12.35	6.54	0.97	10.64	1.87	12.06	6.59

Notes: Following Corollary 2 and Corollary 3, for the centralised supply chain, the demarcation values of $z/I(z)$ are 1.010 and 1.105; they are rounded to 1 for simplicity. For the decentralised supply chain, the demarcation value for greenness and wholesale price is −1; the demarcation value for the retail price is 0.2691.

'gdc' and 'gdm': represent centralised and decentralised supply chains under deterministic demand, respectively;

'gsc' and 'gsm' represent centralised and decentralised supply chains under stochastic demand, respectively;

'e' and 'r' denote the efficiency of the supply chain ($e = \Pi_{SCm}/\Pi_{SCc}$) and the manufacturer's profit share ($r = \Pi_M/\Pi_{SC}$), respectively;

'd_x' denotes the deviation rate of each variable relative to corresponding deterministic values, i.e., $d_x = (x^{gs} - x^{gd})/x^{gd}$ where $x \in \{\theta, p, Q, R, M, SC\}$ and please note that $Q^{gd} = D^{gd}$.

Therefore, taking into account the setting of the lower bound $A = -2.5 \times 10^5$ or 0 under uniform, normal, and exponential distributions, we analyse five stochastic cases, namely, (1) $\xi \sim U(-2.5\times 10^5, 2.5\times 10^5)$, (2) $\xi \sim N(0, 8.33 \times 10^4)$ bounded in $[A, B] = [-2.5 \times 10^5, 2.5 \times 10^5]$, (3) $\xi \sim Exp(1.25 \times 10^5)$ bounded in $[A, B] = [0, 2.5 \times 10^5]$, (4) truncated uniform $\xi \sim U(0, 2.5 \times 10^5)$, and (5) truncated normal $\xi \sim N(1.25\times 10^5, 4.17\times 10^4)$ bounded in $[A, B] = [0, 2.5\times 10^5]$. For ease of expression, we refer to the five cases in the later analysis as negative uniform, negative normal, exponential, nonnegative uniform, and nonnegative normal cases, respectively. Further, cases (1) and (2) are referred to as negative distributions, while cases (3), (4), and (5) are referred to as nonnegative distributions. The optimal numerical solutions are provided in Table 5.

Remark 2. The solution procedure is efficient and effective in obtaining optimal values of decision variables and profits.

To assess whether the results obtained by our proposed solution procedure are reliable, we resort to the Optimisation and DirectSearch optimisation packages in Maple to find the optimal solutions by exhaustive searches. The optimisation packages generate the same results as our solution scheme but take 30 percent more time. The comparison validates the robustness of the proposed solution procedure. The code is available from the corresponding author upon request.

5.4 Comparison analysis

5.4.1 Impact of demand uncertainty

Figure 2 and Figure 3 demonstrate how z affects stochastic profits, comparing with deterministic profits. As the graphs and Table 5 show, the optimal service levels in decentralised decision-making are smaller than those in centralised decision-making due to supply chain inefficiency. We make the following additional observations:

(1) The consideration of demand uncertainty significantly affects the predicted environmental and economic performance of the supply chain of MDIGPs. In decentralised supply chains, stochasticity leads to increases in greenness by up to 7%, retailer's profit by 9%, and manufacturer's profit by 14% (see Figure 3(b)). Allowing for a negative lower bound of the service level gives even larger impacts: for greenness up to 22%, for the retailer's profit as high as 41%, and for the manufacturer's profit 39% (see Figure 2(a)).

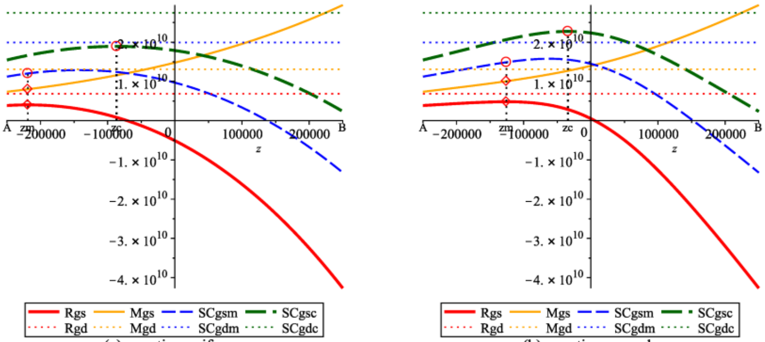
(2) Compared to the deterministic demand setting, the presence of stochasticity reduces supply chain efficiency, i.e., the ratio of decentralised supply chain profit to centralised profit. The maximum reduction reaches 9% when the demand shock ξ is uniformly distributed with a negative lower bound.

(3) When the demand shock follows a uniform distribution, supply chain efficiency reaches 68% in the case with a nonnegative lower bound, versus 64% in the negative lower bound case. For the normal distribution, efficiency reaches 70% in a nonnegative lower bound case, versus 65% in the negative setting. Although the manufacturer receives a smaller profit share (i.e., the retailer's profit share increases) in the nonnegative lower bound cases, this does not offset the efficiency increase, so both actors' profits increase. Supply chain efficiency and the retailer's profit share are highest in the case of an exponential distribution.

It is noteworthy that the general direction of our findings is insensitive to the distributional assumption because of the nature of decentralised decision-making and power structure. Compared to the deterministic demand setting, optimal decentralised service levels are consistently smaller than optimal centralised service levels; stochasticity always reduces supply chain efficiency and makes the manufacturer divide more profit in all cases. The shape of the distribution will only influence the magnitude of these impacts.

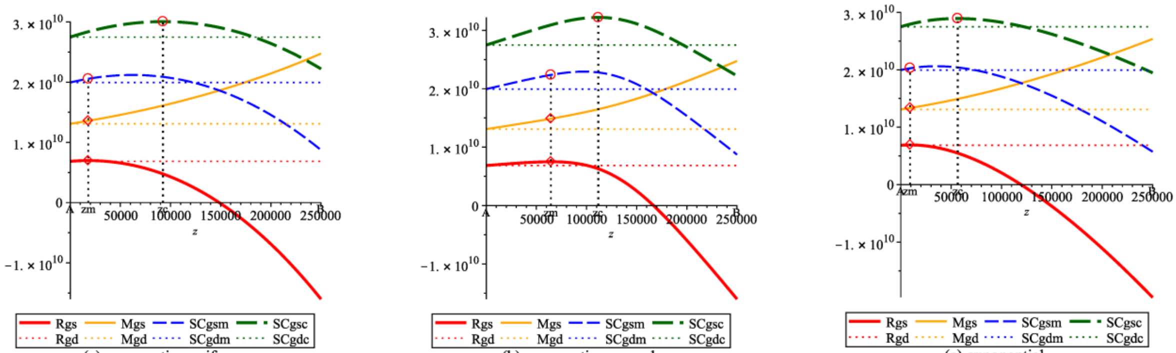
The above findings have practical implications for the retailer's ordering decision. The range of the demand shock also represents the range of the service level. As we define $z = Q - D(p, \theta)$, the sign of the lower bound of the service level z reflects whether or not the order quantity is lower than the deterministic demand when the retailer places his orders, which affects the potential profit of the decentralised supply chain and its allocation among the supply chain members. A nonnegative lower bound, i.e., when the retailer does not order less than the deterministic demand, could increase supply chain efficiency and the retailer's profit share, which means that supply chain firms would benefit from the stochasticity. This goes against the intuition that uncertainty and instability in the market hurt the profits of manufacturers (UNIDO, 2018).

It could be important in practical cases to study the characteristics above with an empirically observed demand distribution, as the assumption concerning shape and parameters is relevant to the outcomes. If one assumes a uniform distribution, while the actual demand turns out to follow a normal distribution, the efficiency and manufacturer's profit share are underestimated. Reversely, if the actual demand distribution is uniform but is assumed to be normal, one should expect an overestimation. Unfortunately, actual demand distributions are complicated to characterise and usually unknown (Perakis & Roels, 2008). Therefore, in practice, collecting information concerning the range, mean, and variance of demand to describe the distribution will be useful.



(a) negative uniform (b) negative normal

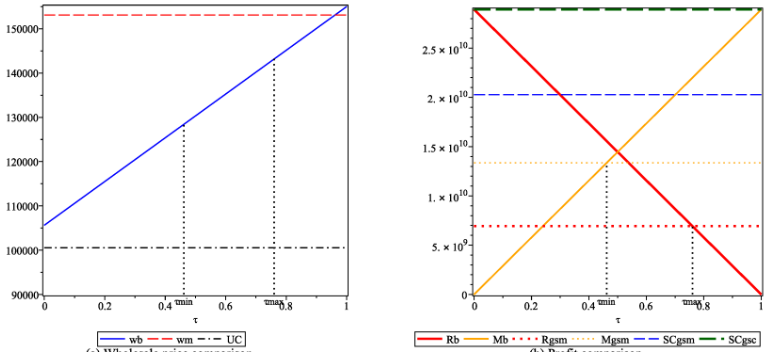
Figure 2: Profits under negative distributions



(a) nonnegative uniform (b) nonnegative normal (c) exponential

Notes: Setting a strictly positive lower bound yields similar properties to cases with zero lower bound, but has larger differences relative to corresponding deterministic solutions. Red circles mark the profits at optimal values of service levels under stochastic demand.

Figure 3: Profits under nonnegative distributions



(a) Wholesale price comparison (b) Profit comparison

Notes: 'wb': the wholesale price in the bargaining game; 'wm': the wholesale price under deterministic demand with decentralised decision-making; 'UC': unit production cost under stochastic demand with centralised decision-making. 'Rb' and 'Mb': the profit of the retailer and the manufacturer in the bargaining game, respectively.

Figure 4: Wholesale price and profits comparison of decentralised and coordinated cases

5.4.2 Impact of coordination

As analysed in the previous section, committing to a higher service level is a simple measure to improve the supply chain's profitability without perfect coordination. While specifying the greenness and the retail price, as well as the service level, firms bargain on the wholesale price, and then the supply chain can be fully coordinated. Below we compare coordination and non-coordination cases. As observed, all the cases demonstrate the same insights but yield different values. Therefore, to keep the exposition simple, we use the exponential distribution $\xi \sim Exp(1.25 \times 10^5)$ as a representative case. Figure 4 shows the comparison of the wholesale price and the profit between coordination and non-coordination cases, respectively. We find that to achieve Pareto improvement, the value of τ, i.e., the manufacturer's bargaining power should be limited to $[\tau_{\min}, \tau_{\max}] = [0.46, 0.76]$. The manufacturer's profit share can be lower than 50%, i.e., it is likely for her to forgo a small proportion of profit to facilitate the coordination. As shown in the graph, the coordinated wholesale price is lower than the decentralised wholesale price, and both members are better off from the coordination.

5.5 Sensitivity analysis

The parameters associated with costs and demands may significantly affect decisions regarding greening, pricing and ordering, as well as the resulting profits. In particular, the two crucial parameters in the model are v, the variable cost coefficient, and b_g, the demand sensitivity coefficient to greenness. They are more difficult to observe than the fixed investment cost coefficient β and the price sensitivity coefficient b_p, which can be obtained through public reports, annual financial statements, and market research. As discussed in Section 5.2, there is abundant empirical literature, such as Deng and Ma (2010) and Wu et al. (2019), analysing the impact of parameters similar to β and b_p. However, the question as to what the practical or estimated values of parameters similar to v and b_g are and how their changes influence decisions, has attracted little attention. Based on our numerical analysis, we perform sensitivity analyses regarding v and b_g to assess how they affect production and marketing decisions, and profits. As we have shown the results to be robust for the distribution, we investigate the model using one case: exponential distribution $\xi \sim Exp(1.25 \times 10^5)$.

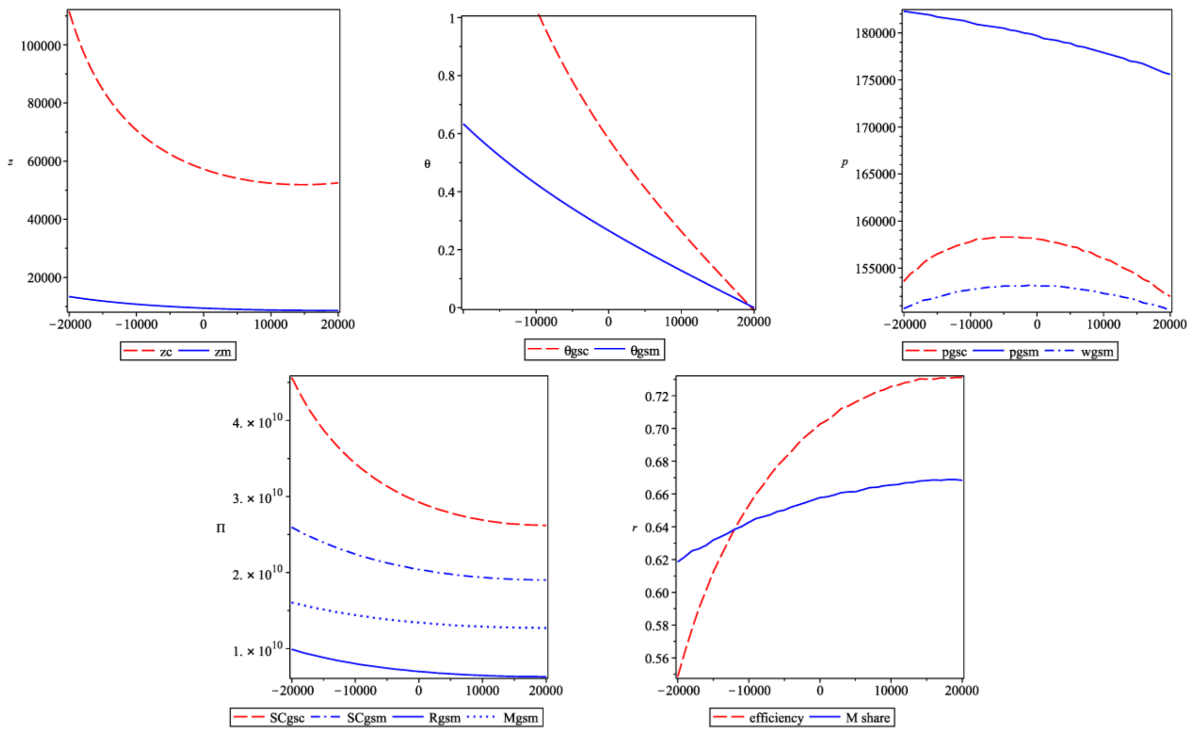


Figure 5: Impact of v on optimal service level, greenness, prices, profits, and resulting ratios

5.5.1 Impact of the variable cost coefficient

We vary v between -2×10^4 and 2×10^4 based on the assumption in Section 3.2 while keeping other parameters unchanged. Figure 5 shows how v affects the optimal decisions, profits, and resulting supply chain efficiency and the manufacture's profit share. As illustrated, a larger variable cost coefficient decreases the service level, the greenness improvement, and decentralised retail price, which is consistent with Corollary 5. Also, cost-reduction activities lead to higher profits for supply chain members but decrease supply chain efficiency. For example, BYD's public information shows that reductions in battery costs bring the unit production cost down and make supply chain firms profitable. However, from the supply chain's perspective, the considerable investment in R&D and skilled labour to achieve cost reduction lowers efficiency.

5.5.2 Impact of demand sensitivity to greenness

Based on assumptions in Section 3 and the constraint that $0 \leq \theta \leq 1$, we vary b_g between 10^4 and 3×10^5, while keeping other parameters unchanged. Figure 6 shows how the optimal solutions and ratios change with b_g. A larger demand sensitivity coefficient to greenness increases the service level, the greenness, and prices, resulting in higher profits for all the supply chain members, as well as allowing the retailer to allocate more profits, although supply chain efficiency is reduced.

Overall, from the manufacturer's perspective, a lower v generates more profits than a higher one, even though it will allocate a larger profit share to the retailer. Nevertheless, a lower v leads to a greater greenness improvement. Instead of investing more in green initiatives that increase the unit-variable cost, it is more profitable for the manufacturer to seek potential cost reductions if her product strategy is being

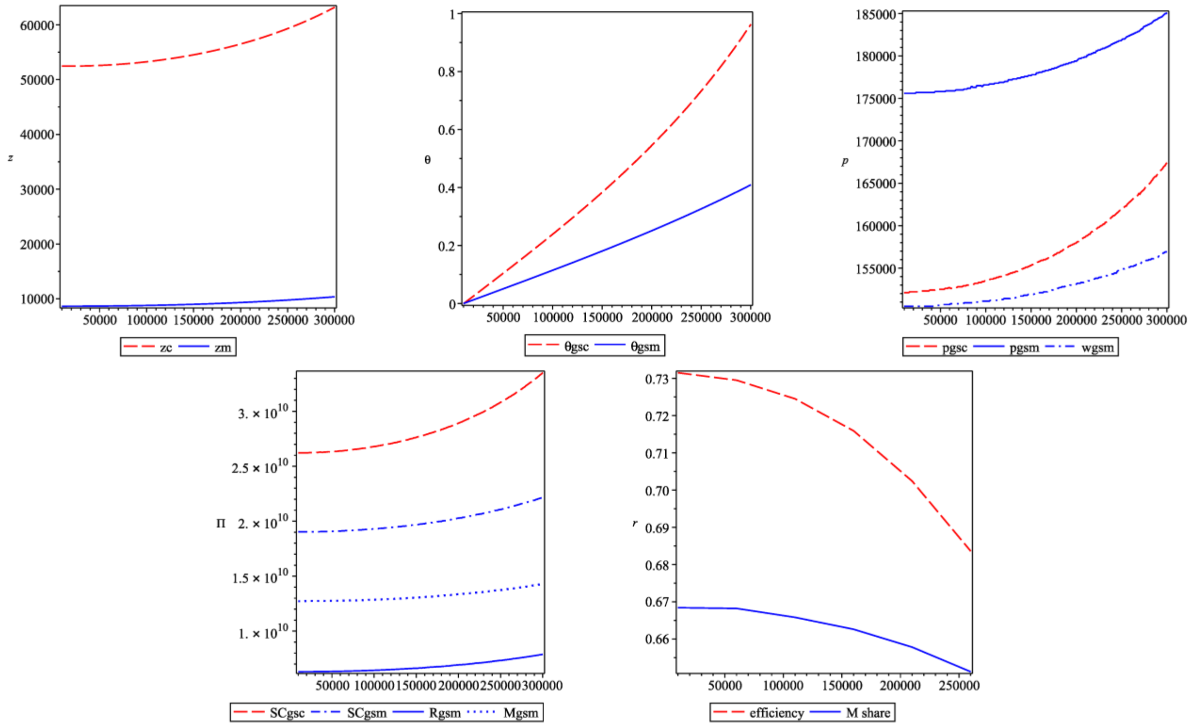


Figure 6: Impact of b_g on optimal service level, greenness, prices, profits, and resulting ratios

MDIGPs.

From the retailer's perspective, a larger b_g generates more profits with a higher retail price. It also makes the manufacturer more profitable with a greater greenness improvement. Therefore, increasing the demand sensitivity to greenness is essential for higher profitability with green products. The retailer can influence this through green marketing.

From the supply chain's perspective, a lower v and a larger b_g lead to greater greenness improvement, although they both induce lower efficiency and lower manufacturer's profit share. The reduction in efficiency implies that profits increase more quickly in centralised decision-making than they do in decentralised decision-making. Therefore, coordination could enhance both economic and green performance. Moreover, coordination could make every member profitable by applying a well-designed profit allocation mechanism (wholesale price contract through bargaining in this paper) and give consumers access to green products at lower retail prices. The decline in the manufacturer's profit shares implies that the retailer's profits increase more quickly than those of the manufacturer. It suggests that the retailer benefits more from greening than the manufacturer.

6 Conclusions

Extending the traditional pricing-setting newsvendor model, we show how greenness can be integrated into decision-making with regard to pricing, greening, and ordering. In particular, we examine how demand stochasticity affects these decisions relative to the deterministic case where stochasticity is ignored. We study a two-echelon supply chain of the marginal and development cost-intensive green product (MDIGP) by including the demand expansion effect and the cost change resulting from greening. The greening cost is not only related to the fixed investment cost but also to the unit-variable production cost. Using a sequential game-theoretic framework, we provide analytical expressions of the profit-optimal solutions for this seemingly complex stochastic problem. We propose a sequential solution procedure and illustrate it through numerical experiments. We also use numerical experiments to demonstrate the impact of demand stochasticity and relevant sensitivity parameters on economic and green performance in the supply chain. Further, a Nash bargaining game on the wholesale price between the manufacturer and the retailer is proposed to coordinate the supply chain.

The main findings are as follows:

(1) The consideration of demand uncertainty significantly affects the environmental and economic performance of the supply chain of MDIGPs. Comparing the results in stochastic demand cases to the deterministic demand case, the performance reduction due to a lack of recognising demand uncertainty would be more substantial than the resultant increase. Therefore, considering demand uncertainty helps to reduce losses.

(2) The relation of optimal decisions in stochastic demand cases to those in deterministic demand cases is different from the traditional study. In the green supply chain context, the specific relationship depends on two important elements: the relative service level and the variable greening cost efficiency. Conventional thinking has it that the presence of demand uncertainty will either raise the retail price of a green product or reduce its greenness. We show that a higher level of greenness and a lower price could be achieved simultaneously for MDIGPs. Moreover, within a stochastic environment, both supply chain firms can achieve greater profitability when the retailer orders no less than the deterministic demand – despite the fact that the presence of stochasticity reduces supply chain efficiency.

(3) Greenness and profits decrease with the variable greening cost coefficient. It suggests that incurring additional manufacturing costs is not as beneficial to firms as creating cost reductions. Nevertheless,

the supply chain efficiency is increasing and concave in the variable greening cost coefficient, i.e., the incremental efficiency reduces with the manufacturing cost.

(4) A wholesale price contract through bargaining can fully coordinate the supply chain and attain Pareto improvement. The coordinated wholesale price is lower than the decentralised wholesale price. In the coordination case, the profit shares of the two supply chain members depend on their bargaining power. Unlike in the non-coordination case, the manufacturer's profit share can be less than 50% in the coordination case.

According to these findings, we offer the following managerial implications for practitioners:

(1) From the manufacturer's perspective, when developing MDIGPs, seeking a reduction of variable costs is more profitable than incurring additional manufacturing costs. Instead of a take-it-or-leave-it scheme, offering a flexible wholesale price contract based on a bargaining framework would contribute to the achievement of full coordination with Pareto improvement of supply chain firms' profitability. Besides, the leading manufacturer does not have to divide a larger profit share in coordination with the retailer.

(2) From the retailer's perspective, several measures can increase his profitability: ordering no less than the deterministic demand, striking a balance between order quantity and leftovers, taking initiatives to improve consumer greenness sensitivity, and coordinating with the manufacturer.

(3) From the supply chain's perspective, the consideration of green initiatives and demand uncertainty significantly affects members' decisions and increases the value of supply chain coordination. Coordination can make supply chain members better off and give consumers access to greener products at lower retail prices.

The following issues could be addressed in future work to expand the research presented here. Firstly, we only look at one single period and restrict our attention to the case within a short time frame. In practice, companies may commonly divide their R&D investments and reap the benefits over multiple periods. Therefore, it may be worthwhile extending the model to include two or more periods and looking at continuous R&D input and output. A second subject has to do with the competition between older products and newly launched products. In reality, green and non-green competing products often have the same or similar functionality and address the same consumer demand. Future research work can examine the competition between homogeneous, mutually substitutable non-green and green products. The third issue concerns empirical knowledge. In practice, it is complicated to get access to the real values of demand functions, cost coefficients and behavioural aspects such as greenness sensitivity coefficients. Given their importance to the analysis, we recommend more systematic, empirical research on these attributes of the supply chain, for different products and markets.

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A Proof of Lemma 1

The backward induction approach is adopted to solve the game-theoretic model: the retailer's response function is determined first. The manufacturer then decides her greenness improvement and wholesale price, taking into account the response function. The optimal response function of the retailer is obtained as follows:

As $\frac{\partial^2 \Pi_R^{gd}}{\partial p^2} = -2b_p < 0$, the profit of the retailer is concave in the retail price, and so the optimal price can be obtained through the first-order optimality condition:

$$\frac{\partial \Pi_R^{gd}}{\partial p} = -2b_p p + b_p w + b_g \theta + a = 0$$

$$p^* = w + \frac{1}{2b_p}(a - b_p w + b_g \theta)$$

Substituting p^* into the profit function of the manufacturer yields $\Pi_M^{gd}(w, \theta | p^*)$. Its second-order derivative $\frac{\partial^2 \Pi_M^{gd}}{\partial w^2} = -b_p < 0$ and the Hessian matrix is negative definite under the restriction that $8\beta b_p - (b_g - v b_p)^2 > 0$; thus, the profit function is jointly concave in w and θ. Then, according to the first-order optimality conditions, the optimal solutions for the manufacturer are defined by:

$$\begin{cases} \frac{\partial \Pi_M^{gd}}{\partial w} = -b_p w + \frac{1}{2}(v b_p + b_g)\theta + \frac{1}{2}(a + b_p c) = 0 \\ \frac{\partial \Pi_M^{gd}}{\partial \theta} = -(2\beta + v b_g)\theta + \frac{1}{2}(v b_p + b_g) w - \frac{1}{2}(v a + b_g c) = 0 \end{cases}$$

Solving the above system of equations yields the following optimal solutions:

$$\begin{cases} \theta_m^{gd} = \frac{(b_g - v b_p)(a - b_p c)}{8\beta b_p - (b_g - v b_p)^2} \\ w_m^{gd} = \frac{\left(4\beta + v(b_g - v b_p)\right)(a - b_p c)}{8\beta b_p - (b_g - v b_p)^2} + c \end{cases}$$

Substituting the expressions listed above into the retailer's response function, we obtain the equilibrium retail price $p_m^{gd} = \frac{\left(6\beta + v(b_g - v b_p)\right)(a - b_p c)}{8\beta b_p - (b_g - v b_p)^2} + c.$ □

B Proof of Corollary 1 and Corollary 2

Substituting the equilibrium solutions in Lemma 2 back into the expected profit function of the manufacturer, we can obtain manufacturer's optimal profit

$$\Pi_M^{gs} = \Pi_M^{gd} + Z_M^{gs}(z) = \frac{\beta\left(a - b_p c + z + I(z)\right)^2}{8\beta b_p - (b_g - v b_p)^2}$$

The first-order derivatives of the equilibrium greenness, wholesale price, and manufacturer's profit with respect to z are respectively given by:

$$\frac{d\theta_m^{gs}}{dz} = \frac{(b_g - v b_p)\left(1 + F(z)\right)}{8\beta b_p - (b_g - v b_p)^2}$$

$$\frac{dw_m^{gs}}{dz} = \frac{\left(4\beta + v(b_g - v b_p)\right)\left(1 + F(z)\right)}{8\beta b_p - (b_g - v b_p)^2}$$

$$\frac{d\Pi_M^{gs}}{dz} = \frac{2\beta\left(a - b_p c + z + I(z)\right)\left(1 + F(z)\right)}{8\beta b_p - (b_g - v b_p)^2}$$

Since $1 + F(z) > 0$, and based on assumptions, we have $b_g - v b_p > 0$, $4\beta + v(b_g - v b_p) > 0$ and $a - b_p c + z + I(z) > 0$, so all the three first-order derivatives are positive, i.e., the greenness, the wholesale price, and the corresponding profit of the manufacturer are increasing in z, which implies that the higher the service level of the retailer is, the greener product the manufacturer would produce and the higher her profit would be.

Also, the solutions show that for the manufacturer in equilibrium, the deviation of the greenness, the wholesale price, and the corresponding profit relative to the deterministic case are determined by the relation of $z+I(z)$ to zero, which can be equivalently formulated as the comparison of the ratio $\frac{z}{I(z)}$ with -1.

Similarly, by the equilibrium retail price, the sign of $(6\beta+v(b_g-vb_p))\,b_p z-(2\beta b_p-b_g(b_g-vb_p))\,I(z)$ determines the relation of the retail price between the stochastic case and the deterministic case, which can be interpreted as the comparison between $\frac{z}{I(z)}$ and $\frac{2\beta b_p-b_g(b_g-vb_p)}{(6\beta+v(b_g-vb_p))b_p}$. □

C Proof of Proposition 1

By substituting the expressions of θ_m^{gs}, w_m^{gs} and p_m^{gs} into Eq. (3), we obtain:

$$\begin{aligned}\Pi_R^{gs}(z|p_m^{gs},w_m^{gs},\theta_m^{gs}) &= \Pi_R^{gd}+Z_R^{gs}(z)\\ &= \frac{4\beta^2 b_p\,(a-b_pc+z+I(z))^2}{(8\beta b_p-(b_g-vb_p)^2)^2}-\frac{(8\beta+v(b_g-vb_p))\,(a-b_pc+z+I(z))\,I(z)}{8\beta b_p-(b_g-vb_p)^2}\\ &\quad+\frac{(I(z))^2}{b_p}-(c+c_o)I(z)-c_s\,(\mu+I(z)-z)\end{aligned}\tag{C.1}$$

Taking the first-order derivative of Eq. (C.1) with respect to z, we get the following expression after simplification:

$$\begin{aligned}\frac{d\Pi_R^{gs}(z|p_m^{gs},w_m^{gs},\theta_m^{gs})}{dz} &= (1-F(z))\,(p_m^{gs}+c_s+c_o)-(w_m^{gs}+c_o)-(1+F(z))\,V(z)\\ &= (1-F(z))\left(p_m^{gs}+c_s+c_o-\frac{w_m^{gs}+c_o}{1-F(z)}-\frac{1+F(z)}{1-F(z)}V(z)\right)\end{aligned}\tag{C.2}$$

where

$$V(z)=\frac{2\beta b_p\left(4\beta b_p-(b_g-vb_p)^2\right)(a-b_pc+z+I(z))+b_g(b_g-vb_p)\left(8\beta b_p-(b_g-vb_p)^2\right)I(z)}{b_p\,(8\beta b_p-(b_g-vb_p)^2)^2}$$

Recalling that $4\beta b_p-(b_g-vb_p)^2$, $a-b_pc+z+I(z)$, b_g-vb_p and all the parameters in the numerator of $V(z)$ are larger than zero, the denominator is also positive, and so $V(z)>0$. Furthermore, its first-order and second-order derivatives with respect to z are

$$\frac{dV(z)}{dz}=\frac{2\beta b_p\left(4\beta b_p-(b_g-vb_p)^2\right)(1+F(z))+b_g(b_g-vb_p)\left(8\beta b_p-(b_g-vb_p)^2\right)F(z)}{b_p\,(8\beta b_p-(b_g-vb_p)^2)^2}>0\tag{C.3}$$

$$\frac{d^2V(z)}{dz^2}=\frac{2\beta b_p\left(4\beta b_p-(b_g-vb_p)^2\right)+b_g(b_g-vb_p)\left(8\beta b_p-(b_g-vb_p)^2\right)}{b_p\,(8\beta b_p-(b_g-vb_p)^2)^2}f(z)>0\tag{C.4}$$

Define $R(z)=p_m^{gs}+c_s+c_o-\frac{w_m^{gs}+c_o}{1-F(z)}-\frac{1+F(z)}{1-F(z)}V(z)$. As $1-F(z)>0$ when $A\le z<B$, we conclude that if $R(z)>0$, $\frac{d\Pi_R^{gs}(z|p_m^{gs},w_m^{gs},\theta_m^{gs})}{dz}>0$, then the profit is increasing in z; if $R(z)<0$, $\frac{d\Pi_R^{gs}(z|p_m^{gs},w_m^{gs},\theta_m^{gs})}{dz}<0$, then the profit is decreasing in z; and for any z in the interval that satisfies $R(z)=0$, $\frac{d\Pi_R^{gs}(z|p_m^{gs},w_m^{gs},\theta_m^{gs})}{dz}=0$, the profit has a local extremum. Then, to find the zeros of $\frac{d\Pi_R^{gs}(z|p_m^{gs},w_m^{gs},\theta_m^{gs})}{dz}$, we can analyse the shape of $R(z)$.

First, at the boundary of z, we have:

$$\begin{aligned}R(A) &= p_m^{gs}(A)+c_s+c_o-\frac{w_m^{gs}(A)+c_o}{1-0}-\frac{(1+0)V(A)}{1-0}\\ &= \frac{8\beta^2 b_p(a-b_pc+A)}{(8\beta b_p-(b_g-vb_p)^2)^2}+c_s>0\\ R(B) &= p_m^{gs}(B)+c_s+c_o-\frac{w_m^{gs}(B)+c_o+2V(B)}{1-1}\ \to -\infty<0\end{aligned}$$

Taking the first-order and second-order derivatives of $R(z)$ with respect to z and using the substitution $h(z) = \frac{f(z)}{1-F(z)}$ with the IFR property to simplify the equations, we obtain:

$$\frac{dR(z)}{dz} = \frac{dp_m^{gs}}{dz} - \frac{1}{1-F(z)}\frac{dw_m^{gs}}{dz} - \frac{(w_m^{gs}+c_o)h(z)}{1-F(z)} - \frac{2V(z)h(z)}{1-F(z)} - \frac{1+F(z)}{1-F(z)}\frac{dV(z)}{dz} \tag{C.5}$$

$$\begin{aligned}\frac{d^2R(z)}{dz^2} &= \frac{d^2p_m^{gs}}{dz^2} - \frac{1}{1-F(z)}\frac{d^2w_m^{gs}}{dz^2} - \frac{1+F(z)}{1-F(z)}\frac{d^2V(z)}{dz^2} \\ &\quad - \frac{1}{1-F(z)}\left(2h(z)\frac{dw_m^{gs}}{dz} + (h^2(z) + \frac{dh(z)}{dz})(w_m^{gs}+c_o)\right) \\ &\quad - \frac{2}{1-F(z)}\left(2h(z)\frac{dV(z)}{dz} + (h^2(z)+\frac{dh(z)}{dz})V(z)\right)\end{aligned} \tag{C.6}$$

According to the expressions of w_m^{gs} and p_m^{gs}, the first-order and second-order derivatives of the equilibrium prices with respect to z are as follows:

$$\frac{dw_m^{gs}}{dz} = \frac{(4\beta + v(b_g - vb_p))\,(1+F(z))}{8\beta b_p - (b_g - vb_p)^2} \qquad \frac{dp_m^{gs}}{dz} = \frac{(6\beta + v(b_g - vb_p))\,b_p - (2\beta b_p - b_g(b_g - vb_p))\,F(z)}{b_p\,(8\beta b_p - (b_g - vb_p)^2)}$$

$$\frac{d^2w_m^{gs}}{dz^2} = \frac{(4\beta + v(b_g - vb_p))\,f(z)}{8\beta b_p - (b_g - vb_p)^2} \qquad \frac{d^2p_m^{gs}}{dz^2} = -\frac{(2\beta b_p - b_g(b_g - vb_p))\,f(z)}{b_p\,(8\beta b_p - (b_g - vb_p)^2)}$$

It is found that $(1-F(z))\,\frac{d^2p_m^{gs}}{dz^2} - \frac{d^2w_m^{gs}}{dz^2} - (1+F(z))\,\frac{d^2V(z)}{dz^2} = -f(z)\left(\frac{dp_m^{gs}}{dz} + \frac{dV(z)}{dz}\right)$, i.e., $\frac{d^2p_m^{gs}}{dz^2} - \frac{1}{1-F(z)}\frac{d^2w_m^{gs}}{dz^2} - \frac{1+F(z)}{1-F(z)}\frac{d^2V(z)}{dz^2} = -h(z)\left(\frac{dp_m^{gs}}{dz} + \frac{dV(z)}{dz}\right)$. So by substitution, Eq. (C.6) can be rewritten as:

$$\begin{aligned}\frac{d^2R(z)}{dz^2} &= -h(z)\left(\frac{dp_m^{gs}}{dz} + \frac{dV(z)}{dz}\right) \\ &\quad - \frac{1}{1-F(z)}\left(2h(z)\left(\frac{dw_m^{gs}}{dz} + \frac{2dV(z)}{dz}\right) + \left(h^2(z) + \frac{dh(z)}{dz}\right)(w_m^{gs} + c_o + 2V(z))\right)\end{aligned} \tag{C.7}$$

Notice here that, since $4\beta + v(b_g - vb_p) > 0$, we have $\frac{dw_m^{gs}}{dz} > 0$.

If $2\beta b_p - b_g(b_g - vb_p) \le 0$, as $\frac{b_g(b_g-vb_p)}{2b_p} \ge \frac{(b_g-vb_p)^2}{4b_p}$, then we have $\frac{(b_g-vb_p)^2}{4b_p} < \beta \le \frac{b_g(b_g-vb_p)}{2b_p}$, and then $\frac{d^2p_m^{gs}}{dz^2} > 0$; so $\frac{dp_m^{gs}}{dz}$ is increasing in z, and therefore when $z = A$, $\frac{dp_m^{gs}}{dz}$ has a positive minimum $\frac{6\beta+v(b_g-vb_p)}{8\beta b_p-(b_g-vb_p)^2}$, i.e., $\frac{dp_m^{gs}}{dz} > 0$ when $\frac{(b_g-vb_p)^2}{4b_p} < \beta \le \frac{b_g(b_g-vb_p)}{2b_p}$. If $2\beta b_p - b_g(b_g - vb_p) > 0$, i.e., $\beta > \frac{b_g(b_g-vb_p)}{2b_p}$, then $\frac{d^2p_m^{gs}}{dz^2} < 0$, so $\frac{dp_m^{gs}}{dz}$ is decreasing in z, and therefore when $z = B$, $\frac{dp_m^{gs}}{dz}$ has a positive minimum $\frac{4\beta b_p+(b_g-vb_p)(b_g+vb_p)}{b_p\left(8\beta b_p-(b_g-vb_p)^2\right)}$, i.e., when $\beta > \frac{b_g(b_g-vb_p)}{2b_p}$, the inequality $\frac{dp_m^{gs}}{dz} > 0$ still holds. In short, when $\beta > \frac{(b_g-vb_p)^2}{4b_p}$, $\frac{dp_m^{gs}}{dz} > 0$.

With positive w_m^{gs}, $\frac{dw_m^{gs}}{dz}$, $\frac{dp_m^{gs}}{dz}$, $h(z)$, $\frac{dh(z)}{dz}$, $\frac{1}{1-F(z)}$, $V(z)$, and $\frac{dV(z)}{dz}$, it can be observed that Eq. (C.7) yields $\frac{d^2R(z)}{dz^2} < 0$, implying that $R(z)$ is concave in z. Given that $R(A) > 0$ and $R(B) < 0$, $R(z) = 0$ then only has one root, which corresponds to a local maximum of Π_R^{gs}. The equation can be rewritten as $F(z) = 1 - \frac{w_m^{gs}(z)+c_o+2V(z)}{p_m^{gs}(z)+c_s+c_o+V(z)}$.
□

D Proof of Proposition 2

By substituting the expressions of p_c^{gs} and θ_c^{gs} into Eq. (1), we obtain $\Pi_{SCc}^{gs}(z|p_c^{gs}, \theta_c^{gs})$. It is easy to see that p_c^{gs} and θ_c^{gs} satisfy the first-order optimality condition, i.e., $\frac{\partial \Pi_{SCc}^{gs}(z|p_c^{gs},\theta_c^{gs})}{\partial p_c^{gs}} = 0$ and $\frac{\partial \Pi_{SCc}^{gs}(z|p_c^{gs},\theta_c^{gs})}{\partial \theta_c^{gs}} = 0$, due to their optimality. Taking the first-order derivative of $\Pi_{SCc}^{gs}(z|p_c^{gs}, \theta_c^{gs})$ with respect to z by the chain rule, we can obtain the following expression after simplification:

$$\begin{aligned}\frac{d\Pi^{gs}_{SCc}(z|p^{gs}_c,\theta^{gs}_c)}{dz} &= \frac{\partial\Pi^{gs}_{SCc}(z|p^{gs}_c,\theta^{gs}_c)}{\partial z} + \frac{\partial\Pi^{gs}_{SCc}(z|p^{gs}_c,\theta^{gs}_c)}{\partial p^{gs}_c}\frac{dp^{gs}_c}{dz} + \frac{\partial\Pi^{gs}_{SCc}(z|p^{gs}_c,\theta^{gs}_c)}{\partial \theta^{gs}_c}\frac{d\theta^{gs}_c}{dz} \\ &= (1-F(z))\,(p^{gs}_c + c_s + c_o) - (c + v\theta^{gs}_c + c_o) \\ &= (1-F(z))\left(p^{gs}_c + c_s + c_o - \frac{c+v\theta^{gs}_c + c_o}{1-F(z)}\right) \end{aligned} \tag{D.1}$$

Define $U(z) = p^{gs}_c + c_s + c_o - \frac{c+v\theta^{gs}_c+c_o}{1-F(z)}$. As $1-F(z) > 0$ when $A \le z < B$, if $U(z) > 0$, $\frac{d\Pi^{gs}_{SCc}(z|p^{gs}_c,\theta^{gs}_c)}{dz} > 0$, and then the profit is increasing in z; if $U(z) < 0$, $\frac{d\Pi^{gs}_{SCc}(z|p^{gs}_c,\theta^{gs}_c)}{dz} < 0$, and then the profit is decreasing in z; and for any z in the interval that satisfies $U(z) = 0$, $\frac{d\Pi^{gs}_{SCc}(z|p^{gs}_c,\theta^{gs}_c)}{dz} = 0$, the profit has a local extremum. Then, to find zeros of $\frac{d\Pi^{gs}_{SCc}(z|p^{gs}_c,\theta^{gs}_c)}{dz}$, we can analyse the shape of $U(z)$.

First, considering the boundary values A and B, we obtain:

$$\begin{aligned} U(A) &= p^{gs}_c(A) + c_s + c_o - \frac{c + v\theta^{gs}_c(A) + c_o}{1-0} \\ &= \frac{2\beta(a - b_p c + A)}{4\beta b_p - (b_g - v b_p)^2} + c_s > 0 \\ U(B) &= p^{gs}_c(B) + c_s + c_o - \frac{c + v\theta^{gs}_c(B) + c_o}{1-1} \to -\infty < 0 \end{aligned}$$

Recalling the IFR property that $h(\xi) = \frac{f(\xi)}{1-F(\xi)}$ and $\frac{dh(\xi)}{d\xi} > 0$ for all ξ in the range $[A, B]$, now we study how $U(z)$ behaves in z by analysing its first-order and second-order derivatives:

$$\frac{dU(z)}{dz} = \frac{dp^{gs}_c}{dz} - \frac{v}{1-F(z)}\frac{d\theta^{gs}_c}{dz} - \frac{(c+v\theta^{gs}_c + c_o)h(z)}{1-F(z)} \tag{D.2}$$

$$\frac{d^2U(z)}{dz^2} = \frac{d^2p^{gs}_c}{dz^2} - \frac{v}{1-F(z)}\frac{d^2\theta^{gs}_c}{dz^2} - \frac{2vh(z)}{1-F(z)}\frac{d\theta^{gs}_c}{dz} - \frac{(c+v\theta^{gs}_c+c_o)}{1-F(z)}\left(h^2(z) + \frac{dh(z)}{dz}\right) \tag{D.3}$$

According to the equations in Lemma 4, the first-order and second-order derivatives of the equilibrium greenness improvement and the retail price with respect to z are:

$$\frac{d\theta^{gs}_c}{dz} = \frac{(b_g + v b_p)\,(1-F(z)) - 2v b_p}{4\beta b_p - (b_g - v b_p)^2} \qquad \frac{dp^{gs}_c}{dz} = \frac{2(\beta + v b_g)\,(1-F(z)) - v(b_g + v b_p)}{4\beta b_p - (b_g - v b_p)^2}$$

$$\frac{d^2\theta^{gs}_c}{dz^2} = -\frac{(b_g + v b_p) f(z)}{4\beta b_p - (b_g - v b_p)^2} \qquad \frac{d^2p^{gs}_c}{dz^2} = -\frac{2(\beta + v b_g) f(z)}{4\beta b_p - (b_g - v b_p)^2}$$

From these expressions, we can observe that $\frac{d^2\theta^{gs}_c}{dz^2} < 0$ and $\frac{d^2p^{gs}_c}{dz^2} < 0$. Moreover, it is found that $(1-F(z))\,\frac{d^2p^{gs}_c}{dz^2} - v\frac{d^2\theta^{gs}_c}{dz^2} = -f(z)\frac{dp^{gs}_c}{dz}$, i.e., $\frac{d^2p^{gs}_c}{dz^2} - \frac{v}{1-F(z)}\frac{d^2\theta^{gs}_c}{dz^2} = -h(z)\frac{dp^{gs}_c}{dz}$, which means that Eq. (D.3)can be rewritten as

$$(\frac{d^2U(z)}{dz^2} = -h(z)\left(\frac{dp^{gs}_c}{dz} + \frac{2v}{1-F(z)}\frac{d\theta^{gs}_c}{dz}\right) - \frac{(c+v\theta^{gs}_c + c_o)}{1-F(z)}\left(h^2(z) + \frac{dh(z)}{dz}\right) \tag{D.4}$$

Recalling that the zeros of $U(z)$ correspond to the extrema of Π^{gs}_{SCc}, we now analyse the shape of $U(z)$ by considering the following two cases: firstly, if $\frac{dU(z)}{dz} = 0$ has no root, then $U(z)$ is monotone. More specifically, $U(z)$ is then decreasing in z, i.e., $\frac{dU(z)}{dz} < 0$, in conjunction with $U(A) > 0$ and $U(B) < 0$. The sign change of $U(z)$ corresponds to the shape of the profit function, first increasing in z and then decreasing. Therefore, $U(z)$ has only one root at which $\Pi^{gs}_{SCc}(z|p^{gs}_c,\theta^{gs}_c)$ reaches its maximum. So $\Pi^{gs}_{SCc}(z|p^{gs}_c,\theta^{gs}_c)$ has a maximum at the unique value of z that satisfies $U(z) = 0$. Secondly, if $\frac{dU(z)}{dz} = 0$ has roots, then by substitution, we have:

$$\frac{d^2U(z)}{dz^2} = -\frac{1}{1-F(z)}\left((c+v\theta^{gs}_c + c_o)\left(2h^2(z) + \frac{dh(z)}{dz}\right) + 3vh(z)\frac{d\theta^{gs}_c}{dz}\right)\Bigg|_{\frac{dU(z)}{dz}=0} \tag{D.5}$$

As analysed earlier, we have $1-F(z)$, $c+v\theta_c^{gs}+c_o>0$, $h(z)>0$ *and* $\frac{dh(z)}{dz}>0$; so the sign of $v\frac{d\theta_c^{gs}}{dz}$ determines the sign of $\frac{d^2U(z)}{dz^2}$. Obviously, if $0\le v\le\frac{b_g(1-F(z))}{b_p(1+F(z))}$, then $v\frac{d\theta_c^{gs}}{dz}\ge 0$, which guarantees $\frac{d^2U(z)}{dz^2}<0$. This indicates that $U(z)$ first increases and then decreases with z. It has only one root as its sign changes from positive to negative. So $\Pi_{SCc}^{gs}(z|p_c^{gs},\theta_c^{gs})$ has a maximum at the unique value of z that satisfies $U(z)=0$.

The range of the unit-variable cost coefficient is $-\frac{b_g}{b_p}<v<\frac{b_g}{b_p}$. However, in the complementary interval of $0\le v\le\frac{b_g(1-F(z))}{b_p(1+F(z))}$, we can see that $v\frac{d\theta_c^{gs}}{dz}<0$; then, the condition to keep $\frac{d^2U(z)}{dz^2}<0$ is $(c+v\theta_c^{gs}+c_o)\left(2h^2(z)+\frac{dh(z)}{dz}\right)+3vh(z)\frac{d\theta_c^{gs}}{dz}>0$, which can be rewritten as $\frac{v}{c+v\theta_c^{gs}+c_o}\frac{d\theta_c^{gs}}{dz}>-\frac{1}{3h(z)}\left(2h^2(z)+\frac{dh(z)}{dz}\right)$. The rewritten inequality can also represent the positive interval of v. It is complex to present an explicit expression about the interval of v other than $0\le v\le\frac{b_g(1-F(z))}{b_p(1+F(z))}$ due to the incorporation of the problem parameter θ_c^{gs}. However, it is still numerically tractable. We can first obtain an optimal value of z by following the proposed solution procedure in Section 5.1, and then return to the condition to check whether or not the inequality holds. Generally, v satisfies the inequality $\frac{v}{c+v\theta_c^{gs}+c_o}\frac{d\theta_c^{gs}}{dz}>-\frac{1}{3h(z)}\left(2h^2(z)+\frac{dh(z)}{dz}\right)$.

Therefore, given that $\frac{v}{c+v\theta_c^{gs}+c_o}\frac{d\theta_c^{gs}}{dz}>-\frac{1}{3h(z)}\left(2h^2(z)+\frac{dh(z)}{dz}\right)$, $U(z)$ is either monotone or unimodal, and then $\Pi_{SCc}^{gs}(z|p_c^{gs},\theta_c^{gs})$ has a maximum at the unique value of z that satisfies the first-order optimality condition $\frac{d\Pi_{SCc}^{gs}(z|p_c^{gs},\theta_c^{gs})}{dz}=(1-F(z))\,U(z)=0$, i.e., $U(z)=0$, which can be rewritten as $F(z)=1-\frac{c+v\theta_c^{gs}(z)+c_o}{p_c^{gs}(z)+c_s+c_o}$. □

E Proof of Corollary 4

From the first-order optimality conditions for z_m^{gs} and z_c^{gs} in the propositions, we can see that the in-stock probability $F(z)$ is increasing in z. Then, by analysing corresponding equations and first-order derivatives with respect to $z$detailed in the proof of Proposition 1 and Proposition 2, it is found that $p_c^{gs}(z)-(c+v\theta_c^{gs}(z))-(p_m^{gs}(z)-w_m^{gs}(z))-V(z)>0$ satisfies since the left part of the inequality is increasing in z and has a positive minimum. This inequality implies that $1-\frac{w_m^{gs}(z)+c_o}{p_m^{gs}(z)+c_s+c_o+V(z)}<1-\frac{c+v\theta_c^{gs}(z)+c_o}{p_c^{gs}(z)+c_s+c_o}$ for any $A\le z<B$. The optimal service level has unique solution, therefore, $z_m^{gs}<z_c^{gs}$. □

F Proof of Corollary 5

It is shown that $\frac{dp_m^{gs}}{dz}-\frac{dw_m^{gs}}{dz}<0$ given that $\frac{1}{3}\le F(z)\le 1$ according to the expressions of the first-order derivatives in Appendix C. Thus, We find that $\frac{dR(z)}{dz}<0$. As the function relation between z and v is given by the implicit function in Proposition 1, when analysing the first-order derivative of z with respect to v, we have $\frac{dz}{dv}=-\frac{\partial R(z)/\partial v}{\partial R(z)/\partial z}$, where the expression of $\frac{\partial R(z)}{\partial z}$ is provided by $\frac{dR(z)}{dz}$ before. For notational convenience, let $J>0$, $K>0$, and $L>0$ denote $a-b_pc+z+I(z)$, $8\beta b_1-(b_2-vb_1)^2$ and b_g-vb_p, respectively. Now, taking the derivative $\frac{\partial R(z)}{\partial v}$, we can have

$$\frac{1}{(1-F(z))\,K^3}\left(32\beta^2{b_p}^2\left((1+F(z))Jvb_p+b_g\left(2(1+F(z))I(z)-(1-F(z))J\right)\right)-b_gL^4\left((J+I(z))F(z)+I(z)\right)\right)$$

As $-1<\frac{1-F(z)}{1+F(z)}-\frac{2I(z)}{J}<1$, so when $-\frac{b_g}{b_p}<v<\left(\frac{1-F(z)}{1+F(z)}-\frac{2I(z)}{J}\right)\frac{b_g}{b_p}$, $\frac{\partial R(z)}{\partial v}<0$, and then $\frac{dz}{dv}<0$.

The equilibrium greenness improvement and retail price are given in Lemma 2. Regarding z as a function of v, we have

$$\frac{d\theta_m^{gs}}{dv}=\frac{1}{K^2}\left((1+F(z))LK\frac{dz}{dv}-b_p\left(8\beta b_p+L^2\right)J\right)$$
$$\frac{dp_m^{gs}}{dv}=\frac{1}{b_1K^2}\left(\left(2\beta b_p(3-F(z))+L(b_gF(z)+vb_p)\right)K\frac{dz}{dv}-\left(4\beta b_p(b_g+vb_p)+b_gL^2\right)b_pJ\right)$$

By substituting $\frac{dz}{dv}$, it is observed that $\frac{d\theta_m^{gs}}{dv}<0$ and $\frac{dp_m^{gs}}{dv}<0$. □

Table 6: Profits of each player in deterministic and stochastic demand models

	Deterministic	Stochastic
R	$\Pi_R^{gd} = \frac{4\beta^2 b_p {D_b}^2}{K^2}$	$\Pi_R^{gs}(z_m^{gs}) = \frac{4\beta^2 b_p J^2}{K^2} - \frac{I(z)(8\beta + vL)J}{K} + \frac{(I(z))^2}{b_1} - (c + c_o)I(z) - c_s(\mu + I(z) - z)$
M	$\Pi_M^{gd} = \frac{\beta {D_b}^2}{K}$	$\Pi_M^{gs}(z_m^{gs}) = \frac{\beta J^2}{K}$
SCm	$\Pi_{SCm}^{gd} = \frac{\beta(K + 4\beta b_p){D_b}^2}{K^2}$	$\Pi_{SCm}^{gs}(z_m^{gs}) = \Pi_R^{gs} + \Pi_M^{gs}$
SCc	$\Pi_{SCc}^{gd} = \frac{\beta {D_b}^2}{K - 4\beta b_p}$	$\Pi_{SCc}^{gs}(z_c^{gs}) = \frac{\beta(J - I(z))^2 - I(z)((2\beta + vL)(J - I(z)) - (\beta + vb_g)I(z))}{K - 4\beta b_p} - (c + c_o)I(z) - c_s(\mu + I(z) - z)$

Note: For notational convenience, $J = a - b_p c + z + I(z)$, $K = 8\beta b_p - (b_g - vb_p)^2$, $L = b_g - vb_p$, and $D_b = a - b_p c$.

G Proof of Corollary 6

For ease of recall, we present the profits in Table A1. The manufacturer's profit share in the deterministic demand and stochastic demand models are $r^{gd} = \frac{\Pi_M^{gd}}{\Pi_{SCm}^{gd}}$ and $r^{gs} = \frac{\Pi_M^{gs}}{\Pi_{SCm}^{gs}}$, respectively. To compare the profit share of deterministic and stochastic demand models, we now analyse the relation between $r^{gs} - r^{gd}$ and zero. For brevity, we do not present the positive denominator here but focus on the numerator that could determine the relation. Here, the decisive factor in the expression of $r^{gs} - r^{gd}$ is $b_p K(c_o I(z) + c_s(\mu + I(z) - z)) + I(z)(b_p(8\beta + vL)(a - b_p c + z) + K b_p c + b_g L I(z))$. Recalling that the overage and shortage cost $c_o I(z) + c_s(\mu + I(z) - z) \geq 0$ and values of parameters and expressions such as $I(z)$, K, L, and $a - b_p c + z$ mentioned in previous analysis are positive, it is observed that the factor is positive, i.e., $r^{gs} - r^{gd} > 0$. Then, for the profit share in the deterministic demand situation, we have $r^{gd} = \frac{\Pi_M^{gd}}{\Pi_{SCm}^{gd}} = \frac{K}{K + 4\beta b_p} > \frac{1}{2}$. Therefore, the relation $r^{gs} > r^{gd} > \frac{1}{2}$ holds. □

H Proof of Proposition 3

By taking the first-order derivative of the logarithmic function of Eq. (4) with respect to the wholesale price, we can obtain $\frac{d\Pi_b}{dw} = \Pi_b \left(\frac{\tau}{\Pi_{Mb}^{gs}} \frac{d\Pi_{Mb}^{gs}}{dw} + \frac{1-\tau}{\Pi_{Rb}^{gs}} \frac{d\Pi_{Rb}^{gs}}{dw} \right)$. Given that the first-order derivative equals zero, it is shown that the second-order derivative is negative. Therefore, the optimal wholesale price w_b can be obtained by solving $\frac{\tau}{\Pi_{Mb}^{gs}} \frac{d\Pi_{Mb}^{gs}}{dw} + \frac{1-\tau}{\Pi_{Rb}^{gs}} \frac{d\Pi_{Rb}^{gs}}{dw} = 0$, which can be simplified to $\frac{\Pi_{Mb}^{gs}}{\Pi_{Rb}^{gs}} = \frac{\tau}{1-\tau}$ after substituting the derivatives which satisfy the equation $\frac{d\Pi_{Mb}^{gs}}{dw} + \frac{d\Pi_{Rb}^{gs}}{dw} = 0$. Solving the equation $\frac{\Pi_{Mb}^{gs}(w)}{\Pi_{Rb}^{gs}(w)} = \frac{\tau}{1-\tau}$ yields the result in Proposition 3. As the manufacturer's profit is increasing in her wholesale price and bargaining power, the coordinated wholesale price is also increasing in τ and it is larger than the unit production cost. □