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Delft University of Technology

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Dissertation

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Dedicated to my mom and to all the places
where my heart settles

Content

Summary

In the evolving landscape of global business, the pursuit of environmental sustainability has emerged as a central pillar of corporate strategy, compelling companies to integrate green practices within their supply chains. This doctoral thesis investigates green supply chain management through the lens of asymmetric information, with a particular focus on the pervasive issue of greenwashing—the act of misleading stakeholders about a firm’s green innovation practices or the greenness of a product.

Guided by a series of research questions, this thesis aims to uncover the mechanisms of greenwashing within supply chain management and explore how asymmetric information influences the implementation of green practices and coordination across the supply chain. Chapter 2 initiates this exploration by providing an extensive review of game-theoretic models in the context of sustainable supply chains with asymmetric information. Through a systematic literature review, this research outlines the current state of the field, identifying a significant gap in quantitative modelling studies that address greenwashing in supply chain contexts. This gap underscores the nascent stage of research in this area and highlights the need for sophisticated analytical tools to better understand the complexities of greenwashing.

Employing game-theoretic modelling approaches, this thesis thoroughly examines across the following three chapters, the decision-making and coordination in supply chains considering both demand expansion and cost reduction effects of green innovation and marketing practices. Specifically, Chapter 3 addresses the challenges posed by stochastic demand in green supply chains, particularly focusing on marginal and development cost-intensive green products. Utilising a sequential game-theoretic framework, this chapter examines how demand uncertainty affects product pricing, greening decisions, and overall supply chain coordination. With cost reduction effects, it is able to identify scenarios where demand uncertainty could, paradoxically, enhance product greenness and market efficiency. Chapter 4 continues the investigation into pathways to green innovations in supply chains with asymmetric process innovation information. It critically examines the interplay between green product innovation, process innovation, and the transparency of these innovations, demonstrating how information asymmetry can lead to greenwashing and negatively impact

supply chain dynamics. The chapter proposes contractual and technological solutions to mitigate these adverse effects and encourage genuine green innovation. Finally, Chapter 5 explores green marketing strategies in the context of asymmetric information about product greenness. Developing a signalling game model that considers green marketing as both an influencer of consumer behaviour and a signal of product greenness, this chapter provides insights into the strategic choices firms face in balancing market transparency, greenwashing, and distinctive signalling. It offers a detailed understanding of how market dynamics shape green marketing strategies and their implications for consumer and social welfare. In summary, each chapter contributes to the academic exploration of green supply chain management, paving the way for future research directions and emphasising the importance of information sharing, coordination, and genuine green practices.

Looking ahead, the thesis identifies three promising directions for future research: the development of advanced quantitative models to integrate green practices and study greenwashing, the investigation of the impact of information asymmetry on the diffusion of green innovations, and the exploration of strategies to enhance coordination in green supply chains amidst asymmetric information. These areas offer a rich basis for advancing our understanding of supply chain management with green innovation practices and developing robust strategies to mitigate greenwashing.

In conclusion, this thesis contributes to the rapidly growing field of green supply chain management by shedding light on the challenges and opportunities presented by information asymmetry and greenwashing. By offering a comprehensive analysis and proposing avenues for future research, it lays the groundwork for the development of more sustainable, transparent, and efficient supply chain practices. As the pursuit of environmental sustainability continues to shape the global business landscape, the insights derived from this research will undoubtedly play a crucial role in guiding companies towards more genuine and impactful green initiatives.

Samenvatting

In het evoluerende landschap van het wereldwijde bedrijfsleven is het streven naar milieuduurzaamheid uitgegroeid tot een centrale pijler van de bedrijfsstrategie, waarbij bedrijven worden aangezet tot het integreren van groene praktijken in hun toeleveringsketens. Deze doctoraatsproefschrift onderzoekt groen toeleveringsketenbeheer door de lens van asymmetrische informatie, met een bijzondere focus op het wijdverspreide probleem van greenwashing—het misleiden van stakeholders over de groene innovatiepraktijken van een bedrijf of de groenheid van een product.

Geleid door een reeks onderzoeksvragen, beoogt deze thesis de mechanismen van greenwashing binnen het beheer van toeleveringsketens te onthullen en te verkennen hoe asymmetrische informatie de implementatie van groene praktijken en de coördinatie over de toeleveringsketen beïnvloedt. Hoofdstuk 2 begint deze verkenning met een uitgebreid overzicht van speltheoretische modellen in de context van duurzame toeleveringsketens met asymmetrische informatie. Door een systematisch literatuuroverzicht schetst dit onderzoek de huidige staat van het vakgebied, en identificeert een significant tekort in kwantitatieve modelleringsstudies die greenwashing binnen toeleveringsketens aanpakken. Dit tekort benadrukt het beginstadium van onderzoek op dit gebied en onderstreept de behoefte aan geavanceerde analytische tools om de complexiteit van greenwashing beter te begrijpen.

Met behulp van speltheoretische modelleringsbenaderingen onderzoekt deze thesis uitvoerig in de volgende drie hoofdstukken de besluitvorming en coördinatie in toeleveringsketens, rekening houdend met zowel de effecten van vraaguitbreiding als kostenverlaging van groene innovatie- en marketingpraktijken. Specifiek, Hoofdstuk 3 behandelt de uitdagingen gesteld door stochastische vraag in groene toeleveringsketens, met een bijzondere focus op marginale en ontwikkelingskostenintensieve groene producten. Met behulp van een sequentieel speltheoretisch kader onderzoekt dit hoofdstuk hoe vraagonzekerheid productprijzing, vergroeningsbeslissingen, en algehele coördinatie van de toeleveringsketen beïnvloedt. Met de effecten van kostenreductie kan het scenario's identificeren waar vraagonzekerheid, paradoxaal genoeg, de groenheid van het product en marktefficiëntie kan verhogen. Hoofdstuk 4 zet het onderzoek voort naar paden naar groene

innovaties in toeleveringsketens met asymmetrische informatie over procesinnovatie. Het onderzoekt kritisch de wisselwerking tussen groene productinnovatie, procesinnovatie en de transparantie van deze innovaties, en toont aan hoe informatieasymmetrie kan leiden tot greenwashing en negatief de dynamiek van de toeleveringsketen kan beïnvloeden. Het hoofdstuk stelt contractuele en technologische oplossingen voor om deze negatieve effecten te mitigeren en echte groene innovatie aan te moedigen. Ten slotte verkent Hoofdstuk 5 groene marketingstrategieën in de context van asymmetrische informatie over de groenheid van producten. Door een signaleringsspelmodel te ontwikkelen dat groene marketing beschouwt als zowel een beïnvloeder van consumentengedrag als een signaal van productgroenheid, biedt dit hoofdstuk inzichten in de strategische keuzes waarmee bedrijven worden geconfronteerd bij het balanceren van markttransparantie, greenwashing, en onderscheidende signalering. Het biedt een gedetailleerd inzicht in hoe marktdynamiek groene marketingstrategieën vormgeeft en hun implicaties voor consumentenwelzijn en maatschappelijk welzijn.

Samenvattend draagt elk hoofdstuk bij aan de academische exploratie van groen toeleveringsketenbeheer, baant de weg voor toekomstige onderzoeksrichtingen en benadrukt het belang van informatiedeling, coördinatie, en authentieke groene praktijken.

Vooruitkijkend identificeert de thesis drie beloftevolle richtingen voor toekomstig onderzoek: de ontwikkeling van geavanceerde kwantitatieve modellen om groene praktijken te integreren en greenwashing te onderzoeken, het onderzoeken van de impact van informatieasymmetrie op de verspreiding van groene innovaties, en het verkennen van strategieën om de coördinatie in groene toeleveringsketens te verbeteren te midden van asymmetrische informatie. Deze gebieden bieden een vruchtbare basis voor het bevorderen van ons begrip van toeleveringsketenbeheer met groene innovatiepraktijken en het ontwikkelen van robuuste strategieën om greenwashing tegen te gaan.

In conclusie draagt deze thesis bij aan het snelgroeiende veld van groen toeleveringsketenbeheer door licht te werpen op de uitdagingen en kansen die door informatieasymmetrie en greenwashing worden gepresenteerd. Door een uitgebreide analyse aan te bieden en wegen voor toekomstig onderzoek te voorstellen, legt het de basis voor de ontwikkeling van duurzamere, transparantere en efficiëntere toeleveringsketenpraktijken. Naarmate het streven naar milieuduurzaamheid het wereldwijde bedrijfslandschap blijft vormgeven, zullen de inzichten die uit dit onderzoek zijn verkregen ongetwijfeld een cruciale rol spelen bij het sturen van bedrijven naar meer oprechte en impactvolle groene initiatieven.

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Kailan 开兰

TU Delft Library, February 2024

Chapter 1 Introduction

This chapter establishes the essential foundation for investigating the complex dynamics of green supply chain management under the lens of asymmetric information. It underscores the vital necessity of integrating environmental sustainability within supply chain operations, highlighting the dual challenges of green product development and the widespread issue of information asymmetry that leads to greenwashing. By examining the decisions and coordination mechanisms in supply chains with green innovations, this research identifies the crucial roles of transparency and collaboration in navigating the obstacles presented by asymmetric information. Additionally, the chapter delineates the research questions and the methodologies employed in this research, culminating in a structure overview of the thesis.

1.1 Background and motivation

The transition towards environmental sustainability has become a paramount goal for industries worldwide, driven by increasing environmental awareness, regulatory pressures, and consumer demand for green products. Green Supply Chain Management (GSCM) stands out as a strategic approach to embed environmental considerations into supply chain management, encompassing product design, material sourcing, manufacturing processes, distribution and end-of-life management of the product to enhance environmental sustainability (Srivastava, 2007). Unlike traditional supply chains that focus solely on profit maximisation, green supply chains incorporate environmental management into their operations. Based on Ahi and Searcy (2013), this research defines the green supply chain as a coordinated decentralised network that integrates environmental sustainability into supply chain operations, facilitating more efficient and effective material, information, and capital flows to meet green demands from the market, competitive, governmental, and self-development sources.

1.1.1 Green product development and green practices

Green Product Development (GPD), addressing environmental sustainability through product and process innovations, is central to GSCM (Chen, 2001; Li et al., 2021). Green products are more resource-efficient and environmentally friendly throughout their lifecycle compared to conventional products (European Commission, 2013, 2018). The concept of "greenness" of products is not uniformly defined across practices and literature (Sdrolia and Zarotiadis, 2019). This research refers to greenness as the environmental friendliness level of products, services, production and business activities. It is usually associated with the improvement of manufacturing technology, the utilisation of sustainable materials, resource efficiency, and emission reductions. It is a quantifiable and measurable attribute, even though different standards have been used (Dong et al., 2019; Guo et al., 2020; Nouira et al., 2014).

Green products tend to cost more than conventional products due to more expensive investments in R&D and sustainable components. Researchers like Zhu and He (2017) use the factor costs to categorise green products into development-intensive green products (DIGPs), marginal cost-intensive green products (MIGPs), and marginal and development cost-intensive green products (MDIGPs), i.e. products of which the driving force of greenness improvement mainly affects either the fixed costs, the variable manufacturing costs, or both. Integrating environmental considerations into product development has significantly affected supply chain decision-making and performance, which has been examined by growing GSCM research work. While most of the literature has considered MIGPs and DIGPs (e.g., Dey et al., 2019; Li et al., 2020; Nielsen et al., 2020; Zhu and He, 2017), studies for MDIGPs are underdeveloped. It would be helpful to investigate the case where greening affects both the marginal and the development costs of the product to gain further insights into GSCM. This research focuses on MDIGPs to explore the impacts of changes in cost structures on supply chain decisions.

Green practices implemented by supply chain firms yield three primary effects: price premium, demand expansion, and cost reduction (Ghosh et al., 2018; Ramani et al., 2019). The first two effects stem from environmentally-conscious consumers' preferences towards green products and willingness to pay more for them. Generally, green product innovation and marketing practices contribute to these two effects as they improve product greenness and consumers' perception and preference for green products (Zhu et al., 2018). The cost reduction effect arises from increased resource productivity and process efficiencies. It is usually associated with the process innovations (Qudrat-Ullah, 2018; Wong et al., 2020). While price premium and demand expansion effects have been extensively discussed in the literature by integrating them into the demand function, the cost reduction effect and comprehensive analyses of these effects in the context of supply chain management have been underexplored. This research aims to bridge this gap by considering both demand expansion and cost reduction effects of green innovation and marketing practices within the supply chain context.

1.1.2 Information asymmetry and greenwashing

Integrating green innovation practices within supply chains introduces complexity and uncertainty that significantly alter the business landscape for participating firms. While pivotal for environmental sustainability, these innovations complicate interactions among supply chain members by introducing a broader range of influential factors and potentially altering information sharing. In many instances, the complete acquisition of information is either impossible or prohibitively expensive. This limitation is compounded by the reluctance of some informed members to share information fully or truthfully, either to maintain competitive advantages or to mitigate risks associated with regulatory oversight. Opportunistic firms may exploit these complexities and uncertainties, manipulating their private information to influence the decisions of other supply chain members for their own benefit (Voigt, 2011).

Information asymmetry arises in transactions where there is a disparity in the information possessed by the involved parties. This condition is particularly prevalent in green supply chains, where one party may have access to more or superior information about green practices or product attributes than the other. Such imbalances can lead to greenwashing, a deceptive practice where companies mislead stakeholders about their greening initiatives (firm-level greenwashing) or the environmental benefits of their products or services (product-level greenwashing) (Delmas and Burbano, 2011; Lee et al., 2018; Netto et al., 2020).

The consequences of information asymmetry and greenwashing extend beyond mere ethical considerations. They fundamentally undermine consumer trust and loyalty, eroding the foundation for sustainable business practices. Moreover, they can significantly impede the effective coordination and optimisation of green supply chains, as they distort the information landscape that is crucial for making informed decisions (Inês et al., 2023). The deceptive nature of greenwashing not only misleads consumers but also creates an uneven playing field for companies genuinely investing in green practices, potentially discouraging such investments.

The exploration of information asymmetry and greenwashing in green supply chains is not only critical for understanding the barriers to genuine environmental sustainability but also for developing strategies to overcome these challenges. Therefore, this research explores the nuanced dynamics of information asymmetry within the context of green innovations in supply chains. Specifically, this research examines the phenomena of firm-level greenwashing, driven by asymmetric information regarding green process innovations, and product-level greenwashing, influenced by disparities in information about product greenness. By exploring these dimensions, the study aims to shed light on how information asymmetry affects supply chain decision-making and performance and the potential coordination mechanism.

1.1.3 Green supply chain coordination

Effective coordination is crucial for optimising environmental and economic performance and advancing GSCM. It involves collaborative efforts across the supply chain to implement green practices effectively, share information, and align incentives and pricing strategies. The complexity of achieving such coordination is magnified in the context of asymmetric information, presenting a significant challenge that this research seeks to address.

Literature suggests that a supply chain achieves coordination when equilibrium decisions optimise overall performance, a challenge in decentralised supply chains where individual profit optimisation pursued by each supply chain member can lead to inefficiencies (Cachon, 2003; Tsay et al., 1999). Contracts, especially revenue/cost-sharing contracts and two-part tariff contracts, are prevalent mechanisms for coordinating green supply chains, even under asymmetric information situations (Agi et al., 2020; Chauhan and Singh, 2018; Kraft et al., 2020; Raj et al., 2021). In addition, screening and signalling contracts, characterised by whether the uninformed or informed party takes the initiative to offer contracts, have also been explored for their effectiveness in addressing asymmetric information in green supply chains (Arya et al., 2014; Kim and Netessine, 2013; Lee et al., 2018; Liu et al., 2019; Ma et al., 2018; Wu et al., 2020). Coordination mechanisms applied in the studies concerning asymmetric information are more diversified than those in symmetric information cases. Green supply chain coordination under asymmetric information is a complex endeavour that requires further exploration.

1.2 Research questions and methodology

Given the increasing significance of environmental sustainability across various industries, understanding the impact of information asymmetry on GSCM is essential for developing more effective and sustainable supply chain coordination strategies. Accordingly, we introduce our central research question:

How does asymmetric information influence decision-making and sustainability performance in supply chains with green practices?

This question mainly looks at three issues faced by firms operating in green supply chains:

(1) What role do green practices play in shaping supply chain sustainability?

This question aims to pinpoint and evaluate emerging green practices, assessing their potential impacts on supply chain operations. With this question, we would be able to delineate essential demand and cost functions, alongside profit functions, necessary for the development and analysis of the game-theoretic models. This exploration also gives insights into the potential motivation of firms' greenwashing behaviour driven by information asymmetry regarding these green practices, thereby facilitating a comprehensive understanding of their implications for supply chain sustainability.

(2) What are the effects of asymmetric information on greening investment and pricing decisions within supply chains?

This question allows us to identify the types of information asymmetry that can lead to greenwashing behaviours and analysing the responses of supply chain players. This investigation lays the groundwork for modelling and decision analyses, enabling an examination of the impacts of asymmetric greening information on supply chain firms' investment and pricing decisions, and identifying coordination opportunities. It offers insights into the implications of asymmetric information for the design and implementation of coordination mechanisms in green supply chains.

(3) What incentive contracts can firms employ to effectively coordinate the green supply chain?

This question seeks to devise contractual arrangements and evaluate their effectiveness in coordination to align incentives and optimise environmental and economic performance in the supply chain. It aims to propose plausible strategies that can mitigate greenwashing, promote genuine green practices while ensuring the economic viability of supply chain firms.

Each of these sub-research questions contributes to the overarching investigation by dissecting the complexities of GSCM under asymmetric information conditions. After answering these three research questions, we will be able to advance our understanding about the decisions and coordination in green supply chains with asymmetric information.

To address these research questions, we first conduct a systematic literature review on game theory-based models in green supply chains with asymmetric information. Game theory is one of the dominant approaches in studying information sharing and contracting in SCM. This review aims to ascertain the current state of research and identify gaps in the literature. For the modelling research work, this research develops a range of mathematical models primarily grounded in game theory, contract theory, principal-agent theory, and coordination theory. More specifically, simple and advanced wholesale price contracts and generalised two-part contracts are studied within various game-theoretic frameworks, including sequential games, bargaining games, and signalling games. Through analytical and numerical analysis, optimal solutions are derived, allowing for comparative insights. These approaches enable a deep exploration into the decisions and coordination mechanisms essential for advancing GSCM under asymmetric information. Table 1.1 provides a summary of the research questions and methodologies employed across the chapters of this thesis.

Table 1.1 An overview of research questions and methodologies in each chapter of this thesis

Chapters	Research questions	Methodologies
2 Game-theoretic Models for Sustainable Supply Chains with Asymmetric Information: A Review	What sustainable practices have been incorporated and investigated by supply chain models based on game theory with information considerations? Which members possess which types of asymmetric information in the sustainable supply chain? What are the impacts of information asymmetry on sustainability performance? What types of games have been applied to characterise and treat information asymmetry in this field?	Systematic literature review
3 Decision Analysis and Coordination in Green Supply Chains with Stochastic Demand	How does the demand uncertainty affect supply chain members' decisions and profits? How are supply chain members' decisions and profits affected if greening products implies changes in both development costs and marginal costs? How should the focal firm structure contracts to coordinate the decisions and increase profitability in the supply chain?	Sequential game, bargaining game
4 Decisions and Coordination under Asymmetric Information: Pathways to Green Innovation in Supply Chains	Under what conditions might the manufacturer choose greenwashing? How does unobservability in green process innovation impact the manufacturer's investment decisions and the green supply chain's performance? How can the green supply chain achieve coordination?	Sequential game, bargaining game
5 Green Marketing Strategies in a Supply Chain under Asymmetric Information	Under what conditions might a firm opt for a greenwashing or a distinctive signalling strategy? Does increased market transparency consistently lead to higher green marketing investment and profits?	Signalling game

1.3 Research outline and contribution

This thesis is structured into six chapters, each dedicated to deepening our understanding of decision-making and coordination within green supply chains, especially under asymmetric information. Figure 1.1 illustrates the structure and developmental trajectory of this thesis. Following this introductory chapter, Chapter 2 embarks on a systematic literature review of sustainable supply chain models based on game theory, with a focus on information asymmetry, identifying opportunities for further research. Chapter 3 investigates the decision-making and coordination in supply chains of marginal and development cost-intensive green products (MDIGPs), highlighting the importance of the cost structure of green product development in the decision-making with regard to greening and pricing and performance of green supply chains. Chapter 4 comprehensively considers both green product and process innovations by upstream firms and explores decisions and coordination under asymmetric process greenness information which may induce firm-level greenwashing. Chapter 5 examines the green marketing strategies of downstream firms within the context of asymmetric product greenness information which may lead to product-level greenwashing. Finally, Chapter 6 synthesises the research findings, outlines implications for theory and practice, and suggests the directions for future research.

The culmination of this research offers significant contributions to the field, summarised in three key aspects:

(1) Advancement in theoretical understanding

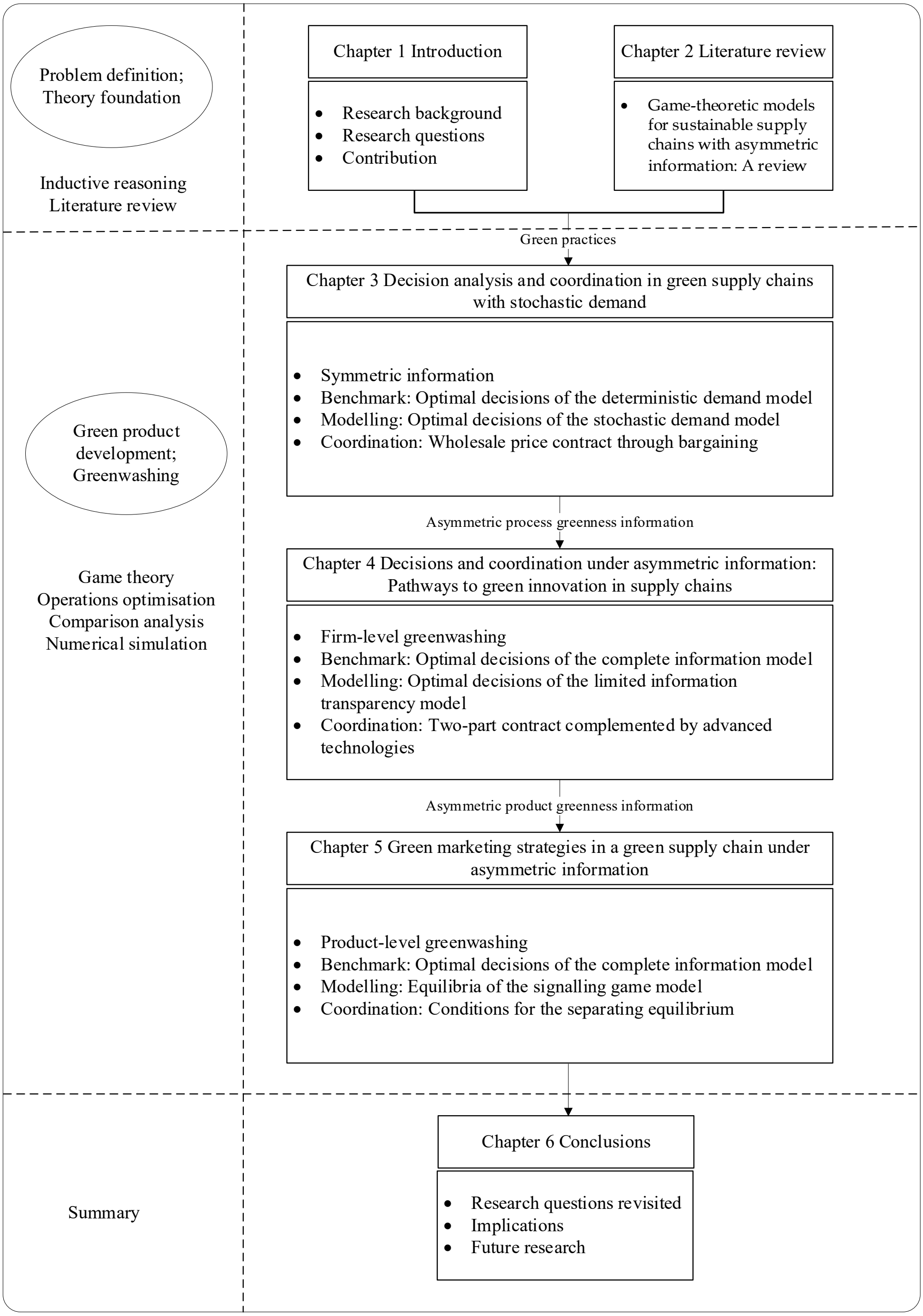
This research enriches the theoretical landscape of GSCM examining the complex effects of asymmetric information on supply chain operations and performance. Through the development and analysis of game-theoretic models, it provides a deeper understanding of how information asymmetry shapes decision-making processes, particularly in the context of green product innovation, green process innovation, and green marketing practices. This theoretical advancement lays the groundwork for future studies, offering a comprehensive framework for exploring the interplay between sustainability initiatives and supply chain coordination.

(2) Practical insights for green supply chain coordination

Beyond theoretical contributions, this research offers practical insights into the design and implementation of effective coordination contracts within green supply chains. By identifying and evaluating various coordination schemes, it presents plausible solutions for practitioners to align incentives, mitigate greenwashing, and enhance the sustainability performance of supply chains. These insights are invaluable for supply chain managers and policymakers aiming to foster more sustainable and efficient supply chain operations.

(3) Guidelines for mitigating greenwashing

A significant contribution of this thesis is the development of strategies to reduce greenwashing in supply chains. Through a comprehensive analysis of the conditions for the firms to engage in greenwashing and corresponding consequences, the research proposes targeted measures for different levels of transparency in green practices and the green market. These guidelines not only help in distinguishing genuine green initiatives from greenwashing but also contribute to building consumer confidence in green products and practices, thereby supporting the broader goal of environmental sustainability.



Decisions and coordination in green supply chains with asymmetric information

Figure 1.1 Thesis roadmap

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Chapter 2 Game-theoretic Models for Sustainable Supply Chains with Asymmetric Information: A Review

Abstract: Game-theoretic models are frequently used to investigate the effects of information availability and quality on supply chain decision-making. Although information asymmetry plays a vital role in shaping sustainable supply chains, a comprehensive review of these models for this area is still lacking. This study implemented a systematic literature review and identified 73 papers for an in-depth content-based analysis. Models were classified according to their assumptions concerning supply chain structure, information structure, and interaction between supply chain members. Several directions for future research relevant to sustainable supply chain management were identified. We find that researchers are extending traditional supply chain models to embrace the emerging challenges and opportunities led by sustainable practices under asymmetric information. However, the research remains in a preliminary phase, and much theoretical work still has to be backed up by real-world practices. Our findings highlight the importance of information sharing and coordination for driving sustainability, and also underline the relevance of game-theoretic models for sustainable supply chain management.

Keywords: green and sustainable supply chain management; supply chain coordination; game theory; information asymmetry; systematic literature review

Frequently used abbreviations: SSC: sustainable supply chain; GSC: green supply chain; CLSC: closed-loop supply chain; SCM: supply chain management; CSR: corporate social responsibility; GT: game theory; SLR: systematic literature review

2.1 Introduction

Sustainable supply chain management (SSCM) has gained prominence due to the increasing recognition of the environmental and social impacts of supply chain operations. Achieving sustainability goals further necessitates coordination of decision-making across various stakeholders, such as suppliers, manufacturers, retailers, and customers. However, information asymmetry, characterised by disparities in knowledge and information within supply chains, may lead to suboptimal decisions, consequently lowering supply chain sustainability performance and coordination efficiency and hindering the implementation and development of SSCM.

Real-life cases such as Volkswagen's (VW) emissions scandal (Dieselgate)[1] and Schaeffler's vital component stockout crisis[2] exemplify the impact of information asymmetry on coordination in the green and sustainable supply chain context. In 2015, the German carmaker VW was revealed to deliberately deceive regulators and customers by installing emissions cheating devices in its 11 million vehicles globally to greenwash their emissions data, resulting in significantly higher pollutant emissions than reported and substantial reputational damage. Facing litigation in several countries, VW has paid more than €30 billion worldwide for penalties like fines, compensation, and buyback schemes. The fallout has been continuing until June 2023, and the company continues working to rebuild trust. This "Dieselgate" scandal exposed a striking information asymmetry in VW's SSCM. Similarly, Schaeffler, a leading auto parts maker, provided another example. This company suffered a severe shortage of needle bearings in 2017 because its sole supplier of this vital component was closed by local authorities due to environmental violations. The CEO claimed that the supply disruption would leave more than 200 models of 49 automobile producers without key parts, resulting in an estimated economic loss of 300 billion RMB. The vast potential losses and the negative impact on the green supply chain could be alleviated if the company would have communicated well with its supplier and local environmental organisations. Relevant environmental organisations repeatedly warned about the supplier's illegal production as it lacked Environmental Impact Assessment (EIA) reports. However, due to information asymmetry and inefficient environmental management, the company failed to handle the supplier's environmental compliance issue promptly and faced significant risks in this incident.

These examples demonstrate how information asymmetry can have far-reaching consequences in green and sustainable supply chains. They have generated widespread attention in industry and academia. The increased awareness and calls for improved coordination highlight the urgent need to understand and address the challenges posed by information asymmetry in SSCM. Analytical modelling research is a general approach to investigating supply chains with information considerations (Shen et al., 2019). It has been increasingly used to study the impacts of information asymmetry on SSCM. However, current studies in this field have not yet been thoroughly evaluated. A systematic literature review can fill this void and provide insights into how sustainability goals can be achieved in the presence of information asymmetry challenges. This research, therefore, reviews modelling research on sustainable supply chains with asymmetric information, and identifies promising areas for future investigation. We narrow down the scope of our review to models based on game theory (GT) due to their widespread and successful applications in SCM literature.

Game theory is an effective tool for modelling and analysing scenarios where the decisions of multiple players influence each other's payoff (Cachon and Netessine, 2006;

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[1] https://www.bbc.com/news/business-61581251

[2] https://autonews.gasgoo.com/70010051.html

Shekarian, 2020; Yin et al., 2016). As the decisions of some players may convey private information that is relevant and useful for the decisions of other players, asymmetric information plays an important role in game theory, especially in dynamic games. Traditional SCM literature reviews have well documented the application of game theory (see Cachon and Netessine, 2006; Leng and Parlar, 2005; Nagarajan and Sošić, 2008) and the impact of information asymmetry on supply chain decisions and coordination (see Shen et al., 2019; Vosooghidizaji et al., 2020). However, the adoption of sustainable practices complicates the situation as it covers more influencing elements and involves multiple stakeholders. Findings and insights obtained in SSCs with symmetric information or traditional supply chains with asymmetric information do not necessarily carry over to SSCs with asymmetric information. For example, it is commonly understood that information asymmetry negatively affects economic performance in traditional supply chains. However, in sustainable supply chains, the negative impacts can be reduced or eliminated with the influence of various factors such as CSR efforts cost (Ma et al., 2017), demand uncertainty (Yu and Cao, 2019), and firms' concerns (Wu et al., 2020; Zhou et al., 2021). It is because supply chain firms' cost and demand structures are influenced by sustainable practices, and practices like CSR can usually be used as a proxy for signalling their information, such as product greenness. The use of coordination mechanisms such as screening contracts (Kim and Netessine, 2013; Liu et al., 2019b; Zhang et al., 2021) to address information asymmetry in the context of SSCs can also be changed due to different incentives and conditions to provide the contracts. Although growing research has been devoted to applying game theory in SSCM, there is a lack of systematic understanding of SSC models based on game theory which take information asymmetry into account. In this context, we seek to synthesise relevant literature and address the following main research questions:

(1) What sustainable practices have been incorporated and investigated by supply chain models based on game theory with information considerations?

(2) Which members possess which types of asymmetric information in the sustainable supply chain?

(3) What are the impacts of information asymmetry on sustainability performance?

(4) What types of games have been applied to characterise and treat information asymmetry in this field?

The remaining sections are organised as follows. Section 2.2 and Section 2.3 introduce the background and the review methodology, respectively. Section 2.4 presents the in-depth content-based analysis results and identifies existent gaps, followed by a discussion about the potential directions for further investigation. Section 2.5 concludes the chapter by summarising the findings and implications.

2.2 Background

2.2.1 Sustainable supply chain management and sustainable practices

Supply chain management (SCM) is an effective strategy for firms to support sustainable development. Ahi and Searcy (2013) propose a comprehensive definition for sustainable SCM (SSCM) as "the creation of coordinated supply chains through the voluntary integration of economic, environmental, and social considerations with key inter-organisational business systems designed to efficiently and effectively manage the material, information, and capital flows associated with the procurement, production, and distribution of products or services in order to meet stakeholder requirements and improve the profitability, competitiveness, and resilience of the organisation over the short- and long-term". Conceptually, Sauer and Seuring (2017) grouped the core practices of SSCM based on their links to supply chain strategy, structure, and processes into six categories: orientation, continuity, collaboration, risk management, proactivity, and government intervention. Knowledge of prominent practices can inspire researchers and practitioners to develop a suitable mapping for an effective shift to SSCM. Players can differentiate themselves within traditional supply chains through the implementation of sustainable practices while pursuing sustainability goals (Beske and Seuring, 2014). Empirically, Mathivathanan et al. (2018) presented specific practices from managerial, governmental, and societal perspectives. Practices identified in the literature to help sustainability transformation include but are not limited to regulation and monitoring, corporate social responsibility (CSR) practices, carbon-reducing activities, green product development, adoption of green technologies, and closed-loop supply chain (CLSC) practices.

For a better understanding of how firms can become sustainable and the impact of integrating sustainability, this chapter summarises the main forms of sustainable practices through an operations management lens, using the modelling literature. To distinguish from traditional supply chain management, we require that at least one player in the SSC needs to engage in at least one type of practice linking with the environmental and/or social dimension of sustainability. This requirement also indicates that we do not restrict our concerns to the realisation of all three dimensions of sustainability, truly or fully sustainable (Markman and Krause, 2016), because few players achieve this goal. Literature reviews verify that the social dimension lags behind the economic and environmental dimensions due to the challenge of quantifying relevant indicators (Ahmadi et al., 2017; Barbosa-Póvoa et al., 2018; Moreno-Camacho et al., 2019; Qorri et al., 2018). However, these dimensions of SSCM are all included in this review to provide insights into the practices covered in current academic research.

2.2.2 Asymmetric information

Effective information sharing among supply chain players is crucial for implementing sustainable practices and for constructing sustainable supply chains (SSCs). Sustainability-related information not only facilitates and coordinates decision-making, but also influences the sustainable choices in production and consumption of other players while building a sustainable reputation and trust. However, supply chain management is severely challenged by the phenomenon of information asymmetry, when different supply chain players possess varying levels of information about the same decision variables, and one party has more or better information than the other for decision-making (Rasmusen, 1989).

Compared to traditional supply chain management, information asymmetry is more prevalent in sustainable supply chains, for several reasons. Firstly, there can be a mismatch of sustainable incentives among supply chain members. Autonomous members with individual sustainable transformation capabilities and resources face varying stakeholder demands and regulations. They have different preferences and objectives in attaining sustainability, e.g., some members aim to maximise profits while others prioritise environmental and social benefits. These different sustainable values and objectives may lead some players to keep certain information private to align with their preferences and maintain competitive advantage. Secondly, the lack of information transparency which is typical in sustainable supply chains, significantly contributes to information asymmetry. Sustainable transformations influence what information the decision-makers require from other stakeholders and how they communicate it. Supply chain members demand more trustworthy information regarding sustainable manufacturing and distribution of the product to make informed decisions. However, the implementation of sustainable practices introduces considerable changes, complexities, and uncertainties to the business operations and decision-making of supply chain firms and consumers (Chelly et al., 2019), making it impossible or too costly for them to obtain complete information. Thirdly, stakeholders may adopt different information signals, such as eco-labelling schemes, to inform and motivate sustainable practices. The overwhelming amount of sustainability-related information without a standardised and comparable framework complicates the decision-making process further, as it may bring out varying perceptions and interpretations of the same information among decision-makers (Nikolaou and Kazantzidis, 2016). Finally, some private sustainability-related information is challenging to observe, monitor, and verify, allowing opportunistic members to strategically withhold or misreport their private information to secure individual interests and a more favourable bargaining position (Kerrigan and Kulasooriya, 2020; Kim, 2021). Consequently, insufficient or ineffectual information exchange causes some critical information being unknown to all supply chain stakeholders, exacerbating information asymmetry in sustainable supply chains.

2.2.3 Previous literature reviews and positioning of this chapter

There are numerous review papers that synthesise the evolution of green and sustainable supply chains. The existing literature reviews cover various issues, such as supply chain practices, drivers and barriers, performance measures, and dimensions of sustainability in GSCM/SSCM. Overviews of the topics studied in the literature reviews are available in Rajeev et al. (2017) and Barbosa-Póvoa et al. (2018). Moreover, Carter and Washispack (2018) and Martins and Pato (2019) conduct tertiary studies on SSCM and provide comprehensive reviews of the literature reviews in this area. Based on the focus of the reviews, Moreno-Camacho et al. (2019) identify five types of reviews, namely, general reviews, theory-building reviews, reviews on solution methodologies, reviews on specific supply chain functions, and reviews on sustainability performance metrics. Our current review chapter belongs to the solution methodologies stream, specifically, game-theoretic models used to address asymmetric information problems in sustainable supply chains.

For general literature reviews on GSCM/SSCM, readers are referred to de Oliveira et al. (2018); Fahimnia et al. (2015); Maditati et al. (2018); Malviya and Kant (2015); Panigrahi et al. (2019); Rajeev et al. (2017); Tseng et al. (2019). In those wide-ranging topics reviews, research methods, especially modelling approaches, have not been the main focus but rather discussed briefly in subsections in the results. The authors find that although qualitative research approaches like surveys, case studies, and conceptual models are predominant, quantitative modelling has become an increasingly important area for investigating SSCM problems. As Carter and Washispack (2018) point out, general reviews have reached a point of saturation; further systematic literature reviews need to focus on quantitative models for SSCM. However, few reviews of modelling papers have been published.

Chelly et al. (2019) provide a most recent overview of six literature reviews on modelling-based GSCM published over the period of 2007-2016. We update the list and present details of another eight reviews in Table 2.1. These reviews on modelling-based research have demonstrated various methods and approaches, ranging from optimisation techniques to operational research methods (see Brandenburg et al., 2014 for an analytic categorisation), that have been applied extensively in diverse areas of GSCM/SSCM. Among the investigated methods, game theory is used prominently in the literature. Chauhan and Singh (2018) study 87 mathematical model-based papers in GSCM and find that only five out of 87 articles include quantitative models other than based on game theory. Game theory-based models in the literature are systematically reviewed by Agi et al. (2020) and Shekarian (2020), focusing on forward GSCM and CLSCM, respectively. Although the reviews identify seven and sixteen papers with information considerations, importantly, neither of them explicitly discusses the specific features of these models regarding information asymmetry, which is known to complicate decision-making considerably. Including both forward and reverse supply chains, our main contribution, therefore, is a systematic literature review of SSCM models based on game theory and considering information asymmetry. Based on this review, as a second contribution, we formulate opportunities for research.

Table 2.1 Literature reviews on quantitative models for SSCM

No.	Authors	Scope	Methodology	Database	Time range	No. of papers
1	Brandenburg and Rebs (2015)	quantitative models in forward SSCM	CAM	publications assessed in previous reviews, journal-specific search	1994-2014	185
2	Barbosa-Póvoa et al. (2018)	OR methods in SSCM	SLR	Thomson Reuters Web of Knowledge (TR), Science Direct (SD)	NA	220
3	Chauhan and Singh (2018)	mathematical models in GSCM	SLR	Google Scholar, Ebsco, ProQuest, Scopus	NA	87
4	Xu et al. (2019)	quantitative models in GSCM under carbon policies	CAM	Science Direct, Emerald Insight, Taylor and Francis, Inderscience	NA	85
5	Chelly et al. (2019)	mathematical models for LCSCM	NA	NA	2007-2016	83
6	De Giovanni and Zaccour (2019)	GT models for CLSCM	selective survey	journal-specific search	NA	73
7	Shekarian (2020)	GT models for CLSCM	SLR	WoS	2004-2018	215
8	Agi et al. (2020)	GT models for forward GSCM	SLR	Scopus	2001-2019	108

Notes: NA: not available; SLR: systematic literature review; CAM: content analysis method.

Table 2.1 (continued)

No.	Authors	Main findings
1	Brandenburg and Rebs (2015)	Formal SSCM models are increasingly important, but currently, they are underrepresented. Most existing models concentrate on deterministic methods and the environmental aspect, overlooking stochastic modelling and social sustainability.
2	Barbosa-Póvoa et al. (2018)	The study of social aspects of sustainability has been left behind in economic and environmental aspects. Optimization models are predominant in current studies. Comprehensive models on SSC, considering uncertainty, need to be developed. Conflicting objectives in SSC can be tackled by using game theory approaches.
3	Chauhan and Singh (2018)	About 90% of the research articles on GSCC apply GT, which mostly considers contract coordination and assumes complete information.
4	Xu et al. (2019)	Most studies consider the cap-and-trade scheme, with the carbon tax and the carbon cap following behind. The design of GSCs should not solely consider carbon policies. The choice of a quantitative model should be based primarily on the stakeholders involved and the decisions to be made.
5	Chelly et al. (2019)	The task of modelling carbon emissions is challenging in LCSCM. Stochastic approaches are more appropriate for developing uncertain and realistic models and need to be more investigated in future research.

6	De Giovanni and Zaccour (2019)	Dynamic games are needed to study issues such as pricing, product quality over time, and stochastic returns. More coordination mechanisms, rather than common cost- and revenue-sharing contracts, should be developed in CLSC.
7	Shekarian (2020)	Sharing mechanisms, such as sharing on revenue, cost, and collection process, have received considerable attention, while information sharing among the game players still needs to be examined.
8	Agi et al. (2020)	Simple deterministic and two-echelon SC models dominate the current literature. There is a need to extend the models to consider uncertainty related to greening, evolutionary nature, and more intricate multi-echelon structures. Most reviewed literature deals with non-cooperative games under complete information. Models considering information asymmetry are required to analyse more complicated and realistic GSCs.

2.3 Methodology

Systematic literature review (SLR) is a structured methodology that identifies and analyses critical scientific contributions to a specific field or question (Tranfield et al., 2003). Drawing on general SLR guidelines, Durach et al. (2017) adapted this methodology to the SCM field. We follow their six-step process:

(1) **Develop a theoretical framework**. An initial theoretical framework is developed for subsequent selection, coding, synthesis, and discussion. The framework defines the review scope by specifying analysis units, research settings, and construct definitions.

(2) **Establish selection criteria for primary studies**. Inclusion and exclusion criteria are devised to define the required characteristics of the potential articles and assess their relevance and the initially developed framework.

(3) **Retrieve a baseline literature sample**. Potentially pertinent publications are retrieved by keyword searches in databases.

(4) **Select relevant literature**. The selection criteria are applied in titles, abstracts, and full texts to refine the baseline sample to a concise synthesis sample.

(5) **Synthesise literature**. The theoretical framework is refined to analyse and integrate the results from the synthesis sample.

(6) **Report the results of the review**. The results are presented with different levels of detail.

2.3.1 Theoretical framework

The analysis framework provided in Figure 2.1 is constructed based on the model setup and analysis. With different analysis units, we emphasise the characterisation of asymmetric information, game models, and the operational context of the supply chain. We explain these analysis units below.

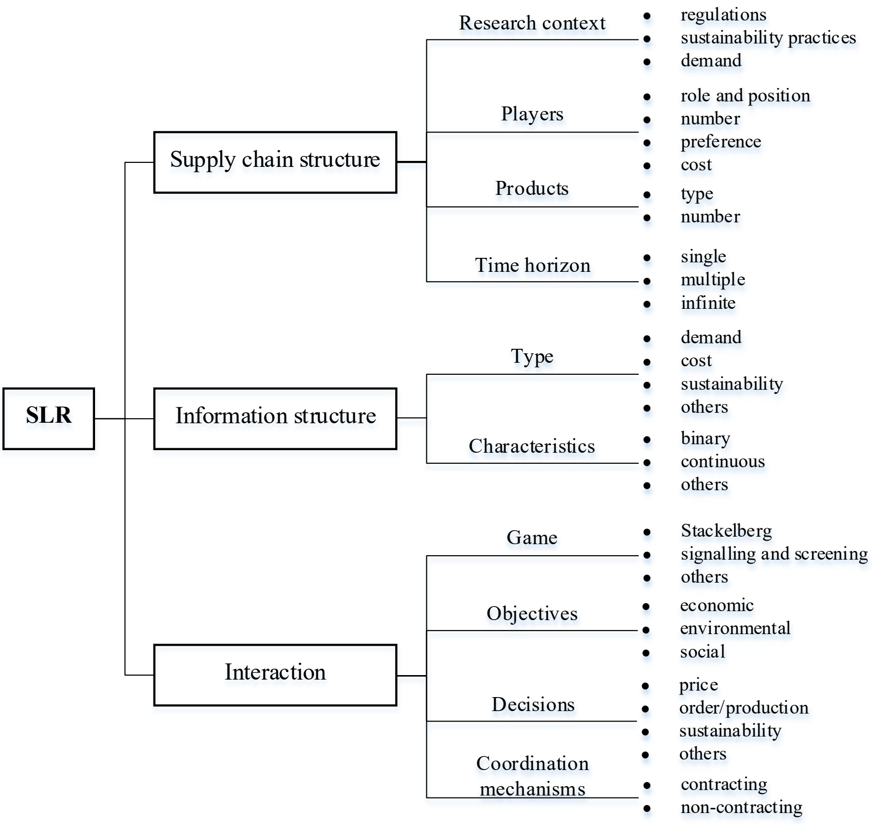

Figure 2.1 SLR analysis framework

Supply chain structure

In this chapter, the analysis of supply chain structure comprises research context, players, products, and time horizon.

(1) **Research context**. The research context relates to diverse questions such as: What sustainable practices have the supply chain members implemented? Who does incur the related costs? How do these practices impact the demand and the cost functions?

(2) **Players**. The position and the number of players in the supply chain can affect the complexity of the supply chain structure and the game sequence. Moreover, the operation of SSCs usually faces uncertainty and risk in terms of demand and cost. Players may show different preferences towards these risks (e.g., risk-averse, risk-taker), affecting their decisions and utilities.

(3) **Products**. Firms in SSCs usually promote new products to the market. Ordinary and innovative green products may coexist in the market. The consideration of single or multiple products has a leading role in shaping supply chain competition.

(4) **Time horizon**. Considering a single period, multiple periods, or infinite periods can affect the choice of games.

Information structure

Players possess different information about the same decision variables when making decisions owing to an absence of information exchange. We analyse the asymmetric information from the types and characteristics angles:

(1) **Types**. Most studies focus on asymmetric demand and cost information in the SCM literature. The coordination of SSCs copes with more information, such as sustainability efforts and capabilities.

(2) **Characteristics**. Typically, there are two main fashions to model asymmetric information: binary opposite values and continuous distribution (Ma et al., 2018).

Interaction

Interactions between players in decentralised supply chains are characterised by games, decisions, objectives, and coordination mechanisms.

(1) **Games**. Generally, game-theoretic models can be categorised into non-cooperative and cooperative games based on the interaction between the decision makers (Leng and Parlar, 2005). In non-cooperative games, the Nash game is applied when players make decisions simultaneously as they have equal power or cannot communicate. The Stackelberg game applies when players make decisions sequentially in a leader-follower environment. The presence of information asymmetry prompts players to engage in signalling or screening games depending on the power balance (Chen, 2003). In signalling games, the informed player offers a contract revealing the private information credibly, while in screening games, the uninformed player offers the contract (Lee and Yang, 2013; Voigt, 2011). Following Cachon and Netessine (2006) and Leng and Parlar (2005), we summarise the taxonomy of GT in traditional SCM in Figure 2.2.

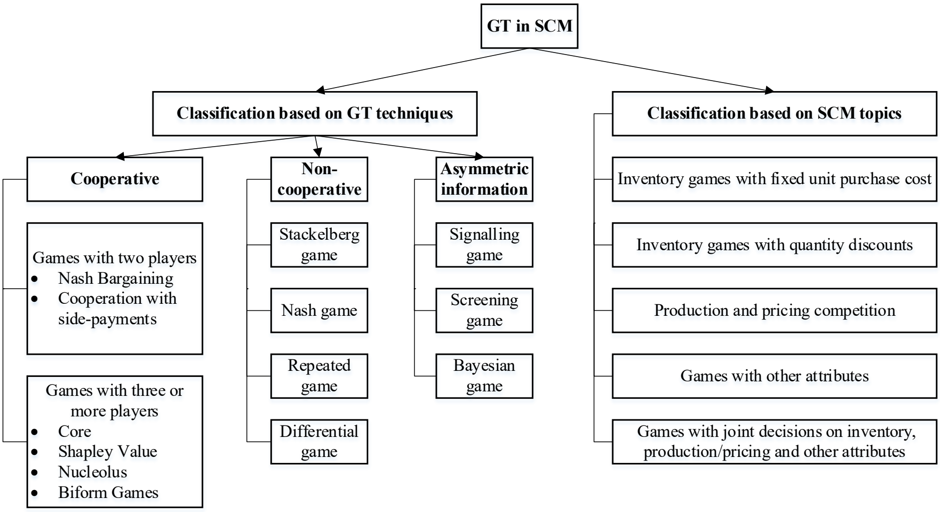

Figure 2.2 Taxonomy of GT in traditional SCM

(2) **Objectives**. Objective functions related to the environmental and social dimensions can be formulated apart from predominant profit functions (economic dimension).

(3) **Decisions**. In addition to the typical pricing and ordering (production) decisions, decision variables related to sustainability (e.g., greening of products) are introduced in SSCs.

(4) **Coordination mechanisms**. From the game-theoretic and supply chain perspectives, the definition of coordination in the literature can be classified into four streams (Albrecht, 2010; Stadtler, 2009). The most stringent one defines a supply chain as coordinated if and only if mechanisms result in a supply chain optimum and a unique Nash equilibrium (Cachon, 2003). A weaker alternative only requires a supply chain optimum. A third and even weaker definition results if implementing coordination mechanisms contributes to an enhanced supply chain profit compared to the default solution where no coordination exists. The default solution is considered the loosest coordination definition. Since the first two definitions can be regarded as special cases of the third alternative and the last definition ignores looking at improvement feasibility, we adopt the third definition as the general starting point of our review. Contracting is an extensively employed coordination mechanism, as the majority of transactions within supply chains are managed through contracts.

2.3.2 Characteristics of the primary studies

Exclusion and inclusion criteria are developed to identify articles that are both relevant to the overarching topic and meet academic rigor. The exclusion criteria aim to eliminate publications that do not directly contribute to the thematic core of our research questions. Conversely, the inclusion criteria serve a dual purpose: firstly, to guarantee the selection of high-quality publications adhering to scholarly standards for rigorous analysis; and secondly, to specify this study's emphasis on examining game-theoretic models in sustainable supply chains, especially those with asymmetric information. This structured approach ensures a focused and comprehensive literature review. Table 2.2 shows the specific selection criteria applied in this study.

Table 2.2 Paper selection criteria

Exclusion criteria	Inclusion criteria
Studies on performance measurement, supplier evaluation and selection Papers only involving simulation or role-play games, e.g., beer game, trading agent competition (TAC) SCM game Application of information and communication technologies Conference papers, editorials, and books	English papers published in peer-reviewed journals Supply chain players should get involved in at least one form of sustainable practices Papers based on game-theoretic approaches with information considerations

2.3.3 Baseline sample

Scopus and Web of Science (WoS) Core Collection were employed for the keyword search. Scopus was suggested as a reliable source of supply chain peer-reviewed papers (Fahimnia et al., 2015). WoS was selected as a complementary database because it provided interdisciplinary coverage in high-quality articles (Tseng et al., 2019). It is noteworthy that the operator AND has higher precedence than OR in WoS, while Scopus applies the order of precedence conversely. Parentheses can be used to group compound operators and override operator precedence. Also, double quotation marks in WoS (curly brackets in Scopus) turn off lemmatisation, an automatic processing that helps to find variations such as plurals and spelling variations. Wildcards can be used to account for variations when lemmatisation is turned off, e.g., the dollar sign ($) is used in WoS search to find the British and American spelling of the same word.

The keyword search strategy is the most common approach to acquire papers for SLR. We defined three sets of keywords after rigorous trials and test searches to ensure the selected papers were relevant to the topic. The first set of keywords (K1) combined supply chain with sustainability to retrieve the literature in the domain of SSCM: "supply chain" AND ("sustainab*" OR "green*" OR "environment*" OR "carbon" OR "corporate social responsibility" OR "closed-loop" OR "reverse" OR "remanufacturing" OR "recycl*"). The second set of keywords (K2) sought to narrow the search scope to the papers concerning game-theoretic models: "game" OR "game theor*" OR "equilibri*" OR "bargaining" OR "screening" OR "signal$ing". The last set of keywords (K3) was defined to identify papers that dealt with information structure: ("asymmetr*" OR "part*" OR "shar*" OR "private" OR "incomplete" OR "imperfect") AND "information". Consequently, the search string used for the database search was a combination of all sets of keywords through Boolean operators[3].

The initial search was performed in the topic field, including article title, abstract, and keywords. The publication was limited to English articles and reviews. Publication time was not specified, but the final update of the retrieval data was compiled in June 2021. The identification of duplicated papers was completed in Endnote. In the end, 250 synthesis available papers were obtained after eliminating duplicates. The keyword search process and results are presented in Table 2.3.

Table 2.3 Keyword search in the database

Search strings	Databases	Results	Unique results	Synthesis available
K1	Scopus	23,827		
	WoS	21,423		
K1 AND K2	Scopus	1,744	377	1854
	WoS	1,817	450	
K1 AND K2 AND K3	Scopus	168	40	250
	WoS	214	86	

2.3.4 Synthesis sample and descriptive analysis

The inclusion and exclusion criteria were employed to reduce the number of articles to 135 for a full-text review after reading all the titles and abstracts. Subsequently, the review process was continued by a full-text reading, resulting in 66 articles included in the synthesis sample. To complement the database search, we used snowballing techniques (Jalali and Wohlin, 2012) and located another seven relevant articles with the help of the bibliometric software HistCite [4]. Thus, a total of 73 papers were included for a detailed review. Figure 2.3 provides the paper screening methodology and results.

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[3] Adding an asterisk (*) to the root word helps identify all derivative words, e.g., "green*" will search for green, greening, greenness, etc.

[4] Note that HistCite is no longer officially updated by Clarivate Analytics, the present analysis is based on its 12.3.17 version. Installer is available in https://support.clarivate.com/ScientificandAcademicResearch/s/article/HistCite-No-longer-in-active-development-or-officially-supported?language=en_US

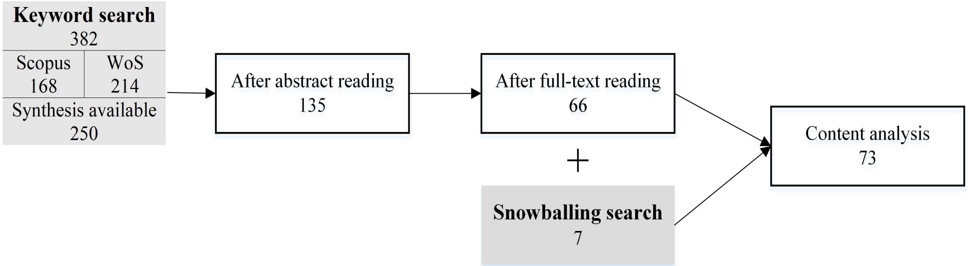

Figure 2.3 Paper screening methodology and results

As a first result, almost all the articles were published during the past five years in a total of 35 journals. Figure 2.4 shows the journals that published at least three articles, covering 42 out of 73 reviewed papers. *Journal of Cleaner Production* (JCP) is the largest contributor to the sample, with nine publications. The little difference in publication numbers between each journal suggests that there is no authoritative journal at present. In addition, Chinese scholars contribute the most publications (79%) in this field.

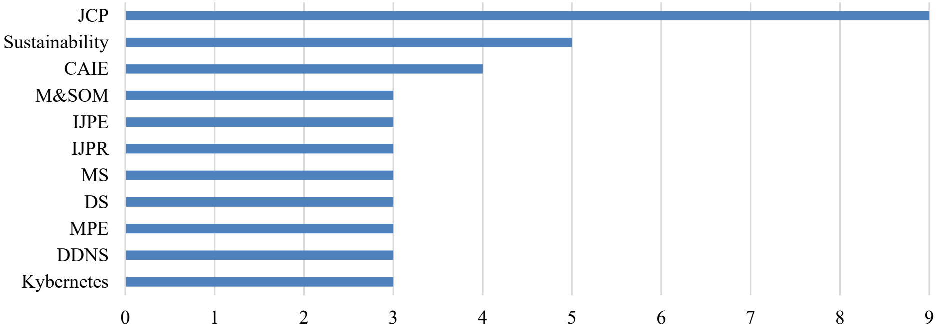

Figure 2.4 Journals where three or more reviewed papers are published

Notes: JCP: Journal of Cleaner Production; CAIE: Computers & Industrial Engineering; M&SOM: Manufacturing & Service Operations Management; IJPE: International Journal of Production Economics; IJPR: International Journal of Production Research; MS: Management Science; DS: Decision Sciences; MPE: Mathematical Problems in Engineering; DDNS: Discrete Dynamics in Nature And Society.

Network analysis is useful for exploring relationships between various factors. Using a bibliographic database file from Scopus as an input, we employ VOSviewer software developed by van Eck and Waltman (2010) to generate a visual network relationship between the keywords of the reviewed papers. Figure 2.5 provides the greatest set of connected keywords, with 480 author and index keywords. The size of the corresponding circle and label represents the occurrences of keywords. It is found that "supply chains" and "supply chain management" are the two most common keywords with a total of 53 occurrences, which is followed by "game theory" and "asymmetric information", both occur 25 times. Synonyms of and related phrases to "asymmetric information" such as "information sharing", "information asymmetry", and "private information" also have relatively high occurrences. Regarding sustainability, keywords related to "green supply chain", "closed-loop supply chain", "corporate social responsibility", and "carbon emissions" occur frequently. There is a high concentration of keywords related to the research scope.

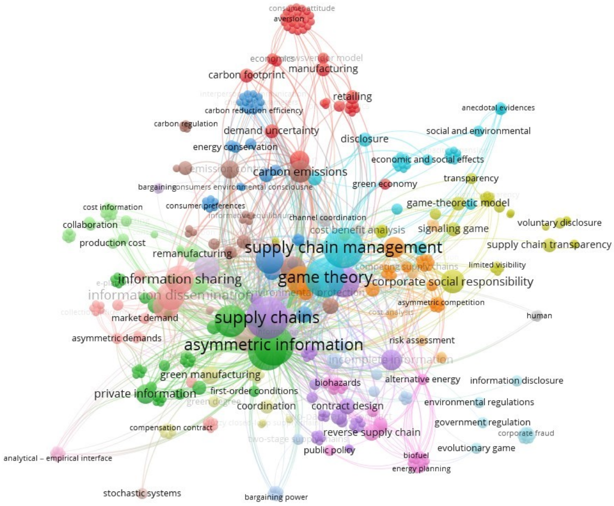

Figure 2.5 Co-occurrence of keywords clusters

We engage HistCite to identify important papers in the synthesis sample using a bibliographic database file from WoS as an input. Figure 2.6 shows the mapping of local citations ordered by the local citation score (LCS) indicator. The size of each circle indicates the occurrence of citations received by the paper pointed out. The larger the circle is, the more citations the paper receives. The arrow represents the citation relationship. There are six representative papers. Three out of these six papers model CLSCs; among them, Zhang et al. (2014) (Circle 4) and Wang et al. (2017) (Circle 13) design information screening contracts where the retailer's information on collection effort is asymmetric; Wei et al. (2015) (Circle 16) analyse pricing and collection decisions with symmetric and dual asymmetric information between the two supply chain members. Considering upstream firms' cost information asymmetry, Kim and Netessine (2013) (Circle 3) explore how screening contracts with different commitment strategies affect supply chain members' new product development collaboration, while Ma et al. (2017) (Circle 6) develop two-part tariff contracts (TPTC) to improve the CSR level. Plambeck and Taylor (2016) (Circle 8) examine how a supplier's effort to hide information about unsafe practices or environmental problems impacts a buyer's auditing policies.

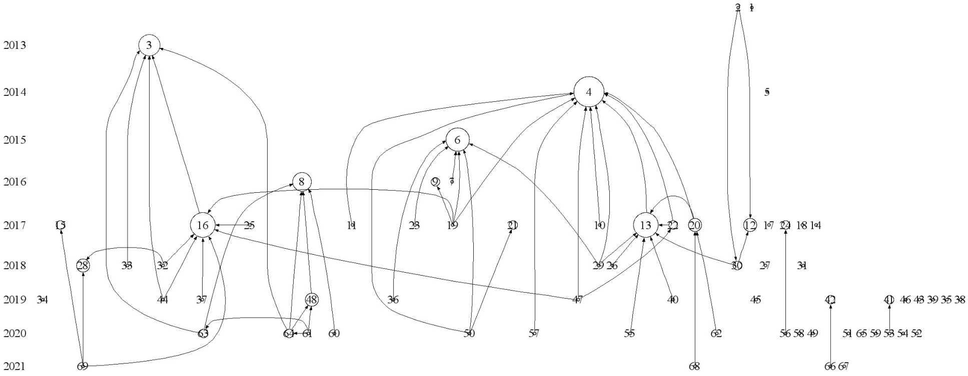

Figure 2.6 Mapping of local citations inside the synthesis sample

2.4 Results and discussion

The reviewed papers were assigned numbers and classified according to the framework and corresponding results in Figure 2.1. All analyses refer to the synthesis sample of 73 papers on sustainable supply chain analysis based on game-theoretic models under information asymmetry. Appendix A1, A2, and A3 present the details and statistics in full lists. This section first reports the review results using a refined analysis framework to increase readability. After that, research gaps and future directions are identified and explained.

2.4.1 Supply chain structure

We mainly focus on the sustainable practices studied by supply chain models and their impacts on cost and demand. Table 2.4 summarises an overview of the studied sustainable practices and Figure 2.7 illustrates the distribution of relevant factors according to the frequency of occurrence.

We observe that most game-theoretic models with asymmetric information consider government interventions (26%), followed by closed-loop supply chain management (CLSCM, 23%). The government engages in SCM through policy regulations and financial incentives to monitor and improve sustainability performance. Out of the 27 papers that consider government interventions, 16 papers analyse regulations on manufacturers (e.g., Chen and Li, 2021; Liu and Chen, 2019; Ma et al., 2018; Xia and Niu, 2021). These government regulations are mainly carbon policies and reward-penalty mechanisms (RPM). Only seven papers consider the regulation applicable to all supply chain firms, mainly via subsidies (e.g., Qu and Zhou, 2017; Wu et al., 2019; Zhang et al., 2020). Accordingly, manufacturers are the most active members (45%) in taking green initiatives and incurring relevant costs. CLSCM has been developed into a self-contained subdiscipline in the supply chain and sustainability research domain. Developing models with asymmetric information is an area of increasing importance for CLSCM. CLSCs integrate information flows in both forward and reverse activities. On top of the information in forward chains such as demand forecast (e.g., Huang and Wang, 2017a, b), models in this area also address asymmetric information related to reverse activities, e.g., recycling and remanufacturing of returned products (Sane-Zerang et al., 2019; Wang et al., 2017; Wei et al., 2015; Zhang et al., 2020). Carbon emission-dependent activities (14%) and forward GSCM (13%) are also two of the most commonly investigated sustainable practices in the reviewed papers. The former usually considers carbon price, low-carbon R&D cooperation, and carbon reduction efficiency under governmental carbon regulations (e.g., Liu and Song, 2017; Wang and He, 2018; Xia and Niu, 2021; Yang et al., 2016). The latter usually considers innovation and production costs, selling efforts, willingness-to-pay, and market demand in green products' manufacturing and distribution process (e.g., Liu et al., 2019a; Raj et al., 2021; Zhang et al., 2021).

Regarding demand curves, the gap between the deterministic demand (36%) and stochastic demand (31%) settings is not significant as other reviews have found, e.g., Barbosa-Póvoa et al. (2018) and Vosooghidizaji et al. (2020). With different research scopes, we focus on the game-theoretic models for SSCs with asymmetric information. Also, the implementation of sustainable practices introduces uncertainty factors to supply chain operations. Stochastic modelling techniques are more appropriate to characterise these configuration features than deterministic ones. Therefore, their adoption increases in this stream of literature.

The apparent difference exists in the linear versus nonlinear demand curves. For tractable modelling and analysis, 61% of the papers employ the assumption that demand has a linear relationship with the selling price or sustainability attributes (e.g., De Giovanni, 2017; Raj et al., 2021; Sane-Zerang et al., 2019). Only three papers (Wan et al., 2019; Wang et al., 2018a; Yang et al., 2016) adopt nonlinear demand curves that are either iso-elastic or exponential. Moreover, there are two common ways to model demand uncertainty: additive or multiplicative forms (Petruzzi and Dada, 1999). Out of 23 papers that have considered random demand, 18 apply additive forms (e.g., Jha et al., 2017; Liu and Chen, 2019; Nie et al., 2020; Wei et al., 2021b) and only one uses a multiplicative form (Wan et al., 2019). The remaining papers assume the demand as a random variable. Other forms of demand functions are also presented in the literature, e.g., market demand based on consumers' willingness-to-pay (WTP) and utility from green products and services (Kraft et al., 2020; Lee et al., 2018; Li et al., 2017; Wu et al., 2020; Zhang and Wang, 2019), and fuzzy variables (Gao et al., 2020; Zhao et al., 2017).

Most models operate under the assumption that decision makers are rational and risk-neutral. These models often construct a dyadic one-to-one structure with a single product in a single-period setting, i.e., one upstream firm (like a supplier or a manufacturer) and one downstream firm (like a retailer or a buyer) in the supply chain. Limited consideration has been given to studying other supply chain configurations, especially the supply chain members' behavioural preferences that can significantly affect their decisions and performance (Wei et al., 2021a).

Table 2.4 Sustainable practices studied in the reviewed papers

Practices	Articles	Brief explanations
NPD	1, 11	A set of activities that transfer "a market opportunity into a differentiated product or service for sale" (Krishnan and Ulrich, 2001)
Greenwashing; corporate fraudulent behaviours	24, 39, 62	"the act of misleading consumers regarding the environmental practices of a company or the environmental benefits of a product or service" (Lee et al., 2018)
SCT	32, 52, 53, 54, 60	A firm voluntarily discloses its supplier lists to the public.
CSR activities	6, 12, 14, 21, 24, 37, 38, 54, 62	In addition to focusing on economic interests, firms also integrate public concerns related to the environment and society into their operations, such as improving product quality, environmental friendliness, employee welfare, and work environment (Dahlsrud, 2008; Liu et al., 2019c)
Carbon emission-dependent activities	7, 13, 15, 16, 25, 27, 30, 42, 44, 45, 52, 59, 61, 63, 64	Carbon emission reduction by means of governmental carbon regulations, firms' investment in carbon-reducing initiatives including low-carbon technologies and energy-efficient projects, and contracting and cooperation in supply chains.
GSCM/SSCM	35, 36, 43, 46, 50, 56, 57, 66, 68, 69, 70, 72, 73	The supply chain does not focus on the above-mentioned specific activities, just on manufacturing and distributing green products with investment in green technologies and green marketing.
Government interventions	7, 15, 16, 17, 19, 21, 25, 28, 30, 31, 33, 35, 39, 43, 44, 45, 47, 49, 55, 58, 59, 61, 63, 64, 65, 66, 67	Low-carbon policies: cap-and-trade, carbon tax, etc. RPM: combining government rewards with penalties for recycling, remanufacturing, and carbon emissions. The government prescribes a target rate and reward-penalty intensity. The regulated firm will be rewarded or punished when its performance is better or worse than the target rate (Zhang et al., 2020). Subsidies for green products and technologies Monitoring and inspection of firms' related information and actions
CLSC/RSC: recycling, remanufacturing, etc.	3, 4, 5, 8, 9, 10, 13, 17, 18, 19, 20, 22, 23, 28, 29, 31, 33, 34, 40, 41, 48, 51, 65, 67	"A CSLC integrates forward and reverse activities into a single system." Reverse activities refer to product acquisition, reverse logistics, recycling, remanufacturing, reselling, etc. (De Giovanni and Zaccour, 2019)
Other	2, 26, 32, 58, 60, 71	quality testing; green consumption; safety production; responsible sourcing; dual channels

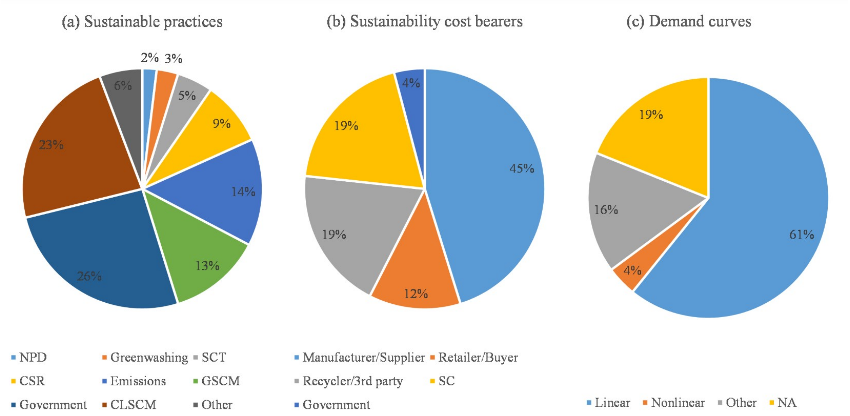

Figure 2.7 Distribution of sustainable practices

After reviewing the preceding observations, we identify potential areas for further investigation regarding the supply chain structure as follows:

(1) Supply chain transparency (SCT): Researchers use and define SCT differently based on their own viewpoints and research objectives. In general, there are two perspectives: information visibility and disclosure (Montecchi et al., 2021; Schäfer, 2022). This research defines it as a type of sustainable practice in which a firm voluntarily discloses its supplier lists to the public. The adoption of this definition is based on the reviewed paper where information asymmetry is a consequence of the lack of transparency. This stream of research is mainly concerned with the social aspect of sustainability. SCT and the related phenomenon of greenwashing are widely observed in practice and significantly impact the decisions and performance of leading firms like Apple, H&M, and Nike (Chen and Duan, 2023). However, they are insufficiently presented in the literature. SCT is considered a relatively recent information-sharing development and an effective tool for enhancing sustainability performance (Chen et al., 2019). More transparency facilitates the reduction of information asymmetry (Shao et al., 2020). Moreover, independent third parties such as nongovernmental organisations (NGOs) play a critical role in enhancing SCT, e.g., the Institute of Public and Environmental Affairs (IPE)[5] monitors and publicises supply chain firms' environmental performance through websites, apps, and reports. Only a few papers have investigated the impact of NGOs and SCT on information sharing and sustainability within supply chains (Chen and Duan, 2023; Chen et al., 2019; Kraft et al., 2020; Plambeck and Taylor, 2016). Further research on this issue is recommended.

(2) Analyses from the perspective of consumers: The demand for sustainable products and services is largely driven by consumers willing to pay for sustainable options. As a result, consumers play a critical role in promoting sustainability throughout the supply chain. The influence of information on customers' behaviour shift toward more sustainable choices is receiving increased attention, e.g., firms launch eco-labelling schemes and green marketing campaigns to inform and educate conscious consumers (Nikolaou and Kazantzidis, 2016; Singh and Pandey, 2012). The government issues environmental subsidies to consumers for purchasing green products (Bian et al., 2020). These actions broaden consumers' knowledge about sustainable practices and products and improve

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[5] http://www.ipe.org.cn/

consumer welfare. Utility-based willingness-to-pay demand models that existing GSCM/SSCM studies have ignored seem more suitable for investigating the impact of sustainable practices and information sharing on consumers' purchase choices. Therefore, it could be helpful to consider such utility models (Huang et al., 2013).

(3) Supply chain competition and dynamics: Multiple players and products compete in multiple periods. Facing sustainability and economic globalisation issues, a focal firm usually interacts with multiple suppliers or retailers within an extended time frame to source, produce, and sell products to satisfy consumers' demands. Therefore, one-to-many, many-to-one, or many-to-many supply chain structures, as well as chain-to-chain competition, are common in practice (Lee and Yang, 2013). The information sharing in those structures is more complicated than in the simple one-to-one structure. There is still a need for more research on how multiple firms collaborate and compete with each other (Cachon, 2003), including the impact of information sharing. Firms in SSCs usually promote new products to the market. In modelling-based studies, many scholars assume that the launch of new products immediately makes older products obsolete, so the research is limited to a single product in a single period. According to the European Commission (2013, 2018), green products and ordinary products possess the same or similar functionality and address the same consumer demand. Multiple products coexist in the market for a certain time. Competition between homogeneous and substitutable products needs to be considered.

(4) Dual-channel supply chains (offline/online sales patterns of green products): The accelerating advancement in e-commerce enables more consumers to purchase online. Numerous firms, such as Haier, Lenovo, and Nike, build dual-channel supply chains by broadening sales patterns from traditional retail channels to direct selling through the Internet or live-streamed selling to distribute green products (Jamali and Rasti-Barzoki, 2018). E-commerce can also be developed as a tool for improving sustainability performance through, e.g. smart logistics with the application of artificial intelligence (Issaoui et al., 2020). More importantly, the big data about consumers' preferences and demands acquired on e-platforms enables firms to minimise the adverse effects of information asymmetry and optimise their sustainable practices (Wei et al., 2021b). For example, Alibaba Group uses its big data to analyse consumers' green purchasing behaviours and predict the demand more precisely, which increases green product sales and nurtures more green consumers (Alibaba Group, 2016). The introduction of online direct selling channels and the information advantage of e-tailers may reshape the competition in the supply chains by employing different information sharing strategies.

2.4.2 Information structure

Figure 2.8 shows the distribution of information structure in the synthesis sample. Similar as in the previous reviews by Shen et al. (2019) and Vosooghidizaji et al. (2020), demand and cost information asymmetries are still among the most often investigated types of asymmetric information in the SSCM literature, wherein the demand and the cost are usually sensitive to the actions or outcomes of sustainable practices such as greenness, emission reduction investment, and CSR efforts. The asymmetric demand information mainly concerns downstream firms' demand forecast when they face a stochastic demand (e.g., Huang and Wang, 2017b; Jha et al., 2017; Nie et al., 2020; Qu and Zhou, 2017; Wei et al., 2021b; Xia and Niu, 2021; Yu and Cao, 2020; Yu and Li, 2018; Zhou et al., 2021). Nevertheless, the cost asymmetry ranges from upstream firms or the third parties' production, green R&D investment, or remanufacturing costs (e.g., Arya et al., 2014; Gao et al., 2020; Kim and Netessine, 2013; Liu and Song, 2017; Liu et al., 2019c; Wei et al., 2015; Zhang et al., 2021) to downstream firms' selling or collection costs (e.g., Raj et al., 2021; Sane-Zerang et al., 2019; Wang and He, 2018; Zhang et al., 2014; Zhang et al., 2018; Zhang et al., 2020; Zhao et al., 2017).

Asymmetric information on sustainable practices has received significant attention, though researchers have modelled a limited number of practices. For example, the CLSC models usually consider asymmetric information on the collection effort (e.g., Hu et al., 2019; Wang et al., 2017; Wang et al., 2018b; Yan and Cao, 2017; Zheng et al., 2017; Zhu and Yu, 2019). A handful of SCT literature investigates buyers' strategy of revealing their suppliers based on the information about the suppliers' sustainability compliance capabilities or environmental impacts (Chen et al., 2019; Kalkanci and Plambeck, 2020a, b; Kraft et al., 2020; Shao et al., 2020). Plambeck and Taylor (2016) and Mei et al. (2020) examine a supplier's attempt to conceal information about possible safety issues from a buyer. Wu et al. (2020) study a firm's greenwashing strategies considering the transparency of CSR information. Xia and Niu (2020) propose a carbon contractual policy to address the carbon-reducing information asymmetry between the government and the manufacturer.

Comparatively, the study of asymmetric information on product attributes of quality and greenness alike (Hong et al., 2016; Lee et al., 2018; Li et al., 2017; Ma et al., 2018; Zhang and Wang, 2017) and supply chain players' preferences like altruism and fairness (Shu et al., 2019; Wan et al., 2019; Wei et al., 2021a; Zhao and Chen, 2019) have attracted less attention. It is probably because evaluating and quantifying product attributes and preferences takes tremendous effort. Significantly, preference information asymmetry is an emerging topic. Researchers face the challenge of borrowing from other theories, such as prospect theory (Kahneman and Tversky, 2013; Liu and Chen, 2019), to model and explain the phenomena of interest.

Some papers investigate how information asymmetry affects supply chain performance through comparative analyses. Compared to the case with symmetric information settings, most studies found that information asymmetry is profitable for the informed player with higher prices. In contrast, it may be detrimental to the profit of the uninformed player and the supply chain (Ding and Wang, 2020; Huang and Wang, 2017a, b; Jha et al., 2017; Wang et al., 2018a; Wu and Kung, 2020; Zhang et al., 2014). Nevertheless, various factors can affect the value of information and then cause different relationships between symmetric and asymmetric information cases. Investigated factors in the reviewed papers include but are not limited to governmental policies (Li et al., 2020; Nie et al., 2020; Yang et al., 2016), contract types (Liu et al., 2019b; Wang and He, 2018; Zhang et al., 2021), market demand states (Lee et al., 2018; Li et al., 2020; Li et al., 2021; Yu and Cao, 2019, 2020; Yu and Li, 2018), innovation cost efficiency (Jha et al., 2017; Li et al., 2017; Wei et al., 2021b), firms' altruism preference and risk-aversion degree (Wan et al., 2019; Xia and Niu, 2020), dimensions of information asymmetry (Qin et al., 2017; Xia and Niu, 2020; Zhang and Xiong, 2017), and competition (Lee et al., 2018; Yu and Cao, 2019, 2020; Yu and Li, 2018). With the influence of these factors, information asymmetry could even exert beneficial effects on sustainability performance under certain conditions. For instance, Zhang and Xiong (2017) report that the retailer and the supply chain could gain larger profits in the non-information sharing case if the collection efficiency is low. Lee et al. (2018) and Wu et al. (2020) reveal positive aspects of greenwashing: it can incentivise firms to contribute to higher environmental quality or socially beneficial investment and promote green consumption if customers are sufficiently informed. Chen et al. (2019) demonstrate that buyers are more inclined to disclose their supplier list in the asymmetric information case compared to those in the symmetric information case. Increased transparency would be beneficial to enhance suppliers' social and environmental sustainability performance. Zhang et al. (2021) identify cases wherein information asymmetry improves sales channel efficiency by alleviating the double marginalisation effect and inducing higher environmental innovation. As aforementioned studies indicated, the impacts of information asymmetry on environmental and social performance depend on complicated factors. A handful of papers have compared and showed that information asymmetry may decrease firms' sustainability effort and lower product environmental innovation, greenness, carbon reduction, or CSR level (Ding and Wang, 2020; Jha et al., 2017; Kalkanci and Plambeck, 2020b; Kraft et al., 2020; Liu and Chen, 2019; Liu et al., 2019b; Wang and He, 2018; Wei et al., 2021b; Zhang et al., 2021; Zhou et al., 2021). Noticeably, the analysis of social sustainability performance is rare.

Regarding the treatment for information asymmetry, about half of the reviewed papers assume that the asymmetric information belongs to two specific types, i.e., the uninformed party knows that an independent binary random variable takes one type with probability ρ and $1-\rho$ otherwise (e.g., Chen et al., 2019; Huang et al., 2019; Kalkanci and Plambeck, 2020a; Lee et al., 2018; Liu and Song, 2017; Shao et al., 2020; Wu et al., 2020; Xia and Niu, 2021). Fewer researchers relax the assumption and process the asymmetric information as following a continuous distribution with its density function (e.g., Arya et al., 2014; Kim and Netessine, 2013; Kraft et al., 2020; Ma et al., 2017; Ma et al., 2018; Raj et al., 2021). Additionally, a couple of papers assume that the uninformed party treats the asymmetric information as a subjective estimator (e.g., Jha et al., 2017; Liu and Chen, 2019; Nie et al., 2020) or a misreporting factor (e.g., Liu et al., 2019c; Plambeck and Taylor, 2016; Qu and Zhou, 2017).

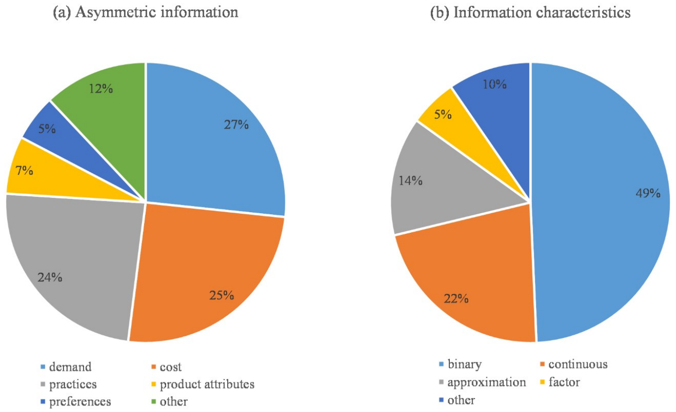

Figure 2.8 Distribution of information structure

After reviewing the preceding observations, we identify potential areas for further investigation regarding the information structure as follows:

(1) Fitting more sustainability-related asymmetric information types into SSC models: The issue of demand and cost information asymmetries has been widely recognised for both traditional and sustainable supply chains. There are also other types of information related to sustainability that can be highly influential in the decisions and performance of SSCs, for example, carbon emissions and carbon prices (Yang et al., 2016), consumers' attitudes and willingness-to-pay for product greenness (Zhang and Wang, 2019), and supply chain members' behavioural preferences (Wei et al., 2021a; Wu et al., 2020; Zhao and Chen, 2019). Identifying and studying asymmetric information can support the development of SSCM.

(2) Extending the model to study bilateral or multilateral information asymmetry: unilateral and single information asymmetry, i.e., only one party is more knowledgeable about a

single type of information, is predominant in current models. Very few papers study unilateral and two-dimensional information asymmetry (Liu et al., 2019a; Xia and Niu, 2020; Zhang and Wang, 2019; Zheng et al., 2017; Zhu and Yu, 2019), bilateral and single information asymmetry (Qin et al., 2017; Wang et al., 2018b; Zhang and Xiong, 2017), and bilateral and two-dimensional information asymmetry (Sane-Zerang et al., 2019; Wei et al., 2015; Yang et al., 2016). There is no paper model multilateral information asymmetry with more than two parties and two types of information, which is more likely to present in real supply chains (Vosooghidizaji et al., 2020).

(3) Exploring other characteristics of asymmetric information: Current models primarily rely on the known discrete or continuous probability of parameters to characterise the type of information asymmetry. However, probability theory may be inappropriate when the observed data is unavailable for the estimate, which is common in practice. In this case, researchers like Gao et al. (2020) and Ma et al. (2020) resort to using fuzzy theory and uncertainty theory to characterise information asymmetry. It could be helpful to consider such characteristics to expand the view of information asymmetry.

(4) Integrating new data-related technologies and their implications for information sharing and sustainability to SSCM: There is an increasing prevalence and interest of firms in adopting emerging technologies like blockchain, Internet of Things (IoT), artificial intelligence (AI), and eco-labelling to inform sustainability performance and improve SCT (Ashraf and Ali, 2023; Bai and Sarkis, 2020; Dong et al., 2023; Liu et al., 2020; Manavalan and Jayakrishna, 2019). These innovative technologies alter supply chain firms' sustainable operations and coordination modes, which may bring about new decision-making models with information considerations (Shao et al., 2020). Despite the prevalence of new technologies and their strategic roles in SSCs, research directly addressing and modelling new technologies' impacts is relatively scarce in the literature (Shen et al., 2019).

2.4.3 Interaction

As shown in Figure 2.9, the majority of papers use Stackelberg games to model imbalanced power or sequential moves in the supply chains. The papers with upstream firms being Stackelberg leaders are three times more than those with downstream firms acting as leaders. Most of the modelling papers are located in the manufacturing industry, as manufacturers get more involved in sustainability practices than downstream firms. Only Wei et al. (2015) investigate the optimal pricing and collection decisions in a CLSC with symmetric and asymmetric information considering the influence of power structure. The authors report that the leading firm has an advantage of obtaining a higher profit in both symmetric and asymmetric information settings. In comparison, the follower earns a higher profit in the asymmetric information case than in the symmetric information case.

Moreover, if the government is a player in the game, it usually acts as a leader (e.g., Yang et al., 2021; Zhang and Wang, 2017). The simultaneous-move Nash game is applicable when supply chain players have comparable bargaining power or cannot observe partners' actions and information. It is the least examined model among the three game models.

Signalling and screening game models based on the principal-agent theory are recognised as reasonable and effective methods to deal with information asymmetry problems (Cachon and Netessine, 2006; Voigt, 2011). There typically exist two players in signalling games; the player who owns the private information acts as a sender, and the uninformed player acts as a receiver (Connelly et al., 2011). The sender can signal its private information to the receiver directly through information sharing (e.g., Yu and Cao, 2019, 2020) or indirectly through observable practices. For example, Li et al. (2017) regard supplier CSR activities as signals of product quality. Chen et al. (2019) argue that buyers can employ the revelation strategy to signal suppliers' compliance capability to NGOs. Lee et al. (2018) and Wu et al. (2020) report that the price or CSR investments can signal the consumer regarding the firm's environmental quality or greenwashing behaviour. Shao et al. (2020) investigate both price signalling and direct disclosure mechanisms that a firm can use to publicise its responsible sourcing practices. They found that disclosure can increase the responsible sourcing degree under asymmetric information situations compared to signalling.

In screening games, the uninformed party usually offers a contract menu to induce the informed party to disclose its real private information. Screening contract menus could be a menu of price-quantity contracts (Kim and Netessine, 2013; Ma et al., 2018; Zhou et al., 2021), effort requirement contracts (Zhang et al., 2014; Zhang et al., 2021), and two-part contracts including a unit price or lump-sum payment and a factor such as effort, carbon reduction, revenue sharing ratio, and government subsidy (Hu et al., 2019; Liu and Song, 2017; Xia and Niu, 2020; Yang et al., 2018; Yang et al., 2021; Yuan et al., 2020; Zhang et al., 2018; Zhang et al., 2020; Zhu and Yu, 2019).

In the overwhelming majority of papers, the objective of the decision-makers is profit maximisation. It is not surprising as these papers model and analyse from rational firms' perspective, and firms are profit-driven. Ensuring profitability is fundamental for firms to undertake sustainable practices. Only some papers formulate other sustainability objective functions, such as maximizing social welfare or minimizing environmental impacts (Hu et al., 2019; Xia and Niu, 2020; Yang et al., 2021; Zhang and Wang, 2017; Zhao and Chen, 2019). The objective of supply chain members with different preferences is to achieve maximal utilities (Shu et al., 2019; Wan et al., 2019; Wei et al., 2021a; Xia and Niu, 2020; Zhou et al., 2021; Zhu and Yu, 2019).

There are four coordination mechanisms extensively discussed in the literature: contracts, information technology, information sharing, and joint decision-making (Arshinder et al., 2008). Coordination through contracts is predominantly used in both practice and literature. Except for the aforementioned screening contracts, two-part tariff contracts and sharing contracts are also widely applied in the synthesis sample. Other contracts such as bargaining and rebate are relatively scarce in the literature. Apart from common coordination contract design under information asymmetry, a handful of papers explore non-contracting coordination mechanisms, e.g., information sharing (Kalkanci and Plambeck, 2020b; Kraft et al., 2020; Nie et al., 2020; Yu and Cao, 2019, 2020), commitments and auditing (Kim and Netessine, 2013; Plambeck and Taylor, 2016), and governmental financial incentives (Wu and Kung, 2020; Wu et al., 2019; Zhao and Chen, 2019). For a thorough understanding of supply chain coordination, readers are referred to Cachon (2003) and Govindan et al. (2013) for contracts under complete information and Voigt (2011) for information sharing and contracting under asymmetric information.

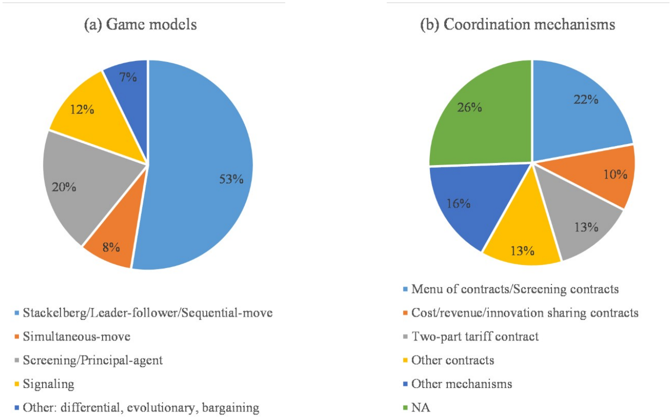

Figure 2.9 Distribution of games and coordination mechanisms

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. Only under certain conditions will the coordination contract take effect. However, deriving a contract that leads to coordination in a specific setting is often not an enormous contribution anymore. There are already so many papers like that, and it does not reflect how firms actually work with each other. Contracts in practice are almost always less precise, multi-dimensional, dynamic, and often not rigorously enforced as assumed in current literature. Instead, the question is how the sustainability context leads to different objective functions and results than the usual context. Models that reflect actual contracting and sustainable coordination practices more accurately would be worthwhile.

After reviewing the preceding observations, we identify potential areas for further investigation regarding the interaction in the supply chains as follows:

(1) Developing game-theoretic models in dynamic or cooperative settings: From the classification of GT techniques in Figure 2.2, we can see that so far, game theory has only been applied to a limited extent (Geisler, 2014). Primarily simple single-period Stackelberg games are presented. Complex game-theoretic models in dynamic or cooperative settings still need to be further exploited to provide more realistic views, e.g., differential games (De Giovanni, 2017), evolutionary games (Peng et al., 2019; Zhang et al., 2017), and bargaining games (Wu and Kung, 2020; Wu et al., 2019; Zhang and Wang, 2019). It is noted that, in reality, supply chain members' decisions do not always follow a specific sequence as the leader-follower relationship assumed in most papers (Chen et al., 2019). Further, the informed players' informational advantage does not give complete leverage to the leading informed players (Kim and Netessine, 2013). Therefore, it is more reasonable to consider that players engage in a simultaneous-move game when they cannot directly observe private information.

(2) Understanding how information revelation strategies work in practice: As discussed in the signalling and screening games, the uninformed players do not know the true information, but they may infer it via other observed actions in practice (Kalkanci and Plambeck, 2020b; Wu et al., 2020). For instance, they can use observable carbon abatement and relevant investment as a proxy for unobservable environmental innovation (Yalabik and Fairchild, 2011). However, they can hardly observe all the innovative actions. The informed players can take advantage of this partial observability

and engage in greenwashing, which may bring different results compared to games with perfectly observable actions. Getting into the details of how informed players reveal private information through observed actions contributes to a better understanding of SCT and coordination.

(3) Evaluating sustainability performance and impacts of information asymmetry from broader perspectives of the triple bottom line: In the reviewed literature, prices, sales, costs, and profits have been generally used as metrics to analyse economic performance and impacts of information asymmetry. The generic metrics for the environmental dimension include energy savings, carbon emission reductions, CSR efforts, product greenness, innovation, and collection of used products. In contrast with economic and environmental dimensions, social performance, primarily related to employee welfare and working conditions, is less studied as relevant information is challenging to access and quantify. Recent research proposes some approaches to address this issue (Qorri et al., 2018). Evaluation of social sustainability or integration of three sustainability dimensions would enable stakeholders to gain a broader perspective and a thorough understanding of sustainability-related decisions and concomitant performance effects. For the success of SSCM, it would be helpful to apply broader metrics to analyse sustainability performance and the impacts of information asymmetry.

(4) Exploring coordination failure and non-contracting coordination mechanisms: Given the impact of asymmetric information, coordination failure is common in both practice and literature because of complicated decision-making situations and imperfect execution. For example, in the models developed by Ma et al. (2017) and Raj et al. (2021), two-part tariff contracts, usually effective in coordinating SSCs under symmetric information, can still achieve coordination under asymmetric information. However, it cannot coordinate in Zhang et al. (2014) and Li et al. (2021)'s asymmetric information settings. Existing literature in GSCM/SSCM seldom investigates the issue of imperfect contract execution (Liu et al., 2019a) and the rationale and insights behind the coordination failure. Moreover, while information asymmetry makes coordination more challenging, the benefits are not as significant as they would be with symmetric information (Sane-Zerang et al., 2019; Voigt, 2011). With the development of information technology, non-contracting coordination mechanisms are worth exploring in future work considering asymmetric information.

2.4.4 Summary of the results and future research agenda

In this subsection, we revisit the research questions that guide our systematic literature review, focusing primarily on the research status of information asymmetry presented in the reviewed papers. We endeavour to discern the types of information asymmetry and the application of game theory-based modelling within this context. Additionally, we provide a succinct summary of the future research agenda.

(1) What sustainable practices have been incorporated and investigated by supply chain models based on game theory with information considerations?

This study marks the inaugural comprehensive review dedicated to a systematic exploration of prevailing sustainable practices within the domain. The findings indicate that government interventions, CLSCM, activities contingent upon carbon emissions, and forward GSCM for the production and distribution of green products are the most frequently investigated sustainable practices.

Not all core sustainable practices have been well established in the literature sample. Significantly, the insufficient presentation in literature but accelerating development in practice suggest further potential for incorporating sustainable practices such as SCT and e-commerce dual-channel supply chains into the study of SSCM with information considerations.

(2) Which members possess which types of asymmetric information in the sustainable supply chain?

Similar to the reviews on traditional supply chain coordination under information asymmetry by Shen et al. (2019) and Vosooghidizaji et al. (2020), unilateral demand and cost information asymmetries continue to receive the most attention in the SSCM literature with two subtle differences. Firstly, the demand and the cost are usually sensitive to the actions or outcomes of sustainable practices such as greenness, emission reduction investment, and CSR efforts. Asymmetric information types have been extended from common market demand and production cost information to those related to sustainable practices, e.g., e-tailer's demand forecast, quality testing cost, and recycling cost. Secondly, the position and manner of informed and uninformed members vary. For instance, not only downstream retailers but also upstream manufacturers can get access to the demand forecast due to the development of various information-sharing formats. The uninformed member can also infer some private information by looking at the public information revealed by the monitor of the third-party organisations or the participation in the cap-and-trade scheme. Consequently, bilateral or multilateral information asymmetry stimulates significant interest and calls for further research.

(3) What are the impacts of information asymmetry on sustainability performance?

In contrast to the findings by Shen et al. (2019), information asymmetry may not consistently have detrimental impacts on sustainability performance within the SSCM context. With the implementation of sustainable practices, information asymmetry may even potentially incentivise some firms to go genuinely green and enhance SSC efficiency under certain conditions. Moreover, the transformative influence of emerging technologies, such as blockchain and AI, on reshaping sustainability within supply chains is increasingly apparent. Further research incorporating the effects of these advanced technologies on information sharing and coordination in SSCs holds significant potential for advancing the field. Such endeavours can substantially contribute to the development of innovative decision-making models with information considerations. This can provide fresh perspectives and profound insights into the intricate relationship between information asymmetry and sustainability performance.

(4) What types of games have been applied to characterise and treat information asymmetry in this field?

Similar to the review on GT models in forward GSCM without information consideration by Agi et al. (2020), Stackelberg game models are still the most often applied approach to describe the power structure in the SSCM with asymmetric information literature. With information consideration, signalling and screening game models are adopted frequently to deal with information asymmetry problems. They are advanced in SSCM by incorporating some factors affected by sustainable practices. To better understand how information asymmetry impacts SSC decision-making and performance, complex game-theoretic models in dynamic or cooperative settings need to be further exploited to provide more insights.

It is noted that the future research opportunities we suggest mainly lie in modelling more closely to reality to address practical problems. There is a trend in recent research that considers model extensions. However, the studies are limited, primarily because of the difficulty in solving resulting complex models. Researchers often sacrifice the attempt to address real-world problems for tractable modelling and analysis. What we want to point out is that researchers do not always need to derive optimal closed-form solutions. Other solution methodologies, such as simulation or numerical analysis based on real data, are also reasonable and acceptable and deserve exploration. On top of that, researchers could try to strike a balance between the analytical and nonanalytic solutions, optimal and sub-optimal solutions, and focus more on answering questions rooted in practice and bridging the gap between practice and theoretical work instead of purely filling the gap in the literature.

Additionally, this research provides valuable insights for practitioners by expanding their comprehension of how information asymmetry affects decision-making in sustainable supply chains. By understanding the potential ramifications like the exacerbation of information asymmetry through unclear product labelling or recognising that greenwashing may not universally undermine sustainability performance, practitioners can formulate production and marketing strategies to manage information asymmetry effectively. The analytical models and coordination mechanisms developed in modelling literature can also offer practitioners insights into how to tackle such issues in real-world scenarios. Finally, our study emphasises the significance of information sharing and coordination in promoting sustainability. Nevertheless, extensive analytical modelling research lacks applicable cases and data support from real-world practices. Bridging the gap between theoretical study and practical application calls for a concerted effort from practitioners to collaborate with academic researchers. Through such collaborations, practitioners can contribute to the integration of theoretical findings and practical knowledge, leading to more effective sustainability solutions.

2.5 Conclusion

Sustainable supply chain coordination taking information asymmetry into account is an important issue of interest in both practice and academic literature. We have conducted a systematic literature review of game-theoretic models that address this topic. An analysis framework has been presented to structure the literature. The review demonstrates that researchers are extending traditional supply chain models to embrace the emerging challenges and opportunities led by sustainable practices under asymmetric information. However, the research is still at a preliminary stage and much theoretical work has not been supported by real practices. Our findings highlight the importance of information sharing and coordination in driving sustainability and formulating game-theoretic models. As the primary focus of the research was game-theoretic approaches for sustainable supply chains with asymmetric information, explicit methods for constructing models and deriving equilibria have not been discussed. The review could be extended for a further understanding of this stream of research.

Based on observations from the extant literature and current practices, we put forward various promising opportunities for future research in this field. Concerning supply chain structures, limited sustainable practices are studied in common dyadic one-to-one structures with one product in one period by tractable linear demand curves. We propose (1) the exploration of other sustainable practices, such as supply chain transparency and e-commerce dual-channel supply chains, (2) the development of new demand models from a consumer perspective, and (3) the extension of models to complex supply chain structures with competition and time dynamics. Concerning information structures, demand and cost information asymmetries are among the most commonly investigated types of asymmetric information via binary opposite values. Comparative analyses reveal mixed impacts of information asymmetry on supply chain performance, depending on diverse factors. The lack of models with bilateral or multilateral sustainability-related information asymmetry is a notable research gap. Furthermore, the exploration of other characteristics of asymmetric information and the application of new data-related technologies also provide new directions for research. Concerning interactions, a large number of models have been developed based on Stackelberg, signalling, and screening non-cooperative games in pursuit of profit maximisation. Supply chain coordination under asymmetric information settings is dominated by screening contracts, two-part tariff contracts, and sharing contracts. We find a lack of comprehensive evaluations of three-dimensional sustainability performance and non-contracting coordination mechanisms. Researchers are encouraged to understand how contracting and information revelation work in practice and extend game-theoretic models for dynamic or cooperative settings. In conclusion, these results can inspire practitioners and researchers to develop new models and technologies to manage sustainable supply chains under asymmetric information.

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Chapter 3 Decision Analysis and Coordination in Green Supply Chains with Stochastic Demand[1]

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 chapter 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

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3.1 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; Chen, 2001; Day and 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 and 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 chapter, 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; Liu et al., 2012; Qian, 2011). 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 and 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 chapter, 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 chapter 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 chapter is structured as follows. Section 3.2 reviews related literature. Section 3.3 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 3.4. The sequential solution procedure is illustrated by numerical experiments in Section 3.5. 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 3.6. Some proofs of the analytical results are deferred to the appendix.

3.2 Literature review

This chapter 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 3.1 shows a comparison with the papers that are most relevant to this study.

Table 3.1 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
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
Liu and Chen (2019)	DIGP	√	√		√	√	
Wang et al. (2021)	DIGP	√	√	√		√	reward contract with/without target green degree
This chapter	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.

3.2.1 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 and Dada, 1999; 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 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, 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. 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 chapter, 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.

3.2.2 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 (Chen, 2001; Zhu and 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 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 Chen et al., 2017; Dong et al., 2016; Ghosh and Shah, 2012, 2015; Ghosh et al., 2020; Hong and Guo, 2019; Jiang and Chen, 2016; Murali et al., 2018; Swami and Shah, 2013; Yalabik and Fairchild, 2011; 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; Li et al., 2020; Liu et al., 2012; Zhang and Liu, 2013; Zhang et al., 2014). Different cost functions can produce different decision-making results, including the level of greenness improvement (Chambers et al., 2006; Krishnan and Zhu, 2006; Qian, 2011). Dey et al. (2019); Gao et al. (2020); Krishnan and Zhu (2006); Li et al. (2020); 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), Chen (2001), and Zhang et al. (2017) include both fixed and unit-variable costs in their deterministic models. Therefore, this chapter 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.

3.2.3 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 and 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 and Bisi, 2020; Bhaskaran and Krishnan, 2009; Ghosh and Shah, 2015; Heydaryan and Taleizadeh, 2017). In this chapter, we develop a bargaining wholesale price contract to coordinate the supply chain of MDIGPs with stochastic demand.

3.3 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 3.1 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 and Guo, 2019; Li et al., 2020). The manufacturer is in the position of making the contract offer and coordinating the supply chain.

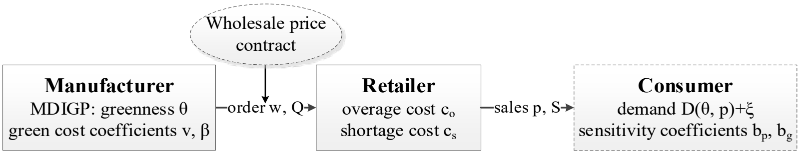

Figure 3.1 The proposed supply chain

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[2] 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 3.2 provides a summary of relevant notations. For brevity, we sometimes only use the function name without including variables in later sections.

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[2] 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 3.2 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

3.3.1 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 and 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; Zhu and 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 and 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 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 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 chapter 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 and Jacquemin, 1988; Ghosh and 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 and Singh, 2018 for details), i.e., $v=0$ always holds. In the current chapter, 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; 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 $a - b_1 c + A > 0$.

3.3.2 Expected profit functions

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

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

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., $\Pi_{SC}^{gd}(p,\theta) = \left(p - (c + v\theta)\right)D(p,\theta) - \beta\theta^2$, and the expected profit loss caused by the presence of uncertainty, i.e., $Z_{SC}^{gs}(p,\theta,z) = \left(p - (c + v\theta) + c_s\right)z - (p + c_o + c_s)I(z) - c_s\mu$.

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:

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

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

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

3.4 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.

3.4.1 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 and 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 3.1 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 $\theta_m^{gd}=\frac{(b_g-vb_p)(a-b_pc)}{8\beta b_p-(b_g-vb_p)^2}$, $w_m^{gd}=\frac{\left(4\beta+v(b_g-vb_p)\right)(a-b_pc)}{8\beta b_p-(b_g-vb_p)^2}+c$, and $p_m^{gd}=\frac{\left(6\beta+v(b_g-vb_p)\right)(a-b_pc)}{8\beta b_p-(b_g-vb_p)^2}+c$, respectively.

Proof. See Appendix A. □

Correspondingly, the demand and profits at equilibrium greenness improvement and prices are $D_m^{gd}=\frac{2\beta b_p(a-b_pc)}{8\beta b_p-(b_g-vb_p)^2}$, $\Pi_R^{gd}=\frac{4\beta^2 b_p(a-b_pc)^2}{\left(8\beta b_p-(b_g-vb_p)^2\right)^2}$, $\Pi_M^{gd}=\frac{\beta(a-b_pc)^2}{8\beta b_p-(b_g-vb_p)^2}$, and $\Pi_{SCm}^{gd}=\frac{\beta\left(12\beta b_p-(b_g-vb_p)^2\right)(a-b_pc)^2}{\left(8\beta b_p-(b_g-vb_p)^2\right)^2}$, 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 3.2 The equilibrium greenness improvement and prices in the decentralised supply chain with stochastic demand are, respectively:

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

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

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 3.1 and Corollary 3.2 can be directly obtained from Lemma 3.2.

Corollary 3.1 The higher the retailer's service level is, the greener the product and the higher the manufacturer's profit will be.

Corollary 3.2 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 $\frac{z}{I(z)} \ge -1$ 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., $\theta_m^{gs} \ge \theta_m^{gd}$, $w_m^{gs} \ge w_m^{gd}$, and $\Pi_M^{gs} \ge \Pi_M^{gd}$; if $\frac{z}{I(z)} < -1$, the equilibrium outcomes for the manufacturer are smaller than the deterministic solutions.

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

Proof. See Appendix B. □

Noticeably, we have $\frac{2\beta b_p - b_g(b_g - vb_p)}{\left(6\beta + v(b_g - vb_p)\right)b_p} > -1$ according to the condition $\beta > \frac{(b_g - vb_p)^2}{4b_p}$. Therefore, by Corollary 3.2, we can see that when $-1 \le \frac{z}{I(z)} < \frac{2\beta b_p - b_g(b_g - vb_p)}{\left(6\beta + v(b_g - vb_p)\right)b_p}$, the inequalities $\theta_m^{gs} \ge \theta_m^{gd}$ 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 $\max\limits_{z} \Pi_R^{gs}(z \mid p_m^{gs}, w_m^{gs}, \theta_m^{gs})$. Proposition 3.1 provides the optimal solution for z.

Proposition 3.1 The unique optimal service level z_m^{gs} ($A \le z_m^{gs} < B$) that maximises the expected profit of the retailer in a decentralised supply chain with stochastic demand is implicitly determined by $F(z) = 1 - \dfrac{w_m^{gs}(z) + c_o + 2V(z)}{p_m^{gs}(z) + c_s + c_o + V(z)}$, where

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

Proof. See Appendix C. □

3.4.2 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: $-\dfrac{b_g}{b_p} < v < \dfrac{b_g}{b_p}$ and $\beta > \dfrac{(b_g - vb_p)^2}{4b_p}$.

Lemma 3.3 The profit-optimal greenness improvement and retail price in the centralised supply chain with deterministic demand are $\theta_c^{gd} = \dfrac{(b_g - vb_p)(a - b_p c)}{4\beta b_p - (b_g - vb_p)^2}$ and $p_c^{gd} = \dfrac{\left(2\beta + v(b_g - vb_p)\right)(a - b_p c)}{4\beta b_p - (b_g - vb_p)^2} + c$, respectively.

The corresponding deterministic demand and profit at the equilibrium greenness improvement and retail price are $D_c^{gd} = \dfrac{2\beta b_p(a - b_p c)}{4\beta b_p - (b_g - vb_p)^2}$ and $\Pi_{SCc}^{gd} = \dfrac{\beta(a - b_p c)^2}{4\beta b_p - (b_g - vb_p)^2}$, 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 3.4 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 $p_c^{gs}(z) = p_c^{gd} + \frac{\left(2\beta + v(b_g - vb_p)\right)z - 2(\beta + vb_g)I(z)}{4\beta b_p - (b_g - vb_p)^2}$, respectively.

According to the equations in Lemma 3.4, we can obtain Corollary 3.3.

Corollary 3.3 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 3.2 and Corollary 3.3, we formulate:

Remark 3.1 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[3], 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[4]. 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

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

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

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 and 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 $\Pi_{SCc}^{gs}(z \mid p_c^{gs}, \theta_c^{gs})$. Then the problem comes to $\max_z \Pi_{SCc}^{gs}(z \mid p_c^{gs}, \theta_c^{gs})$. If we find the optimal z , the optimal solutions for θ and p are also obtained. Proposition 3.2 provides the optimal solution for z .

Proposition 3.2 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} ($A \le z_c^{gs} < B$) 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. □

3.4.3 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), Li and Atkins (2002), and 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 3.2 and Corollary 3.3. 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 3.4.

Corollary 3.4 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 $v \ge 0$. 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 3.5 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 $-\frac{b_g}{b_p} < v < \frac{-(2\beta b_p - b_g^2) + 2\sqrt{\beta b_p(\beta b_p - 2b_g^2)}}{b_p b_g} < 0$. 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 3.3 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 3.3 Manufacturer's optimal greenness and profit for DIGPs and MDIGPs

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

3.4.4 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 3.6 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 $w_m^{gs}(z_m^{gs}) = c + v\theta_m^{gs}(z_m^{gs}) - \left(1 + F(z_m^{gs})\right)V(z_m^{gs})$, 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 and Sošić, 2008; Nash, 1950), which is denoted by the subscript 'b':

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

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 and 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 3.3 shows the wholesale price through bargaining between firms. For notational convenience, let $J > 0$, $K > 0$, and $L > 0$ denote $a - b_p c + z + I(z)$, $8\beta b_p - (b_g - v b_p)^2$ and $b_g - v b_p$, respectively.

Proposition 3.3 The profit is divided between the two players by determining the wholesale price cooperatively as

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

Proof. See Appendix H. □

From Proposition 3.3, 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 $\Pi_{Mb}^{gs} \ge \Pi_M^{gs}$ and $\Pi_{Rb}^{gs} \ge \Pi_R^{gs}$ 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 $\frac{\Pi_M^{gs}}{\Pi_{SCc}^{gs}} \le \tau \le 1 - \frac{\Pi_R^{gs}}{\Pi_{SCc}^{gs}}$, 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 A1.

3.5 Numerical analysis

3.5.1 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.

3.5.2 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:

(1) Since the Chinese government[5] 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 $a = 2\times10^6$.

(2) Several empirical studies have estimated demand, cost, and related parameters for the Chinese automobile market (e.g., Deng and 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[6], 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 $A = -2.5\times10^5$ and $B = 2.5\times10^5$.

(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 $b_g = 2\times10^5$ according

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[5] 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

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

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 3.4 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.

Table 3.4 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

3.5.3 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 Liu and Chen, 2019; Tsao and 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 $[A,B]=[-2.5\times10^5, 2.5\times10^5]$ discussed before can be used for the uniform and normal distributions. We truncate the range to $[A,B]=[0,2.5\times10^5]$ 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.

Therefore, taking into account the setting of the lower bound $A=-2.5\times10^5$ or 0 under uniform, normal, and exponential distributions, we analyse five stochastic cases, namely, (1) $\xi\sim U(-2.5\times10^5, 2.5\times10^5)$, (2) $\xi\sim N(0, 8.33\times10^4)$ bounded in $[A,B]=[-2.5\times10^5, 2.5\times10^5]$, (3) $\xi\sim Exp(1.25\times10^5)$ bounded in $[A,B]=[0,2.5\times10^5]$, (4) truncated uniform $\xi\sim U(0,2.5\times10^5)$, and (5) truncated normal $\xi\sim N(1.25\times10^5, 4.17\times10^4)$ bounded in $[A,B]=[0,2.5\times10^5]$. 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 3.5.

Remark 3.2 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.

Table 3.5 Optimal solutions under different demand settings

Demand	Deterministic		Stochastic case 1 $U(-2.5\times10^5, 2.5\times10^5)$		Stochastic case 2 $N(0, 8.33\times10^4)$		Stochastic case 3 $Exp(1.25\times10^5)$		Stochastic case 4 $U(0, 2.5\times10^5)$		Stochastic case 5 $N(1.25\times10^5, 4.17\times10^4)$	
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 (×10⁹)		6.854		4.012		4.811		6.929		6.977		7.502
M (×10⁹)		13.09		8.002		10.04		13.36		13.59		14.88
SC (×10¹⁰)	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_θ (%)			-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 3.2and Corollary 3.3, 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 $Q^{gd} = D^{gd}$.

3.5.4 Comparison analysis

Impact of demand uncertainty

Figure 3.2 and Figure 3.3 demonstrate how z affects stochastic profits, comparing with deterministic profits. As the graphs and Table 3.5 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 3.3(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 3.2(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

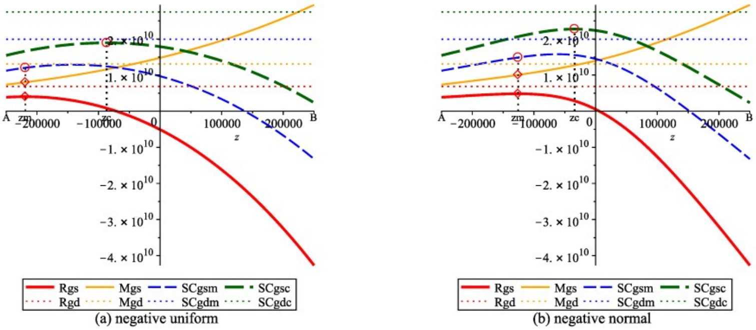
profit. The maximum reduction reaches 9% when the demand shock ξ is uniformly distributed with a negative lower bound.

(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).

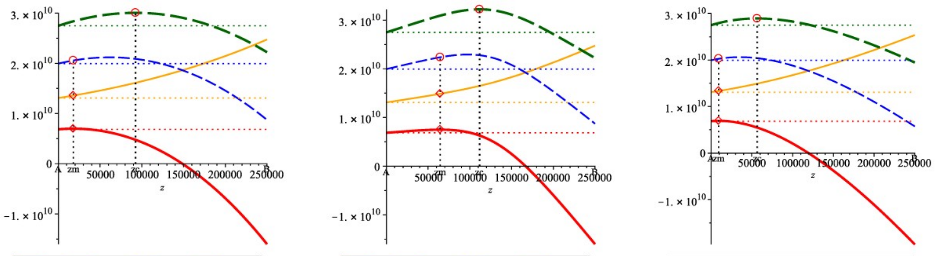
It could be important in practical cases to study the characteristics above with an empirically observed demand distribution, as the assumption concerning shape and parameters is relevant to the outcomes. If one assumes a uniform distribution, while the actual demand turns out to follow a normal distribution, 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 and 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 3.2 Profits under negative distributions



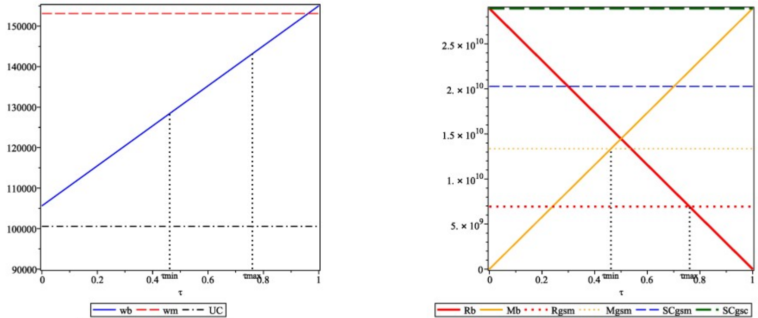
(a) nonnegative uniform (b) nonnegative normal (c) exponential

Figure 3.3 Profits under nonnegative distributions

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.

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 $\xi \sim Exp(1.25\times10^5)$ as a representative case. Figure 3.4 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 $[\tau_{\min},\tau_{\max}]=[0.46,0.76]$. In contrast to the non-coordinated case, 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.



(a) Wholesale price comparison (b) Profit comparison

Figure 3.4 Wholesale price and profits comparison of decentralised and coordinated cases

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.

3.5.5 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 $\xi \sim Exp(1.25\times10^5)$.

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 3.5 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 3.5. 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.

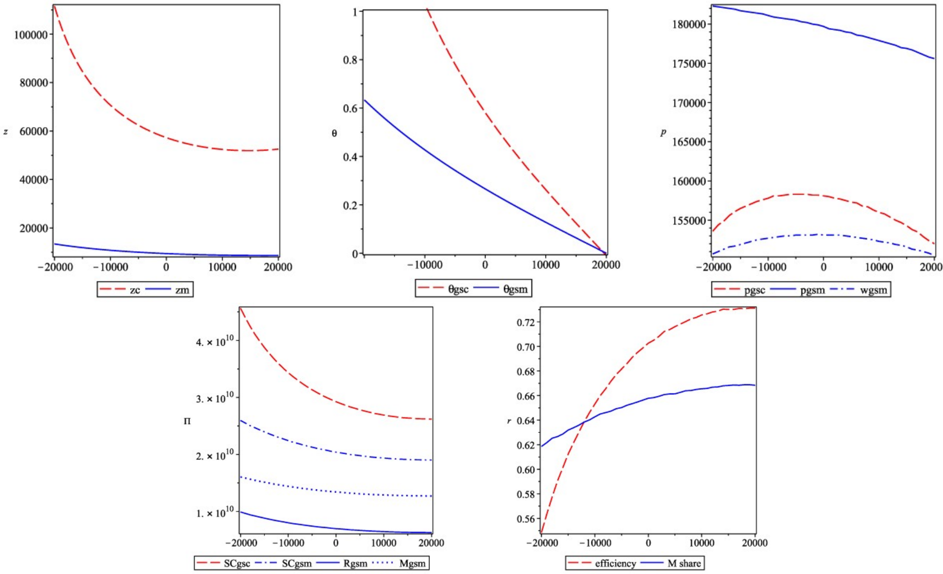


Figure 3.5 Impact of v on optimal service level, greenness, prices, profits, and resulting ratios

Impact of demand sensitivity to greenness

Based on assumptions in Section 3 and the constraint that $0 \le \theta \le 1$, we vary b_g between 10^4 and 3×10^5, while keeping other parameters unchanged. Figure 3.6 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.

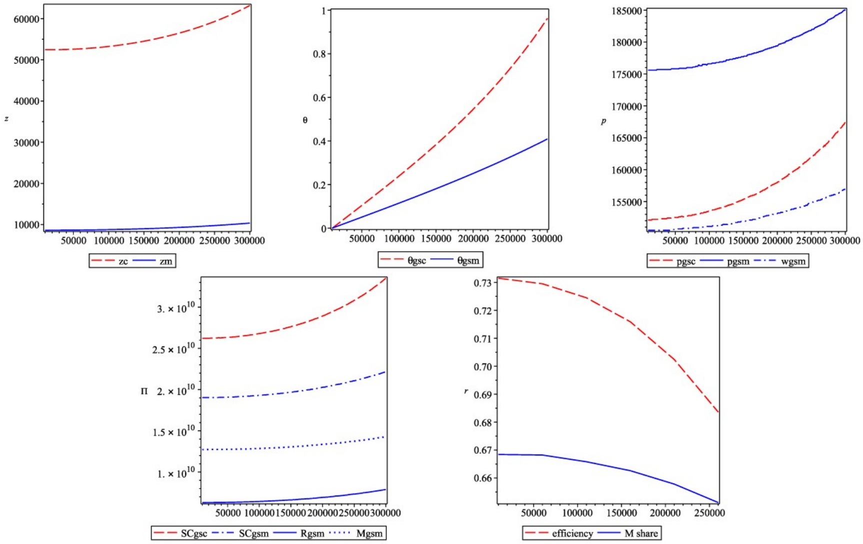


Figure 3.6 Impact of b_g on optimal service level, greenness, prices, profits, and resulting ratios

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 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 chapter) 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.

3.6 Conclusions

Extending the traditional pricing-setting newsvendor model, we have shown how greenness can be integrated into decision-making with regard to pricing, greening, and ordering. In particular, we have examined how demand stochasticity affects these decisions relative to the deterministic case where stochasticity is ignored. We have studied 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 has been not only related to the fixed investment cost but also to the unit-variable production cost. Using a sequential game-theoretic framework, we have provided analytical expressions of the profit-optimal solutions for this seemingly complex stochastic problem. We have proposed a sequential solution procedure and have illustrated it through numerical experiments. We have also used 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 has been 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.

Based on 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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Chapter 4 Decision-Making and Coordination under Asymmetric Information: Pathways to Green Innovation in Supply Chains

Abstract This chapter investigates a green supply chain, comprising a manufacturer engaged in two types of green innovation: green product innovation and process innovation, the latter of which can result in cost reduction benefits for both the manufacturer and the retailer. Considering innovation unobservability and information asymmetry, we employ sequential game models to explore the decision-making and coordination issues in the green supply chain. Our findings highlight how the transparency level and spillover intensity of the green process innovation critically influence the manufacturer's investment choices and the supply chain performance. Specifically, we analyse the conditions prompting manufacturers to misrepresent green process innovation investments and the subsequent effects on supply chain dynamics. It is demonstrated that greenwashing adversely affects genuine green product innovation, pricing strategies, and the profitability of the supply chain. A two-part contract, supported by advanced technologies, is proposed to mitigate greenwashing and to facilitate coordination.

Keywords: green supply chain management; green innovation; information asymmetry; greenwashing; supply chain coordination; game theory

4.1 Introduction

In the evolving landscape of global business, the push towards sustainability has become a paramount concern for companies across various industries. As consumers become increasingly aware of environmental issues, their demand for green products has surged, compelling firms to integrate green innovation practices into their supply chains. Studies have recognised that two types of green innovation practices—product and process innovations—play crucial roles in green supply chain management (Silva et al., 2019; Wong et al., 2020). Green product innovation enhances product greenness, directly appealing to eco-conscious consumers and expanding market demand. On the other hand, green process innovation focuses on reducing production costs through adjustments in production processes, albeit with its implementation and effects less visible to external stakeholders (Ni et al., 2021; Qudrat-Ullah, 2018; Takalo and Tooranloo, 2021).

This contrast between visibility and obscurity lays the groundwork for information asymmetry, a fertile ground for firm-level greenwashing, where firms untruthfully claim their green practices without substantive innovation investments (Delmas and Burbano, 2011; Netto et al., 2020). Notable instances include Volkswagen's carbon emissions scandal[1] and H&M's manipulation of environmental scores[2], showcasing the discrepancy between proclaimed and actual green practices (Ye et al., 2022). Various examples underscore the complexity of greenwashing and its implications for green supply chain management. The deceptive nature of greenwashing not only affects the firm involved but also has broader implications for the supply chain's environmental and economic performance, including greening and pricing strategies, demand, and overall profitability. As such, understanding the conditions that lead firms to engage in greenwashing and the subsequent effects on supply chain dynamics is crucial for driving genuine sustainability.

Therefore, this chapter explores the intricate dynamics of firm-level greenwashing within the context of green supply chain management through the lens of asymmetric information and unobservability in green process innovations. Specifically, we consider a two-echelon green supply chain consisting of a manufacturer who implements green innovation practices and may engage in process innovation greenwashing due to its limited transparency and a retailer who receives a cost-reduction benefit due to the spillover effect of the manufacturer's green process innovation. We focus on innovation investment and pricing decisions and coordination mechanisms, aiming to address the following research questions:

(1) Under what conditions might the manufacturer choose greenwashing?

(2) How does unobservability in green process innovation impact the manufacturer's investment decisions and the green supply chain's performance?

(3) How can the green supply chain achieve coordination?

To answer these questions, we develop game-theoretic models and investigate six scenarios: (1) absence of green process innovation investment by the manufacturer with complete information; (2) investment in green process innovation by the manufacturer with complete information; (3) non-engagement in greenwashing by the manufacturer with limited information transparency; (4) engagement in greenwashing by the manufacturer with limited information transparency; (5) a scenario involving an integrated supply chain; and (6) a case of supply chain coordination. Through analytical, numerical, and comparative analyses, we seek

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[1] https://en.wikipedia.org/wiki/Volkswagen_emissions_scandal

[2] https://qz.com/2180075/hm-showed-bogus-environmental-higg-index-scores-for-its-clothing

to offer insights into how supply chain firms can make informed decisions to mitigate greenwashing and enhance environmental and economic performance.

Our research indicates that adopting green process innovation practices yields beneficial environmental and economic impacts throughout the supply chain. Nevertheless, limited transparency concerning green process innovations significantly impacts profit-optimal decision-making and alters relationships within the supply chain. In this context, the transparency level and the extent of spillover from process innovations play crucial roles. The decision of the manufacturer to engage in greenwashing hinges on the probability and potential losses of being exposed for greenwashing. Such engagement detrimentally affects the retailer's profitability, reducing retail prices which, while possibly advantageous for consumers, results in a compromise on product greenness. To enhance the transparency of green process innovation practices, we advocate for the integration of advanced technologies into the coordination process. Technologies such as AI and blockchain significantly improve communication, decision-making, and collaboration within the supply chain, playing a crucial role in aligning incentives and verifying the genuineness of green practices, thereby effectively mitigating greenwashing (Bai and Sarkis, 2020; Liu and De Giovanni, 2019; Pournader et al., 2021). Leveraging these technologies, we develop a two-part contract that can achieve full coordination, allowing both parties to remain profitable while delivering a greener product at a more affordable price to consumers.

The rest of this chapter is structured as follows: the next section briefly reviews literature closely related to this research and introduces our contributions. Section 4.3 presents the model setup, followed by analytical and numerical analyses in Section 4.4. The coordination scheme is proposed in Section 4.5. Section 4.6 concludes the chapter by summarising the findings and insights. All the proofs are presented in the Appendix.

4.2 Literature review

Green supply chain management (GSCM) is a broad strategy for environmental sustainability, garnering significant interest from both industry practitioners and academic researchers. Literature reviews suggest that implementing GSCM faces challenges related to information transparency, particularly in the incorporation of green innovations (Chauhan and Singh, 2018; Schäfer, 2022; Vosooghidizaji et al., 2020). A considerable volume of research has examined decision-making and coordination within green supply chains under asymmetric information, focusing on variables such as demand (Jha et al., 2017; Li et al., 2021; Zhou et al., 2021), cost (Kim and Netessine, 2013; Liu et al., 2019; Raj et al., 2021; Zhang et al., 2021), and product attributes (Lee et al., 2018; Ma et al., 2018; Zhang and Wang, 2017). Despite this, the asymmetric green information on green innovation practices and the resulting tendency towards greenwashing within GSCM, remains relatively underexplored (Inês et al., 2023; Wong et al., 2020). Addressing this gap is essential for advancing environmental sustainability.

Some related works study greenwashing based on the game theory model. For example, Wu et al. (2020) employ signalling game models to explore the impacts of corporate social responsibility (CSR) activities and their information transparency on a firm's greenwashing strategies and social welfare. They find that sufficiently high transparency eliminates greenwashing. Fatehi et al. (2023) extend this discussion by examining the competitive dynamics of greenwashing under different market structures, revealing that the strategic interaction between firms significantly influences their propensity to engage in greenwashing. Their findings suggest that greenwashing prevents consumers from making informed purchase decisions but raises overall CSR spending. Chen and Duan (2023) challenge the common belief that greater transparency invariably leads to enhanced supply chain sustainability by introducing NGO audits in greenwashing. Dong et al. (2023) examine the impact of logistics outsourcing decisions on green innovation, considering the roles of greenwashing and blockchain technology. They show that blockchain technology can serve as a deterrent to greenwashing by enhancing supply chain transparency, thus fostering a more genuine commitment to green innovation. These studies underscore the importance of strategic decision-making and information transparency in shaping firms' approaches to green innovation within supply chains. However, these models usually assume that green innovations do not affect the firm's production costs and focus on strategic decision analysis. The joint effects of process innovations and greenwashing driven by information asymmetry on decisions, sustainability performance, and coordination have been underexplored in GSCM.

Our research aligns with prior studies in that we also model the manufacturer's greenwashing behaviour with limited transparency in green practices. However, we extend the model by simultaneously considering the presence of product and process innovations. Unlike the majority of existing GSCM literature, which primarily focuses on the demand expansion effect attributed to product innovation (e.g. Ghosh et al., 2018; Yang et al., 2022; Yenipazarli, 2017), our study also explores the spillover effect from investing in process innovation, a relatively nascent area of research (Ghosh et al., 2020; Yan and Yang, 2018). Although advanced technologies such as AI and blockchain have proven effective in mitigating firm-level greenwashing (Jayaram, 2023; Liu et al., 2020), the challenge lies in their integration into green supply chains to foster coordination. Our contribution to this field involves proposing a coordination mechanism that utilises a two-part incentive contract supported by these technologies. This research enriches the existing literature by offering a deeper understanding of the dynamics of decisions and coordination within green supply chains affected by greenwashing, and by highlighting the role of advanced technologies in enhancing supply chain transparency and trustworthiness.

4.3 Model setup

We study a two-echelon green supply chain consisting of a manufacturer (denoted as M, female pronouns) and a retailer (denoted as R, male pronouns). Both firms are risk-neutral; they make rational decisions to maximise their expected profits. The manufacturer sells a green product with greenness level θ at a unit wholesale price of w to the retailer who resells them to consumers at retail price p. According to previous studies (e.g. Vosooghidizaji et al., 2022; Zhu et al., 2018; Zhu and He, 2017), the demand for green products decreases with the retail price and increases with the product greenness. It is modelled as $D = a - b_p p + b_g \theta$ (a, b_p, $b_g > 0$), where a denotes the potential market size, b_p and b_g represent market sensitivity coefficients to the product price and greenness, respectively.

The focal manufacturer is the driver of the green supply chain. She can invest in two types of green practices—green product innovation, which is directly associated with product greenness improvement, and green process innovation, which is dedicated to production cost reduction (Wong et al., 2020). Accordingly, the investment costs for exerting greenness θ and cost reduction effort g are $\beta\theta^2$ and γg^2, respectively. The parameters β and γ are respectively the cost coefficient of green product and process innovation, and they should be costly enough. The quadratic cost function reflecting the diminishing returns on greening investments is widely applied in the literature (e.g. Ghosh et al., 2020; Li and Wan, 2017; Yang et al., 2022). With the cost reduction effort, the innate marginal production cost c can be reduced to $c-g$. To avoid trivial cases that entail negative outcomes, the relationship $p>w>c>c-g>0$ should be satisfied in the model analysis.

Moreover, we consider the presence of a direct positive investment externality. That is, the manufacturer's greening process investment not only contributes to her production cost reduction but also generates a direct benefit for the retailer (Ghosh et al., 2020). Following Bolton and Dewatripont (2005); Che and Hausch (1999); Yan and Yang (2018), we assume that the positive investment externality the retailer obtains from the manufacturer's cost-reduction investment is xg , where $x\in[0,1]$ represents the spillover intensity.

The green product innovation practice is mostly observable, as it involves product greenness—an integral product attribute that the manufacturer, along with her supply chain partners and other relevant organisations such as green labelling authorities, endeavours to convey to consumers to stimulate demand expansion. In contrast, the green process innovation practice is often unobservable, given its association with confidential production cost-related information managed internally inside the firm (Li, 2020; Ni et al., 2021). Referring to the existing literature such as Dong et al. (2023); Fatehi et al. (2023); Wu et al. (2020), we introduce a transparency parameter $\phi\in(0,1)$ to indicate the extent to which the manufacturer's green innovation investments are observable to other supply chain players. When considering limited transparency, the demand function is adapted to $D=a-b_p p+b_g(1-\phi)\theta$ and the positive investment spillovers generated from the manufacturer's green process innovation is adapted to $x\phi g$.

The limited transparency allows the opportunistic manufacturer to mislead outsiders regarding the greening practices of the firm to foster short-term profitability, which we refer to as firm-level greenwashing (Delmas and Burbano, 2011; Dong et al., 2023; Inês et al., 2023). The manufacturer without substantive investments in the unobservable green process innovation, pretends to be green by taking advantage of the investment unobservability to report the green level in unobservable process innovation untruthfully, whenever such reporting is profitable. Information asymmetry emerges between supply chain members. In this setting, the parameter x can be interpreted more broadly as the probability that the retailer believes the manufacturer practices unobservable green process innovation. Then, the retailer can still obtain the spillovers from the manufacturer's green practices. However, the manufacturer may suffer from a loss with a probability of $k\in[0,1]$ that the greenwashing behaviour is exposed to the public. The expected loss such as corporate reputation and trust damage and penalties imposed by relevant authorities for greenwashing exposure is kF , where F denotes the aggregate monetary loss. Considering innovation unobservability and its effects, the generalised profit functions of the supply chain members can be expressed as:

$$\Pi_M^{nwu}=\big(w-(c-\phi g)\big)\big(a-b_p p+b_g(1-\phi)\theta\big)-(1-\phi)\beta\theta^2-\phi\gamma g^2 \tag{5}$$

$$\Pi_M^{wu}=(1-k)\big(w-(c-\phi g)\big)\big(a-b_p p+b_g(1-\phi)\theta\big)-(1-\phi)\beta\theta^2-kF \tag{6}$$

$$\Pi_R=(p-w+x\phi g)\big(a-b_p p+b_g(1-\phi)\theta\big) \tag{7}$$

The superscripts "nwu" and "wu" distinguish between scenarios without and with greenwashing behaviour, respectively, in situations characterised by the unobservability of the manufacturer's green innovation practices. The sequence of events is organised as follows. The leading manufacturer first chooses the greening investments in unobservable process innovation g and observable product innovation θ as strategic decisions. After that, the manufacturer announces the innovation levels according to her greenwashing choice and determines the wholesale price w. The retailer then sets the retail price based on the manufacturer's innovation reporting. Finally, consumers purchase the green product and demand and profits are realised. The major notations are summarised in Table 4.1 for convenience.

Table 4.1 Summary of notations

Notation	**Definition**
a	Potential market demand
b_p	Demand sensitivity coefficient to the retail price
b_g	Demand sensitivity coefficient to product greenness
c	Initial unit production cost
β	Investment cost coefficient for green product innovation
γ	Investment cost coefficient for green process innovation
ϕ	Transparency level of the manufacturer's green practices
x	Spillover that the retailer receives from manufacturer's cost-reduction investments
k	Probability that the greenwashing is publicly exposed
F	Monetary loss caused by greenwashing exposure
T	Decision variable. Technology adoption cost to enforce the coordination mechanism
t	Decision variable. Contract parameter: fixed transfer payment
τ_1	Decision variable. Contract parameter: process innovation-dependent side payment coefficient
τ_2	Decision variable. Contract parameter: product innovation-dependent side payment coefficient
y	Decision variable. Process innovation transparency improvement level through advanced technology applications
g	Decision variable. Green process innovation level, i.e. cost reduction effort
θ	Decision variable. Green product innovation level
w	Decision variable. Wholesale price
p	Decision variable. Retail price
Π_i^j	Profit of i in the scenario of j
	Subscripts i: $i \in \{M, R, SC\}$, manufacturer, retailer, supply chain
	Superscripts j: $j \in \{ngo, go, nwu, wu, iu, cu\}$, case without green process innovation under complete information, case with green process innovation under complete information, case without greenwashing behaviour under unobservable green innovation, case with greenwashing behaviour under unobservable green innovation, integrated case under unobservable green innovation, coordination case under unobservable green innovation

4.4 Model analysis and comparison

Now that the model set-up has been provided, we solve the model through the backward induction approach and use software Maple 2022.2 to conduct the analyses in this section.

Throughout the model analysis, constraints on green investment cost coefficients that $\beta > \frac{b_g^2}{2b_p}$ and $\gamma > \frac{2\beta b_p(a + b_p c)}{(8\beta b_p - b_g^2)c}$ are applied to secure optimality conditions and to avoid negative performance. For notational convenience, we will simplify expressions by denoting $D_0 = a - b_p c > 0$, $B_0 = 8\beta b_p - b_g^2 > 0$, $B_1 = 8\beta b_p - (1-\phi)b_g^2 > 0$, $B_2 = 8\beta b_p - (1-k)(1-\phi)b_g^2 > 0$, $B_3 = \left(8\beta b_p - (1-\phi)b_g^2\right)\gamma - \phi(1+x)^2 \beta b_p^2 > 0$, $B_4 = \left(4\beta b_p - (1-\phi)b_g^2\right)\gamma - 4\phi\beta b_p^2 > 0$, and $B_5 = 4\beta b_p^2 + 3\gamma b_g^2 > 0$. All the technical proofs are presented in the Appendix.

To illustrate the insights from the analytical analysis and to gain a better understanding of the impacts of innovation unobservability and greenwashing, we perform numerical analyses. Based on the feasible constraints analysed earlier, the fixed values for the baseline parameters are set as $a = 10, b_p = 1, b_g = 1.2, c = 3, \beta = 2, \gamma = 1.7$.

4.4.1 Benchmark cases with complete information

Benchmark cases under complete information are first investigated to illustrate how unobservability affects supply chain decision-making and performance. Under complete information, we have $x = 1$. Consequently, the profit functions are given as follows:

$$\Pi_M = \left(w - (c - g)\right)(a - b_p p + b_g \theta) - \beta\theta^2 - \gamma g^2 \tag{8}$$

$$\Pi_R = (p - w + g)(a - b_p p + b_g \theta) \tag{9}$$

The investigation initiates by examining a scenario in which the manufacturer refrains from investing in green process innovation, i.e. $g = 0$. Subsequently, a comparative analysis is conducted with a scenario where the manufacturer actively engages in green process innovation, aiming to analyse the impacts of this innovation. The observable cases are denoted by superscripts “ngo” and “go” to represent cases without and with green process innovation, respectively. The first-order optimality condition is applied to solve the model and the proof is omitted due to its simplicity. The equilibrium outcome is presented in Table 4.2 and the following lemma summarises the key observations.

Lemma 4.1 Given complete information, the manufacturer’s engagement in green process innovation results in: (a) heightened product greenness, (b) reduced retail price, and (c) amplified profits for both the manufacturer and the retailer.

It is demonstrated that the integration of green process innovation within manufacturing operations, often characterised by the adoption of more sustainable and efficient practices, effectively reduces production costs. This cost reduction not only benefits the retailer through innovation spillover but also can then be passed on to the consumers in the form of a lower retail price for the green product, contributing to a broader product market penetration. Consequently, embracing green process innovation practices manifests positive economic and environmental effects across the entire supply chain. It unveils the allure of greenwashing as a potential ploy for opportunistic manufacturers.

Table 4.2 Equilibrium outcomes under complete information

Indicator	**Case: ngo**	**Comparison**	**Case: go**
g^j	0		$\frac{2\beta b_p D_0}{B_0\gamma - 4\beta b_p^2}$
θ^j	$\frac{b_g D_0}{B_0}$	<	$\frac{\gamma b_g D_0}{B_0\gamma - 4\beta b_p^2}$
w^j	$\frac{4\beta D_0}{B_0} + c$	<	$\frac{2(2\gamma - b_p)\beta D_0}{B_0\gamma - 4\beta b_p^2} + c$
p^j	$\frac{6\beta D_0}{B_0} + c$	>	$\frac{2(3\gamma - 2b_p)\beta D_0}{B_0\gamma - 4\beta b_p^2} + c$
D^j	$\frac{2\beta b_p D_0}{B_0}$	<	$\frac{2\gamma\beta b_p D_0}{B_0\gamma - 4\beta b_p^2}$

Π_M^j	$\frac{\beta D_0^2}{B_0}$	<	$\frac{\gamma\beta D_0^2}{B_0\gamma - 4\beta b_p^2}$
Π_R^j	$\frac{4b_p\beta^2 D_0^2}{B_0^2}$	<	$\frac{4b_p\gamma^2\beta^2 D_0^2}{(B_0\gamma - 4\beta b_p^2)^2}$

4.4.2 Decision analysis with limited transparency

We now consider the information structure implied by innovation unobservability. In the practical realm, the assurance of complete information is challenging, creating a scenario where a manufacturer is both incentivised and presented with an opportunity to engage in greenwashing, especially when her green practices remain unobservable to the retailer. We use backward induction to determine the equilibrium decisions for the scenarios without and with greenwashing and then compare the two cases.

Lemma 4.2 Innovation unobservability significantly shapes the manufacturer's reporting strategy, exerting a profound influence on supply chain decision-making and performance. The equilibrium outcomes for the unobservable scenarios without and with greenwashing are detailed in Table 4.3.

Table 4.3 Equilibrium outcomes with innovation unobservability

Indicator	**Case: nwu**	**Comparison**	**Case: wu**
g^j	$\frac{(1+x)\beta b_p D_0}{B_3}$	=	$\frac{(1+x)\beta b_p D_0}{B_3}$
θ^j	$\frac{\gamma b_g D_0}{B_3}$	>	$\frac{(1-k)B_1\gamma b_g D_0}{B_2 B_3}$
w^j	$\frac{\left(4\gamma - \phi(1+x)b_p\right)\beta D_0}{B_3} + c$	>	$\frac{\beta D_0}{B_2}\left(4 - \frac{\phi(1+x)b_p\left((1-x)4\beta b_p - (1-k)(1-\phi)b_g^2\right)}{B_2}\right) + c$
p^j	$\frac{\left(6\gamma - \phi(1+x)^2 b_p\right)\beta D_0}{B_3} + c$	>	$\frac{\beta D_0}{B_2}\left(6 - \frac{\phi(1+x)^2 b_p\left(2\beta b_p - (1-k)(1-\phi)b_g^2\right)}{B_3}\right) + c$
D^j	$\frac{2\gamma\beta b_p D_0}{B_3}$	>	$\frac{2B_1\gamma\beta b_p D_0}{B_2 B_3}$
Π_M^j	$\frac{\gamma\beta D_0^2}{B_3}$	conditional	$\frac{(1-k)B_1^2\gamma^2\beta D_0^2}{B_2 B_3^2} - kF$
Π_R^j	$\frac{4b_p\gamma^2\beta^2 D_0^2}{B_3^2}$	>	$\frac{4B_1^2 b_p\gamma^2\beta^2 D_0^2}{B_2^2 B_3^2}$

To investigate the impacts of unobservability, we first analyse the first-order derivatives of the equilibriums in the unobservable innovation without greenwashing case with respect to ϕ. Then, we compare the equilibriums of the complete-information and unobservable cases by evaluating the difference in corresponding decisions. The transparency level ϕ and the spillover intensity x are two key influential parameters. Specifically, the observations are presented as follows.

Corollary 4.1 Within the equilibrium context, assuming $x_0 = \frac{b_g\sqrt{\gamma\beta}}{\beta b_p} - 1$, the manufacturer's green investments in observable product innovation and unobservable process innovation decrease with ϕ when $0 \le x \le x_0$, and increase with ϕ when $x_0 < x \le 1$. Compared with the complete information case, the unobservability of green process innovation diminishes the manufacturer's investments in both types of green innovations, consequently reducing her profit.

Corollary 4.2 Within the equilibrium context, assuming $\phi_0 = \dfrac{4b_p(2\beta b_p - b_g^2)}{6b_g^2\gamma + b_p\left((1+x)^2(2\beta b_p - b_g^2) - 4b_g^2\right)}$, the retailer's pricing decision is decreasing in ϕ. In situations of low transparency ($0 < \phi < \phi_0$), the retailer exploits the unobservability to set higher prices ($p^{go} < p^{nwu}$). Conversely, as transparency improves ($\phi_0 \le \phi < 1$), the retail price in scenarios of unobservability declines ($p^{go} \ge p^{nwu}$). The unobservability leads to decreased demand and, ultimately, lower profits for the retailer.

Corollary 4.1 and Corollary 4.2 are visualised in Figure 4.1 by taking ϕ and x as independent variables. They show that higher transparency regarding the green process innovation facilitates the pass of the resulting cost reduction to the consumers in terms of a lower retail price. The manufacturer may be motivated to overstate the extent of their green process innovations to enhance market perception and profits under the veil of unobservability.

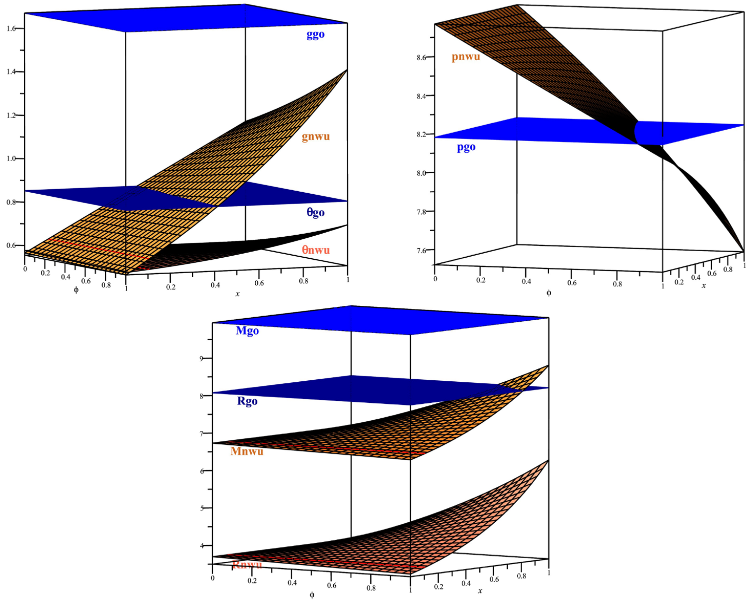

Figure 4.1(a-c) Impacts of transparency on innovation investments, retail prices, and profits

Based on the equilibrium outcomes and comparative analyses, we can derive the following proposition.

Proposition 4.1 When the probability that the greenwashing is publicly exposed and the ensuing loss satisfy the conditions $0 \le k \le k_0$ and $0 \le F \le \dfrac{(1-k)\gamma\beta B_1^2 D_0^2}{kB_2B_3^2}$, the manufacturer will choose greenwashing to gain a higher profit. The optimal product greenness, wholesale price, retail price, demand, and profits of both players are decreasing in the probability k.

The probability threshold for the manufacturer to determine whether or not engage in greenwashing is given as

$$k_0 = \frac{-\left(B_1B_3^2F + \gamma\beta^2 b_p D_0^2\left(8B_3 + \phi b_p(1+x)^2 B_1\right)\right) + \left(\left(B_1B_3^2F + \gamma\beta^2 b_p D_0^2\left(8B_3 + \phi b_p(1+x)^2 B_1\right)\right)^2 + 4\phi b_p^2 D_0^2 B_1 B_3^2 F\right)^{\frac{1}{2}}}{2(1-\phi) b_g^2 B_3^2 F}.$$

This proposition suggests that a manufacturer's decision to engage in greenwashing for higher profits depends on the risk of exposure and its financial consequences. When the likelihood of detection is low and the resultant loss minor, the risks to the manufacturer are considered manageable and potentially outweighed by the benefits of being perceived as more environmentally friendly than in reality. Such conditions often prevail in regulatory environments with lenient penalties for greenwashing or in markets where environmental claim scrutiny is minimal. Moreover, these scenarios might arise when public awareness or concern about greenwashing is low, diminishing both the probability of exposure and the severity of any penalties.

Consequently, as exposure risk increases, the attractiveness of greenwashing decreases, influencing the entire pricing strategy and potentially diminishing profits. Take a car manufacturer that exaggerates fuel efficiency or underreports emissions for instance; if the chance of exposure is low and penalties are minor, due to regulatory gaps or ineffective enforcement, the immediate sales boost could seem worth the gamble. Yet, once greenwashing is unveiled, as observed in several real-world scandals, the enduring harm to brand reputation and the penalties incurred underscore how the dynamics of risk and consequences alter the firm's decisions regarding greenwashing.

Corollary 4.3 Greenwashing the unobservable green process innovation undermines genuine green product innovation efforts, lowering the retail price and profit for the retailer, i.e. $\theta^{wu} < \theta^{nwu}$, $p^{wu} < p^{nwu}$, and $\Pi_R^{wu} < \Pi_R^{nwu}$.

We set $x = 0.5, F = 2$ to illustrate Proposition 4.1 in Figure 4.2(a). When the probability of greenwashing exposure is sufficiently low to afford the manufacturer additional profit, i.e. $\Pi_M^{wu} \geq \Pi_M^{nwu}$, she will resort to greenwashing. Conversely, if the risk of exposure is high, she will engage in genuine green practices as claimed. Further, Figure 4.2(b) demonstrates the impact of greenwashing on product greenness by adding an extra setting of $\phi = 0.5$. It shows that the manufacturer's greenwashing behaviour lowers product greenness, which decreases with the exposure probability. The retailer's selling price and profit exhibit analogous patterns. In this case, the reduction in the retail price, while potentially beneficial for consumers, comes at the cost of diminished product greenness and retailer profitability.

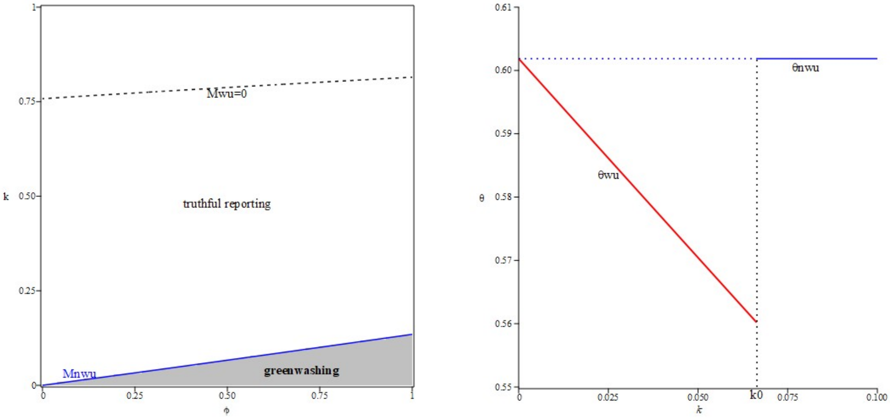

Figure 4.2(a-b) Manufacturer's greenwashing choice and its impact on product greenness

4.5 Technology adoption and supply chain coordination

In this section, we consider the coordination for the green supply chain with limited transparency on the green process innovation practices. We first analyse the benchmark centralised case (denoted by the superscript “iu”) where a vertically integrated virtual headquarters governs the transactions between the manufacturer and the retailer so that its objective is to align the two divisions’ incentives and maximise the total profit of the integrated system. Given centralisation, we have $x=1$. The profit function of the integrated supply chain is given as:

$$\Pi_{SC}^{iu}=(p-c+2\phi g)\left(a-b_p p+b_g(1-\phi)\theta\right)-(1-\phi)\beta\theta^2-\phi\gamma g^2 \tag{10}$$

Using the first-order optimality condition to solve the model and comparing the results with the decentralised case, we have Lemma 4.3.

Lemma 4.3 In the centralised case, the system-optimal equilibrium outcomes are as follows: $g^{iu}=\dfrac{2\beta b_p D_0}{B_4},\theta^{iu}=\dfrac{\gamma b_g D_0}{B_4},p^{iu}=\dfrac{2\beta(\gamma-2\phi b_p)D_0}{B_4}+c,\Pi_{SC}^{iu}=\dfrac{\gamma\beta D_0^2}{B_4}$. The vertically-integrated solution enhances innovation levels and total supply chain profit while providing consumers with a lower retail price, i.e. $g^{iu}>g^{nwu},\theta^{iu}>\theta^{nwu},p^{iu}<p^{nwu},\Pi_{SC}^{iu}>\Pi_{SC}^{nwu}$.

Now, we consider the coordination contract design. The retailer obtains positive free-riding externalities from the manufacturer’s green practices. Under limited transparency, the manufacturer is able to greenwash her internal innovation investments. A properly-developed scheme should allow us to address these issues, avoid greenwashing and achieve coordination. Technologies like artificial intelligence (AI) and blockchain offer significant potential to improve sustainability reporting quality by securing observability and accountability regarding a firm’s green practices and thereby help to eliminate greenwashing (Dong et al., 2023; Forlee, 2023; Jayaram, 2023). For instance, using AI for initial greenwashing detection and blockchain for secure and unchangeable data management, firms can foster information transparency and genuine green practices.

We consider that these innovative technologies are adopted by the manufacturer with a lump-sum investment cost T for a process innovation transparency improvement of $y\in(0,1-\phi)$. The adoption of technology and the subsequent increase in transparency are expected to guarantee the genuine implementation of the manufacturer’s green practices, so we have $x=1$. This proactive measure by the manufacturer seeks to eliminate greenwashing and incentivise the retailer to engage in coordination. In addressing the issue of the retailer’s free-riding, the manufacturer generalises the simple wholesale price contract to a two-part linear contract, which includes both a wholesale price and a side payment from the retailer to the manufacturer. This transfer payment structure is widely applied in supply chain management (Corbett et al., 2004; Leng and Zhu, 2009; Wang et al., 2021). Its selection over other potential options, such as cost-sharing or quantity discount contracts (Wang and Choi, 2020; Yang et al., 2018), is motivated by the balance it offers between ease of implementation and effectiveness in aligning the incentives of supply chain members. In our study, the side payment is formulated as $t+\tau_1 g+\tau_2\theta$ ($t,\tau_1,\tau_2>0$). What differentiates this improved side-payment coordination contract from the existing contracts is the consideration of the transparency improvement caused by the adoption of new technology. The interaction between the manufacturer and the retailer in the coordination process is illustrated in Figure 4.3. The profit functions in the coordination case (denoted by the superscript “cu”) are expressed as follows:

$$\Pi_M^{cu} = \big(w - (c - (\phi + y)g)\big)\big(a - b_p p + b_g(1 - \phi - y)\theta\big) - (1 - \phi - y)\beta\theta^2 - (\phi + y)\gamma g^2 - T + (t + \tau_1 g + \tau_2\theta) \quad (11)$$

$$\Pi_R^{cu} = \big(p - w + (\phi + y)g\big)\big(a - b_p p + b_g(1 - \phi - y)\theta\big) - (t + \tau_1 g + \tau_2\theta) \quad (12)$$

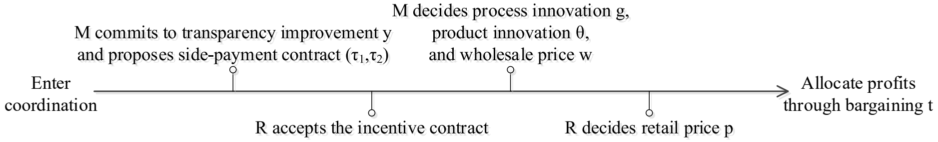

Figure 4.3 Sequence of coordination

Solving the cooperative game model and considering the incentive compatibility and the individual rationality constraints (Corbett et al., 2004; Leng and Zhu, 2009), we have the following propositions.

Proposition 4.2 The manufacturer can avoid greenwashing and align green innovation and pricing decisions with centralised optimal solutions through the proposed coordination scheme by exactly setting the terms

$$y = \frac{4\gamma\beta b_p}{B_5}, \tau_1 = \frac{8(\phi B_5 + 4\gamma\beta b_p)\gamma^2\beta b_p b_g^2 D_0}{B_4 B_5^2}, \tau_2 = \frac{4\big((1 - \phi)B_5 - 4\gamma\beta b_p\big)\gamma^2\beta b_g^3 D_0}{B_4 B_5^2}.$$

Proposition 4.3 The technology adoption cost to enforce the two-part incentive contract affects the realised coordination profit and efficiency. Assuming $T_0 = \frac{\big(B_4 B_5^2 + 4\gamma\beta b_p(4\beta b_p^2 + \gamma b_g^2)(4\beta b_p^2 - 3\gamma b_g^2)\big)\gamma\beta D_0^2}{B_4^2 B_5^2}$, the feasible scope of the cost to ensure a nonnegative profit is $0 < T \le T_0$. Only when $T = \frac{4(4\beta b_p^2 + \gamma b_g^2)(4\beta b_p^2 - 3\gamma b_g^2)b_p\gamma^2\beta^2 D_0^2}{B_4^2 B_5^2}$ can the contract take effect with the maximum profit for full coordination, i.e. $\Pi_{SC}^{cu} = \Pi_{SC}^{iu}$.

The propositions suggest that adopting advanced technologies, such as AI and blockchain, can strategically bridge the information gap and align incentives between supply chain partners, leading to more sustainable and profitable outcomes. Proposition 4.2 presents precise requirements for reaching the desired centralised outcomes, whereas Proposition 4.3 reveals how the cost of technology adoption adds a critical layer of flexibility to the coordination scheme by highlighting the balance between contract enforcement costs and the economic benefits of coordination. These insights indicate that while the two-part contract can indeed guide the supply chain toward optimal green innovation and pricing decisions, the financial viability and overall success of the coordination scheme depend on the precise calibration of additional costs. This specificity points to the broader implication that achieving effective coordination within green supply chains is not just a matter of contractual design but also of managing associated costs to unlock the full potential of such a coordination scheme. Suppose that the manufacturer has improved the process innovation transparency $y = \frac{4\gamma\beta b_p}{B_5}$ and proposes the incentive contract, satisfying all the conditions for full coordination. Now, we need to consider the profit allocation in the supply chain to satisfy the individual rationality constraint, i.e. both players should be more profitable under the coordination case than under the non-coordination case so that the manufacturer does not choose the greenwashing strategy and the retailer will participate in the coordination, i.e. $\Pi_M^{cu} \ge \max(\Pi_M^{nwu}, \Pi_M^{wu})$ and $\Pi_R^{cu} \ge \Pi_R^{nwu}$. Therefore, the constant payment t should be appropriately selected. The feasible scope of the fixed transfer payment is $\Pi_M^{bcu} - \max(\Pi_M^{nwu}, \Pi_M^{wu}) \le t \le \Pi_R^{bcu} - \Pi_R^{nwu}$, where Π_M^{bcu} and Π_R^{bcu} are obtained by substituting $g^{iu}, \theta^{iu}, p^{iu}$ and $w^{cu} = \dfrac{2\left(-\phi b_p B_5 + 2\gamma(2\beta b_p^2 + \gamma b_g^2)\right)\beta D_0}{B_4 B_5} + c$ into $\Pi_M^{cu} - t$ and $\Pi_R^{cu} + t$, respectively. The Nash bargaining scheme can be applied to accomplish profit allocation. According to Leng and Zhu (2009); Nagarajan and Sošić (2008), a simple way is to set $t = \frac{1}{2}(\Pi_R^{bcu} - \Pi_M^{bcu})$ by solving the problem $\max\limits_{\Pi_M^{cu}>0, \Pi_R^{cu}>0} \Pi_M^{cu}\Pi_R^{cu}$, after which the two players equally allocate the realised maximal centralised profit. Setting $k = 0.1$ and taking ϕ as the independent variable, Figure 4.4(a) numerically demonstrates the relationship of the profits of the two players in coordination and non-coordination cases. Figure 4.4 shows that the coordination scheme allows both players to be profitable while offering a greener product to consumers with a lower retail price.

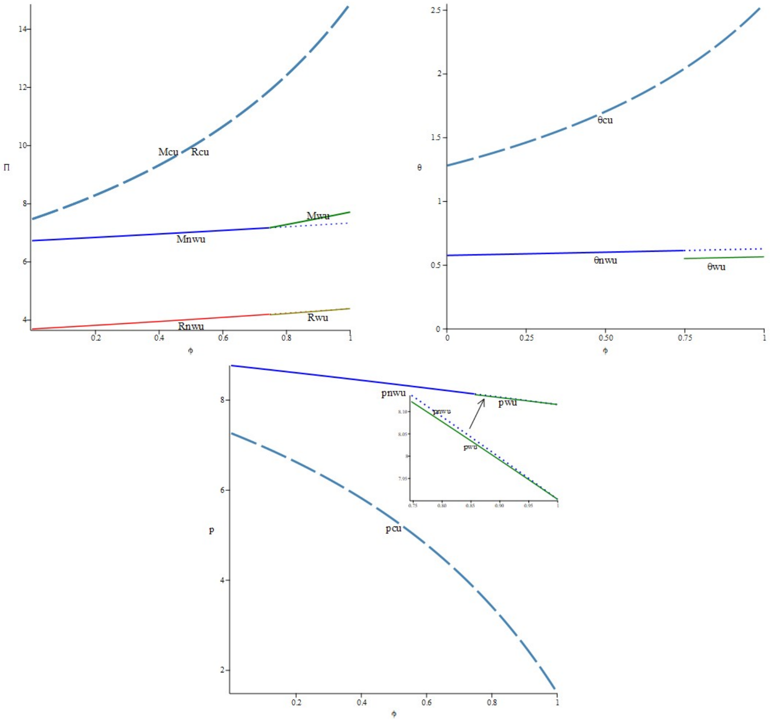

Figure 4.4(a-c) Comparisons of profits, product innovation levels, and retail prices between coordination and unobservable cases

4.6 Conclusion

This research has examined the phenomenon of firm-level greenwashing within the context of green supply chain management, focusing on the manufacturer's green innovation investment and reporting decisions and their consequential impacts on the supply chain. Our analysis uncovers the specific circumstances under which a manufacturer might resort to greenwashing— the act of misrepresenting green process innovations due to challenges in observability and information asymmetry. Such misleading practice not only undermines genuine green product innovation efforts but also affects the economic dynamics of the supply chain, including retail pricing strategies and overall profitability.

Our findings suggest that the decision-making and performance within the green supply chain are significantly sensitive to the transparency level and spillover intensity of the green process innovation, the probability and ensuing loss of greenwashing exposure. The insights derived from the model analysis collectively highlight the necessity for the supply chain players to engage in transparent and cooperative strategies to mitigate the risks associated with greenwashing. To this end, we propose a two-part coordination contract, with advanced technologies serving as a facilitator for incentive alignment and coordination. These technologies can streamline information sharing and ensure the authenticity of green claims, making them invaluable coordination tools in this context. Consequently, managers should prioritise enhancing transparency and cooperation within their supply chains to effectively manage greenwashing risks.

However, our model presents certain limitations that open avenues for future research. Firstly, the model studies a simplified two-echelon supply chain, which may not capture the complexity of real-world networks. Future studies could explore the impact of third-party involvement in monitoring and preventing greenwashing practices. Secondly, while our study primarily focuses on the manufacturer's viewpoint, it may not fully account for the retailer's strategies and consumer reactions to greenwashing. A broader exploration of these dimensions would further enrich our understanding of green supply chain dynamics. Thirdly, this research only examines a one-period setting; addressing evolving strategies over extended periods and incorporating broader systemic changes like government policies is worth further exploration to gain a comprehensive understanding of green innovations in supply chains.

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Chapter 5 Green Marketing Strategies in a Supply Chain under Asymmetric Information

Abstract This chapter examines the decision-making in a supply chain with asymmetric information in the context of green marketing. Specifically, the firm has private information on product greenness and faces the problem of conveying this information to uninformed consumers through self-labelling. We develop a game-theoretic model where green marketing functions as both an influencer of consumer willingness to pay and a signalling tool. The findings highlight the dependence of the pooling or separating equilibrium on the fraction of informed consumers in the market. The solutions are characterised by the range of market transparency and offer insights into firms' profitable strategy choices. These include adopting greenwashing or distinctive signalling strategies, or opting to be recognised solely as an influencer of green purchase behaviour, rather than as a signal of product greenness. It is shown that continuously increasing market transparency is not always beneficial regarding green marketing investment and consumer surplus. Although greenwashing hampers informed consumer choices, it encourages the firm offering low-greenness products to increase investments in green marketing, temporarily boosting consumer willingness to pay for green products and enhancing consumer surplus and social welfare.

Keywords: green marketing; asymmetric information; market transparency; greenwashing; signalling game

5.1 Introduction

In recent years, green consumers have been demanding greater transparency on the environmental performance of green products to make more informed purchase decisions. An increasing number of supply chain firms have responded to this trend by employing green marketing practices to communicate their product greenness level (Simula et al., 2009). Ecolabelling is a powerful visual communication tool for green marketing (Dangelico and Vocalelli, 2017; Rahbar and Wahid, 2011). Notably, self-developed carbon footprint labels have become a popular ecolabeling scheme, frequently used by retailers to highlight the "greenness" of their products. The product greenness level is accordingly quantified by calculating the carbon footprint of products in this study, more specifically, the percentage of carbon emission reductions in each unit of the product. Numerous organisations such as Carbon Trust, UNFCCC, and the European Commission contribute to this measure through various standards like PAS2050, GHG Protocol Product Standard, and ISO14067. Recognisable brands such as Tesco, Oatly, Lenovo, and Apple have featured their product carbon footprints.

These carbon labels serve as signals to consumers about the product greenness and profoundly influence their environmental awareness and purchase behaviours (Sharma, 2021). As a result, the global market has seen a surge in self-labelled green products. Supply chain firms that promote these labelled products often invest additional marketing efforts and employ differential pricing strategies compared to non-labelled counterparts. The rewards of these endeavours are evident as consumers increasingly seek greener products and are willing to pay a premium price for them.

However, a fundamental challenge emerges with self-labelled products: consumers may find it challenging to independently verify the environmental claims made by firms, leading to an information asymmetry in the market (Murali et al., 2018; Yang et al., 2021). This information asymmetry, where consumers lack full information compared to firms, leaves room for opportunistic firms with low-greenness products, termed standard firms in this chapter, to engage in product-level greenwashing (Delmas and Burbano, 2011; Netto et al., 2020). In essence, standard firms masquerade as high-greenness labels and imitate the marketing and pricing strategies of genuinely green firms without offering appropriate products. This practice is all too familiar, with instances of greenwashing identified in various sectors, including fashion brands like H&M[1].

The prevailing belief is that greenwashing has predominantly negative implications (Brouwer, 2016; Chen et al., 2020). Appropriate knowledge and transparency play a critical role in green purchase behaviour. It is widely held that more informed consumers, armed with knowledge about true product greenness, can reduce information asymmetry and help to mitigate or eliminate greenwashing (Lee et al., 2018). This research defines the fraction of informed consumers in the market as "market transparency", a key influential factor for firms' marketing and pricing strategies.

Motivated by these observations, this chapter aims to shed light on the impact of market transparency on firms' decisions and performance. Specifically, we seek to answer the following research questions:

(1) Under what conditions might a firm opt for a greenwashing or a distinctive signalling strategy?

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[1] https://qz.com/2180075/hm-showed-bogus-environmental-higg-index-scores-for-its-clothing

(2) Does increased market transparency consistently lead to higher green marketing investment and profits?

To address these questions, we develop a signalling game and characterise strategies for different types of firms. Our findings demonstrate that the absence of informed consumers motivates a standard firm to resort to greenwashing, imitating genuinely green firms' strategies. Although greenwashing hampers informed consumer choices, it encourages the standard firm to increase investments in green marketing, consequently boosting consumer willingness to pay for green products and enhancing consumer surplus and social welfare. The presence of informed consumers eliminates the greenwashing equilibrium. When a certain level of transparency is reached, a green firm opts to increase investment in green marketing and set the price above those under complete information to separate from the standard firm. As market transparency further increases, this additional investment and overpricing converge to the complete information benchmarks.

Please note an important caveat: while this research acknowledges the potential short-term economic benefits of greenwashing, it does not justify the practice as ethically sound, nor do we support it. However, we cannot overlook the roles that greenwashing can play in spreading sustainability concepts and educating green consumers, especially in the early stages of developing a highly sustainable society. As Glavas et al. (2023)suggest, greenwashing can serve as a stepping stone towards genuine environmental commitment if firms are encouraged to follow through on their claims.

The remainder of this chapter is structured as follows: the next section briefly reviews literature closely related to this research and introduces our contributions. Section 5.3 presents the model setup, followed by analytical and numerical analyses in Section 5.4. Section 5.5 concludes the chapter by summarising the findings and insights.

5.2 Literature review

A substantial body of literature is pertinent to the subject of this research, which primarily centres on the implications of green marketing. Dangelico and Vocalelli (2017) and Sharma (2021) offer comprehensive reviews encompassing fundamental concepts for green marketing. They underscore the effectiveness of ecolabelling and its impacts on consumers' green purchase decisions. Green marketing integrates environmental sustainability into the marketing for green products, possessing multifaceted functions. We specifically focus on the analytical modelling research considering promotional functions of green marketing, namely, an influencer to green purchase behaviour and a signalling tool, within the context of green supply chain management.

An abundance of empirical studies has shown that green marketing has the potential to increase consumers' awareness regarding product greenness or their willingness to pay and drive consumer behaviour towards greener choices, and therefore stimulates product demand and contributes to the success of green supply chains (Li et al., 2017a; Rahbar and Wahid, 2011). To capture these features in operations models, a stream of research develops demand functions that are sensitive to green marketing efforts (e.g. Fadavi et al., 2021; Guo et al., 2020; Hong and Guo, 2019; Li et al., 2021; Yang et al., 2022; Zhu et al., 2018). The positive impact on consumer demand is either directly integrated into the demand function as a parameter through an additive or multiplicative way or is embedded within the consumer utility. Few studies consider utility-based models. We contribute to this body of literature by formulating a demand function wherein the effectiveness of green marketing on consumers' willingness to pay for green products is incorporated into consumer utility through a multiplicative framework.

Despite the demand expansion for green products facilitated by green marketing, the implementation of these practices is costly. Researchers such as Fadavi et al. (2021); Hong and Guo (2019); Li et al. (2021) have raised the issue that many retailers may hesitate to invest in green marketing due to these associated costs. Nonetheless, green marketing cost-sharing contracts, wherein manufacturers share a proportion of the marketing expenses, can enhance retailers' willingness to exert green marketing efforts and, under symmetric information settings, achieve supply chain coordination. The positive messages conveyed through voluntary green labels and credible accompanying marketing strategies raise green awareness. However, they could be misleading and open avenues for opportunistic firms with poor environmental performance to adopt greenwashing strategies for economic gain. As a result, the signalling role of green marketing can reshape retailers' willingness for green marketing and influence decision-making and performance in green supply chains (Dangelico and Vocalelli, 2017; Delmas and Burbano, 2011; Li et al., 2017b; Shao et al., 2020; Zhao, 2000).

Explorations into the implications of greenwashing are extending into the realm of green supply chain and operations management. For example, in the context of corporate social responsibility (CSR) practices, Wu et al. (2020) identify both favourable and unfavourable aspects of greenwashing, exploring the impact of CSR information transparency, i.e. the degree to which the firm's CSR activities are observable, on the firm's strategies and the social welfare. Lee et al. (2018) analytically show that greenwashing may not necessarily increase the positive environmental externality of green products but can facilitate the implementation of CSR practices particularly in the highly competitive market with some informed customers. This study aligns with previous work in terms of recognising positive aspects of greenwashing concerning a standard firm's green marketing investment and consumer surplus. What sets this study apart is the comprehensive consideration given to the firm marketing products under green labels, utilising green marketing not only as a signalling tool but also as a means to influence consumer willingness to pay. Through this comprehensive perspective, we compare the settings with and without signalling based on profitability analysis to examine the conditions under which firms will adopt signalling strategies.

The primary contribution of this chapter lies in its capacity to offer insights into the interplay between market transparency and a firm's green marketing strategies, illuminating the conditions under which greenwashing and separating strategies may be adopted and the subsequent effects on a firm's sustainability performance.

5.3 Model setup

We base our model on a signalling game framework and consider a two-echelon green supply chain consisting of a firm and downstream consumers. The firm is a reseller who promotes a green product at a price p to consumers. The fraction of the informed consumers who know the true product greenness in the market is $0 \le \delta \le 1$, termed market transparency in this study. The remaining $1-\delta$ represents uninformed consumers with asymmetric information. The genuine greenness of the product θ is exogenously determined and it is either high (H) or low (L), i.e. $\theta \in \{H, L\}$ and $H > L \ge R \ge 0$. The entrance greenness R is the minimal product greenness to be accepted by the market. The product with greenness below the entrance level will not be considered by the consumers or allowed by the authority to enter the marketplace. For simplicity, we assume that $L = R$, which can also reflect that this type of firms is relatively less concerned about sustainability than the firms offering high-greenness products, so they would only sell products with entrance greenness. We call such a firm the "standard firm" and a firm offering a high-greenness product the "green firm".

The firm privately knows the genuine product greenness while informing consumers of product greenness through a self-label $s \in \{H, L\}$. To support its self-label claim, the firm invests green marketing effort η $(\eta \geq 0)$ which results in a quadratic fixed cost $\alpha\eta^2$. If the firm with a low-greenness product labels a higher greenness $(s > \theta)$ and misleads consumers regarding the product's environmental benefits through observable green marketing and pricing signals, we define the act as a product-level greenwashing behaviour. The firm is risk-neutral and makes rational decisions to maximise its expected profit. Given that the marketing of a large majority of green products tends to involve some degree of exaggeration (UL Environment, 2014), we assume that the firm with the high-greenness product will not signal a lower greenness due to its lack of economic benefits (Lee et al., 2018), i.e. $s \geq \theta$. This is also validated by our model analysis in later sections. In contrast, the firm with the low-greenness product may have incentives to greenwash its product greenness. Overall, three signalling strategies exist for the firm with certain product greenness $(\theta, s) \in \{(H,H),(L,L),(L,H)\}$. It is noted that the presence of informed consumers could expose deceptive practices, so we assume that the lack of full credibility of a self-label will only be exploited by the standard firm to claim to be green. The fraudulent exaggerated self-labelling behaviour by green firms is outside the scope of this study.

We consider a utility-based model to formulate the market demand. Consumers make purchase decisions based on their perceived surplus greenness and charged price, provided a positive utility.

Given the firm's green marketing practices, the consumer utility from a product with greenness being believed as $\hat{\theta}$ sold at price p is $u = V - b_p p + \eta b_g(\hat{\theta} - R)$. According to Guo et al. (2020); Hong and Guo (2019), environmentally conscious consumers who have a preference for greener products derive utility from two dimensions of the product attribute: functionality and environmental friendliness. Being green should not overshadow the functional purpose of the product. Consumers are heterogeneous in their functionality needs, which is characterised by V, a nonnegative variable uniformly distributed over $[0,1]$. Their price sensitivity parameter and marginal willingness to pay (WTP) for the perceived surplus greenness are represented by b_p and b_g, respectively.

The reseller's green marketing effort cannot change true product greenness. However, it can influence the consumers' perceived surplus greenness and preference for green products (UL Environment, 2014; Zhao, 2000; Zhu et al., 2018), which is characterised in a multiplicative form in the utility function. The multiplicative form captures the feature that the greenness of the product cannot be perceived by the consumers without the firm's marketing effort and the firm's green marketing is ineffective on consumer utility if the product greenness is not improved at all, thus making no impact on market demand (Yang et al., 2022). We can also interpret η as the firm's credibility to reflect its green marketing effectiveness on consumers' WTP for the green product. The firm can use green marketing practices both to shape consumers' preference for greener products and to signal the product greenness.

The potential market size is normalised to 1. Informed consumers know the genuine product greenness and will disregard the signal sent by the firm, i.e. $\hat{\theta} \equiv \theta$, while uninformed consumers base their perceived greenness to make rational purchase decisions on the firm's stated product greenness signal. Let the probability of the uninformed consumers' being convinced that the product greenness is high after observing the firm's signal $\hat{\rho} = \Pr(\hat{\theta} = H \mid s)$, and the probability of being low greenness $1 - \hat{\rho} = \Pr(\hat{\theta} = L \mid s)$. The prior probabilities the consumers believe the product greenness being high and low respectively are ρ and $1-\rho$. The demand function is derived as $D(\eta, p \mid \delta, \theta, \hat{\theta}) = \delta\left(1 - b_p p + \eta b_g(\theta - R)\right) + (1-\delta)\left(1 - b_p p + \eta b_g(\hat{\theta} - R)\right)$.

We formulate the expected profit function of the firm as $\Pi_\theta(\eta, p \mid \delta, \theta, \hat{\theta})$ according to the assumptions and analyses above. The acquisition costs of the two types of green products are insignificant and assumed to be c. This assumption allows us to isolate the acquisition cost effect on the firm's signalling strategy to focus on the impact of the green marketing investment. Then, the firm's profit can be expressed as $\Pi_\theta(\eta, p \mid \delta, \theta, \hat{\theta}) = (p-c)D(\eta, p \mid \delta, \theta, \hat{\theta}) - \alpha\eta^2$.

5.4 Model analysis

5.4.1 Benchmark case with complete information

We start with the benchmark case where all consumers know the true product greenness and make informed purchase decisions, i.e. $\delta = 1$, and the firm shares all information credibly in such a fully transparent market. Green marketing is only used to influence consumers' WTP for the green product. The green firm and the standard firm's profit functions are $\Pi_H(\eta, p) = (p-c)\left(1 - b_p p + \eta b_g(H-R)\right) - \alpha\eta^2$ and $\Pi_L(\eta, p) = (p-c)(1 - b_p p) - \alpha\eta^2$, respectively. Satisfying the second-order conditions, the profit function is jointly concave in the decision variables under the feasibility condition $\alpha > \frac{\left(b_g(H-R)\right)^2}{4b_p}$, which indicates green marketing practices are costly and holds throughout the model analysis. Therefore, applying first-order optimality conditions yields the optimal solutions. We can obtain the firm's specific strategy $(\eta_\theta^{ci}, p_\theta^{ci})$ as follows:

For the green firm, $(\eta_H^{ci}, p_H^{ci}) = \left(\frac{b_g(H-R)(1-b_p c)}{4b_p\alpha - \left(b_g(H-R)\right)^2}, \frac{2\alpha(1-b_p c)}{4b_p\alpha - \left(b_g(H-R)\right)^2} + c \right)$, gaining a profit $\Pi_H^{ci} = \frac{\alpha(1-b_p c)^2}{4b_p\alpha - \left(b_g(H-R)\right)^2}$.

For the standard firm, $(\eta_L^{ci}, p_L^{ci}) = \left(0, \frac{1-b_p c}{2b_p} + c\right)$, gaining a profit $\Pi_L^{ci} = \frac{(1-b_p c)^2}{4b_p}$.

By analysing the first-order derivatives of the optimal results with greenness, we can get the following lemma.

Lemma 5.1 Given complete information, the green firm's optimal green marketing effort, selling price, and profit are increasing in product greenness.

The monotonicity of the decision variables with respect to the asymmetric parameter suggests that the green firm can use its profit-optimal decisions on green marketing efforts and selling prices as potential signals to the consumers of the product greenness information. In the complete information case, no signalling is needed. The standard firm disregarding the consumers' environmental utility is not motivated to invest in green marketing, while the green firm offering a high-greenness product will make additional investment in green marketing and set a higher price for its product.

5.4.2 Equilibrium analysis of asymmetric information case

We now consider the situation where a fraction of consumers do not know the true product greenness and have incomplete information about the firm's type. In this market with limited transparency $0 \le \delta < 1$, green marketing serves both to influence consumers' WTP for green products and to signal product greenness. The uninformed consumers base their purchase decisions on their beliefs about the firm's type after observing its signalling strategies. To shape consumer beliefs, the standard firm is incentivised to greenwash to mimic the green firm, while the green firm has motivations to distinguish itself from the standard firm.

Utilising the pure-strategy Perfect Bayesian Equilibrium (PBE) concept for dynamic games of incomplete information (Peters, 2015), we solve and analyse our asymmetric information game model. The equilibrium strategy $\{((\eta_\theta, p_\theta),(B,u)), \theta \in \{H,L\}, B \in \{0,1\}\}$, where B indicates whether the consumer purchases the product with 1 representing purchase, should satisfy the following conditions:

(1) sequential rationality

The firm's best response strategy is $(\eta_\theta, p_\theta) \in \arg\max B\Pi_\theta(\eta, p)$.

The consumers' best response strategy is $B = 1, \text{if } u(\eta_\theta, p_\theta, \hat{\rho}) > 0$.

(2) Bayesian consistency of beliefs

If $(\eta_H, p_H) = (\eta_L, p_L)$, then $\hat{\rho} = \rho$.

If $(\eta_H, p_H) \ne (\eta_L, p_L)$, then $\hat{\rho} = 1$ and $\Pr(\hat{\theta} = H \mid \eta_L, p_L) = 0$.

In general, there are two categories of perfect Bayesian equilibria: the pooling PBE (denoted with a superscript g) and the separating PBE (denoted with a superscript s). In a pooling equilibrium, the signal is uninformative as both types of firms signal the same message and consumers cannot distinguish their types. In this chapter, it implies that the firm always self-labels its product greenness as H and the standard firm engages in product-level greenwashing. Thus, we refer to the pooling equilibrium as greenwashing equilibrium. In a separating equilibrium, different types of firms signal different messages to distinguish from each other.

Greenwashing equilibrium

We first establish the case when uninformed consumers do not infer product greenness through the observed signal, i.e. $\hat{\rho} = \rho$, and they take the expected product greenness $\hat{\theta} = \rho H + (1-\rho)L$ as the greenness to derive their utilities. Then, the firm's objective is to maximise its profit given the following functions:

$$\begin{aligned} \Pi_H(\eta, p) &= (p-c)\Big(\delta\big(1 - b_p p + \eta b_g (H - R)\big) + (1-\delta)\big(1 - b_p p + \eta b_g\left(\rho H + (1-\rho)L - R\right)\big)\Big) - \alpha\eta^2 \\ \Pi_L(\eta, p) &= (p-c)\Big(\delta\big(1 - b_p p\big) + (1-\delta)\big(1 - b_p p + \eta b_g\left(\rho H + (1-\rho)L - R\right)\big)\Big) - \alpha\eta^2 \end{aligned} \tag{13}$$

We first analyse the scenario that the firm with different types of green products makes individual profit-maximising decisions, i.e. greenwashing behaviour is not allowed, the firm cannot take advantage of the consumers' uncertainty about product greenness to greenwash and reap more benefits. Solving this optimisation problem yields the following solutions.

The optimal green marketing effort is $\eta_H^{ns} = \frac{\left(\rho + (1-\rho)\delta\right) b_g (H-R)(1-b_p c)}{4b_p \alpha - \left(\left(\rho + (1-\rho)\delta\right) b_g (H-R)\right)^2}$ and $\eta_L^{ns} = \frac{(1-\delta)\rho b_g (H-R)(1-b_p c)}{4b_p \alpha - \left((1-\delta)\rho b_g (H-R)\right)^2}$.

The optimal selling price is $p_H^{ns} = \frac{2\alpha(1-b_p c)}{4b_p \alpha - \left(\left(\rho + (1-\rho)\delta\right) b_g (H-R)\right)^2} + c$ and $p_L^{ns} = \frac{2\alpha(1-b_p c)}{4b_p \alpha - \left((1-\delta)\rho b_g (H-R)\right)^2} + c$.

Substituting these optimal decisions into corresponding profit functions yields each type of the firm's optimal expected profit $\Pi_H^{ns} = \frac{\alpha(1-b_p c)^2}{4b_p \alpha - \left(\left(\rho + (1-\rho)\delta\right) b_g (H-R)\right)^2}$ and $\Pi_L^{ns} = \frac{\alpha(1-b_p c)^2}{4b_p \alpha - \left((1-\delta)\rho b_g (H-R)\right)^2}$.

When some consumers are uncertain regarding the true product greenness and perceive greenness as the expected value based on their prior probabilities, the standard firm will raise its green marketing effort and selling price for a larger profit compared to the complete information case. In contrast, the green firm tends to reduce its green marketing investment and lower selling price, resulting in a lower profit. Under such conditions, the investment in green marketing does not effectively signal the firm's type but rather shapes consumers' WTP.

When the firm employs green marketing as a signalling tool and reaches the greenwashing equilibrium, both types of firms self-label the product as high-greenness and adopt the same strategy (η^g, p^g) so that the firm's type is indistinguishable for consumers. To ensure that neither type of firm has profitable deviation from the equilibrium strategy, the equilibrium strategy should satisfy the following conditions:

$$\begin{cases} \Pi_H^g(\eta^g, p^g, \hat{\rho} = \rho) \geq 0 \\ \Pi_L^g(\eta^g, p^g, \hat{\rho} = \rho) \geq \Pi_L^{ci} \\ u(\eta^g, p^g, \hat{\rho} = \rho) > 0 \end{cases}$$

Analysing Eq. (13) and its solutions, we can find that only when the market is totally nontransparent, i.e. $\delta = 0$, can we obtain the pooling profit-optimal strategy $(\eta^g, p^g) = \left(\frac{\rho b_g (H-R)(1-b_p c)}{4b_p \alpha - \left(\rho b_g (H-R)\right)^2}, \frac{2\alpha(1-b_p c)}{4b_p \alpha - \left(\rho b_g (H-R)\right)^2} + c \right)$, which results in an identical profit $\Pi_L^g = \Pi_H^g = \frac{\alpha(1-b_p c)^2}{4b_p \alpha - \left(\rho b_g (H-R)\right)^2}$. The consumers' belief that supports the equilibrium and survives the refinement by the intuitive criterion (Cho and Kreps, 1987) is that $\hat{\rho} = \rho$ if they observe (η^g, p^g) and $\hat{\rho} = 0$ otherwise. Figure 5.1 demonstrates the greenwashing equilibrium by analysing the iso-payoff contour of both types of firms and consumers when $\delta = 0$. The grey-shaded area in the figure represents the intersection region that satisfies the above constraint conditions. The bold line of the best response strategy function $p^{g*} = \frac{1 + b_p c + \rho \eta b_g (H-R)}{2b_p}$

confined in the feasible region is the firm's strategy set satisfying these constraints. Its optimal profit is achieved at (η^g, p^g).

By comparison, we have $\Pi_L^{ci} < \Pi_L^{ns} < \Pi_L^g = \Pi_H^g < \Pi_H^{ns} < \Pi_H^{ci}$. It becomes apparent that when some consumers are uncertain about product greenness, market transparency plays a crucial role in favouring green firms. The presence of informed consumers incentivises green firms to disclose their true product type. On the other hand, opportunistic standard firms can exploit consumer uncertainty to their advantage. If all consumers are uninformed, a standard firm may engage in greenwashing due to perceived economic benefits. This behaviour can be strategic, especially when launching products under green labels. However, it raises significant ethical concerns as it misleads consumers about the true environmental benefits of the products. Such deception can erode trust, damage the firm's reputation, and undermine the integrity of the green market in the long run (Chen et al., 2020; Seele and Gatti, 2017). Therefore, despite the potential short-term economic benefits, the ethical implications and risk of consumer deception must be carefully considered.

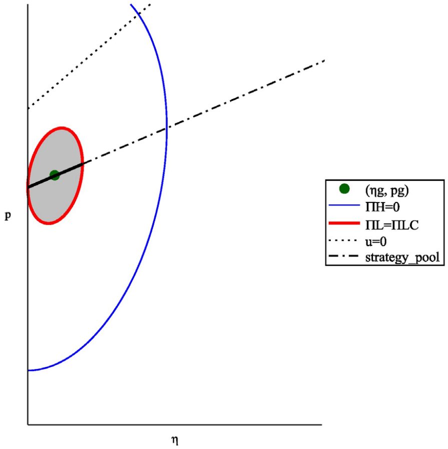

Figure 5.1 Characterisation of the greenwashing equilibrium

Separating equilibrium

In the separating equilibrium, the firm reveals its true product type by its signalling strategy. Consumers are fully informed of the product greenness after observing the firm's signals. The green firm chooses a strategy differently from the standard firm, solving the following constrained optimisation problem:

$$\begin{aligned}
&\Pi_H^s(\eta_H, p_H, \hat{\rho}=1) = \max_{\eta,p}(p-c)\left(1-b_p p+\eta b_g(H-R)\right)-\alpha\eta^2 \\
&\text{s.t. } \Pi_H^s(\eta_H, p_H, \hat{\rho}=1) \geq \Pi_H^{ns} \\
&\quad \Pi_H^s(\eta_H, p_H, \hat{\rho}=1) \geq \Pi_{HL} \\
&\quad \Pi_L^s(\eta_H, p_H, \hat{\rho}=1) \leq \Pi_L^{ci} \\
&\quad u(\eta_H, p_H, \hat{\rho}=1) > 0
\end{aligned} \tag{14}$$

where $\Pi_{HL} = \max_{\eta,p}(p-c)\left(\delta\left(1-b_p p+\eta b_g(H-R)\right)+(1-\delta)\left(1-b_p p\right)\right)-\alpha\eta^2$ is the profit of the green firm with high-greenness product but being believed to be low greenness. Solving the optimisation problem yields $\Pi_{HL} = \dfrac{\alpha(1-b_p c)^2}{4b_p\alpha - \left(\delta b_g (H-R)\right)^2}$. Furthermore, the standard firm's profit gained by mimicking the green firm's strategy and successfully deceiving the uninformed consumers into believing that its product is of the high-greenness type is $\Pi_L^s(\eta_H, p_H, \hat{\rho}=1) = (p_H - c)\left(\delta(1-b_p p_H) + (1-\delta)\left(1 - b_p p_H + \eta_H b_g (H-R)\right)\right) - \alpha\eta_H^2$. The first two constraints suggest that in the separating equilibrium, the green firm will signal and avoid being misperceived as a low-greenness firm. By comparison, we have $\Pi_H^{ns} > \Pi_{HL}$, thus allowing the consolidation of the two constraints into the first constraint. The third constraint indicates that the standard firm is not willing to mimic the green firm's strategy due to its lack of economic advantages. Then, it is intuitive that the standard firm's strategy is its strategy under complete information (η_L^{ci}, p_L^{ci}). We next analyse the green firm's strategy by employing the method of Lagrange multipliers (Pindyck and Rubinfeld, 2013).

We first analyse the green firm's optimal strategy under complete information (η_H^{ci}, p_H^{ci}), which corresponds to the scenario with a zero Lagrange multiplier in the separating equilibrium analysis. By comparing the profits, we can find that the constraint $\Pi_H^{ci} \geq \Pi_{HL}$ always holds. Now, substituting (η_H^{ci}, p_H^{ci}) into Π_L^s yields the standard firm's profit $\dfrac{\left(4b_p\alpha - (1+2\delta)\left(b_g(H-R)\right)^2\right)\alpha(1-b_p c)^2}{\left(4b_p\alpha - \left(b_g(H-R)\right)^2\right)^2}$. We can find that this strategy satisfies the constraint $\Pi_L^s < \Pi_L^{ci}$ under the restriction condition $\delta_u < \delta < 1$ where $\delta_u = \dfrac{4b_p\alpha - \left(b_g(H-R)\right)^2}{8b_p\alpha}$. That is, when market transparency satisfies the condition, the green firm's equilibrium strategy in the complete information case (η_H^{ci}, p_H^{ci}) is in the feasible region where the standard firm cannot profitably mimic it. Therefore, under this condition, the separating equilibrium is the same as the equilibrium under complete information.

We next focus on the situation when $0 < \delta \leq \delta_u$, the green firm's complete information strategy is in the non-feasible region where the standard firm would think of mimicry and the constraint $\Pi_L^{as}(\eta_H, p_H, \hat{\rho}=1) = \Pi_L^{ci}$ applies. The solutions of this constrained optimisation problem are $\eta_H^s = X(1-b_p c)$ and $p_H^s = \dfrac{(1+\sqrt{1+16b_p\alpha X^2})(1-b_p c)}{4b_p} + c$, where $X > 0$ and its specific expression is given below:

$$\begin{aligned}
X &= \frac{2^{\frac{2}{3}}\left(x_3^2 + 2^{\frac{2}{3}}(b_p\alpha)^2(64b_p\alpha - 19x_2)\right)}{12x_2x_3b_p\alpha} + \frac{2x_1}{3x_2} \\
x_1 &= (1-\delta)b_g(H-R) \\
x_2 &= 4b_p\alpha - x_1^2 \\
x_3 &= \left((b_p\alpha)^2\left(3^{\frac{3}{2}}x_2(x_2 - 6b_p\alpha)\sqrt{x_2 + 28x_1^2} + (27x_2^2 - 164b_p\alpha x_2 + 512(b_p\alpha)^2)x_1\right)\right)^{\frac{1}{3}}
\end{aligned} .$$

The green firm setting (η_H^s, p_H^s) obtains the optimal profit $\Pi_H^s = \dfrac{\left((1+\sqrt{1+16b_p\alpha X^2})(\frac{1}{2} + b_g(H-R)X) - 8b_p\alpha X^2\right)(1-b_p c)^2}{4b_p}$ under the existence condition

$\delta_l \le \delta \le \delta_u$ where δ_l is uniquely determined by the equation $4b_p\alpha - \left((1+\sqrt{1+16b_p\alpha X^2})(\frac{1}{2}+b_g(H-R)X)-8b_p\alpha X^2\right)\left(4b_p\alpha - \left((\rho+(1-\rho)\delta)b_g(H-R)\right)^2\right)=0$.

Therefore, we put forward the following proposition about the separating equilibrium:

Proposition 5.1 A separating equilibrium exists when $\delta_l \le \delta \le \delta_u$. The strategy of the standard firm is (η_L^{ci}, p_L^{ci}) and the green firm's strategy is (η_H^{s}, p_H^{s}). The consumers' belief is that the product greenness is high while upon observing (η_H^{s}, p_H^{s}), i.e. $\hat{\rho}=1$, and low otherwise.

Proof: See Appendix A.

Figure 5.2 depicts the separating equilibrium by presenting the profit contours for the green firm with a profit Π_H^{ns} and the mimicking standard firm with a profit Π_L^{ci}, respectively. The tan-shaded area in the figure is the feasible region satisfied the above constraint conditions. The bold part of the best response strategy function confined in the feasible region is the green firm's strategy set satisfying these constraints. Figure 5.2(a) and Figure 5.2(b) show the cases where the green firm's complete information strategy is in the feasible region and non-feasible region respectively. In Figure 5.2(a), market transparency is sufficiently large. The green firm prefers to adopt a strategy from the solution set, the effective part of $p_H^{ci*}=\frac{\eta b_g(H-R)}{2b_p}+\frac{1+b_p c}{2b_p}$ inside the feasible region, to make a higher profit. Its unique dominant equilibrium strategy is (η_H^{ci}, p_H^{ci}) at which the highest profit is obtained.

In Figure 5.2(b), market transparency is moderately small. The green firm will pursue a strategy following the function $p^{s*}=\frac{\eta b_g(H-R)\left(1-(1-\delta)\lambda\right)}{2b_p(1-\lambda)}+\frac{1+b_p c}{2b_p}$ inside the feasible region. In this case, (η_H^{s}, p_H^{s}) is its unique dominant separating equilibrium that effectively signals high product greenness while deterring the standard firm from mimicking and achieving the optimal profit. From the above analysis, we have Lagrange multiplier $0<\lambda<1$. Considering this condition, the slope of the green firm's best response strategy function p^{s*} is greater than that of p_H^{ci*}. Therefore, we can propose the following remark to describe a feature of the separating equilibrium:

Remark 5.1 In the separating equilibrium of the case when market transparency is moderately small, the green firm will invest more in green marketing effort and charge a higher price than its respective complete information benchmarks.

Rather than simply adopting the optimal strategy under complete information to separate from the standard firm when consumers are sufficiently informed, information asymmetry at a lower market transparency level compels the green firm to elevate its marketing and pricing strategy beyond the complete information level, rendering it unprofitable for the standard firm to mimic. We refer to the former equilibrium as "effortless separating equilibrium" and the latter as "effortful separating equilibrium" for simplicity.

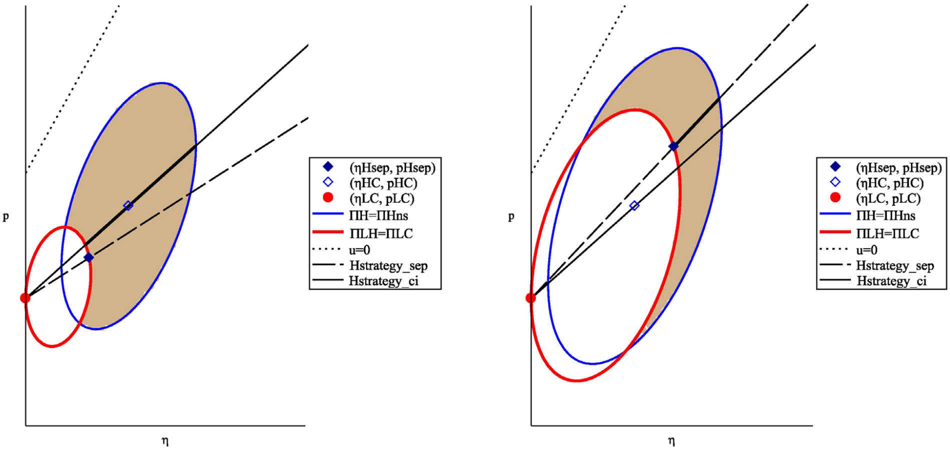

Figure 5.2(a-b) Characterisation of the separating equilibrium when market transparency is sufficiently large (a) and small (b)

Table 5.1 summarises the equilibrium outcomes in the asymmetric information case and Proposition 5.2 presents the conditions under which the standard firm engages in greenwashing and under which the green firm adopts separating strategies.

Proposition 5.2 The existence of a greenwashing or separating equilibrium depends on the fraction of the informed consumers in the market. Greater market transparency facilitates easier separation, specifically:

(1) In the absence of informed consumers, i.e. $\delta = 0$, the standard firm will greenwash to mimic the green firm's strategy, making it indistinguishable from the green firm to the uninformed consumers;

(2) When the informed consumers are minimal, i.e. $0 < \delta < \delta_l$, both types of firms favour using green marketing to influence consumer WTP, rather than employing it as a signalling tool, as it is more profitable;

(3) With low market transparency, i.e. $\delta_l \le \delta \le \delta_u$, the green firm needs to increase its strategies above the complete information benchmark to separate from the standard firm;

(4) High market transparency, i.e. $\delta_u < \delta < 1$, leads both types of firms to adopt optimal strategies as in the complete information case.

Table 5.1 Equilibrium under asymmetric information

	Standard firm	Green firm		
Equilibrium outcome	Greenwashing	No signalling	Effortful separating	Effortless separating
Existence condition	$\delta = 0$	$0 < \delta < \delta_l$	$\delta_l \le \delta \le \delta_u$	$\delta_u < \delta < 1$
Strategy (η, p)	(η^g, p^g)	(η_H^{ns}, p_H^{ns})	(η_H^s, p_H^s)	(η_H^{ci}, p_H^{ci})

5.4.3 Impacts of market transparency

The analytical analysis reveals that market transparency significantly affects decisions, profits, and corresponding comparative relationships. The profit variations influencing the firm's strategies depend on specific thresholds of market transparency. However, the complexity of the analytical expressions in the separating equilibrium poses challenges in deriving tractable solutions. To gain a holistic understanding of the impacts of market transparency and visualise the insights, we perform numerical analyses employing Maple 2022.0 software in this section. The fixed values throughout for the baseline parameters are $R = 0.2, H = 0.6, v = 0.8, b_p = 1, b_g = 3, c = 0.3, \alpha = 1.5, \rho = 0.5$. Then, the thresholds are $\delta_l = 0.034, \delta_u = 0.38$.

Figure 5.3(a) presents the impact of market transparency on green marketing strategies. Similar patterns are observed in pricing strategies, but we omit the graph for brevity. Figure 5.3(b) demonstrates the firm's strategy choices determined by its relative profitability in the asymmetric information case. In line with aforementioned propositions, limited transparency incentivises a standard firm to invest in green marketing and may engage in greenwashing when the transparency is zero to gain a higher profit. This would not occur in cases of complete information or when the consumers can tell the firm's type.

A green firm will adopt a separating equilibrium strategy when the potential profit surpasses that of not utilising the signalling tool. The effective transparency range for this purpose is $[\delta_l, 1)$. The equilibrium profit increases with transparency until it reaches the complete information level at the threshold δ_u, beyond which transparency ceases to impact the firm's strategy and profit. In the effortful separating equilibrium when $\delta \in [\delta_l, \delta_u]$, the green firm will increase its green marketing investment and price above their respective levels under complete information and those without using signalling tools. The increased investment costs are offset by the benefits derived from expanded consumer willingness to pay. Moreover, the green marketing and pricing strategies is decreasing in transparency until they converge with the effortless complete information levels when $\delta \in (\delta_u, 1)$.

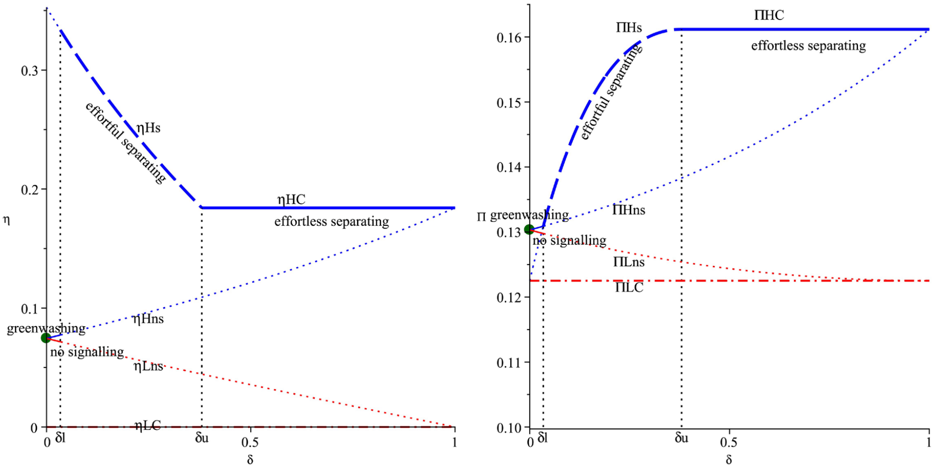

Figure 5.3(a-b) Impacts of market transparency on green marketing efforts and profits

In addition to the firm's economic benefits, we assess societal impacts through a widely accepted social welfare measure. Social welfare, expressed as $SW = \Pi + CS + EB$, is the sum of firm profit, consumer surplus, and environmental benefits (Guo et al., 2020; Pindyck and Rubinfeld, 2013), with $EB = D\theta$. Individual consumer surplus is the difference between the maximum price a consumer is willing to pay for the green product and the actual price, and then the aggregate $CS = \frac{1}{2}\left(D^{-1}(0) - p\right)D(p)$. We derive specific social welfare functions for each case and accordingly depict them with respect to market transparency. Figure 5.4(a) illustrates consumer surplus, while similar trends in environmental benefits exist, though we exclude the graph for brevity. Figure 5.4(b) displays social welfare. Notably, a standard firm's greenwashing behaviour raises consumer surplus and social welfare compared to the complete information case. This increase is primarily attributed to the heightened immediate sales resulting from increased investments in green marketing. Therefore, greenwashing does not always have negative impacts in terms of fostering green consumerism and short-term profitability. In the case where a green firm engages in effortful separating, consumer surplus and environmental benefits decrease as market transparency increases but remain higher than complete information levels. The social welfare is concave in transparency and it may be lower than the complete information level when the transparency is relatively small within the effective range.

In summary, we make the following remark to characterise the impacts of market transparency on firms' sustainability performance:

Remark 5.2 Given asymmetric information, greater market transparency can lead to higher firm profits but doesn't necessarily result in increased consumer surplus, environmental benefits, or social welfare.

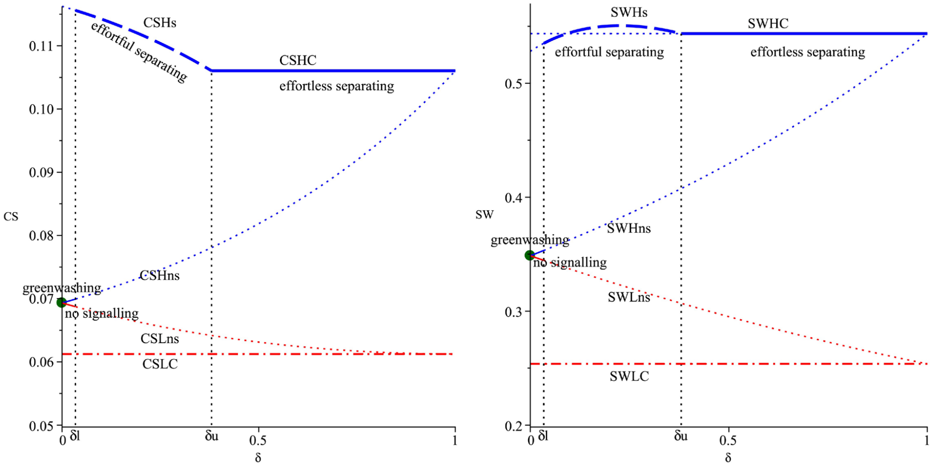

Figure 5.4(a-b) Impacts of market transparency on consumer surplus and social welfare

5.4.4 Implications and discussions

In this section, we discuss the broader implications of greenwashing within the context of green marketing. The discussion is divided into three subsections: managerial, ethical, and sustainability implications. Each subsection addresses the practical, ethical, and sustainability-related consequences of green marketing practices and offers insights into how these can be leveraged to promote genuine sustainability efforts.

Managerial implications

Green firms can exert efforts to influence the level of market transparency, namely, the proportion of informed green consumers in the market. Success in green marketing requires a profound understanding of market composition (Francis, 2023; Nekmahmud and Fekete-Farkas, 2020), necessitating detailed market research to evaluate consumer awareness and perceptions of green products labelled with carbon emission information, such as Oatly's carbon labelling (Oatly, 2024), and their willingness to pay for these products.

The findings of this research suggest that tailoring green marketing strategies to suit markets with varying levels of transparency enables green firms to effectively communicate genuine product greenness while preventing imitation by standard firms, thereby reducing product-level greenwashing. Therefore, green firms are advised to launch campaigns to educate consumers, thus enhancing the credibility of their green marketing initiatives and cultivating a more informed consumer base. Such campaigns could include the development of interactive online platforms that offer engaging and educational content on the environmental impacts of products (Ma and Liu, 2022), social media challenges that promote sustainable practices among consumers and create viral awareness (Brereton, 2018; Ktisti et al., 2022), and educational workshops or events that provide direct engagement on sustainability topics. These initiatives not only inform consumers about the environmental efforts of firms but also actively involve them in the sustainable movement, bridging the gap between green intentions and actions.

However, the observation that increased transparency leads to profit growth does not directly translate to increased green marketing investment or consumer surplus; our findings reveal that heightened market transparency does not consistently result in greater green investments or consumer surplus. This underscores the need for firms to carefully modulate their transparency efforts, either by providing sufficient information to foster a certain fraction of informed consumers or by strategically withholding information to leverage information asymmetry. This underscores the strategic application of market transparency as a tool for enhancing green marketing effectiveness and fostering a deeper consumer engagement with green products.

Ethical implications

Greenwashing presents significant ethical challenges, raising questions about the moral responsibilities of firms in their marketing practices. While greenwashing can increase consumer awareness and willingness to pay for green products, it inherently involves deception, as firms present their products as more environmentally friendly than they truly are. From a moral standpoint, this deception is problematic because it violates the principle of honesty and can undermine consumer trust (Chen and Chang, 2013; Christensen et al., 2013). The ethical implications of greenwashing extend beyond individual firms, potentially damaging overall trust in green markets and hindering genuine sustainability efforts (Chen et al., 2020; Seele and Gatti, 2017).

Philosophical frameworks highlight the moral responsibility of firms to engage in ethical marketing strategies that prioritise truthfulness and transparency (Ferrell et al., 2005). Therefore, moral firms should recognise the ethical and market risks associated with greenwashing and balance short-term profitability with long-term sustainability by avoiding greenwashing and embracing genuine green marketing practices. Nevertheless, as highlighted by Glavas et al. (2023) and Yildirim (2023), those firms can use transparency to build credibility and leverage incidents of greenwashing as opportunities to enhance their sustainability efforts. In the long run, firms that adhere to truthful marketing and rigorous environmental standards gain competitive advantages in an increasingly eco-conscious market (Gatti et al., 2019; Sharma, 2021).

Sustainability implications

Firms should recognise that while greenwashing is ethically questionable and potentially harmful to consumer trust, the market's response to perceived greenness can drive a more profound commitment to genuine green practices (Yildirim, 2023). Our analysis highlights the complex role of greenwashing, which, despite its traditionally negative perception, can signal a firm's green preferences, investments, or efforts—even if these do not always meet the highest standards. This introduces a counterintuitive aspect to the investigation on greenwashing, suggesting that suboptimal green efforts communicated through greenwashing can positively message a firm's environmental commitment, and thereby increase consumers' willingness to pay (Christensen et al., 2013). The paradoxical effect of greenwashing, potentially motivating standard firms to amplify their green marketing investments, illustrates a sophisticated dynamic where perceived green efforts may encourage a deeper commitment to sustainability. This suggests that firms could strategically use the competitive pressure generated by green marketing to enhance their green initiatives, thereby transforming potential negative impacts into catalysts for positive change (Glavas et al., 2023).

However, this strategy requires careful navigation to ensure that increased marketing investments are indeed matched by substantive improvements in product greenness. Ultimately, this approach could lead to a virtuous cycle, where the desire to maintain competitive advantage drives not only more aggressive green marketing but also significant advancements in corporate sustainability. Firms adopting this strategy can contribute to a shift in industry standards, where genuine environmental responsibility becomes a critical component of brand identity and consumer value, fostering a market environment where informed choices support broader social welfare and sustainability goals.

5.5 Conclusion

This research has investigated supply chain firms' green marketing and pricing strategies, considering information asymmetry regarding product greenness between the firm and consumers. Our analysis underscores the pivotal role of market transparency in shaping firms' strategy choices. We find that adopting a greenwashing or a separating equilibrium strategy critically depends on the fraction of informed consumers in the market, with greater transparency facilitating easier separation between genuine green firms and opportunistic standard firms.

Specifically, when transparency is appropriately low, firms tend to prioritise green marketing as a tool to influence consumer willingness to pay. Greenwashing occurs when the market is entirely nontransparent. However, under high transparency conditions, green firms can prevent standard firms' greenwashing practices by opting for strategies that are either above or the same as those in the complete information case. It is noted that there is a discontinuity in transparency when shifting between the strategies. When transparency reaches the threshold leading to the effortless separating equilibrium, outcomes remain invariant, mirroring those at complete information levels. Continuously increasing market transparency is implausible and not always beneficial regarding green marketing investment and consumer surplus.

The numerical analyses further reveal the impact of market transparency on sustainability performance. Notably, we observe that limited transparency incentivises standard firms, which initially lack the motivation to invest in green marketing within fully transparent markets, to engage in green marketing to maximise their profits. This contributes to enhanced consumer willingness to pay. Consequently, greenwashing may not invariably entail negative implications for societal welfare, challenging the prevailing belief that it predominantly disadvantages consumers and the environment.

This research establishes a foundation for exploring the complexities of green marketing under asymmetric information, using a simplified signalling game framework. Future studies can extend this investigation by utilising more sophisticated analytical models that more accurately reflect the complexities of real-world market conditions and consumer behaviours. Such models would include considerations of (1) supply chain competition, illustrating the strategic interactions between competing firms' green marketing efforts; (2) an analysis of green marketing's effectiveness and consumer reaction across multiple selling periods, considering the long-term ethical implications of greenwashing on consumer trust and corporate reputation; (3) strategies to enhance the credibility of self-labelling, examining the effects of third-party certifications, regulatory standards, and mechanisms for building consumer trust; (4) and the dynamics of consumer bargaining power, concentrating on how a deeper understanding of consumers' inherent evaluations of greenness and their sensitivity to price could impact market outcomes. By incorporating these aspects, future research could reveal fresh insights into the dynamics of the green product market, offering a comprehensive understanding of how green marketing strategies influence both environmental sustainability and consumer engagement.

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Chapter 6 Conclusion

This concluding chapter revisits the research questions that have steered our exploration of decisions and coordination in green supply chains with asymmetric information. It integrates the findings, highlighting both the theoretical advancements and practical insights gained. Additionally, this chapter looks beyond the current study to outline directions for future research, identifying promising areas and domains yet to be explored that merit further academic attention. The aim is to encapsulate the essence of the research, offering a comprehensive summary of its contributions while setting the stage for ongoing exploration in the ever-evolving field of green supply chain management.

6.1 Research questions revisited and implications

In this section, we revisit the research questions proposed in Chapter 1, summarising their answers and implications for modellers, industrial practitioners, and policymakers.

RQ1 What role do green practices play in shaping supply chain sustainability?

This research investigates the effects of demand expansion and cost reduction resulting from the adoption of green practices.

Demand expansion, driven by green product innovation and green marketing practices, is incorporated into the demand functions of our game-theoretic models through the increased consumer sensitivity to green products. It reflects the capitalisation effectiveness of consumers' green preference, enhancing firm profitability through increased investment in green initiatives.

On the cost reduction front, we study this effect from two perspectives: adjusting the cost parameter for marginal and development cost-intensive green products (Chapter 3) and integrating the direct cost reductions and spillovers from green process innovations into cost functions (Chapter 4). We find that cost reduction, particularly through green process innovations, is a compelling incentive for greening investments, benefiting both the supply chain firms and consumers by enabling lower retail prices and wider market penetration. However, the potential for greenwashing arises when the visibility and spillover effects of green innovations are manipulated, affecting the pass of cost reductions, green product innovation investments, and overall supply chain profitability.

Theoretical implications: This research highlights the dual role of green practices in driving demand and reducing costs, presenting a sophisticated perspective on their strategic significance. It underscores the necessity for a thorough incorporation of these effects within both demand and cost modelling frameworks. By doing so, it enriches the theoretical understanding of how green initiatives can serve as pivotal elements in enhancing supply chain sustainability, advocating for a more integrated approach in the game model development and analysis.

Managerial insights:

(1) Invest strategically in green innovations: Firms can strategically invest in green product innovations and marketing to leverage the demand expansion effect. This involves not only developing green products but also effectively communicating their benefits to consumers to enhance profitability and market penetration.

(2) Emphasise cost-effective green processes: It would be beneficial for firms to prioritise green process innovations that lead to cost reductions within the supply chain. These innovations not only improve the environmental footprint but also benefit green consumers by enabling lower retail prices, thereby increasing market penetration and competitive advantage. Policymakers can consider offering incentives, such as tax breaks or subsidies, for firms that make verifiable investments in green process innovations (Nie et al., 2020; Yang et al., 2022; Zhang and Wang, 2017). Such incentives can encourage firms to pursue genuine sustainability efforts and reduce greenwashing(Wu et al., 2019).

(3) Monitor and manage spillover effects: Focal firms should be conscious about the spillover effects of green innovations and foster collaboration for spillover management (Yan and Yang, 2018). Collaborative efforts can facilitate the implementation of green practices, enhancing the overall sustainability of the industry (Hu et al., 2019; Iida, 2012).

RQ2 What are the effects of asymmetric information on greening investment and pricing decisions within supply chains?

This research examines asymmetric information regarding the greenness of processes and products. Asymmetric process greenness information leads to firm-level greenwashing, where firms without substantive investments in green process innovations untruthfully report their green levels in process innovations to exploit the unobservability of such investments for profit (Chapter 4). Similarly, asymmetric information on product greenness results in product-level greenwashing, where firms misrepresent the environmental benefits of products with lower greenness through visible green marketing and pricing signals (Chapter 5).

The research finds that firm-level greenwashing undermines genuine green innovation efforts, negatively impacting retail pricing and profitability. In contrast, product-level greenwashing motivates firms to enhance their green marketing investments, thereby increasing consumer willingness to pay for green products, consumer surplus, and potentially social welfare. As a result, firms engaged in greenwashing can charge higher prices and achieve greater profits.

Transparency is identified as a critical factor in scenarios of asymmetric information. This study distinguishes between two types of transparency: transparency in green innovation practices and transparency in the green market. The former pertains to the observability of a firm's green innovation investments to other supply chain participants, particularly relevant in the context of firm-level greenwashing. The latter refers to the proportion of consumers informed about the true greenness of products, which is crucial in addressing product-level greenwashing. The findings suggest that the impact of transparency on supply chain firms' decisions and performance is complex and nonmonotonic. For instance, greater transparency in green process innovations can lead to cost reductions being passed on to consumers through lower retail prices. However, the effect of transparency on investments in green product and process innovations, as well as on profitability, also depends on the spillover intensity of the green process innovation. Meanwhile, in the context of asymmetric product greenness information, increased market transparency can facilitate the separation from greenwashing, potentially leading to higher firm profits but not necessarily resulting in greater green marketing investment, product pricing, consumer surplus, environmental benefits, or social welfare.

Theoretical implications: This research broadens the application of game theory to model and analyse greenwashing in supply chain management, which deserves further research (Inês et al., 2023). The findings extend the theoretical landscape concerning the effects of asymmetric greening information in supply chains with green practices. Considering transparency in green innovations and market informedness, this research contributes to a deeper understanding of how information asymmetry shapes the firms' greening investment and pricing decisions. This contribution not only deepens the theoretical discourse but also sets a foundation for future investigations into the strategic interplay between transparency, information asymmetry, and green practices in supply chains.

Managerial insights:

(1) Maintain transparency and verification mechanisms: To mitigate the risks associated with greenwashing, it is crucial for managers to maintain certain levels of transparency regarding their green practices. This involves clear communication the true greenness of processes and products, ensuring that claims about green practices and environmental benefits of products are substantiated and verifiable. Third-party certifications or adopting technologies like AI and blockchain can provide traceability and enhance transparency (Bai and Sarkis, 2020; Dos Santos et al., 2021).

(2) Educate consumers and stakeholders: Both practitioners and policymakers can invest in educational campaigns to raise awareness about the environmental and economic benefits of green practices and products. It can enhance consumers and stakeholders' appreciation and willingness to support green practices and products. An informed consumer base is more likely to support companies with genuine green practices, thereby driving market competition towards genuine sustainable transition (Hojnik et al., 2019).

(3) Develop policies to discourage greenwashing: Policymakers can develop and implement regulatory measures that discourage greenwashing by requiring detailed disclosures of green efforts and third-party verification of environmental claims, as exemplified by California's voluntary carbon market disclosures act[1] and the EU's sustainable finance disclosure regulation[2].

RQ3 What incentive contracts can firms employ to effectively coordinate the green supply chain?

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[1] https://corpgov.law.harvard.edu/2023/11/18/california-enacts-anti-greenwashing-requirements/

[2] https://www.pwc.ch/en/insights/sustainability/esg-disclosures-are-you-at-risk-for-greenwashing.html

This research employs a bargaining wholesale price contract to coordinate the green supply chain under symmetric information (Chapter 3) and a two-part contract complemented by advanced technologies to mitigate greenwashing and coordinate the green supply chain under asymmetric information (Chapter 4). The effectiveness of the bargaining wholesale price contract depends on supply chain firms' 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. The coordination efficiency of the two-part contract is influenced by the technology adoption cost to enforce the incentive contract. With favourable technology cost to improve the process innovation transparency, mitigation of greenwashing and full coordination are achievable, enhancing the overall sustainability performance of the supply chain.

Theoretical implications: This research advances the theoretical landscape of incentive contracts in green supply chains, particularly under asymmetric information. It provides a novel perspective on the interplay between advanced technology adoption, contract design, and supply chain coordination efficiency, enriching the discourse on green supply chain management strategies.

Managerial insights:

(1) Adopt flexible contractual arrangements: Firms can consider flexible contractual arrangements, like bargaining contracts and two-part contracts, that can be adapted based on the specific dynamics and bargaining power within the supply chain. These contracts can be particularly effective in aligning incentives across the supply chain, leading to enhanced sustainability performance (Chauhan and Singh, 2018).

(2) Leverage technology for better transparency and coordination: Firms can invest in advanced technologies that improve transparency and traceability of green practices (Yang et al., 2021). Technologies such as AI and blockchain can facilitate the sharing of verifiable information across the supply chain, enhancing coordination and reducing the likelihood of greenwashing (Charles et al., 2023). It is noted that practitioners should carefully evaluate the costs associated with adopting new technologies to ensure that it is economically viable. Policymakers can promote and support policies that facilitate the adoption of advanced technologies within supply chains. This could include subsidies for technology adoption, tax incentives for sustainable practices, or funding for research and development in green technologies. Examples of such initiatives are the EU's Digital Europe Programme[3] and China's blockchain project for the Belt and Road Initiative[4].

6.2 Contributions

To provide a clear overview, this section summarises the intuitive and salient results of the research, highlighting outcomes that align with conventional expectations and those that stand out due to their counter-intuitive nature or unexpected complexity. This distinction underscores the relevance and robustness of the game-theoretic models used and reveals the intricate nature of the interactions between supply chain members, induced by varying informational and

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[3] https://commission.europa.eu/funding-tenders/find-funding/eu-funding-programmes/digital-europe-programme_en

[4] https://www.ccn.com/news/crypto/chinese-public-blockchain-belt-road-initiative/

market conditions. The analysis enhances our understanding of the nuanced effects of information asymmetry on green supply chain practices.

Chapter 2 Game-theoretic Models for Sustainable Supply Chains with Asymmetric Information: A Review

Intuitive results:

(1) Government interventions, closed-loop supply chain management, carbon emissions-related activities, and forward green supply chain management are the most frequently investigated sustainable practices.

(2) Unilateral demand and cost information asymmetries receive the most attention, aligning with traditional supply chain coordination literature.

(3) Stackelberg game models are predominantly used to describe power structures within sustainable supply chain management under asymmetric information.

Salient results:

(1) Information asymmetry does not consistently have detrimental impacts on sustainability performance, contrary to traditional beliefs.

(2) Emerging technologies like blockchain and AI are reshaping information sharing and sustainability in supply chain management, necessitating integrated models to study their impacts on green practices and performance.

(3) Despite the prevalence of game-theoretic models, there is significant room for integrating real-world practices to validate theoretical work in sustainable supply chains.

Chapter 3 Decision Analysis and Coordination in Green Supply Chains with Stochastic Demand

Intuitive results:

(1) Higher retailer service levels lead to greener products and increased manufacturer profits.

(2) The dominant manufacturer always retains a profit allocation advantage, which is amplified in the stochastic demand setting.

(3) A wholesale price contract through bargaining can fully coordinate the supply chain and attain Pareto improvement, with the coordinated wholesale price being lower than the decentralised wholesale price.

Salient results:

(1) Demand uncertainty can positively impact product greenness and pricing, challenging the notion that uncertainty typically results in conservative strategies.

(2) Variable cost-reduction green initiatives by the manufacturer can result in greener products at lower prices in the stochastic demand setting.

Chapter 4 Decision-Making and Coordination under Asymmetric Information: Pathways to Green Innovation in Supply Chains

Intuitive results:

(1) The manufacturer’s investment in green process innovation results in higher product greenness, lower retail prices, and greater profits for both the manufacturer and the retailer.

(2) Firm-level greenwashing adversely affects genuine green product innovation, pricing strategies, and the profitability of the supply chain.

(3) The decision to engage in greenwashing depends on the risk of exposure and its financial consequences, with low detection likelihood making greenwashing more attractive, while increased exposure risk diminishes its appeal.

(4) A two-part contract, supported by advanced technologies like AI and blockchain, can align incentives between supply chain partners, mitigating greenwashing and facilitating coordination.

Salient results:

(1) Greenwashing unobservable green process innovation undermines genuine green product innovation, lowering retail prices and retailer profits.

(2) Transparency levels and spillover intensity of green process innovation critically influence supply chain performance and decision-making.

(3) The technology adoption cost to enforce the two-part incentive contract impacts the realised coordination profit and efficiency.

Chapter 5 Green Marketing Strategies in a Supply Chain under Asymmetric Information

Intuitive results:

(1) Under complete information, the green firm's optimal green marketing effort, selling price, and profit increase with product greenness.

(2) Limited market transparency can lead opportunistic firms offering low-greenness products to engage in greenwashing to gain higher profits, a strategy not viable under complete information.

(3) Informed consumers incentivise green firms to disclose their true product type, while firms' green marketing strategy choices depend on market transparency levels.

Salient results:

(1) Product-level greenwashing does not always negatively impact green consumerism and short-term profitability. It encourages firms to invest more in green marketing efforts, thereby enhancing consumer awareness and willingness to pay for green products.

(2) Greater market transparency can lead to higher firm profits but does not necessarily result in increased consumer surplus, environmental benefits, or social welfare.

6.3 Future work

The current research on green supply chain management under asymmetric information highlights significant insights while also revealing limitations, particularly in the simplification of mathematical models which abstract away from the complexities inherent in real-world supply chains. This simplification, while necessary for tractability, opens avenues for future research aimed at enriching our understanding and implementation of green practices within supply chains. Below are elaborated future research directions that are promising to advance the field significantly:

(1) Advanced quantitative models for green practices and greenwashing analysis in supply chain management

The exploration of greenwashing within supply chain management, as noted by Inês et al. (2023), is still in its infancy, with a notable gap in quantitative modelling studies that investigate greenwashing behaviour systematically. Despite the prevalence of greenwashing discussions in real word and empirical research, there is a scarcity of models specifically designed for supply chain contexts. Future research can focus on developing sophisticated game-theoretic models, such as bargaining and evolutionary games, that reflect the dynamic and cooperative nature of supply chain interactions more accurately. These models should account for the non-linear and simultaneous decision-making processes among supply chain members, moving beyond the traditional leader-follower dynamics to embrace more realistic scenarios where private information on green practices is not directly observable (Chen et al., 2019). Additionally, the model development in this field is heavily dependent on the definition of greenwashing. The multifaceted nature of greenwashing, lacking a universally accepted definition (Lyon and Montgomery, 2015; Netto et al., 2020), necessitates a careful operationalisation of the term in future models to capture its various dimensions and impacts accurately.

(2) Impact of information asymmetry on green innovations diffusion

Investigating the impact of information asymmetry on the diffusion of green innovations across supply chains presents a fertile area for research. This direction could examine how the lack of transparent and reliable information about the environmental benefits of innovations affects their adoption by firms and acceptance by consumers. Studies could assess mechanisms to reduce information asymmetry, such as standardisation of sustainability metrics, third-party verification, and blockchain-based traceability systems. Furthermore, research could explore the role of information asymmetry in creating barriers to the implementation of green innovations and identify strategies to overcome these barriers, thereby facilitating a more rapid and widespread adoption of green practices.

(3) Strategies for enhancing coordination in green supply chains with asymmetric information

The challenge of coordinating actions among green supply chain participants in the presence of asymmetric information is a critical area for future investigation. Research should aim to identify and develop innovative coordination mechanisms, such as collaborative platforms and integrated management systems, that facilitate the effective sharing of information and resources. The exploration of policy interventions, industry standards, and collective action as tools for improving supply chain coordination is also essential. Analysing cases of successful coordination can offer practical insights for building resilient and collaborative green supply chain networks. Additionally, the exploration of non-contractual coordination mechanisms in the context of asymmetric information, leveraging advancements in information technology, could provide novel approaches to enhancing supply chain sustainability.

There is a significant need for research on strategies that enhance coordination among participants in green supply chains, particularly in the face of challenges posed by green innovations and information asymmetry. Research should aim to identify and develop innovative coordination mechanisms, such as collaborative platforms and integrated information management systems, that enable effective sharing of information and resources for the implementation of green innovations. Studies could also examine the role of policy interventions, industry standards, and collective action initiatives in improving coordination. By analysing successful cases of coordination in green supply chains, research could provide actionable insights for practitioners on building resilient, sustainable, and collaborative supply chain networks. Additionally, the exploration of non-contractual coordination mechanisms in the context of asymmetric information, leveraging advancements in information technology, could provide novel approaches to enhancing supply chain sustainability.

Moreover, the literature like Zhang et al. (2014) and Li et al. (2021) reveals a common occurrence of coordination failures due to complex decision-making and imperfect contract execution (Liu et al., 2019). Investigating the reasons behind these failures and the limited effectiveness of traditional coordination mechanisms under asymmetric information will be crucial. This research could uncover insights into the conditions under which various coordination strategies succeed or fail, offering guidance for practitioners on navigating the complexities of green supply chain operations with asymmetric information.

These future research directions not only aim to bridge the current gaps in the literature but also to propel the field of green supply chain management towards more effective, sustainable, and transparent practices. By addressing these areas, researchers can contribute to the development of robust frameworks and strategies that support the widespread adoption of green innovations and green supply chain coordination under asymmetric information.

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List of Abbreviations

CSR Corporate Social Responsibility (mainly presented in Chapter 2)

DIGPs Development-Intensive Green Products (mainly presented in Chapters 1 and 3)

GPD Green Product Development (mainly presented in Chapters 1 and 3)

GSCM Green Supply Chain Management (mainly presented in Chapters 1 and 2)

GT Game Theory (mainly presented in Chapter 2)

MDIGPs Marginal and Development cost-Intensive Green Products (mainly presented in Chapters 1 and 3)

MIGPs Marginal cost-Intensive Green Products (mainly presented in Chapters 1 and 3)

SSCM Sustainable Supply Chain Management (mainly presented in Chapter 2)

WTP Willingness To Pay (mainly presented in Chapter 5)

Appendix

Appendix of Chapter 2 Game-theoretic Models for Sustainable Supply Chains with Asymmetric Information: A Review

A1. Article lists and occurrences

Criteria and results	Articles	No. of occurrences
Supply chain structure		
Practices		**104**
NPD	1, 11	2
Greenwashing; corporate fraudulent behaviours	24, 39, 62	3
SCT	32, 52, 53, 54, 60	5
CSR activities	6, 12, 14, 21, 24, 37, 38, 54, 62	9
Carbon emission-dependent activities	7, 13, 15, 16, 25, 27, 30, 42, 44, 45, 52, 59, 61, 63, 64	15
GSCM, SSCM	35, 36, 43, 46, 50, 56, 57, 66, 68, 69, 70, 72, 73	13
Government interventions	7, 15, 16, 17, 19, 21, 25, 28, 30, 31, 33, 35, 39, 43, 44, 45, 47, 49, 55, 58, 59, 61, 63, 64, 65, 66, 67	27
CLSC, RSC: recycling, remanufacturing, etc.	3, 4, 5, 8, 9, 10, 13, 17, 18, 19, 20, 22, 23, 28, 29, 31, 33, 34, 40, 41, 48, 51, 65, 67	24
Other	2, 26, 32, 58, 60, 71	6
Demand_1		**74**
Deterministic	3, 4, 7, 8, 14, 18, 21, 23, 26, 27, 31, 34, 36, 37, 38, 40, 41, 43, 61, 63, 66, 67, 68, 69, 70, 72, 73	27
Random	1, 9, 10, 11, 13, 15, 16, 17, 20, 25, 28, 30, 35, 36, 42, 44, 45, 50, 53, 55, 56, 59, 71 Additive: 9, 10, 11, 13, 15, 17, 20, 28, 30, 35, 36, 44, 45, 50, 55, 56, 59, 71 Multiplicative: 42.	23
Other	12, 22, 24, 46, 47, 51, 54, 57, 60, 62	10
NA	2, 5, 6, 19, 29, 32, 33, 39, 48, 49, 52, 58, 64, 65	14
Demand_2		**74**
Linear	3, 4, 8, 9, 10, 11, 13, 14, 15, 17, 18, 20, 21, 22, 23, 27, 28, 30, 31, 34, 35, 36, 37, 38, 40, 41, 43, 44, 45, 50, 51, 55, 56, 57, 59, 61, 63, 66, 67, 68, 69, 70, 71, 72, 73	45
Nonlinear	7, 26, 42	3
Other	1, 12, 16, 24, 25, 46, 47, 53, 54, 57, 60, 62	12
NA	2, 5, 6, 19, 29, 32, 33, 39, 48, 49, 52, 58, 64, 65	14
SC members		**82**
one-to-one	1, 2, 3, 4, 5, 6, 7, 8, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 26, 27, 29, 30, 32, 34, 35, 37, 38, 42, 43, 46, 50, 54, 55, 56, 57, 58, 59, 61, 62, 63, 66, 69, 70, 71, 72, 73	49

one-to-many	30, 41, 44, 45, 53, 67, 68	7
many-to-one	14, 25, 31, 36	4
three-echelon	9, 10, 28, 40, 41, 48, 51, 60	8
government	19, 21, 32, 33, 39, 47, 49, 64, 65	9
chain-to-chain	21, 43, 61	3
Other	24, 52	2
Cost bearers		**73**
Manufacturer, Supplier	8, 10, 11, 12, 15, 18, 20, 21, 25, 27, 30, 35, 36, 37, 38, 43, 44, 45, 46, 49, 55, 56, 57, 58, 59, 61, 62, 64, 68, 70, 71, 72, 73	33
Retailer, Buyer	3, 4, 17, 22, 28, 40, 52, 60, 67	9
Recycler, 3rd party	5, 9, 19, 23, 28, 29, 31, 33, 34, 40, 41, 48, 51, 65	14
SC	1, 2, 6, 7, 13, 14, 24, 32, 50, 53, 54, 63, 66, 69	14
Government	19, 39, 47	3
Preferences		**73**
Rational and risk-neutral	The rest	56
Risk, inequity, loss aversion	16, 33, 35, 36, 48, 57, 64	7
Altruistic	24, 42, 70	3
Limited rationality	19, 39	2
Fairness concern	41, 73	2
Other	46, 47, 62	3
Products		**73**
Single	The rest	59
Multiple	21, 24, 31, 34, 36, 43, 61	7
Other: service, data	32, 33, 37, 39, 49, 58, 64	7
Time horizon		**74**
Single	The rest	68
Multiple	1, 13, 33, 52	4
Infinite	8, 39	2
Information structure		
Asymmetric information		**75**
Demand	4, 9, 10, 11, 15, 16, 20, 30, 35, 44, 45, 50, 55, 56, 57, 59, 63, 68, 71, 73	20
Cost	1, 2, 3, 4, 13, 14, 22, 27, 29, 31, 34, 37, 38, 40, 49, 51, 67, 69, 72	19
Practices	6, 17, 18, 23, 28, 32, 33, 36, 48, 52, 53, 54, 58, 60, 62, 64, 65, 66	18
Product attributes	5, 12, 21, 24, 25	5
Preferences	41, 42, 47, 70	4
Other	7, 8, 19, 26, 36, 39, 43, 46, 61	9
Information characteristics		**73**
Binary	5, 12, 13, 17, 19, 21, 22, 24, 26, 27, 28, 29, 30, 31, 32, 33, 34, 36, 37, 39, 43, 44, 45, 48, 52, 55, 58, 60, 61, 62, 63, 65, 66, 67, 68, 70	36

Continuous	1, 2, 3, 14, 15, 20, 25, 40, 46, 47, 54, 64, 69, 71, 72, 73	16
Approximation	9, 10, 11, 18, 35, 41, 42, 50, 56, 59	10
Factor	6, 7, 16, 38	4
Other	4, 8, 23, 49, 51, 53, 57	7
Interactions		
Game models		**97**
Stackelberg, Leader-follower, Sequential-move	4, 7, 8, 9, 10, 11, 14, 15, 16, 17, 18, 20, 21, 22, 23, 25, 26, 27, 28, 29, 31, 33, 34, 35, 36, 37, 38, 40, 41, 42, 44, 45, 46, 48, 50, 51, 52, 53, 54, 55, 56, 57, 59, 63, 65, 66, 67, 68, 69, 70, 71	51
Simultaneous-move	1, 6, 24, 32, 43, 44, 51, 67	8
Screening, Principal-agent	1, 3, 13, 17, 25, 26, 28, 29, 31, 33, 47, 48, 49, 64, 65, 66, 67, 72, 73	19
Signalling	2, 5, 12, 24, 27, 30, 32, 44, 45, 58, 60, 62	12
Other: differential, evolutionary, bargaining, competition	8, 19, 39, 43, 46, 51, 61	7
Coordination mechanisms		**86**
Menu of contracts, Screening contracts	1, 3, 13, 17, 25, 26, 28, 29, 31, 33, 37, 48, 63, 64, 65, 66, 67, 72, 73,	19
Cost, revenue, innovation sharing contracts	7, 8, 11, 13, 18, 40, 42, 48, 57	9
Two-part tariff contract	3, 14, 18, 23, 27, 40, 50, 63, 68, 69, 72	11
Other contracts	3, 16, 20, 22, 26, 29, 36, 37, 38, 46, 57	11
Other mechanisms	1, 6, 9, 10, 39, 43, 44, 45, 47, 49, 53, 54, 59, 61, 62	14
NA	2, 4, 5, 12, 15, 19, 21, 24, 30, 32, 34, 35, 41, 51, 52, 55, 56, 58, 60, 70, 71	22
Objective functions		**74**
Profit	The rest	51
Utilities	21, 24, 26, 33, 41, 42, 46, 48, 49, 50, 54, 60, 62, 64, 65, 69, 70, 73	18
Other: cost, environmental impact	21, 32, 47, 52, 57	5

A2. Supply chain structure

No.	Literature	Research context		Players			Products	Time horizon
		practices	demand	members	cost	preferences		
1	Kim and Netessine (2013)	NPD	random variable	one S-one M	M/S: cost reduction efforts	-	single	two
2	Arya et al. (2014)	quality testing	-	one S-one B	S: quality testing cost. B: converting cost	-	single	single
3	Zhang et al. (2014)	remanufacturing	[De, li]: RP	one M-one R	R: collection cost	-	single	single
4	Wei et al. (2015)	remanufacturing	[De, li]: RP	one M-one R	R: quadratic collection cost	-	single	single

5	Hong et al. (2016)	recycling of end-of-life (EOL) electronic products	-	one M-one third-party recycler	recycler's quadratic collection effort and unit reward money	-	single	single
6	Plambeck and Taylor (2016)	Supplier social and environmental responsibility practices	-	one S-one B	S: responsibility effort cost to avoid causing a major harm to workers or the environment; hiding effort cost to evade the buyer's audit. B: auditing effort cost	-	single	single
7	Yang et al. (2016)	three low-carbon policies (M and R): carbon emission trading, carbon tax, and a new policy which combined carbon quota and carbon tax mechanism	[De, nli, iso-elastic]: RP	one M-one R	M/R: carbon cost	-	single	single
8	De Giovanni (2017)	remanufacturing	[De, li]: RP, consumers' environmental consciousness	one M-one R	M: marginal collection logistics cost	-	single	Infinite
9	Huang and Wang (2017a)	remanufacturing	[Ra, li, additive]: RP	a manufacturer, a distributor and a third party	distributor/the third party: unit remanufacturing cost, unit licensing fee	-	single	single
10	Huang and Wang (2017b)	remanufacturing	[Ra, li, additive]: RP	one S-one M-one R	S/M: unit remanufacturing cost	-	single	single
11	Jha et al. (2017)	NPD	[Ra, li, additive, normal distribution]: RP, innovation level	one TDC-one PDC[1]	TDC: development cost including quadratic fixed investment cost and time-dependent variable cost	-	single	single
12	Li et al. (2017)	CSR	demand is derived from consumers' WTP based on RP and belief of product quality	one S-one R	S: constant marginal cost of the CSR conduct	-	single	single
13	Liu and Song (2017)	low-carbon R&D cooperation;	[Ra, li, additive]: researcher's recycling	a low-carbon R&D supplier; a	producer gives promotion and return policy with costly	-	single	two-stage

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[1] TDC: Technology Development Company; PDC: Product Development Company

		recycling	effort and green R&D effort; producer's effort to increase sales revenue	leading electronic innovation-oriented producer	effort; cost of the carbon emissions for the producer researcher's cost of exerting green R&D effort and the cost of handling the recycling product in the second stage			
14	Ma et al. (2017)	CSR	[De, li]: RP, R's marketing efforts, M's CSR efforts	one M-one R; extension: two Ms-one R	R: quadratic marketing efforts cost. M: quadratic CSR efforts cost	-	single	single
15	Qin et al. (2017)	cap-and-trade (M); carbon reduction	[Ra, li, additive]: RP, carbon emission reduction per unit	one M-one R	M: quadratic emission reduction investment cost	-	single	single
16	Qu and Zhou (2017)	government's subsidy for low-carbon products (M and R)	random variable	one M-one R	-	customers have an aversion to a new low-carbon product under certain condition	single	single
17	Wang et al. (2017)	RPM (M); remanufacturing	[Ra, li, additive, uniform distribution]: RP	one M-one R	R: quadratic collection cost	-	single	single
18	Yan and Cao (2017)	online shopping; product returns	[De, li]: RP, return policy	one M-one online R	M: buy back cost	-	single	single
19	Zhang et al. (2017)	Recycling of waste cooking oil-to-energy; the government provides the subsidies for the biofuel companies as well as supervises and fines the restaurants	-	government, biofuel enterprises and restaurants	biofuel enterprises: R&D cost. G: supervision cost; remedy cost	All players have limited rationality	single	single
20	Zhang and Xiong (2017)	remanufacturing	[Ra, li, additive, normal distribution]: RP	one M-one R	M: quadratic collection cost	-	single	single
21	Zhang and Wang (2017)	CSR; government's environment tariff (SC): constant tax or subsidy; chain-to-chain competition	[De, li]: RPs, government's tariffs (competition)	one G; two competing SCs consisting of one M-one R	M: proportional disposal cost	-	two different but substitutable types of product	single

22	Zhao et al. (2017)	remanufacturing	[fuzzy, li]: RP	one M-one R	R: quadratic collecting cost	-	single	single
23	Zheng et al. (2017)	remanufacturing	[De, li]: RP	a remanufacturer and a collector	collector's quadratic collection effort cost	-	single	single
24	Lee et al. (2018)	CSR; greenwashing	Hotelling model: RP, perceived environmental quality, quality signal (competition)	one green firm and one brown firm	two firms: linear environmental cost per unit	consumers experience altruistic utility from the environmental quality of a product	two horizontally differentiated products	single
25	Ma et al. (2018)	emissions trading scheme (M);	random variable	multiple Ss-one M	M: emission cost	-	single	single
26	Wang et al. (2018a)	Green consumption; cash-credit payments	[De, nli, exponential]: supplier's credit period	one S-one C	-	-	single	single
27	Wang and He (2018)	carbon reduction	[De, li]: RP, carbon reduction level	one designer-one M	M: quadratic investment cost of carbon reduction	-	single	single
28	Wang et al. (2018b)	RPM (M); Recycling of WEEEs; remanufacturing	[Ra, li, additive, uniform distribution]: RP	a manufacturer, a retailer, a third-party recycler	quadratic cost of collection effort of the third-party recycler and the retailer	-	single	single
29	Yang et al. (2018)	WCO recycling	-	one bio-firm-one recycler	recycler: collection cost; quadratic investment cost	-	single	single
30	Yu and Li (2018)	Cap-and-Trade mechanism (M); carbon reduction	[Ra, li, additive, inverse]: quantities, carbon emission abatement (competition)	one M-one R; one M-two Rs	M: quadratic cost of carbon emission abatement	-	single	single
31	Zhang et al. (2018)	WEEE's recycling and remanufacturing; carbon emission RPM and the recovery ratio RPM (Ms)	[De, li]: RPs (competition)	two Ms-one recycler	quadratic recovery fixed cost of the recycler	-	two substitutable products	single
32	Chen et al. (2019)	SCT; NGOs monitor and ensure SC sustainability; Quality control	-	one NGO; one S-one B	S: compliance effort cost; penalty cost. B: brand damage cost. NGO: auditing effort cost	-	(sourcing)	single

33	Hu et al. (2019)	recycling of construction and demolition waste (CDW) under government incentives (subsidies for recycler's technical level report)	-	one G and one recycler	The recycler invests unobservable efforts at a private cost to recycle CDW	the government is risk-neutral and that the enterprise is risk-averse	technical level of the retailer	one-stage; two-stage
34	Huang et al. (2019)	remanufacturing	[De, li, inverse]: production quantities (competition)	an OEM who produces all-new products and a TPR (Third-party remanufacturer) who remanufactures end-of-use products	TPR's unit remanufacturing cost	-	Two: new product and remanufactured product	single
35	Liu and Chen (2019)	GSCM; M faces environmental constraints (the minimum greening requirements in the production processes) and takes green initiatives	[Ra, li, additive]: green level of the product	one M-one R	M: quadratic investment cost to sustain the green level	inequity-averse	single	single
36	Liu et al. (2019a)	GSCM; green marketing resource allocation	[De/Ra, li, additive]: green effort	multiple Ss-one R	S: quadratic green effort cost	S: loss aversion (bounded rationality)	substitutable products	single
37	Liu et al. (2019b)	CSR	[De, li]: RP, CSR level	one provider-one integrator	provider: unit marginal CSR cost	-	service	single
38	Liu et al. (2019c)	CSR	[De, li]: RP, CSR level	one S-one R	S: quadratic CSR investment cost	-	single	single
39	Peng et al. (2019)	government's regulation of environmental protection tax; corporate fraudulent behaviours when they upload the data of untreated emissions	-	local governments and polluting enterprises	G: monitoring costs including the inspection cost and the investment cost on information disclosure platform	Both enterprises and local governments are limited rationality	data of untreated emissions	countless periods
40	Sane-Zerang et al. (2019)	recycling and remanufacturing	[De, li]: RP, sales efforts	one M, one R, and one-third party	the third party gathers the second hand products and incurs collection cost;	-	single	single

					retailer's sales effort with quadratic cost			
41	Shu et al. (2019)	recycling and remanufacturing	[De, li]: RP	one M-one R-two collectors	collectors: collection costs	the collector is distributional fairness and peer-induced fairness concerned	single	single
42	Wan et al. (2019)	low-carbon tourism	[Ra, nli, iso-elastic, multiplicative]: RP, consumer preference for low-carbon products or services	one TCP-one OTA[2]	-	altruism preference	single	single
43	Wu et al. (2019)	GSCM; use of environmentally friendly technologies; government's subsidy policies (to consumers and production); traditional SC-to-green SC competition	[De, li, inverse]: quantities (competition)	two competing SCs in which each chain is composed of one M-one R	M: higher per-unit production cost in GSC	-	two substitutable products	single
44	Yu and Cao (2020)	cap-and-trade regulation (M); carbon reduction	[Ra, li, additive, inverse]: quantities, carbon emission abatement level (competition)	one M-two Rs	M: quadratic cost of investing in carbon emission abatement	-	single	single
45	Yu and Cao (2019)	cap-and-trade regulation (M); carbon reduction	[Ra, li, additive, inverse]: quantities, carbon emission abatement level (competition)	one M-two Rs	M: quadratic cost of investing in carbon emission abatement	-	single	single
46	Zhang and Wang (2019)	GSCM	demand is derived from consumer utility function based on the consumer's	one M-one R	M: unit production cost of green product is a quadratic function of product greenness	consumer greenness preference	single	single

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[2] TCP: Tour Contents Provider of low-carbon tourism products or services; OTA: Online Travel Agency

			reservation utility for the traditional product and WTP for product greenness					
47	Zhao and Chen (2019)	government formulates the subsidy policy for green products	consumers’ pay for green products is a function of environmental awareness and investors’ investment preference	one G; inventors (i.e., producers and fund suppliers of green products)	G: subsidy costs inventors: green technology cost	investors’ investment preference for green products	single	single
48	Zhu and Yu (2019)	recycling of new energy vehicle power battery	-	a battery manufacturing company, a new energy vehicle company, and a third-party recycler	Recycler: quadratic recovery effort cost	battery manufacturers and new energy auto companies are risk-neutral and completely rational, whereas third-party recyclers are risk-averse	single	single
49	Chen and Li (2021)	The manufacturer receives subsidies from the government and then builds green buildings	-	one G; one M	M: quadratic green effort cost	-	single (sales of green buildings)	single
50	Ding and Wang (2020)	GSCM; retailer exerts promotional effort	[Ra, li, additive]:RP, green degree, promotional effort level	one M-one R	M: quadratic cost of enhancing green degree. R: quadratic cost of enhancing promotional effort level	-	single	single
51	Gao et al. (2020)	remanufacturing	[Fuzzy, li]: RP	a manufacturer (the patent licensor), a remanufacturer (the patent licensee) and an independent retailer	Remanufacturer: unit royalty fee; unit remanufacturing cost	-	single	single

52	Kalkanci and Plambeck (2020a)	disclosure of supplier's social or environmental impacts to investors; GHG emission reduction	-	investors and a manager of a buying firm	B: the cost to learn about supplier's impact; impact-reduction cost	-	-	two
53	Kalkanci and Plambeck (2020b)	SCT	random variable	one S-two Bs	B: search cost, audit costs, violation cost S: responsibility effort cost	-	single	single
54	Kraft et al. (2020)	SCT; Supplier social responsibility (SR) practices	demand is derived from consumer utility based on RP, fraction of socially conscious consumers, revealed SR level	one S-one B	S: SR cost B: investment cost in the S's SR capabilities	-	single	single
55	Li et al. (2020)	government subsidies for energy-saving products (ESPs) (M)	[Ra, li, additive]: RP, energy-saving level	one M-one R	M: quadratic energy saving R&D cost	-	single	single
56	Lin (2020)	GSCM; Manufacturer rebate	[Ra, li, additive]: RP, green level, rebate	one M-one R	M: quadratic green investment cost	-	single	single
57	Ma et al. (2020)	GSCM	[uncertain, li]: RP, product greening improvement level	one M-one R	M: quadratic green investment cost	Both have risk attitudes: risk attitudes: risk-averse, risk-loving	single	single
58	Mei et al. (2020)	Safety production; Suppliers (SMMEs) are punished by the government for accidents	-	one S-one core enterprise	S: higher product cost with high SPL, signalling cost, penalty cost	-	safety certification information	single
59	Nie et al. (2020)	carbon tax (M); carbon reduction	[Ra, li, additive]: RP	one M-one R	M: quadratic carbon emissions reduction cost	-	single	single
60	Shao et al. (2020)	SCT; responsible sourcing	demand is derived from consumer utility based on RP, fraction of socially conscious consumers	one S-one B-consumers	B: unit sourcing cost, penalty cost, disclosure cost	-	single	single
61	Wu and Kung (2020)	carbon emission tax (M); chain-to-chain competition	[De, li, inverse]: quantities (competition)	two competing SCs in which each chain is	M: carbon emission tax of per-unit production	-	two	single

				composed of one M-one R				
62	Wu et al. (2020)	CSR; greenwashing	consumer utility: RP, the perceived probability that the firm is socially responsible	a representative firm (the "sender") and a representative consumer (the "receiver")	Firm: CSR investment costs, signalling cost	firms have different preferences on CSR investment	single	single
63	Xia and Niu (2021)	cap-and-trade regulation (M); carbon reduction	[De, li]: RP, green-marketing efforts, carbon label	one M-one R	M: quadratic carbon-reducing investment cost; R: quadratic green-marketing cost	-	single	single
64	Xia and Niu (2020)	carbon footprint reduction (CFR) by government's carbon contractual policy	-	one G; one M	M: CFR cost	The government is risk-neutral and the firm is risk-averse	amount of CFR	single
65	Yang et al. (2021)	WCO recycling; G's subsidy	-	G-one bio-firm	bio-firm: recycling investment cost	-	single	single
66	Yuan et al. (2020)	GSCM; R makes selling effort; government subsidy strategies: the government subsidizes the manufacturer (unit product subsidy); the government subsidizes the retailer on the basis of the selling cost	[De, li]: RP, product greenness level, retailer's selling effort	one M-one R	R: quadratic selling cost; M: quadratic R&D cost	-	single	single
67	Zhang et al. (2020)	WEEE recycling; carbon emission RPM on M; recovery rate RPM on R	[De, li]: RPs (competition)	One M-two Rs	R1: fixed recovery cost	-	single	single
68	Li et al. (2021)	GSCM; manufacturers improve energy saving performance of products by implementing green technologies	[De, li]: RPs, green degree (competition)	one M-two Rs	M: quadratic development cost	-	single	single

69	Raj et al. (2021)	SSCM; greening and CSR by supplier and buyer	[De, li]: RP, greening effort	one S-one B	S or B: quadratic greening investment cost	-	single	single
70	Wei et al. (2021a)	GSCM	[De, li]: RP, greenness	one M-one R	M: quadratic green investment cost	R: altruistic	single	single
71	Wei et al. (2021b)	(offline/online) sales patterns of green products	single sales pattern: [Ra, li, additive]: RP, green level dual sales patterns:. [Ra, li, additive]: RPs, green level (competition)	one S-one e-tailer	S: quadratic cost of achieving greening improvement	-	single	single
72	Zhang et al. (2021)	GSCM	[De, li]: RP, environmental innovation level	one S-one R	S: environmental innovation costs	-	single	single
73	Zhou et al. (2021)	GSCM	[De, li, inverse]: quantity, greenness	one M-one R	M: quadratic green investment cost	R: fairness concern	single	single

Notes: NPD: new product development; SCT: supply chain transparency; RPM: reward-penalty mechanism; G: government; S: supplier; B: buyer; C: customer; M: manufacturer; R: retailer; De: deterministic; Ra: random; li: linear; nli: nonlinear; RP: retail price; WTP: willingness to pay; WP: wholesale price; CP: collection price; BP: buyback price; WCO: waste cooking oil.

A3. Information structure and Interactions

No.	Literature	Information structure		Interactions						
		types	characteristics	games	objectives	coordination mechanisms	prices	order/production	sustainability	others
1	Kim and Netessine (2013)	S: unit production cost	continuous	SMG; screening	profit	screening contract (unit price, quantity); expected margin commitment	WP	q	efforts	
2	Arya et al. (2014)	S: quality testing cost	continuous	signalling	profit	-	-	q	S: quality	
3	Zhang et al. (2014)	R: collection cost efficiency	continuous	screening	profit	menu of contracts: TPTC; collection effort	WP; RP	-	return rate	contract parameters

						requirement contract				
4	Wei et al. (2015)	M: unit manufacturing cost and remanufacturing cost R: market base and collecting scale parameter	the type space containing private information pertaining to a player and a probability distribution expressing the uncertainty over a player’s type by other players	UP-Stackelberg; DO-Stackelberg	profit	-	WP; RP	-	collection rate of the remanufactured products	
5	Hong et al. (2016)	M: homogeneity degree of EOL products	binary	Signalling: manufacturer as a leader, third-party recycler as a follower	profit	-	recycler’s reward money for customers returning products; M’s contract rent	-	-	
6	Plambeck and Taylor (2016)	S: information about potentially unsafe practices or conditions	factor: hiding effort	SMG	profit	Penalize supplier for hiding effort, decrease auditing, etc.	-	-	S: responsibility effort and hiding effort. B: auditing effort	
7	Yang et al. (2016)	M/S: carbon emission and carbon price	misreporting factor	UP-Stackelberg	profit	RSC	WP	q	-	misreporting factors; contract parameters

8	De Giovanni (2017)	M: profit sharing parameter	determined by M	differential game; UP-Stackelberg	profit	profit-sharing contract	WP; RP	-	M and R's green advertising efforts	
9	Huang and Wang (2017a)	distributor's market demand forecast	approximation: the certain part of market size	UP-Stackelberg (M)	profit	Information sharing; the manufacturer produces both new and remanufactured products	WP; RP, acquisition price, unit licensing fee	-	-	
10	Huang and Wang (2017b)	R: demand forecast	approximation: the certain part of market size	UP-Stackelberg (S)	profit	information sharing	WP; RP, acquisition price	-	-	
11	Jha et al. (2017)	PDC: demand forecast	approximation: the certain part of market size	UP-Stackelberg	profit	Investment cost sharing; Innovation sharing; Combined investment & innovation sharing	WP; RP	-	innovation level	sharing fractions
12	Li et al. (2017)	S: product quality	binary	signalling	profit	-	WP; RP	-	CSR level	
13	Liu and Song (2017)	S: low-carbon R&D technology level	binary	screening; PAT	profit	revenue sharing contract; screening contract (an upfront payment and a revenue sharing ratio)	-	-	producer's effort to increase sales revenue; researcher's effort in the recycling stage	contract parameters
14	Ma et al. (2017)	M: CSR costs	continuous: uniform distribution	DO-Stackelberg	profit	TPTC	WP; RP	-	CSR efforts level	marketing effort level; contract parameters
15	Qin et al. (2017)	M/R: demand forecast	continuous: normal distribution	UP-Stackelberg	profit	-	WP; RP	-	emission reduction	

16	Qu and Zhou (2017)	R: demand forecast	factor: trust coefficient	DO-Stackelberg	profit	rebate contract	-	qs	-	contract parameters
17	Wang et al. (2017)	R: collection effort level	binary	UP-Stackelberg; screening	profit	information screening contract (WP, buy-back price, and franchise fee)	WP; RP; collection price	-	-	contract parameters
18	Yan and Cao (2017)	R: product return rate	estimate product return rate	UP-Stackelberg	profit	a two-part price contract; RSC plus profit split mechanism	WP; RP; buyback, return price	-	-	contract parameters
19	Zhang et al. (2017)	Each player is usually unable to judge the income, costs or behaviour of other players in making the most strategic choice.	binary	evolutionary game	profit	-	-	-	-	strategy selection
20	Zhang and Xiong (2017)	M/R: demand forecast	random variable: normal distribution M and R have forecasts respectively	UP-Stackelberg	profit	bargaining on the allocation of supply chain profit	WP; RP	M's production level in the MTS	M's collection rate of used products	
21	Zhang and Wang (2017)	type of product (G-SC; M-R)	binary	G-Stackelberg; UP-Stackelberg	SC members: maximize the profits; Government: minimize the environmental impact; maximizes the	-	WP; RP	-	G: environment tariff	

					financial net revenue; maximize its utility					
22	Zhao et al. (2017)	R: collecting scale parameter	binary	UP-Stackelberg	profit	coordination contracts including commission fee	WP; RP	-	collecting rate of used products	contract parameters
23	Zheng et al. (2017)	collector’s the collection scaling parameter and the supply base of the used product	type space containing the collector’s private information and the probability distribution function revealing the remanufacturer’s uncertainty over the collector’s type	UP-Stackelberg (remanufacturer)	profit	TPTC	WP; RP, acquisition price	-	WP; RP, acquisition price	contract parameters
24	Lee et al. (2018)	Consumers: environmental quality (greenness of the product)	binary	SMG; signalling	profit with consumer utility	-	RP	-	environmental quality	
25	Ma et al. (2018)	S: the green degree of raw materials	continuous	DO-Stackelberg; screening	profit	menu of contracts (quantity, transfer payment)	-	q	green degree of the raw materials	contract parameters
26	Wang et al. (2018a)	customer’s credit level	binary	UP-Stackelberg; screening	profit subject to nonnegative customer’s utility	three contracting mechanisms: the screening, checking and insurance mechanisms	-	q	-	contract parameters

27	Wang and He (2018)	M: carbon reduction efficiency	binary	UP-Stackelberg; signalling	profit	TPTC	WP; RP	-	carbon reduction level	contract parameters
28	Wang et al. (2018b)	the collection effort levels of both the retailer and the third-party recycler	binary	UP-Stackelberg (manufacturer); PAT	profit	information screening contract	WP; RP; collection, buyback price	-	-	contract parameters
29	Yang et al. (2018)	downstream recycler: unit recycling cost	binary	UP-Stackelberg (bio-firm); PAT	profit	principal-agent contract (unit purchasing price, transfer payment); quantity discount contract	unit purchasing price	-	recycler's investment level	contract parameters
30	Yu and Li (2018)	incumbent R: demand forecast	binary	signalling	profit	-	WP	q	carbon emission abatement level	
31	Zhang et al. (2018)	recycler's recovery fixed cost (M1-recycler)	binary	UP-Stackelberg (manufacturer); PAT	profit	information screening contract	RP; M1: buyback price	-	recycler can decide the recovery ratio	
32	Chen et al. (2019)	S: capability of compliance (NGO-S)	binary	signalling; SMG	cost	-	-	-	S: compliance effort level; NGO: auditing effort level	B: revelation decision
33	Hu et al. (2019)	dual information asymmetry including the unknown recycling technology level and unobservable recycling efforts	binary	PAT; leader-follower game relationship between the government and the recycler	G: maximize social benefits; Recycler: maximize profit	screening contract (subsidy and fixed payment provided by the government)	-	-	Efforts of the recycler	contract parameters
34	Huang et al. (2019)	TPR's unit remanufacturing cost	binary	Sequential-move game with dominant TPRs	profit	-	-	q	-	

35	Liu and Chen (2019)	R: the market distribution function F	approximation: WP is predetermined	UP-Stackelberg	profit	-	WP	q	green level	
36	Liu et al. (2019a)	S: two-dimensional: green effort level; resource expectation	binary	DO-Stackelberg	profit	wholesale price procurement contract with green marketing resource allocation	-	q	green effort	R: ex-ante resource value (ERV) allocated to supplier
37	Liu et al. (2019b)	provider's CSR cost information	binary	DO-Stackelberg; screening	profit	screening contract; pooling contract (CSR level, transfer payment)	RP	-	CSR level	contract parameters
38	Liu et al. (2019c)	S: CSR cost information	misreporting factor	DO-Stackelberg	profit	Transfer payment mechanism	WP; RP	-	CSR level	
39	Peng et al. (2019)	corporate environmental monitoring data	binary	evolutionary game	payoff	regulatory mechanism of information disclosure platform	-	-	-	probability of strategy
40	Sane-Zerang et al. (2019)	retailer's sales cost coefficient; the third party's collection cost and investment coefficient	continuous	UP-Stackelberg (manufacturer)	profit	TPTC; CSC; revenue-cost sharing contract	WP; RP; collection, transfer price	-	retailer's sales effort level; the third party's collection rate	contract parameters
41	Shu et al. (2019)	collector's fairness concerns	approximation: manufacturer thinks the collector is fairness neutral	UP-Stackelberg (manufacturer)	profit; utility	-	WP; RP; collection, transfer price	-	-	
42	Wan et al. (2019)	Dual: altruism preference	approximation: the optimal decision when OTA doesn't have altruism preference	UP-Stackelberg	utility	RSC (coordination under AS, not for AI)	WP; RP	q	-	

43	Wu et al. (2019)	the outcome of loan application of M2 in GSC	binary	NB on WP; SMG	profit	government's per-unit subsidy policies	WP	q (demand)	-	
44	Yu and Cao (2020)	incumbent R: demand forecast	binary	SMG; DO-Stackelberg; signalling	profit	information sharing	WP	q	carbon emission abatement level	
45	Yu and Cao (2019)	incumbent R: demand forecast	binary	DO-Stackelberg; signalling	profit	informal cheap talk with WPC	WP	q	carbon emission abatement level	
46	Zhang and Wang (2019)	consumers' reservation utility for traditional product and WTP for product greenness	continuous	UP-Stackelberg; NB on WP	profit with consumer utility	bargaining on WP	WP; RP	-	greenness level	
47	Zhao and Chen (2019)	investors' investment preference	continuous	principal-agent model	government's expected net policy gain; investor's profit	government's financial subsidy policies	-	total yield of green products	investment preference level	
48	Zhu and Yu (2019)	dual information asymmetry: recycler's recycling capacity and recycling efforts	binary	principal-agent theory; screening contract; UP-Stackelberg (manufacturer)	profit derived from expected utility	screening contract; revenue sharing contract	M pays the recycler a fixed payment	-	-	contract parameters
49	Chen and Li (2021)	M: effort cost coefficient	N types: a series of values; misreport	PAT; screening	utility	spot check mechanism	-	-	M: effort level (sales volume)	G: subsidy contract parameters
50	Ding and Wang (2020)	R: demand forecast	approximation: the certain part of market size	UP-Stackelberg	profit; (analyse consumer surplus)	A two-part compensation (TPC) contract	WP; RP	-	promotional effort level; green degree	
51	Gao et al. (2020)	manufacturer's unit manufacturing and remanufacturing costs;	nonnegative fuzzy variable	UP-Stackelberg (manufacturer) remanufacturer and the retailer	profit	-	WP; RP; take-back price,	-	-	

		remanufacturer’s unit remanufacturing cost		act simultaneously and compete with Bertrand competition			royalty fee			
52	Kalkanci and Plambeck (2020a)	manager’s decisions about learning and impact reduction	binary	sequential-move game	maximize the buying firm’s current valuation		-	-	impact-reduction cost	learning and disclosure decisions
53	Kalkanci and Plambeck (2020b)	S: responsibility violation (B1-B2)	probability	sequential-move game	profit	commitment to publish a supplier’s identity	-	-	responsibility effort	
54	Kraft et al. (2020)	supplier’s current SR level	continuous	sequential-move game	profit with consumer utility	Non-contracting: (i) investing in a supplier’s SR capabilities, (ii) disclosing SR information to consumers, and (iii) deciding when to voluntarily disclose.	-		SR investment; SR level	
55	Li et al. (2020)	R: demand forecast	binary	DO-Stackelberg	profit	-	WP; RP	-	energy-saving level	
56	Lin (2020)	R: demand forecast	an unbiased estimator	UP-Stackelberg	profit	-	WP; RP	-	green level	rebate value
57	Ma et al. (2020)	demand	mutual independent uncertain variables with uncertainty distributions	DO-Stackelberg; NB on cost sharing parameter	expected profits on confidenc e level	CSC; CSC through bargaining	WP; RP	-	product greening improvement level	contract parameters
58	Mei et al. (2020)	Safe production level (SPL)	binary	signalling	profit	-	-	-	-	S: signalling strategy.

										Firm: supplier selection strategy
59	Nie et al. (2020)	R: demand forecast	an unbiased estimator	UP-Stackelberg	profit (analyse consumer surplus, social welfare)	information sharing	WP; RP	-	carbon reduction level	
60	Shao et al. (2020)	firm's sourcing decision (B-C)	binary	signalling	profit with consumer utility	-	LP	-		sourcing decision
61	Wu and Kung (2020)	outcome of loan application of M2 (M1-M2)	binary	NB on WP; Cournot competition	profit	carbon emission tax	WP	q (demand)	-	
62	Wu et al. (2020)	firms' type (investment in CSR activities)	binary	signalling	The profit maximiser (type L) cares only about its profit. The socially responsible type (H) is concerned about not only its own profit but also the social benefit	cheap signalling	RP	-	investment levels in observed and unobserved CSR activities	
63	Xia and Niu (2021)	R: demand forecast	binary	UP-Stackelberg	profit	menu of contracts: TPTC	WP	q	M: carbon-reducing	contract parameters

									investment efforts; R: green-marketing efforts	
64	Xia and Niu (2020)	single asymmetric information case: firm's carbon-reducing effort is privately known to himself dual asymmetric information case: neither the firm's carbon-reducing capacity nor his effort is visible to the government.	continuous	screening	G: expected welfare; M: expected utility	menu of carbon contracts (a CFR fixed fee, a CFR incentive factor)	-	-	M: carbon-reducing effort	contract parameters
65	Yang et al. (2021)	bio-firm's conversion rate	binary	G-Stackelberg; PAT	firm: profit; G: social utility	screening contract	G's transfer payment	-	investment level	G's subsidy
66	Yuan et al. (2020)	R: level of selling effort	binary	UP-Stackelberg; PAT	profit	screening contract (selling effort level, WP)	WP; RP	-	M's product greenness level; R's level of selling effort	
67	Zhang et al. (2020)	R1: fixed recovery cost	binary	UP-Stackelberg; SMG; Screening; PAT	profit	screening contract	RP; BP	-	WEEE recovery rate	-
68	Li et al. (2021)	potential market demand (asymmetric to R1)	binary	UP-Stackelberg	profit	TPTC (for AS, not for AI)	WP; RP	-	green degree	contract parameters
69	Raj et al. (2021)	B: marginal production cost	continuous	UP-Stackelberg	profit (incorporate CSR efforts in form of consumer surplus)	Linear TPTC	WP; RP	-	product greening improvement level	contract parameters

70	Wei et al. (2021a)	R: behavioural type: either self-interest or altruistic	Binary; Harsanyi doctrine approach	UP-Stackelberg	profit; altruistic R: utility	-	WP; RP	-	greenness	-
71	Wei et al. (2021b)	e-tailer's demand forecast	continuous: normal distribution	UP-Stackelberg	profit	-	WP; RP	-	green level	
72	Zhang et al. (2021)	S: environmental innovation cost efficiency	continuous	PAT, screening	profit	menu of contracts: TPTC; innovation effort requirement contract	WP; RP	-	Environmental innovation level	contract parameters
73	Zhou et al. (2021)	R: demand forecast	continuous	screening	M: profit; R: utility	menu of contracts: (WP, q)	WP	M: q	greenness	contract parameters

Notes: q: quantity; UP: upstream; DO: downstream; PAT: principal-agent theory; SMG: simultaneous-move Nash game; NB: Nash Bargaining game; WPC: wholesale price contract; RSC: revenue sharing contract; CSC: cost sharing contract; TPTC: two-part tariff contract.

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Appendix of Chapter 3 Decision Analysis and Coordination in Green Supply Chains with Stochastic Demand

A. Proof of Lemma 3.1

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 $\Pi_M^{gd}(w, \theta \mid p^*)$. 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:

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

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 3.1 and Corollary 3.2

Substituting the equilibrium solutions in Lemma 3.2 back into the expected profit function of the manufacturer, we can obtain manufacturer's optimal profit $\Pi_M^{gs} = \Pi_M^{gd} + Z_M^{gs}(z) = \dfrac{\beta\left(a - b_p c + z + I(z)\right)^2}{8\beta b_p - (b_g - v b_p)^2}$.

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 our 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 $\dfrac{z}{I(z)}$ with -1.

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

C. Proof of Proposition 3.1

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

$$\begin{aligned}\Pi_R^{gs}(z \mid p_m^{gs}, w_m^{gs}, \theta_m^{gs}) &= \Pi_R^{gd} + Z_R^{gs}(z) \\ &= \frac{4\beta^2 b_p\left(a - b_p c + z + I(z)\right)^2}{\left(8\beta b_p - (b_g - v b_p)^2\right)^2} - \frac{\left(8\beta + v(b_g - v b_p)\right)\left(a - b_p c + z + I(z)\right)I(z)}{8\beta b_p - (b_g - v b_p)^2} \\ &\quad + \frac{\left(I(z)\right)^2}{b_p} - (c + c_o)I(z) - c_s\left(\mu + I(z) - z\right)\end{aligned} \tag{C.15}$$

Taking the first-order derivative of Eq. (C.15) with respect to z, we get the following expression after simplification:

$$\begin{aligned}\frac{d\Pi_R^{gs}(z \mid p_m^{gs}, w_m^{gs}, \theta_m^{gs})}{dz} &= \big(1-F(z)\big)(p_m^{gs}+c_s+c_o)-(w_m^{gs}+c_o)-\big(1+F(z)\big)V(z) \\ &= \big(1-F(z)\big)\left(p_m^{gs}+c_s+c_o-\frac{w_m^{gs}+c_o}{1-F(z)}-\frac{1+F(z)}{1-F(z)}V(z)\right)\end{aligned} \tag{C.16}$$

where

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

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

$$\frac{dV(z)}{dz}=\frac{2\beta b_p\left(4\beta b_p-(b_g-vb_p)^2\right)\big(1+F(z)\big)+b_g(b_g-vb_p)\left(8\beta b_p-(b_g-vb_p)^2\right)F(z)}{b_p\left(8\beta b_p-(b_g-vb_p)^2\right)^2}>0 \tag{C.17}$$

$$\frac{d^2V(z)}{dz^2}=\frac{2\beta b_p\left(4\beta b_p-(b_g-vb_p)^2\right)+b_g(b_g-vb_p)\left(8\beta b_p-(b_g-vb_p)^2\right)}{b_p\left(8\beta b_p-(b_g-vb_p)^2\right)^2}f(z)>0 \tag{C.18}$$

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 $R(z)>0$, $\frac{d\Pi_R^{gs}(z \mid p_m^{gs}, w_m^{gs}, \theta_m^{gs})}{dz}>0$, then the profit is increasing in z; if $R(z)<0$, $\frac{d\Pi_R^{gs}(z \mid p_m^{gs}, w_m^{gs}, \theta_m^{gs})}{dz}<0$, then the profit is decreasing in z; and for any z in the interval that satisfies $R(z)=0$, $\frac{d\Pi_R^{gs}(z \mid p_m^{gs}, w_m^{gs}, \theta_m^{gs})}{dz}=0$, the profit has a local extremum. Then, to find the zeros of $\frac{d\Pi_R^{gs}(z \mid p_m^{gs}, w_m^{gs}, \theta_m^{gs})}{dz}$, we can analyse the shape of $R(z)$.

First, at the boundary of z, we have:

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

$$R(B)=p_m^{gs}(B)+c_s+c_o-\frac{w_m^{gs}(B)+c_o+2V(B)}{1-1}\to-\infty<0$$

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:

$$\frac{dR(z)}{dz}=\frac{dp_m^{gs}}{dz}-\frac{1}{1-F(z)}\frac{dw_m^{gs}}{dz}-\frac{(w_m^{gs}+c_o)h(z)}{1-F(z)}-\frac{2V(z)h(z)}{1-F(z)}-\frac{1+F(z)}{1-F(z)}\frac{dV(z)}{dz} \tag{C.19}$$

$$\begin{aligned}\frac{d^2R(z)}{dz^2}&=\frac{d^2p_m^{gs}}{dz^2}-\frac{1}{1-F(z)}\frac{d^2w_m^{gs}}{dz^2}-\frac{1+F(z)}{1-F(z)}\frac{d^2V(z)}{dz^2}\\&\quad-\frac{1}{1-F(z)}\left(2h(z)\frac{dw_m^{gs}}{dz}+(h^2(z)+\frac{dh(z)}{dz})(w_m^{gs}+c_o)\right)\\&\quad-\frac{2}{1-F(z)}\left(2h(z)\frac{dV(z)}{dz}+(h^2(z)+\frac{dh(z)}{dz})V(z)\right)\end{aligned} \tag{C.20}$$

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:

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

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

It is found that $(1-F(z))\frac{d^2p_m^{gs}}{dz^2}-\frac{d^2w_m^{gs}}{dz^2}-\left(1+F(z)\right)\frac{d^2V(z)}{dz^2}=-f(z)\left(\frac{dp_m^{gs}}{dz}+\frac{dV(z)}{dz}\right)$, 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.20) can be rewritten as:

$$\begin{aligned}\frac{d^2R(z)}{dz^2}&=-h(z)\left(\frac{dp_m^{gs}}{dz}+\frac{dV(z)}{dz}\right)\\&\quad-\frac{1}{1-F(z)}\left(2h(z)\left(\frac{dw_m^{gs}}{dz}+\frac{2dV(z)}{dz}\right)+\left(h^2(z)+\frac{dh(z)}{dz}\right)(w_m^{gs}+c_o+2V(z))\right)\end{aligned} \tag{C.21}$$

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.21) 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 3.2

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

$$\begin{aligned}
\frac{d\Pi_{SCc}^{gs}(z \mid p_c^{gs}, \theta_c^{gs})}{dz} &= \frac{\partial \Pi_{SCc}^{gs}(z \mid p_c^{gs}, \theta_c^{gs})}{\partial z} + \frac{\partial \Pi_{SCc}^{gs}(z \mid p_c^{gs}, \theta_c^{gs})}{\partial p_c^{gs}} \frac{dp_c^{gs}}{dz} + \frac{\partial \Pi_{SCc}^{gs}(z \mid p_c^{gs}, \theta_c^{gs})}{\partial \theta_c^{gs}} \frac{d\theta_c^{gs}}{dz} \\
&= \left(1 - F(z)\right)(p_c^{gs} + c_s + c_o) - (c + v\theta_c^{gs} + c_o) \qquad \text{(D.22)} \\
&= \left(1 - F(z)\right)\left(p_c^{gs} + c_s + c_o - \frac{c + v\theta_c^{gs} + c_o}{1 - F(z)}\right)
\end{aligned}$$

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

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

$$\begin{aligned}
U(A) &= p_c^{gs}(A) + c_s + c_o - \frac{c + v\theta_c^{gs}(A) + c_o}{1 - 0} \\
&= \frac{2\beta(a - b_p c + A)}{4\beta b_p - (b_g - vb_p)^2} + c_s > 0
\end{aligned}$$

$$U(B) = p_c^{gs}(B) + c_s + c_o - \frac{c + v\theta_c^{gs}(B) + c_o}{1 - 1} \to -\infty < 0$$

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:

$$\frac{dU(z)}{dz}=\frac{dp_c^{gs}}{dz}-\frac{v}{1-F(z)}\frac{d\theta_c^{gs}}{dz}-\frac{(c+v\theta_c^{gs}+c_o)h(z)}{1-F(z)} \tag{D.23}$$

$$\frac{d^2U(z)}{dz^2}=\frac{d^2p_c^{gs}}{dz^2}-\frac{v}{1-F(z)}\frac{d^2\theta_c^{gs}}{dz^2}-\frac{2vh(z)}{1-F(z)}\frac{d\theta_c^{gs}}{dz}-\frac{(c+v\theta_c^{gs}+c_o)}{1-F(z)}\left(h^2(z)+\frac{dh(z)}{dz}\right) \tag{D.24}$$

According to the equations in Lemma 3.4, the first-order and second-order derivatives of the equilibrium greenness improvement and the retail price with respect to z are:

$$\frac{d\theta_c^{gs}}{dz}=\frac{(b_g+vb_p)\big(1-F(z)\big)-2vb_p}{4\beta b_p-(b_g-vb_p)^2} \qquad \frac{dp_c^{gs}}{dz}=\frac{2(\beta+vb_g)\big(1-F(z)\big)-v(b_g+vb_p)}{4\beta b_p-(b_g-vb_p)^2}$$

$$\frac{d^2\theta_c^{gs}}{dz^2}=-\frac{(b_g+vb_p)f(z)}{4\beta b_p-(b_g-vb_p)^2} \qquad \frac{d^2p_c^{gs}}{dz^2}=-\frac{2(\beta+vb_g)f(z)}{4\beta b_p-(b_g-vb_p)^2}$$

From these expressions, we can observe that $\frac{d^2\theta_c^{gs}}{dz^2}<0$ and $\frac{d^2p_c^{gs}}{dz^2}<0$. Moreover, it is found that $\big(1-F(z)\big)\frac{d^2p_c^{gs}}{dz^2}-v\frac{d^2\theta_c^{gs}}{dz^2}=-f(z)\frac{dp_c^{gs}}{dz}$, i.e., $\frac{d^2p_c^{gs}}{dz^2}-\frac{v}{1-F(z)}\frac{d^2\theta_c^{gs}}{dz^2}=-h(z)\frac{dp_c^{gs}}{dz}$, which means that Eq. (D.24) can be rewritten as

$$\frac{d^2U(z)}{dz^2}=-h(z)\left(\frac{dp_c^{gs}}{dz}+\frac{2v}{1-F(z)}\frac{d\theta_c^{gs}}{dz}\right)-\frac{(c+v\theta_c^{gs}+c_o)}{1-F(z)}\left(h^2(z)+\frac{dh(z)}{dz}\right) \tag{D.25}$$

Recalling that the zeros of $U(z)$ correspond to the extrema of Π_{SCc}^{gs}, 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 $\Pi_{SCc}^{gs}(z\,|\,p_c^{gs},\theta_c^{gs})$ reaches its maximum. So $\Pi_{SCc}^{gs}(z\,|\,p_c^{gs},\theta_c^{gs})$ has a maximum at the unique value of z that satisfies $U(z)=0$. Secondly, if $\frac{dU(z)}{dz}=0$ has roots, then by substitution, we have:

$$\frac{d^2U(z)}{dz^2}=-\frac{1}{1-F(z)}\left((c+v\theta_c^{gs}+c_o)\left(2h^2(z)+\frac{dh(z)}{dz}\right)+3vh(z)\frac{d\theta_c^{gs}}{dz}\right)\Bigg|_{\frac{dU(z)}{dz}=0} \tag{D.26}$$

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 $0\le v\le\frac{b_g\big(1-F(z)\big)}{b_p\big(1+F(z)\big)}$, 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 $\Pi_{SCc}^{gs}(z \mid p_c^{gs}, \theta_c^{gs})$ 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 $\Pi_{SCc}^{gs}(z \mid p_c^{gs}, \theta_c^{gs})$ has a maximum at the unique value of z that satisfies the first-order optimality condition $\frac{d\Pi_{SCc}^{gs}(z \mid p_c^{gs}, \theta_c^{gs})}{dz} = (1 - F(z))U(z) = 0$, 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 3.4

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 3.1 and Proposition 3.2, it is found that $p_c^{gs}(z) - \left(c + v\theta_c^{gs}(z)\right) - \left(p_m^{gs}(z) - w_m^{gs}(z)\right) - V(z) > 0$ 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 a unique solution, therefore, $z_m^{gs} < z_c^{gs}$. □

F. Proof of Corollary 3.5

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 3.1, 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 $a - b_p c + z + I(z)$, $8\beta b_1 - (b_2 - v b_1)^2$ and $b_g - v b_p$, respectively. Now, taking the derivative $\frac{\partial R(z)}{\partial v}$, we have

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

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 3.2. Regarding z as a function of v, we have $\frac{d\theta_m^{gs}}{dv} = \frac{1}{K^2}\left((1 + F(z))LK\frac{dz}{dv} - b_p\left(8\beta b_p + L^2\right)J\right)$ and $\frac{dp_m^{gs}}{dv} = \frac{1}{b_1 K^2}\left(\left(2\beta b_p(3 - F(z)) + L(b_g F(z) + v b_p)\right)K\frac{dz}{dv} - \left(4\beta b_p(b_g + v b_p) + b_g L^2\right)b_p J\right)$. By substituting $\frac{dz}{dv}$, it is observed that $\frac{d\theta_m^{gs}}{dv} < 0$ and $\frac{dp_m^{gs}}{dv} < 0$. □

G. Proof of Corollary 3.6

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 $b_p K\left(c_o I(z) + c_s(\mu + I(z) - z)\right) + I(z)\left(b_p(8\beta + vL)(a - b_p c + z) + K b_p c + b_g L I(z)\right)$. Recalling that the overage and shortage cost $c_o I(z) + c_s(\mu + I(z) - z) \ge 0$ 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. □

Table A1 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 $D_b = a - b_p c$.

H. Proof of Proposition 3.3

By taking the first-order derivative of the logarithmic function of Eq. (4) with respect to the wholesale price, we 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 3.3. 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.

□

Appendix of Chapter 4 Decision-Making and Coordination under Asymmetric Information: Pathways to Green Innovation in Supply Chains

Proof of Lemma 4.2

Following backward induction approach, we first derive the retailer's optimal response function through the first-order optimality condition of Equation (7) in p : $p^* = w + \frac{1}{2b_p}\left(a - b_p(w + x\phi g) + b_g(1-\phi)\theta\right)$.

Substituting p^* into the ethical manufacturer's profit function Equation (5) yields $\Pi_M^{nwu}(w,\theta,g \mid p^*)$. The second-order conditions are satisfied and the Hessian matrix is negative definite under the restriction that $\left(8\beta b_p - (1-\phi)b_g^2\right)\gamma - \phi(1+x)^2\beta b_p^2 > 0$, which is satisfied with the general setting of $\beta > \frac{b_g^2}{2b_p}$ and $\gamma > \frac{2\beta b_p(a + b_p c)}{(8\beta b_p - b_g^2)c}$ derived from the complete information model analysis; thus, the profit function is jointly concave in the decision variables. Then, according to the first-order optimality conditions, the optimal solutions for the manufacturer are defined by:

$$\begin{cases} \dfrac{\partial \Pi_M^{nwu}}{\partial w} = -b_p w + \dfrac{1}{2}\left(a - ((1-x)\phi g - c)b_p + (1-\phi)b_g\theta\right) = 0 \\ \dfrac{\partial \Pi_M^{nwu}}{\partial \theta} = -2\beta(1-\phi)\theta + \dfrac{1}{2}\left((1-\phi)b_g(w - c + \phi g)\right) = 0 \\ \dfrac{\partial \Pi_M^{nwu}}{\partial g} = -(2\gamma - x\phi b_p)\phi g + \dfrac{\phi}{2}\left(a - ((1-x)w + xc)b_p + (1-\phi)b_g\theta\right) = 0 \end{cases}$$

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

$$\begin{cases} g^{nwu} = \dfrac{(1+x)\beta b_p(a - b_p c)}{\left(8\beta b_p - (1-\phi)b_g^2\right)\gamma - \phi(1+x)^2\beta b_p^2} \\ \theta^{nwu} = \dfrac{\gamma b_g(a - b_p c)}{\left(8\beta b_p - (1-\phi)b_g^2\right)\gamma - \phi(1+x)^2\beta b_p^2} \\ w^{nwu} = \dfrac{\left(4\gamma - \phi(1+x)b_p\right)\beta(a - b_p c)}{\left(8\beta b_p - (1-\phi)b_g^2\right)\gamma - \phi(1+x)^2\beta b_p^2} + c \end{cases}$$

Substituting the above optimal solutions into the retailer's response function, we then obtain the equilibrium retail price $p^{nwu} = \frac{\left(6\gamma - \phi(1+x)^2 b_p\right)\beta(a - b_p c)}{\left(8\beta b_p - (1-\phi)b_g^2\right)\gamma - \phi(1+x)^2\beta b_p^2} + c$.

Accordingly, the demand of the green product is $D^{nwu} = \frac{2\gamma\beta b_p(a - b_p c)}{\left(8\beta b_p - (1-\phi)b_g^2\right)\gamma - \phi(1+x)^2\beta b_p^2}$.

Finally, we have the optimal profits of the manufacturer and the retailer in the unobservable innovation without greenwashing case: $\Pi_M^{nwu} = \frac{\gamma\beta(a-b_pc)^2}{\left(8\beta b_p-(1-\phi)b_g^2\right)\gamma-\phi(1+x)^2\beta b_p^2}$ and $\Pi_R^{nwu} = \frac{4b_p\gamma^2\beta^2(a-b_pc)^2}{\left(\left(8\beta b_p-(1-\phi)b_g^2\right)\gamma-\phi(1+x)^2\beta b_p^2\right)^2}$.

In the greenwashing case, the manufacturer does not genuinely invest in unobservable green process innovation but untruthfully reports that her green process innovation level is g^{nwu}. Given $g^{wu}=g^{nwu}$, we substitute p^* into the manufacturer's profit function Equation (6) and follow a similar analysis as for the above non-greenwashing case, and we can derive the following optimal decisions of the manufacturer seeking to greenwash unobservable green practices:

$$\theta^{wu} = \frac{(1-k)\left(8\beta b_p-(1-\phi)b_g^2\right)\gamma b_g(a-b_pc)}{\left(8\beta b_p-(1-k)(1-\phi)b_g^2\right)\left(\left(8\beta b_p-(1-\phi)b_g^2\right)\gamma-\phi(1+x)^2\beta b_p^2\right)}$$

$$w^{wu} = \frac{\left(4\left(\left(8\beta b_p-(1-\phi)b_g^2\right)\gamma-\phi(1+x)^2\beta b_p^2\right)-\phi(1+x)b_p\left((1-x)4\beta b_p-(1-k)(1-\phi)b_g^2\right)\right)\beta(a-b_pc)}{\left(8\beta b_p-(1-k)(1-\phi)b_g^2\right)\left(\left(8\beta b_p-(1-\phi)b_g^2\right)\gamma-\phi(1+x)^2\beta b_p^2\right)}+c$$

Accordingly, we obtain the retail price $p^{wu} = \frac{\left(6\left(\left(8\beta b_p-(1-\phi)b_g^2\right)\gamma-\phi(1+x)^2\beta b_p^2\right)-\phi(1+x)^2b_p\left(2\beta b_p-(1-k)(1-\phi)b_g^2\right)\right)\beta(a-b_pc)}{\left(8\beta b_p-(1-k)(1-\phi)b_g^2\right)\left(\left(8\beta b_p-(1-\phi)b_g^2\right)\gamma-\phi(1+x)^2\beta b_p^2\right)}+c$ and market demand $D^{wu} = \frac{2\left(8\beta b_p-(1-\phi)b_g^2\right)\gamma\beta b_p(a-b_pc)}{\left(8\beta b_p-(1-k)(1-\phi)b_g^2\right)\left(\left(8\beta b_p-(1-\phi)b_g^2\right)\gamma-\phi(1+x)^2\beta b_p^2\right)}$.

Hence, we have the optimal profits of the manufacturer and the retailer in the unobservable innovation with greenwashing case:

$$\begin{aligned}\Pi_M^{wu} &= \frac{(1-k)\left(8\beta b_p-(1-\phi)b_g^2\right)^2\gamma^2\beta(a-b_pc)^2}{\left(8\beta b_p-(1-k)(1-\phi)b_g^2\right)\left(\left(8\beta b_p-(1-\phi)b_g^2\right)\gamma-\phi(1+x)^2\beta b_p^2\right)^2}\\ \Pi_R^{wu} &= \frac{4\left(8\beta b_p-(1-\phi)b_g^2\right)^2b_p\gamma^2\beta^2(a-b_pc)^2}{\left(8\beta b_p-(1-k)(1-\phi)b_g^2\right)^2\left(\left(8\beta b_p-(1-\phi)b_g^2\right)\gamma-\phi(1+x)^2\beta b_p^2\right)^2}\end{aligned}.\ \square$$

Proof of Proposition 4.1

The manufacturer behaves opportunistically and misreports her green process innovation level which is unobservable to the retailer, whenever such greenwashing behaviour is profitable, i.e. $\Pi_M^{wu} \geq \Pi_M^{nwu}$. We compare Π_M^{wu} with Π_M^{nwu} by evaluating $\Pi_M^{wu}-\Pi_M^{nwu}$. After simplification, it is easy to verify that we need to evaluate the sign of

$F(1-\phi)B_3^2b_g^2k^2+\left(B_1B_3^2F+\gamma\beta^2b_pD_0^2\left(8B_3+(1+x)^2\phi b_pB_1\right)\right)k-(1+x)^2\phi\gamma\beta^2b_p^2B_1D_0^2$. Hence, $\Pi_M^{wu} \geq \Pi_M^{nwu}$ is satisfied under the conditions $0 \leq F \leq \frac{(1-k)\gamma\beta B_1^2D_0^2}{kB_2B_3^2}$ and

$0 \le k \le \frac{-\left(B_1 B_3^2 F + \gamma\beta^2 b_p D_0^2\left(8B_3 + \phi b_p (1+x)^2 B_1\right)\right) + \left(\left(B_1 B_3^2 F + \gamma\beta^2 b_p D_0^2\left(8B_3 + \phi b_p (1+x)^2 B_1\right)\right)^2 + 4\phi b_p^2 D_0^2 B_1 B_3^2 F\right)^{\frac{1}{2}}}{2(1-\phi) b_g^2 B_3^2 F}$. Then, taking the first-order derivatives of the equilibrium outcomes with respect to k, we obtain:

$$\begin{aligned}
\frac{d\theta^{wu}}{dk} &= -\frac{8\gamma\beta b_p b_g B_1 D_0}{B_2^2 B_3} < 0 \\
\frac{dw^{wu}}{dk} &= -\frac{4(1-\phi)\gamma\beta b_g^2 B_1 D_0}{B_2^2 B_3} < 0 \\
\frac{dp^{wu}}{dk} &= -\frac{6(1-\phi)\gamma\beta b_g^2 B_1 D_0}{B_2^2 B_3} < 0 \\
\frac{dD^{wu}}{dk} &= -\frac{2(1-\phi)\gamma\beta b_p b_g^2 B_1 D_0}{B_2^2 B_3} < 0 \\
\frac{d\Pi_M^{wu}}{dk} &= -\frac{8\gamma^2\beta^2 b_p B_1^2 D_0^2}{B_2^2 B_3^2} - F < 0 \\
\frac{d\Pi_R^{wu}}{dk} &= -\frac{8(1-\phi)\gamma^2\beta^2 b_p b_g^2 B_1^2 D_0^2}{B_2^3 B_3^2} < 0
\end{aligned} \quad . \square$$

Proof of Corollary 4.1 and Corollary 4.2

In order to investigate the impact of process innovation unobservability, we first analyse the first-order derivatives of the equilibriums in the unobservable case with respect to ϕ and have:

$$\begin{aligned}
\frac{dg^{nwu}}{d\phi} &= -\frac{\left(b_g^2\gamma - (1+x)^2\beta b_p^2\right)(1+x) b_p D_0}{B_3^2} \\
\frac{d\theta^{nwu}}{d\phi} &= -\frac{\left(b_g^2\gamma - (1+x)^2\beta b_p^2\right)\gamma b_g D_0}{B_3^2} \\
\frac{dw^{nwu}}{d\phi} &= -\frac{\left(4b_g^2\gamma + (1+x) b_p\left(4(1-x)\beta b_p - b_g^2\right)\right)\gamma\beta D_0}{B_3^2} < 0 \\
\frac{dp^{nwu}}{d\phi} &= -\frac{\left(6b_g^2\gamma + (1+x)^2 b_p (2\beta b_p - b_g^2)\right)\gamma\beta D_0}{B_3^2} < 0 \\
\frac{dD_M^{nwu}}{d\phi} &= -\frac{2\left(b_g^2\gamma - (1+x)^2\beta b_p^2\right) b_p\gamma\beta D_0}{B_3^2} \\
\frac{d\Pi_M^{nwu}}{d\phi} &= -\frac{\left(b_g^2\gamma - (1+x)^2\beta b_p^2\right)\gamma\beta D_0}{B_3^2} \\
\frac{d\Pi_R^{nwu}}{d\phi} &= -\frac{8\left(b_g^2\gamma - (1+x)^2\beta b_p^2\right) b_p\gamma^2\beta^2 D_0^2}{B_3^3}
\end{aligned}$$

Given that $\beta > \frac{b_g^2}{2b_p}$ and $\gamma > \frac{2\beta b_p (a + b_p c)}{(8\beta b_p - b_g^2)c}$, it is easy to observe that $\frac{dw^{nwu}}{d\phi} < 0$ and $\frac{dp^{nwu}}{d\phi} < 0$. Moreover, analysing the sign of $b_g^2\gamma - (1+x)^2\beta b_p^2$, we have

$\frac{dg^{nwu}}{d\phi} < 0, \frac{d\theta^{nwu}}{d\phi} < 0, \frac{dD_M^{nwu}}{d\phi} < 0, \frac{d\Pi_M^{nwu}}{d\phi} < 0, \frac{d\Pi_R^{nwu}}{d\phi} < 0$ when $x \in [0, \frac{b_g\sqrt{\gamma\beta}}{\beta b_p} - 1)$. Hence, the wholesale price and retail price is decreasing in ϕ. The innovation levels and profits are decreasing in ϕ when $x \in [0, \frac{b_g\sqrt{\gamma\beta}}{\beta b_p} - 1)$, and increasing in ϕ when $x \in (\frac{b_g\sqrt{\gamma\beta}}{\beta b_p} - 1, 1]$.

Then, we compare the equilibrium outcomes of the complete-information and unobservable cases by evaluating the difference of corresponding decisions:

$$g^{go} - g^{nwu} = \frac{\left((1-x)B_3 + (1+x)\left(B_3 - (B_0\gamma - 4\beta b_p^2)\right)\right)\beta b_p D_0}{(B_0\gamma - 4\beta b_p^2)B_3} > 0$$

$$\theta^{go} - \theta^{nwu} = \frac{\left(B_3 - (B_0\gamma - 4\beta b_p^2)\right)\gamma b_g D_0}{(B_0\gamma - 4\beta b_p^2)B_3} > 0$$

$$w^{go} - w^{nwu} = \frac{\left(\left(4b_g^2\gamma^2 + \left((1-x^2)4\beta b_p - (x+3)b_g^2\right)b_p\gamma - (1-x^2)2\beta b_p^3\right)\phi + 2\gamma b_p b_g^2\right)\beta D_0}{(B_0\gamma - 4\beta b_p^2)B_3}$$

$$p^{go} - p^{nwu} = \frac{\left(\left(6b_g^2\gamma + b_p\left((1+x)^2(2\beta b_p - b_g^2) - 4b_g^2\right)\right)\phi - 4b_p(2\beta b_p - b_g^2)\right)\gamma\beta D_0}{(B_0\gamma - 4\beta b_p^2)B_3}$$

$$D^{go} - D^{nwu} = \frac{2\left(B_3 - (B_0\gamma - 4\beta b_p^2)\right)\gamma\beta b_P D_0}{(B_0\gamma - 4\beta b_p^2)B_3} > 0$$

$$\Pi_M^{go} - \Pi_M^{nwu} = \frac{\left(B_3 - (B_0\gamma - 4\beta b_p^2)\right)\gamma\beta D_0^2}{(B_0\gamma - 4\beta b_p^2)B_3} > 0$$

$$\Pi_R^{go} - \Pi_R^{nwu} = \frac{4\left(B_3^2 - (B_0\gamma - 4\beta b_p^2)^2\right)b_p\gamma^2\beta^2 D_0^2}{(B_0\gamma - 4\beta b_p^2)^2 B_3^2} > 0$$

Using the fact that $B_3 - (B_0\gamma - 4\beta b_p^2) > 0$ under the condition that $x \in [0,1]$ and $\phi \in (0,1)$, it is easy to obtain that $g^{go} > g^{nwu}, \theta^{go} > \theta^{nwu}, D^{go} > D^{nwu}, \Pi_M^{go} > \Pi_M^{nwu}, \Pi_R^{go} > \Pi_R^{nwu}$, i.e. the innovation unobservability decreases the innovation levels and profits. Analysing the relationship between the retail prices, we find that $p^{go} > p^{nwu}$ is satisfied when $\phi \in (\frac{4b_p(2\beta b_p - b_g^2)}{6b_g^2\gamma + b_p\left((1+x)^2(2\beta b_p - b_g^2) - 4b_g^2\right)}, 1)$. □

Proof of Proposition 4.2 and Proposition 4.3

Provided the profit functions under coordination case in Equations (11) and (12), we apply the backward induction approach as demonstrated in previous solution procedure and obtain the following equilibriums:

$$\begin{aligned} g^{cu} &= \frac{\left(8\beta b_p - (1-\phi-y)b_g^2\right)\tau_1 + 2(\phi+y)\beta b_p b_g \tau_2 + 4(\phi+y)\beta b_p D_0}{2(\phi+y)B_6} \\ \theta^{cu} &= \frac{(1-\phi-y)b_p b_g \tau_1 + 2\left(2\gamma - (\phi+y)b_p\right)b_p \tau_2 + (1-\phi-y)\gamma b_g D_0}{(1-\phi-y)B_6} \\ p^{cu} &= \frac{\left(-2\beta b_p + (1-\phi-y)b_g^2\right)\tau_1 + \left(3\gamma - 2(\phi+y)b_p\right)b_g \tau_2 + 2\left(3\gamma - 2(\phi+y)b_p\right)\beta D_0}{B_6} + c \end{aligned} .$$

With $B_6 = \left(8\beta b_p - (1-\phi-y)b_g^2\right)\gamma - 4(\phi+y)\beta b_p^2 > 0$. Referring to Leng and Zhu (2009), the manufacturer and the retailer cooperatively set $g^{cu} = g^{iu}, \theta^{cu} = \theta^{iu}, p^{cu} = p^{iu}$ to satisfy the incentive compatibility constraint and thereby we precisely obtain the parameter setting: $y = \frac{4\gamma\beta b_p}{B_5}, \tau_1 = \frac{8(\phi B_5 + 4\gamma\beta b_p)\gamma^2 \beta b_p b_g^2 D_0}{B_4 B_5^2}, \tau_2 = \frac{4\left((1-\phi)B_5 - 4\gamma\beta b_p\right)\gamma^2 \beta b_g^3 D_0}{B_4 B_5^2}$.

Then, substituting the decisions and contract terms' values into the profit functions yields the total profit of the supply chain $\Pi_{SC}^{cu} = \Pi_M^{cu} + \Pi_R^{cu} = \frac{\left(B_4 B_5^2 + 4\gamma\beta b_p (4\beta b_p^2 + \gamma b_g^2)(4\beta b_p^2 - 3\gamma b_g^2)\right)\gamma\beta D_0^2}{B_4^2 B_5^2} - T$. It shows that the full coordination, i.e. $\Pi_{SC}^{cu} = \Pi_{SC}^{iu}$, can be achieved only if the technological adoption cost satisfies $T = \frac{4(4\beta b_p^2 + \gamma b_g^2)(4\beta b_p^2 - 3\gamma b_g^2) b_p \gamma^2 \beta^2 D_0^2}{B_4^2 B_5^2}$. □

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Appendix of Chapter 5 Green Marketing Strategies in a Supply Chain under Asymmetric Information

Proof of Proposition 5.1

To solve the optimisation problem, we construct the Lagrangian as $L = \Pi_H^s - \lambda(\Pi_L^s - \Pi_L^{ci})$. The determinant of the Hessian matrix according to the Lagrangean is $4b_p\alpha(1-\lambda)^2 - \left((1-(1-\delta)\lambda)b_g(H-R)\right)^2 > 0$ and the second-order condition is satisfied under the restriction $0 < \lambda < 1$. Thus, the Lagrangean is jointly concave in η_H and p_H. Then, the first-order optimality conditions are:

$$\begin{cases} \dfrac{\partial L}{\partial \eta_H} = 2\alpha\eta_H - b_g(p_H - c)(H-R) - \lambda\left(2\alpha\eta_H - b_g(1-\delta)(p_H - c)(H-R)\right) = 0 \\ \dfrac{\partial L}{\partial p_H} = 2b_p p_H - \eta_H b_g(H-R) - (1+b_p c) - \lambda\left(2b_p p_H - \eta_H b_g(1-\delta)(H-R) - (1+b_p c)\right) = 0 \end{cases}.$$

Based on the above expressions, we have $p_H = \dfrac{1 + 3b_p c + \sqrt{16 b_p \alpha \eta_H^2 + (1-b_p c)^2}}{4b_p}$ after discarding the implausible negative root. Substituting it into the constraint $\Pi_L^s(\eta_H, p_H, \hat{\rho} = 1) = \Pi_L^{ci}$ yields the optimal solution $\eta_H^s = X(1-b_p c)$, where,

$$X = \frac{2^{\frac{2}{3}}\left(x_3^2 + 2^{\frac{2}{3}}(b_p\alpha)^2(64b_p\alpha - 19x_2)\right)}{12x_2x_3b_p\alpha} + \frac{2x_1}{3x_2} > 0$$
$$x_1 = (1-\delta)b_g(H-R)$$
$$x_2 = 4b_p\alpha - x_1^2$$
$$x_3 = \left((b_p\alpha)^2\left(3^{\frac{3}{2}}x_2(x_2 - 6b_p\alpha)\sqrt{x_2 + 28x_1^2} + (27x_2^2 - 164b_p\alpha x_2 + 512(b_p\alpha)^2)x_1\right)\right)^{\frac{1}{3}}$$

. Hence, we can derive that $p_H^s = \dfrac{(1+\sqrt{1+16b_p\alpha X^2})(1-b_p c)}{4b_p} + c$.

The green firm's optimal profit $\Pi_H^s = \dfrac{\left((1+\sqrt{1+16b_p\alpha X^2})(\frac{1}{2} + b_g(H-R)X) - 8b_p\alpha X^2\right)(1-b_p c)^2}{4b_p}$ is obtained by substituting (η_H^s, p_H^s) into its profit function. The constraint $\Pi_H^s \geq \Pi_H^{ns}$ further reduces the range of the market transparency to $\delta_l \leq \delta \leq \delta_u$ where δ_l is uniquely determined by the equation $4b_p\alpha - \left((1+\sqrt{1+16b_p\alpha X^2})(\frac{1}{2} + b_g(H-R)X) - 8b_p\alpha X^2\right)\left(4b_p\alpha - \left((\rho + (1-\rho)\delta)b_g(H-R)\right)^2\right) = 0$. □

Curriculum Vitae

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Education

PhD Researcher, Transport and Logistics Group Delft University of Technology, Delft, The Netherlands Thesis: Decision-Making and Coordination in Green Supply Chains with Asymmetric Information	Sep. 2017- Jul. 2024
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Contract Design with Information Asymmetry in Green Supply Chain Collaboration

Skills

Advanced Research & Analysis: Proficient in analysing diverse sustainability challenges within supply chains.

Strategic Planning & Modelling: Skilled in developing optimisation models and proposing effective strategies.

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List of publications

Papers Published

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Papers under Review

Kailan Wu, Lóránt Tavasszy, Jafar Rezaei, & Bart De Schutter. Game-theoretic Models for Sustainable Supply Chains with Asymmetric Information: A Review.

Kailan Wu, Lóránt Tavasszy, Bart De Schutter, & Jafar Rezaei. Decision-Making and Coordination under Asymmetric Information: Pathways to Green Innovation in Supply Chains.

Kailan Wu, Lóránt Tavasszy, Bart De Schutter, & Jafar Rezaei. Green Marketing Strategies in a Supply Chain under Asymmetric Information.

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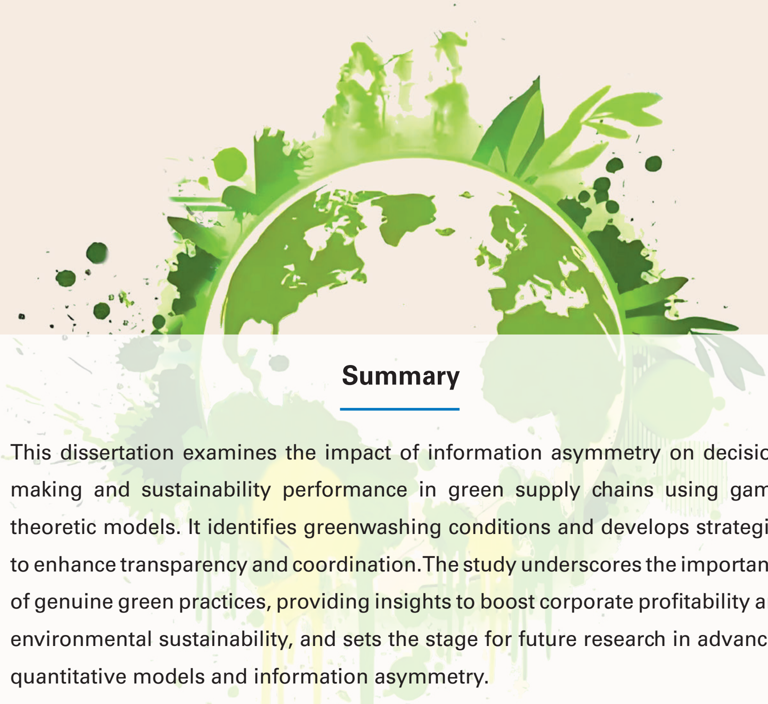

Summary

This dissertation examines the impact of information asymmetry on decision-making and sustainability performance in green supply chains using game-theoretic models. It identifies greenwashing conditions and develops strategies to enhance transparency and coordination. The study underscores the importance of genuine green practices, providing insights to boost corporate profitability and environmental sustainability, and sets the stage for future research in advanced quantitative models and information asymmetry.

About the Author

Kailan Wu is a dedicated researcher specialising in green supply chain management. Passionate about sustainability, her work focuses on reducing carbon emissions and promoting green practices in supply chain operations. Her expertise and areas of interest include green product development, game theory in supply chain decision analysis, contract coordination, information asymmetry, and greenwashing.

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