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Optimising resource recovery from construction waste material reverse supply chain coordination games

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ABSTRACT

The inefficiency of government, recycling, and recovery companies in managing construction waste, especially after an earthquake, highlights the operational challenges of reverse supply chain (RSC) in effectively recycling materials. This study aims to address these inefficiencies by proposing a decision-making supply chain model that enhances coordination within the RSC, and focusing on optimising the management of post-disaster construction waste. Grounded in market demand functions, the model explores three subsidy models to examine their impact on recycling efficiency, the recycling ratio, retail pricing of materials from recycled waste, and overall profit. The study uses manufacturing enterprises-leadership and subsidy-specific Stackelberg game models to find optimal strategies for minimising waste and maximising supply chain profit. The results show that government subsidies significantly influence recycling and pricing strategies within RSC operations, and governments should offer subsidies according to waste dispersion prioritisation and quantity of recoverable construction debris. Based on the study findings, the proposed RSC model substantially enhances recycling efficiency and profitability for both recycling and manufacturing firms. These findings validate the effectiveness of the model and emphasise the prospects for future research on an RSC framework for construction waste material.

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1. Introduction

Recent strides in computer science and technological advancements have bolstered capabilities to address both natural and human-made disasters (Akter & Wamba, 2019; Camacho-Vallejo et al., 2015; Nelan et al., 2018; Paret et al., 2023). Despite these advancements, unanticipated natural disasters, such as earthquakes, typhoons, and floods, continue to have devastating impacts on human life (Nelan et al., 2018). Particularly noteworthy is the generation of substantial volumes of waste in the aftermath of earthquakes due to structural damage to houses and buildings (Ralston et al., 2023). For instance, in the aftermath of the 2008 Wenchuan earthquake in Sichuan, China, the Sichuan earthquake relief headquarters reported staggering figures of approximately 31.28 million tons of waste from damaged houses and over 500 million tons of construction waste, which surpassed the total volume of waste generated by construction projects in China in 2008 (Guha-Sapir & Scales, 2020). This shows the substantial scale of post-earthquake construction waste, and the challenges that extend beyond the immediate seismic impacts. Coseismal landslides, triggered by a single large earthquake, present additional complexities, and require assessments to determine landslide risks and conduct long-term post-earthquake evaluations (Di Filippo et al., 2022). Moreover, mudslides that follow earthquakes pose formidable challenges to reverse supply chain systems during post-disaster recovery efforts (Qin, 2022). RSC refers to the network of processes involved in the collection, processing, and reintegration of waste materials back into the production cycle. It encompasses all activities from waste generation to the final reuse or disposal, aiming to maximise resource efficiency and minimise environmental impact (Rentizelas & Trivyza, 2022).

This research is driven by the important of refining post-earthquake recovery strategies, and recognises that effective waste management has a role to mitigate not only environmental harm but also economic losses and the adverse effects on the affected populations (Pal, 2024; Pal et al., 2023). Within this context, RSCs are identified as a mechanism. They facilitate resource utilisation and introduce innovative approaches to traditional supply chain processes in the aftermath of an earthquake, thereby playing a pivotal role in post-disaster recovery

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and waste management (Brinch et al., 2018; Chien et al., 2022).

The literature on RSCs has witnessed considerable progress in three aspects: (1) government interventions such as subsidies to help victims (e.g. Abualkhair et al., 2020; Akter & Wamba, 2019); (2) game model designs and solutions for RSCs in scenarios without government intervention (e.g. Amato et al., 2019; Anson et al., 2017); and (3) understanding the impact of chemical and physical elements on resource recovery and disposal in RSCs (e.g. Mappas et al., 2022). However, most of these studies focus on high-value goods, such as electronic products (e.g. Chileshe et al., 2015; Tan et al., 2023; Zhu et al., 2020), while few studies pay attention to construction waste material. In addition, existing RSC models primarily focus on pricing strategies (Dill, 2023), coordinating recycling systems (Sigala et al., 2020; Skipper & Hanna, 2009), and government subsidy strategies (Zhang, Tian, et al., 2022), but not on the role of government intervention in the development of RSCs, particularly in post-disaster scenarios (Zhang, Hong, et al., 2020). Thus, we propose the following research question (RQ):

> RQ1: How do government interventions influence the effectiveness of construction waste recycling efforts in the post-disaster context?

Effective evaluation of waste management methods after an earthquake promotes construction waste management after disasters (Li et al., 2015). Costs and environmental impacts can vary with different management scenarios, which results in the complexity of decision-making processes (Amato et al., 2019). Sustainable management of post-disaster waste is of paramount importance to prevent environmental damage and ensure public health and safety. Throughout all of the phases of disaster preparation, response, and recovery, both the private and public sectors have social responsibility (Xing, 2023; Zhang, Aydin, et al., 2022). Corporate social responsibility (CSR) and public policies play vital roles in promoting sustainability and social stability before, during, and after disasters (Liu, Hendalianpour, et al., 2023; Viegas et al., 2019). However, no studies in the existing literature have done a comprehensive exploration of the intricacies involved in implementing RSCs for post-earthquake construction waste management (Pal, 2024; Zhang, Feng, et al., 2023), which leads to our second RQ:

> RQ2: What strategies can enterprises employ to enhance their recycling and remanufacturing operations post-disaster that take the role of government policies into consideration?

To answer these two RQs, this study constructs three Stackelberg game models for RSCs tailored to the unique context of construction waste. Encompassing key stakeholders such as government entities, remanufacturing and recycling enterprises, consumers, and other relevant actors, these three models are used to analyze the profits and overall profitability of the participants under various subsidy models. The ultimate goal is to identify the optimal decision-making model for coordinating the supply chain. Moreover, the study examines how the distinct characteristics of construction waste influence the optimal recycling model, with the aim to enhance the recovery efficiency of post-construction waste. As this study focuses on the manufacturers' responsibility and recycling dynamics, and manufacturers wield considerable influence over the RSC, shaping both production and recycling decisions, we thus utilise a manufacturer-led Stackelberg game to analyze strategic interactions within the RSC. This game-theoretic approach is chosen due to its effectiveness in modelling hierarchical decision-making processes (Fei & Ma, 2023), where manufacturers (leaders) dictate an initial strategy and downstream entities (followers) have to make responses to the strategy.

This study makes three contributions that enhance both the theoretical frameworks and practical applications related to RSC models in the context of construction waste. First, this research enhances the theoretical understanding of RSC models by integrating the concepts of sustainability and post-disaster recovery. The work explores how government interventions can act as catalyzers for effective construction waste recycling. This novel perspective enriches the RSC discourse by linking policymaking with operational efficiency and sustainability outcomes. Second, this study introduces an innovative analytical approach that combines qualitative and quantitative methods to assess the impact of government policies on RSC operations. This hybrid methodology allows for a more nuanced examination of the interplay between regulatory frameworks and RSC effectiveness, thus offering a robust model that can be adapted and utilised in different post-disaster contexts. Third, the findings provide actionable insights for policymakers and industry stakeholders, which facilitate the formulation of targeted strategies to optimise RSC activities. The study provides clear guidelines on how sustainable practices can be effectively incorporated into construction waste management, thus promoting environmental stewardship while ensuring economic viability and contributing to the quick rehabilitation of disaster-affected communities.

The rest of this paper is organised as follows: Section 2 provides an overview of the existing literature. Section 3 defines the variables and establishes the models for the RSC. Section 4 describes the model for construction waste recycling without government subsidies, and Section 5 presents the model with different government subsidies. Section 6 analyzes the equilibrium results, and Section 7 presents the empirical analysis results. Section 8 summarises the implications. Finally, Section 9 discusses the research limitations.

2. Literature review

This study focuses on three areas: (1) the impact of earthquakes on supply chain operations, (2) the role of information and technology in RSC operations, and (3) the application of the game theory to RSC operations.

2.1. Impact of earthquakes on supply chain operations

Cities are increasingly at risk of major disasters due to rapid global urbanisation. While considerable attention has been given to other aspects of urban disaster recovery efforts, construction waste cleanup has been largely neglected (Hooper, 2019). Seismic hazards are rarely considered when studying the environmental impact of buildings, but their environmental impact can be significant (Huang & Simonen, 2020). For example, the 2015 Nepal earthquake resulted in significant destruction in Kathmandu and its neighbouring towns, which led to the accumulation of a substantial amount of construction waste (Hasik et al., 2018), It was estimated that approximately 3.23 million tons of building debris were generated, with 2.17 million tons remaining unused or unrecycled as of 2018 (Uehara et al., 2022; Xiaoli et al., 2015). Following the earthquake, construction and post-earthquake reconstruction projects, mainly provided by the informal construction sector, were carried out to analyze how and whether informal construction workers can further their professional capacity and undergo training to build more resilient buildings (Rose & Chmutina, 2021).

The 2011 Christchurch earthquake which took place on February 22, 2011 and the aftershocks near the central business district (CBD) of Christchurch in the Canterbury region of South Island cost the community more than NZ$40 billion (1 NZD = 0.62 USD), which demolished approximately 60 per cent of their multi-story concrete buildings, and closed the core business district for more than 2 years (Kongar et al., 2017). According to (Salam & Khan, 2020; Tang et al., 2015; Thorne-Lyman et al., 2018), approximately 8 million tons of debris were generated. According to Guerrero-Miranda and Gonzalez (2021) about 7500 houses and 1400 commercial properties were demolished, which resulted in 4 million tons of construction waste.

During the post-earthquake recovery process, geoinformatics play a vital role with the use of 4K-video footage from unmanned aerial vehicle systems (UAVSs), and geo-information methods that are designed to monitor the demolition process and map demolished buildings (Soulakellis et al., 2020). Thorne-Lyman et al. (2018) used Nepal as a case study to explore the role of knowledge, awareness and experience of informal construction stakeholders in disaster reduction measures. One of the ways to inform stakeholders and increase their awareness of hazards, such as the impact of construction waste, is through the use of geoinformatics integrated with disaster risk (DR) strategies, that is, digitally reconstructed radiographs (DRRs) generated from unmanned aerial vehicle (UAV) images. By using DRRs, stakeholders can visually analyze and comprehend the potential risks associated with construction waste, thereby enhancing their preparedness and response capabilities. However, it is also important to consider the cognitive skills of the stakeholders and their ability to engage when finding the best solutions to promote measures that use DRRs (Thorne-Lyman et al., 2018).

Recycling is often used in disaster waste management. Nevertheless, the feasibility, methods, and effects of recycling vary depending on the disaster itself (Li et al., 2016). Efficiently managing perishable products in supply chain networks also poses challenges. Hendalianpour et al. (2021) addressed the complexities of ensuring adequate blood supply and distribution for victims of disasters. They proposed an integrated inventory-routing model with transshipment to minimise costs with uncertain demand. Hendalianpour (2020) focused on industrial supply chain management for healthy foods, and used a game-theoretic model that considers pricing and lot-sizing decisions. Both studies contribute valuable insights, and use mathematical models and optimisation techniques to enhance decision-making for products with limited shelf-life, thus showing practical solutions for these critical industries.

2.2. Role of information and technology in RSC operations

Earthquakes often result in a substantial amount of debris due to the damage or destruction that they cause to residential and commercial structures. In response, this study has conducted a series of on-site inquiries in earthquake-affected locales to assess the degree of correlation between specific types of building frameworks and the resulting construction waste. The proposed mathematical framework (Soulakellis et al., 2020) incorporates a multifaceted statistical analysis that examines the expected volume of detritus from different perspectives. These include the intensity and epicenter of the earthquake, structural resilience of the affected buildings, historical patterns of debris after similar seismic activities, and population density of the impacted area, all of which are crucial for accurately predicting the volume of debris. Liu, Zuo, et al. (2023) emphasised the significance of a systematic and transparent approach to supplier selection, and incorporate CSR practices in a system dynamics model. Amato et al. (2019) underscored the positive impact of reducing the average distance between suppliers and increasing their numbers on profitability, cost reduction, improved delivery times (Liu et al., 2022), and heightened customer satisfaction. Hendalianpour et al. (2022) delved into inventory planning and control by using the economic order quantity (EOQ) model in a multi-echelon supply chain (SC). Incorporating the game theory and fuzzy demand forecasting, the research highlighted the crucial role of accurate forecasting for effective inventory control, especially in the face of increased price elasticity. Kongar et al. (2017) enhanced the profit of retailers and overall profitability of management systems while reducing inventory control costs.

These investigative endeavours provide the constituents and distribution attributes of construction waste in regions stricken by natural disasters (Tang et al., 2015), including the characteristics and composition of construction waste, such as the materials used, and their shape, size, and density. The study also investigates the potential environmental impacts of the waste, including pollution and resource depletion (Win et al., 2019; Zamparas et al., 2019; Zhang et al., 2009). Li et al. (2016) indicated that concrete, brick, and tile are the main types of waste generated in earthquake-stricken areas, while wood and metal debris are less common. Additionally, the size and density of the waste can vary significantly depending on the type of building and its location. The analysis conducted on the gathered data underscores a direct correlation between construction waste volume and several key factors, including the architectural characteristics and age of the buildings, along with the magnitude and duration of the seismic event. The model aims to predict waste generation across various earthquake scenarios, thus serving as a valuable tool for enhancing disaster response and waste management strategies (Ye et al., 2017; Yue et al., 2023; Zhang, Yu, et al., 2022).

A more in-depth investigation into the complexities of supply chain management shows that the retail sector, particularly in the context of omni-channel (OC) retail systems, faces a unique set of challenges. Hendalianpour et al. (2021) addressed the challenges of providing a seamless shopping experience across various channels in an OC retail system. Using an approach with multiple objectives, the study optimised the distribution network, thus minimising costs and maximising customer convenience in terms of shipment delivery time. The integration of meta-heuristic algorithms underscores the effectiveness of the proposed mathematical model in obtaining Pareto points at a lower cost and greater customer satisfaction. Collectively, these studies advance understanding and strategies in supplier selection, inventory control, and distribution network optimisation, thus offering valuable insights into enhancing the efficiency and effectiveness of supply chain operations.

Previous research offers in-depth analysis and understanding of the types and properties of construction debris generated in regions affected by seismic activities (Poudel et al., 2019; Sakai et al., 2019; Tang et al., 2015), which can be used to develop effective waste management practices and reduce the negative impacts on the environment and public health. By understanding the composition and distribution of construction waste, disaster management teams can better plan for the removal and disposal of debris, and implement strategies to recycle and reuse materials in the rebuilding process (Zhang, Wu, et al., 2023; Zhao et al., 2017; Zhao & Ma, 2022).

2.3. Application of game theory to RSC operations

Systematic and consistent standards that are used to address disasters when they do occur allow assets to be determined and reports to be made on the physical impacts of earthquakes due to ground motion (Huang et al., 2017). Assessments of the post-earthquake environment contribute to a better understanding of the long-term changes to the landscape and ripple effects of earthquakes in areas affected by mega-earthquakes (Marc et al., 2017). Scholars in the related field have also focused on post-earthquake building structures and post-disaster emergency responses (Yang et al., 2019; Zhang, Ding, et al., 2022).

Recent research endeavours have sought to unravel the complexities inherent in contractual arrangements and supply chain dynamics (Zhang, Jiang, et al., 2020; Zhou et al., 2019; Zhuang et al., 2014), particularly within the oil and gas sectors and broader supply chain models (Xing, 2023; Yu et al., 2022). Hendalianpour et al. (2022) focused on the impact of various factors that influence oil and gas field development contracts by employing the system dynamics (SD) method to comprehensively assess economic, legal, technical, technological, and social aspects. The findings (Zhang, Hong, et al., 2020) revealed that a production sharing contract is a win-win situation, which fosters productivity enhancement strategies for both national oil companies and host countries. In terms of supply chain dynamics, Liu, Hendalianpour, Razmi, et al. (2021) investigated a two-echelon supply chain with competing manufacturers and a retailer. Utilising game theory approaches and double interval grey numbers (DIGNs), they determined optimum retail and wholesale prices under different competitive scenarios. The research emphasised the effects of different construction waste structures among the supply channel members on optimal pricing decisions and evaluated the impacts of retail substitutability on the decisions and equilibrium profits of the supply chain members. Further building on the theme of supply chain coordination, Liu, Hendalianpour, and Hamzehlou (2021) explored the potential of contracts as a supply chain coordination mechanism under competitive conditions, particularly in a two-echelon supply chain model with two manufacturers and two retailers who face grey stochastic demand. The study considered various contracts such as wholesale price, revenue-sharing, and quantity discount contracts. The findings showed the effectiveness of revenue-sharing contracts in enhancing supply chain performance, with implications for competitive decision-making that involve ordering, pricing, and the nature of demand.

The devastating damage of earthquakes to buildings and infrastructures which result in large volumes of construction waste must be addressed in a timely manner (Yang et al., 2019). The effective recovery and recycling of post-earthquake construction waste are critical to mitigating the environmental impacts and minimising health risks to the local communities (Soulakellis et al., 2020). To this end, research has focused on the development of strategies and technologies for RSC operations in disaster-stricken areas (Marquis et al., 2017; Poudel et al., 2019). This includes analyzing the impact of natural disasters on supply chain operations, assessing the correlation between building structure and the generation of construction waste, and exploring the use of the game theory to optimise RSC operations (Amato et al., 2019; Domingo & Luo, 2017; Li et al., 2016). In addition, there has been growing interest in the role of information and technology in post-disaster recovery efforts. For example, Marquis et al. (2017) conducted an empirical study for multi-story buildings in Christchurch, New Zealand, to better understand the RSC logistics that influence the decision to demolish or repair damaged buildings. They found that the assessed damage, occupation type, heritage status, number of floors, and year of construction are significant factors that affect the likelihood of building demolition.

Furthermore, the participation of recycling and manufacturing companies in the RSC process can greatly affect the efficiency of managing construction waste in terms of its recovery and reuse (Kongar et al., 2017), and generate profit during the process (Haghi et al., 2017). Thus, government subsidies and policies play a role in coordinating the decision-making processes of all participants in an RSC (Zhao et al., 2019; Zheng et al., 2021). A more comprehensive understanding of the subsidies provided by governments and their role can facilitate the development of more effective and efficient resource recovery systems, thereby improving the overall coordination of RSC operations (Zhang, Hong, et al., 2020; Zhang, Lim, et al., 2023).

Exploring effective recovery and recycling strategies for the post-earthquake management of construction waste and enhancing the coordination of decision-making in the RSC process have important theoretical implications and practical significance, as these can provide valuable guidance for managing different types of disasters while contributing to a sustainable future of the local communities (Wells et al., 2022; Wu, 2021; Zhang et al., 2017).

3. Model description and basic assumptions

Government, recycling, remanufacturing, and consumer enterprises form a comprehensive network for managing post-earthquake construction waste. The government plays an essential role in setting regulations and guidelines, notably in establishing a pricing mechanism for waste transfer, which directly impacts the operational dynamics of the supply chain. These regulations aim to balance the economic aspects with environmental sustainability, thus encouraging the recycling and remanufacturing enterprises to efficiently collect and process construction debris. These enterprises transform waste into valuable materials, which are then utilised by manufacturing firms to create new products, thereby supporting a circular economy. Consumer enterprises, which include building materials manufacturers and road construction companies, rely on the continuous flow of recycled materials, which shows the importance of a seamlessly operating RSC. This model not only aims to streamline waste management following seismic events but also aligns with the objectives of sustainable development by minimising the environmental footprint of waste disposal and reducing dependency on virgin materials. Through government oversight and the establishment of strategic pricing for waste transfer, the financial and operational sustainability of the RSC model is safeguarded. Consequently, this approach is distinct as a balanced and effective strategy for facilitating post-disaster recovery, resource conservation, and sustainable growth in the construction sector.

Figure 1 is a visual representation of how post-disaster construction waste can be reintegrated into the economic flow through a sustainable and regulated process. The

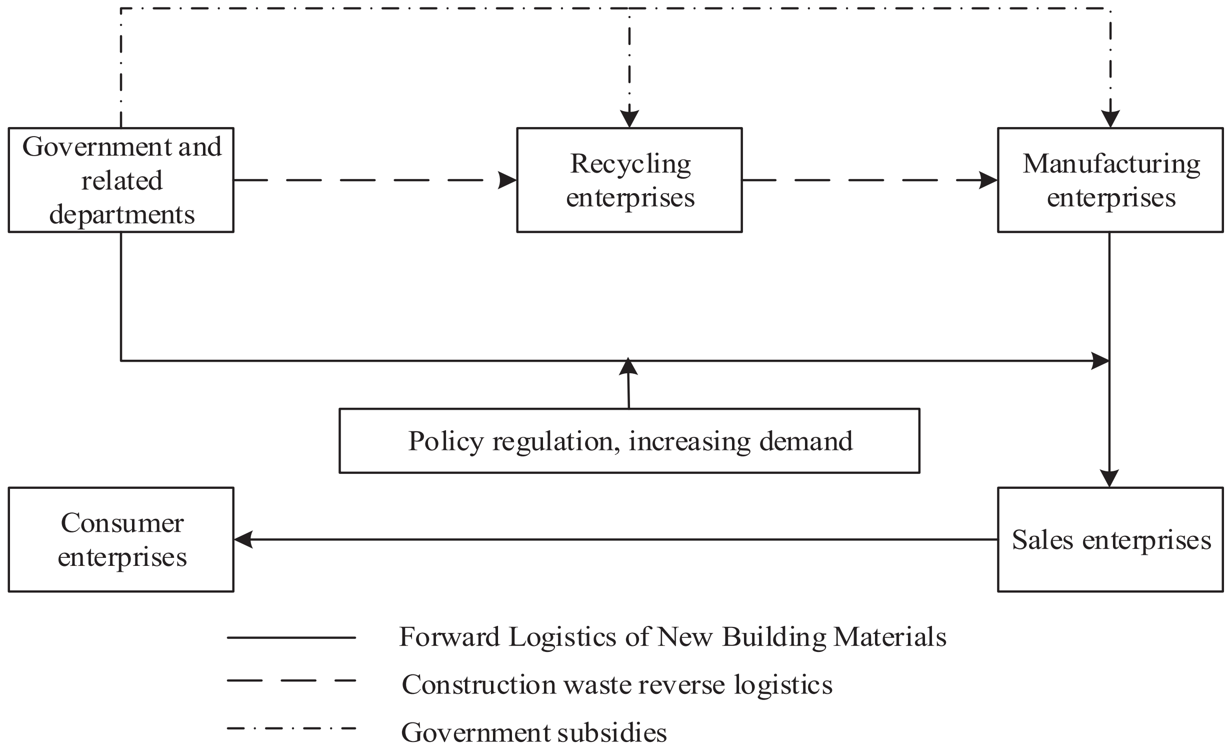

Figure 1. RSC model for resource recovery from post-earthquake construction waste materials.

figure emphasises the importance of government policies in facilitating a circular economy and ensuring that materials are not wasted, but rather reused to benefit the economy and environment. The model underscores the collaborative efforts needed among government bodies and recycling, manufacturing, and consumer enterprises to effectively recover resources in post-earthquake scenarios.

At the beginning of the loop, the government and its related departments are depicted as the initiators of action, who drive the process through policy regulation and the provision of subsidies. These elements are represented by dashed lines that represent the support and direction given to recycling enterprises, which are critical for the initiation of the waste recovery process.

Recycling enterprises are the core node that connects policy inputs with industrial outputs. They receive the construction waste, which is indicated by a dashed line that signifies the reverse logistics involved in bringing waste materials back into the production cycle. Once processed, these materials are transferred to the manufacturing enterprises. This shows the forward logistics of new building materials created from recycled waste.

Manufacturing enterprises then transform the recycled materials into new products, which enter the market via the sales enterprises. This is the final stage of the RSC, where recycled materials are reintroduced into the economy.

The model also shows the influence of consumer enterprises on recycling enterprises. This influence underscores the demand-driven nature of recycling efforts, where the demand for new building materials by consumer enterprises influences the amount and type of waste that is recycled.

A manufacturer-led Stackelberg game model is adopted in this study due to the critical role of manufacturers in the RSCs, as this study highlights manufacturers' capabilities in optimising supply chain operations and use recycling construction waste methods to reduce environmental pollution (Wirths et al., 2024). A Manufacturer-led Stackelberg game model effectively captures strategic decision-making within the RSCs, as manufacturers affect other supply chain members and align their actions with overall objectives (Song et al., 2022). This model is particularly effective in the case of information sharing between the manufacturing enterprises and the recycling enterprises, where manufacturers can leverage their understanding of market dynamics (Wang, 2017).

In the RSC model, seven foundational assumptions guide its implementation.

Assumption 1 underscores the paramount importance of a seamlessly efficient information exchange system among recycling and manufacturing enterprises, government entities, and pertinent government departments within the RSC for optimal resource recovery from post-earthquake waste materials. This assumption envisions a well-established and shared information flow among all of the stakeholders, thus ensuring that the entire RSC process, which includes waste recycling and remanufacturing, proceeds smoothly in a consistent manner. The effectiveness of this communication system is pivotal in coordinating and optimising decision-making processes within the RSC. For instance, timely and accurate information accessible to all relevant parties allows recycling enterprises to efficiently collect and process construction waste, guided by insights from government entities and the relevant departments. At the same time, manufacturing enterprises can leverage this shared information to strategically plan production processes and create new products that are made of recycled materials (Viegas et al., 2019). This comprehensive interoperability and shared information framework significantly enhance the overall efficiency and effectiveness of the RSC, thereby advancing sustainable waste management practices in the aftermath of an earthquake.

Assumption 2 assumes that the market demand function for post-earthquake construction waste is: $D(P) = a - kP$, where a is the market potential demand, k is the market price fluctuation coefficient, and $P > C_m > C_r$ (Fan et al., 2019).

Assumption 3 acknowledges that after an earthquake, buildings often undergo substantial damage, particularly in the case of large earthquakes. The extent of this damage directly influences the volume of construction waste generated. Typically, damaged structures are systematically deconstructed and their materials sorted based on type. This deconstruction process entails breaking down construction waste into smaller components, thus enhancing efficiency in sorting the materials for recycling purposes. The meticulousness in sorting and separating waste, coupled with the integrity of the waste materials, becomes pivotal in optimising recycling efficiency for enterprises within the RSC (Mappas et al., 2022). Therefore, the effectiveness of this sorting and separation process directly contributes to enhanced recycling outcomes, which aligns with the fundamental principles and operations of the RSC.

Assumption 4 posits that the reuse of construction waste is an emerging market with potential substantial demand. In this context, the active involvement of governments becomes pivotal, as they play a central role in efficiently meeting market demand by procuring construction waste. Through their engagement in the recycling and procurement processes, governments ensure a consistent supply of construction waste to manufacturing enterprises (Yu & Kong, 2020). These enterprises, utilising their expertise and resources, transform the waste into viable products. This collaborative synergy fosters the growth of the construction waste reuse market, and maximises its inherent potential within the operational framework of the RSC.

Building on Assumption 4, Assumption 5 asserts that products manufactured with recycled construction waste have a comparable quality and durability as those crafted from organic materials. Using advanced recycling and remanufacturing techniques, the construction waste undergoes meticulous processing to provide high-quality materials suitable for a variety of different applications. These new products not only meet industry standards but also offer the added advantage of sustainable sourcing. Consequently, they command a higher market price, which reflects their value and the environmentally responsible practices integral to their production. This higher price incentivises consumers and industries to prioritise recycled construction waste products, thus creating a circular economy and sustainable development paradigm within the construction sector, in harmony with the principles that guide the RSC.

Assumption 6 states that in an RSC, a recycling enterprise recycles at price f_r, a remanufacturing enterprise recycles and manufactures at price f_m, and sells the product to a consumer enterprise at price $\Delta > f_m > f_r$ (Chileshe et al., 2016; Hosseini-Motlagh et al., 2020).

Assumption 7 assumes that manufacturing enterprises take the forefront in the RSC for construction waste recycling. As the key players, they are the experts in contemporary remanufacturing technologies and market leaders, and have influential discourse power within the industry. They play a pivotal role in setting the sales price for recycling enterprises and the subsequent pricing for consumer enterprises. In collaboration with recycling enterprises, manufacturing enterprises actively contribute to determining government recycling waste prices, which takes recycling efficiency and total recovery into consideration. This assumption aligns with the overarching operational principles of the RSC, where manufacturing enterprises, with their industry knowledge and market influence, steer critical aspects of the recycling process, thus exemplifying their leadership role in construction waste recycling efforts (Dehghan-Sanej et al., 2021). The symbols that correspond to the equations for these assumptions are detailed in Table 1.

4. RSC model for construction waste recycling without government subsidies

The total profit function of the recycling enterprises that follow the direction of the manufacturing enterprises that produce new building materials with construction waste is:

$$\begin{aligned}\pi_m^N &= (P - C_m)D(P) + (\Delta - f_m)G(\omega)\\ &= (P - C_m)(a - kP) + (\Delta - f_m)\omega\delta(a - kP) \quad (1)\end{aligned}$$

Table 1. Symbols for formulas of RSC model.

Symbol	Definition
a	Potential maximum market demand
k	Price fluctuation coefficient
α	Scale of recovery difficulty
β	Dispersion of construction waste per unit area
f_m	Set price of manufacturing enterprises for each unit of recycled waste
f_r	Set price of recycling enterprises for recycling each unit of construction waste
P	Retail price of new building materials
C_m	Unit cost of new building materials for reconstruction projects
C_r	Unit recycling cost of construction waste
ω	Recycling ratio of construction waste
δ	Coefficient of amount of construction waste loss
S	Government subsidies each unit of recycled waste
π_m	Total manufacturing enterprises profit
π_r	Total recycling enterprise profit
N	No subsidies
R	Subsidised recycling enterprises
M	Subsidised manufacturing enterprises
$D(P) = a - kP$	Demand function
$C_m - C_r = \Delta$	Construction waste recycling cost savings
$G(\omega) = \omega\delta D(P) = \omega\delta(a - kP)$	Total recycled construction waste

The total profit function for the recycling enterprises of construction waste is:

$$\begin{aligned}\pi_r^N &= (f_m - f_r)G(\omega) - \alpha\beta\omega^2 \\ &= (f_m - f_r)\omega\delta(a - kP) - \alpha\beta\omega^2 \end{aligned} \tag{2}$$

The inverse method is used to solve this model. First, a second-order derivation of Equation (2) is carried out: $\frac{\partial^2 \pi_r^N}{\partial \omega^2} = -2\alpha\beta < 0$. We know π_r^N is the concave function of ω. Furthermore, $\alpha\beta > 0$, that is, the first-order derivative of the optimal recovery rate of construction waste is applied:

$$\frac{\partial \pi_r^N}{\partial \omega^N} = (f_m - f_r)(a - kP)\delta - 2\alpha\beta\omega^N = 0$$

$$\omega^N = \frac{(f_m - f_r)(a - kP)\delta}{2\alpha\beta} \tag{3}$$

The profit of manufacturing enterprises that produce new building materials is calculated as follows:

$$\begin{aligned}\pi_m^N &= (P - C_m)(a - kP) \\ &+ \frac{(\Delta - f_m)(\Delta - f_r)(a - kP)^2\alpha\beta}{2}\end{aligned} \tag{4}$$

As there is a formula/relationship as follows:

$$\frac{\partial^2 \pi_m^N}{\partial P^2} = -2k + \frac{k^2\delta(\Delta - f_m)(f_m - f_r)}{\alpha\beta} \tag{5}$$

$$\frac{\partial^2 \pi_m^N}{\partial {f_m}^2} = -\frac{(a - kP)^2\delta}{\alpha\beta} \tag{6}$$

$$\frac{\partial^2 \pi_m^N}{\partial P \partial f_m} = \frac{k\delta(a - kP)(2f_m - f_r - \Delta)}{\alpha\beta} \tag{7}$$

$$\frac{\partial^2 \pi_m^N}{\partial f_m \partial P} = \frac{k\delta(a - kP)(2f_m - f_r - \Delta)}{\alpha\beta} \tag{8}$$

The Hessian matrix of the retail price per unit and the recycling price per unit of construction waste market can be obtained:

$$H = \begin{bmatrix} -2k + \dfrac{k^2\delta(\Delta - f_m)(f_m - f_r)}{\alpha} & \dfrac{k\delta(a - kP)(2f_m - f_r - \Delta)}{\alpha} \\ \dfrac{k\delta(a - kP)(2f_m - f_r - \Delta)}{\alpha} & -\dfrac{(a - kP)^2\delta}{\alpha} \end{bmatrix}$$

The profit function is based on the assumption that $k > 0$, and $f_m > f_r$. When the first-order condition is met, profit maximisation is achieved with Equation (4). From the first-order function, the unit retail price of the new materials produced by the manufacturing enterprises with construction waste is set by using:

$$P^N = \frac{-a - C_m k + ak\alpha\beta(\Delta - f_m)(\Delta - f_r)}{-2k + k^2\alpha\beta(\Delta - f_m)(\Delta - f_r)} \tag{9}$$

The price per unit of recycled construction waste provided by the manufacturing enterprises is determined by using:

$$f_m^N = \frac{f_r + \Delta}{2} \tag{10}$$

Substituting Equations (9) and (10) into Equation (3), the optimal ratio of construction waste recycling is:

$$\omega^N = \frac{(f_r - \Delta)(a - kC_m)\delta}{-8\alpha\beta + k\delta^2(f_r - \Delta)^2} \tag{11}$$

Substituting Equations (10) into (9), we obtain the unit material retail price:

$$P^N = \frac{-4C_m k\alpha\beta + a[-4\alpha\beta + k\delta^2(f_r - \Delta)^2]}{k(-8\alpha\beta + k\delta^2(f_r - \Delta)^2)} \tag{12}$$

Substituting Equations (11) and (12) into Equations (1) and (2) gets:

$$\pi_m^N = -\frac{2\alpha\beta(a - kC_m)^2}{-8\alpha\beta k + k^2\delta^2(f_r - \Delta)^2} \tag{13}$$

$$\pi_r^N = \frac{\alpha\beta\delta^2(f_r - \Delta)^2(a - kC_m)^2}{[-8\alpha\beta + k\delta^2(f_r - \Delta)^2]^2} \tag{14}$$

5. RSC model of construction waste recycling under different government subsidies

5.1. Subsidised recycling enterprises

The model for subsidising recycling enterprises that work with manufacturing enterprises is as follows. In the recycling process of construction waste from the government who sells the waste to manufacturing enterprises, the manufacturing enterprises first price the recycling of the construction waste, and the recycling enterprises determine the unit price of the waste from the government in accordance with the recycling price of the manufacturing enterprises. In this model, a subsidy component is added to the profit function of the recycling enterprises. The profit function of manufacturing enterprises that use construction waste as new material when the recycling enterprises are subsidised is:

$$\begin{aligned}\pi_m^R &= (P - C_m)D(P) + (\varDelta - f_m)G(\omega)\\ &= (P - C_m)(a - kP) + (\varDelta - f_m)\omega\delta(a - kP) \quad (15)\end{aligned}$$

The profit function of recycling enterprises when they are subsidised for recycling construction waste is:

$$\begin{aligned}\pi_r^R &= (f_m - f_r + S)G(\omega) - \alpha\beta\omega^2\\ \pi_r^R &= (f_m - f_r + S)\omega\delta(a - kP) - \alpha\beta\omega^2 \quad (16)\end{aligned}$$

The inverse method is used to solve the equation, and the second order derivative of Equation (15) is carried out, because $\frac{\partial^2\pi_r^R}{\partial\omega^2} = -2\alpha\beta < 0$, and $\alpha\beta > 0$, so we know $\pi_r^R$is a concave function of ω. The optimal recovery ratio is obtained from the first-order condition:

$$\omega^R = \frac{(f_m - f_r + S)(a - kP)\delta}{2\alpha\beta} \quad (17)$$

Substituting Equations (17) into (16) to obtain the profit function of the manufacturing enterprises at this time results in:

$$\pi_m^R = (P - C_m)(a - kP) + \frac{(\varDelta - f_m)(f_m - f_r + S)(a - kP)^2\delta}{2\alpha\beta} \quad (18)$$

On account of $\frac{\partial^2\pi_m^R}{\partial P^2} = -2k + \frac{k^2\delta(\varDelta - f_m)(f_m - f_r + S)}{\alpha\beta}$, $\frac{\partial^2\pi_m^R}{\partial {f_m}^2} = -\frac{\delta(a - kP)^2}{\alpha\beta}$, $\frac{\partial^2\pi_m^R}{\partial f_m\partial P} = \frac{\delta(k^2P - ak)(f_r - 2f_m + S + \varDelta)}{\alpha\beta}$, $\frac{\partial^2\pi_m^R}{\partial P\partial f_m} = \frac{\delta(k^2P - ak)(f_r - 2f_m + S + \varDelta)}{\alpha\beta}$, and that the profit function is based on the assumption that

$$P^R = \frac{4\alpha\beta(a + kC_m) - ak(\varDelta + S - f_r)^2\delta}{8Rk + k^2(\varDelta + S - f_r)^2\delta} \text{ and}$$

$$P^R = \frac{4\alpha\beta(a + kC_m) - ak(\varDelta + S - f_r)^2\delta}{8Rk + k^2(\varDelta + S - f_r)^2\delta},$$

Equation (18) is the profit maximisation formula when the first-order condition is met. From the first-order function, in the case where the government subsidises recycling enterprises, manufacturing enterprises set the unit retail price of new materials by using:

$$P^R = \frac{-4C_m k\alpha\beta + a[-4\alpha\beta + k\delta^2(-f_r + S + \Delta)^2]}{k(-8\alpha\beta + k\delta^2(-f_r + S + \Delta)^2)} \quad (19)$$

The unit price of the construction waste recycled by manufacturing enterprises is determined with:

$$f_m^R = \frac{\varDelta + f_r - S}{2} \quad (20)$$

Substituting Equations (19) and (20) into Equation (17) yields the optimal recovery ratio for this model:

$$\omega^R = \frac{(f_r - \varDelta - S)(a - kC_m)\delta}{-8\alpha\beta + k\delta^2(\varDelta + S - f_r)^2} \quad (21)$$

Substituting Equations (20) into (19), we obtain the unit retail price of the material:

$$P^R = \frac{-4C_m k\alpha\beta + a[-4\alpha\beta + k\delta^2(-f_r + S + \Delta)^2]}{k(-8\alpha\beta + k\delta^2(-f_r + S + \Delta)^2)} \quad (22)$$

Finally, substituting Equations (21) and (22) into Equations (15) and (16), the profit functions of the recycling and manufacturing enterprises are:

$$\pi_m^R = -\frac{2\alpha\beta(a - kC_m)^2}{-8\alpha\beta k + k^2\delta^2(\varDelta + S - f_r)^2} \quad (23)$$

$$\pi_r^R = \frac{\alpha\beta\delta^2(\varDelta + S - f_r)^2(a - kC_m)^2}{[-8\alpha\beta + k\delta^2(\varDelta + S - f_r)^2]^2} \quad (24)$$

5.2. Subsidised manufacturing enterprises

In the model where the government subsidises the manufacturing enterprises that produce new building materials, the pricing for recycling post-disaster construction waste is first determined due to the dominant position of the manufacturing enterprises while the recycling enterprises price the recycling of construction waste based on the price of the manufacturing enterprises. The profit function of government subsidised manufacturing enterprises is:

$$\pi_m^M = (P - C_m)D(P) + (\varDelta - f_m + S)G(\omega)$$
$$= (P - C_m)(a - kP) + (\varDelta - f_m + S)\omega\delta(a - kP) \tag{25}$$

The profit function of the recycling enterprises when the manufacturing enterprises receive government subsidies is:

$$\pi_r^M = (f_m - f_r)G(\omega) - \alpha\beta\omega^2$$
$$= (f_m - f_r)\omega\delta(a - kP) - \alpha\beta\omega^2 \tag{26}$$

The inverse method is used to solve the model, and the second order derivative of Equation (26) is carried out, because $\frac{\partial^2 \pi_r^M}{\partial \omega^2} = -2\alpha\beta < 0$, and $\alpha\beta > 0$, so π_r^M is the concave function for ω. The optimal recovery ratio is obtained from the first-order condition:

$$\omega^M = \frac{(f_m - f_r)(a - kP)\delta}{2\alpha\beta} \tag{27}$$

Substituting Equation (26) to obtain the profit function of the manufacturing enterprise at this time:

$$\pi_m^M = (P - C_m)D(P) + (\varDelta - f_m + S)G(\omega) \tag{1}$$
$$= (P - C_m)(a - kP) + (\varDelta - f_m + S)\omega\delta(a - kP) \tag{28}$$

As

$$\frac{\partial^2 \pi_m^M}{\partial P^2} = -2k + \frac{k^2(\varDelta - f_m + S)(f_m - f_r)\delta}{\alpha\beta}$$
$$\frac{\partial^2 \pi_m^M}{\partial {f_m}^2} = -\frac{(a - kP)^2\delta}{\alpha\beta}, \quad \frac{\partial^2 \pi_m^M}{\partial f_m \partial P}$$
$$= \frac{(-ak + k^2P)(f_r - 2f_m + \varDelta - S)\delta}{\alpha\beta},$$
$$\frac{\partial^2 \pi_m^M}{\partial P \partial f_m} = \frac{(-ak + k^2P)(f_r - 2f_m + \varDelta - S)\delta}{\alpha\beta}$$

Furthermore, the profit function is based on the assumptions that $k > 0$ and $f_m > f_r$. When the first-order condition is met, profit maximisation is realised with Equation (28). Using the first-order function, the government subsidised manufacturing enterprises set the unit retail price of the new materials by using:

$$P^M = \frac{4\alpha\beta(a + kC_m) - ak(\varDelta + S - f_r)^2\delta}{8Rk - k^2(\varDelta + S - f_r)^2\delta} \tag{29}$$

The unit price of the recycled construction waste set by the manufacturing enterprises is determined by using:

$$f_m^M = \frac{\varDelta + f_r + S}{2} \tag{30}$$

Substituting Equations (29) and (30) into Equation (27) yields the optimal recovery ratio for this model:

$$\omega^M = \frac{(f_r - \varDelta - S)(a - kC_m)\delta}{-8\alpha\beta + k\delta^2(\varDelta + S - f_r)^2} \tag{31}$$

Substituting Equations (30) into (29), we obtain the unit retail price for the material:

$$P^M = \frac{-4C_m k\alpha\beta + a[-4\alpha\beta + k\delta^2(-f_r + S + \Delta)^2]}{k(-8\alpha\beta + k\delta^2(-f_r + S + \Delta)^2)} \tag{32}$$

Finally, substituting Equations (31) and (32) into Equations (25) and (26) show that the profit functions of the recycling and manufacturing enterprises are:

$$\pi_m^M = -\frac{2\alpha\beta(a - kC_m)^2}{-8\alpha\beta k + k^2\delta^2(\varDelta + S - f_r)^2} \tag{33}$$
$$\pi_r^M = \frac{\alpha\beta\delta^2(\varDelta + S - f_r)^2(a - kC_m)^2}{[-8\alpha\beta + k\delta^2(\varDelta + S - f_r)^2]^2} \tag{34}$$

6. Comparative analysis of models

To compare the three government subsidised models, the Stackelberg game theory was used to analyze the decision-making behaviour of each participant in the RSC. In this model, the government acts as the leader, while the manufacturing and recycling enterprises act as the followers.

In terms of the first government subsidised model, the government provides subsidies to the manufacturing enterprises which can reduce their production cost, thus increasing their profits. Additionally, this can lead to an increase in the supply of recycled materials, thus potentially reducing their retail price. On the other hand, an overly high subsidy may incentivise manufacturing enterprises to prioritise production over recycling, thus leading to a smaller recycling ratio.

Concerning the second government subsidised model, the government provides subsidies to the recycling enterprises, which can reduce their recycling costs, thus increasing their profits. Furthermore, this can lead to an increase in the recycling ratio, thus potentially increasing the supply of recycled materials and reducing the demand for organic materials. Still, an overly high subsidy may incentivise recycling enterprises to prioritise profit over recycling, thus leading to a decrease in the supply of recycled materials.

As for the third government subsidised model where there are no subsidies, each participant in the RSC operates independently. This may result in the lack of coordination and a suboptimal outcome for the supply chain.

A comparison of the three government subsidised models suggests that a government subsidy mechanism can optimise the pricing and behaviour of each participant in the RSC. Yet, it is crucial to carefully consider the optimal subsidy target, dispersion level of construction waste, and amount of salvageable construction waste to achieve Pareto optimality of the RSC under the decision-making model for coordination. As such, the six following findings are provided:

Finding 1: Regardless whether the government continues to subsidise manufacturing enterprises or retail enterprises, this will have the effect of lowering the sales price of construction waste.

The proof is as follows:

$$\frac{dP^M}{dS} = \frac{8(a - C_m k)\alpha\beta\delta^2(f_r - S - \Delta)}{\left[-8\alpha\beta - k\delta^2(-f_r + S + \Delta)^2\right]^2} \tag{35}$$

Since $a - kC_m > 0$, and $\Delta > f_m > f_r$ so $(f_r - S - \Delta) < 0$

$$\frac{dP^M}{dS} = \frac{8(a - C_m k)\alpha\beta\delta^2(f_r - S - \Delta)}{\left[-8\alpha\beta + k\delta^2(-f_r + S + \Delta)^2\right]^2} < 0 \tag{36}$$

Equation (36) shows that there is a negative correlation between the subsidy amount and retail price, which indicates that the government will gradually reduce the sales price of construction waste during the process of subsidising manufacturing enterprises or recycling enterprises. At the same time, the government will also have a certain impact on the consumer market of construction waste, that is, the introduction of government subsidies will further expand the consumer market, attract more consumer groups, and result in a larger number of consumers.

Finding 2: Regardless whether the government chooses to subsidise recycling enterprises or manufacturing enterprises, the rate of recycling after subsidising is the same, but is higher than the rate of recycling when the government does not offer subsidies.

The proof is as follows:

Based on $a - C_m k > 0$, $\Delta > f_m > f_r$. So

$$\omega^M = \omega^R = \frac{(f_r - S - \Delta)(a - C_m k)\delta}{-8\alpha\beta + (-f_r + S + \Delta)^2 k\delta^2} \tag{37}$$

When $8\alpha\beta < k\delta^2(-f_r + S + \Delta)^2, \omega^M = \omega^R < 0, 8\alpha\beta > k\delta^2(-f_r + S + \Delta)^2, \omega^M = \omega^R > 0$.

The final result:

$$\frac{d\omega^M}{dS} = \frac{d\omega^N}{dS} = \frac{(a - kC_m)\left[8\alpha\beta\delta + k\delta^2(\Delta + S - f_r)^2\right]}{\left[-8\alpha\beta + k\delta^2(\Delta + S - f_r)^2\right]^2} > 0 \tag{38}$$

This shows that government subsidies have a role in increasing the rate of recovery of construction waste. For enterprises, subsidies can increase their rate of recycling, and the recovery rate is positively correlated with construction waste subsidies. Enterprises will be more inclined to mobilise more of their own funds and social resources to participate in the recycling of construction waste in the absence of subsidies, so that the rate of construction waste recovery can be quickly increased.

Finding 3: With an increase in government subsidies, the construction waste recycling market will play a positive role in promoting recycling, and the profits of construction waste manufacturers will increase.

The proof is as follows:

$$\frac{d\pi_m^M}{dS} = \frac{d\pi_m^R}{dS} = \frac{4\alpha\beta\delta^2(a - kC_m)(\Delta + S - f_r)}{\left[-8\alpha\beta + k\delta^2(\Delta + S - f_r)^2\right]^2} \tag{39}$$

As $a - kC_m > 0$, and $\Delta > f_m > f_r$, $\frac{d\pi_m^M}{dS} = \frac{d\pi_m^R}{dS} > 0$.

That is, regardless whether the government subsidises recycling enterprises or manufacturing enterprises, the profit of the latter is the same, and government subsidies will further stimulate the enthusiasm of profit-oriented construction waste manufacturing enterprises in the supply chain to recycle and increase their corporate income.

Finding 4: Regardless whether the government subsidises the recycling enterprise or the manufacturing enterprise, the profit of the latter is the same, and higher than that of construction waste manufacturers in the absence of subsidies.

The proof is as follows:

$$\pi_m^N = -\frac{2\alpha\beta(a - kC_m)^2}{-8\alpha\beta k + k^2\delta^2(f_r - \Delta)^2} \tag{40}$$

$$\pi_m^M = \pi_m^R = -\frac{2\alpha\beta(a - kC_m)}{-8\alpha\beta k - k^2\delta^2(\Delta + S - f_r)^2} \tag{41}$$

Based on $a - C_m k > 0$, $\Delta > f_m > f_r$,

$$\pi_m^N - \pi_m^R = \frac{2\alpha\beta(a - kC_m)\left(\frac{1}{8\alpha\beta - k\delta^2(f_r - \Delta)^2} - \frac{1}{-8\alpha\beta + k\delta^2(-f_r + S + \Delta)^2}\right)}{k} \tag{42}$$

When $8\alpha\beta < k\delta^2(f_r - \Delta)^2$, $\pi_m^N < \pi_m^R$, $8\alpha\beta > k\delta^2(f_r - \Delta)^2$, $\pi_m^N > \pi_m^R$.

So, it follows that when $\pi_m^N - \pi_m^R < 0$, the profit of manufacturers that receive government subsidies will change. Regardless whether the government subsidises recycling enterprises or manufacturer enterprises, the profit of the latter is the same, and higher than that in the absence of government subsidies, When $\pi_m^N - \pi_m^R > 0$, the profit of manufacturer enterprises with government subsidies will change. Regardless whether the government subsidises recycling enterprises or manufacturer enterprises, the profit of the latter is the same, but less than in the case of no government subsidies.

Finding 5: Regardless of whether the government subsidises manufacturing enterprises or recycling enterprises, the retail price of construction waste in the market is the same, and government subsidies have a certain effect on the retail price of construction, and will have a price impact on consumer groups and the market.

The proof is as follows:

Since

$$P^M = P^R = \frac{-4C_m k\alpha\beta + a[-4\alpha\beta + k\delta^2(-f_r + S + \Delta)^2]}{k(-8\alpha\beta + k\delta^2(-f_r + S + \Delta)^2)} \tag{43}$$

Despite government subsidies maintaining uniform retail prices for construction waste, whether allocated to manufacturing or recycling enterprises. Subsidies by influencing retail prices, offer predictability for consumers, potentially boosting consumption and recycling rates. It is crucial to continually evaluate the impact of these subsidies, adjusting them based on market responses, technological advancements, and shifts in consumer behaviour to ensure they achieve their environmental objectives.

As $C_m > C_r$, $C_m - C_r > f_r$, and $\Delta > f_m > f_r$, $a - kC_m > 0$,

$$P^M - P^N = \frac{4(a - C_m k)S\alpha\beta\delta^2(-2f_r + S + 2\Delta)}{(8\alpha\beta - k\delta^2(f_r - \Delta)^2)(8\alpha\beta - k\delta^2(-f_r + S + \Delta)^2)} \tag{44}$$

Hence, when $8\alpha\beta < k\delta^2(f_r - \Delta)^2$ or $8\alpha\beta > k\delta^2(-f_r + S + \Delta)^2$, so that $P^M - P^N > 0$, it can be shown that government subsidies can somewhat provoke the consumer market to increase the sales price of new construction waste. However, when $k\delta^2(f_r - \Delta)^2 < 8\alpha\beta < k\delta^2(-f_r + S + \Delta)^2$, so that $P^M - P^N < 0$, it can be shown that the government subsidies can somewhat provoke the consumer market to reduce the sales price of new construction waste.

Finding 6: More intact construction waste means that the recycling is overall more effective, that is, a larger volume of recycled material.

The proof is as follows:

$$\omega^N = \frac{(f_r - \Delta)(a - kC_m)\delta}{-8\alpha\beta + k\delta^2(f_r - \Delta)^2} \tag{45}$$

$$\frac{d\omega^N}{d\delta} = (a - C_m k)(f_r - \Delta) \tag{46}$$

As $a - kC_m > 0$, and $\Delta > f_m > f_r$, then $(f_r - \Delta) < 0$, thereby $\frac{d\omega^N}{d\delta} < 0$.

This shows that a larger δ means less construction waste loss, and a smaller loss coefficient of the construction waste. That is, more intact construction waste means more efficient overall recycling process of the RSC.

Finding 7: When subsidising manufacturing enterprises, the recycling price of construction waste is higher than the price of manufacturing enterprises without subsidies, and higher than the recycling price of construction waste when subsidising recycling enterprises.

The proof is as follows:

As $f_m^N = \frac{f_r+\Delta}{2}, f_m^M = \frac{\Delta+f_r+S}{2}, f_m^R = \frac{\Delta+f_r-S}{2}$

Proving: $f_m^M - f_m^N = \frac{S}{2} > 0, f_m^N - f_m^R = \frac{S}{2} > 0.$

We can conclude that:

$$f_m^M > f_m^N > f_m^R \tag{47}$$

According to Equation (45), subsidising manufacturing enterprises can better promote the construction waste recycling market, which is conducive to the recycling and reusing of a large volume of construction waste. This shows that government subsidies have a role in promoting the construction waste market to a certain extent.

7. Numerical analysis

The proposed model was validated by using data from a 7.0 magnitude earthquake that occurred in Lushan County in Sichuan Province on April 20, 2013. The Central Ministry of Finance allocated 20 million USD for post-earthquake reconstruction efforts, and water and power supply and other emergency repair projects in the affected areas of Lushan County (Tang et al., 2015). The corresponding numerical settings are used for numerical analysis. Our market demand function is $D(P) = 500 - P$, the unit cost of the production of new materials is $C_m = 50$ USD, unit cost for reproduce the waste is $C_n = 25$ USD, and unit price of construction waste recycler equipment is $f_r = 5$ USD, at a recycling cost $T = 150\omega^2$, $\alpha = 150$, original $k = 1$, $\beta = 1$, $S = 15$ and $\delta = 0.5$. Based on these factors, the total amount of recovery and profit of each participant in the RSC under the three subsidy models (no subsidy, subsidy for recycling enterprise and subsidy for manufacturing enterprise) can be calculated.

To observe the RSC under the three subsidy models, and show the relationships between government subsidy and the following variables, and the influence of government subsidies with S = [10, 15, 20, 30, 40, 50, 60, 70, 80, 90, and 100], Figure 2 plots the total profit of recycling and manufacturing enterprises (Figure 2(a) and (b)), recycling ratio of the construction waste (Figure 2(c)), and retail price set by the manufacturing enterprises (Figure 2(d)).

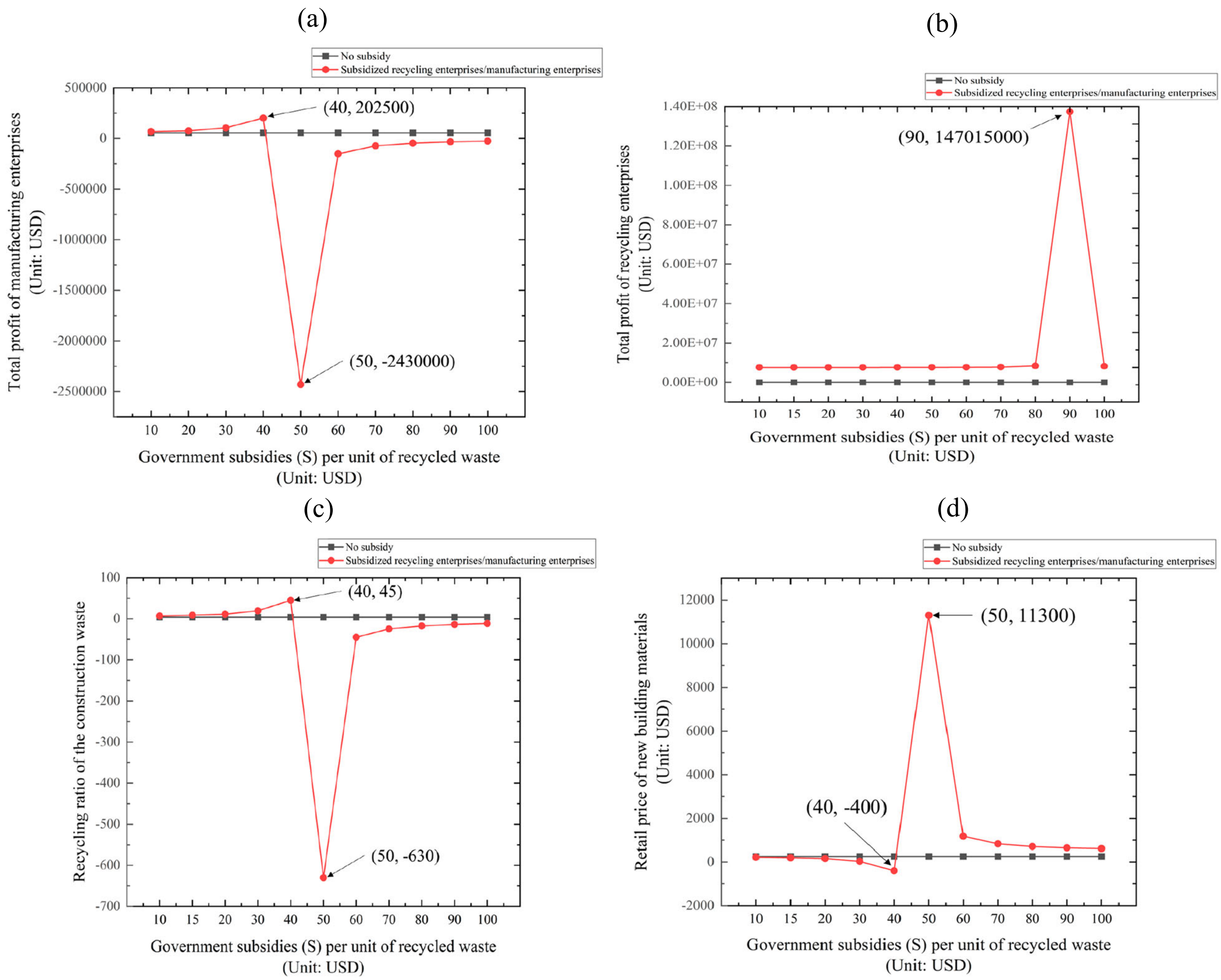

Figure 2. Plotted relationships under different types of government subsidies (Unit: USD).

Figure 2(a) and (b) highlights the intricate relationship between government subsidies and the economic performance of manufacturing and recycling enterprises in the RSC. Without subsidies, both the manufacturing and recycling enterprises maintain consistent profit levels across various levels of construction waste salvageability (S). However, the introduction of subsidies to either party results in distinct profit trajectories, this indicates that while subsidies can initially boost profitability, there is a threshold beyond which their effectiveness diminishes, potentially due to overcompensation or market saturation (Zou & Zhang, 2020).

According to Hypothesis 6, it follows that $f_r < S + \Delta$. To avoid the occurrence of singularities, the subsequent data settings are configured to satisfy this condition. For manufacturers, regardless of the subsidy recipient, when the government subsidy amount reaches a certain threshold (S = 40), their profits peak. Once this threshold is exceeded, the profits sharply decline, eventually turning negative, with the lowest profit occurring at a subsidy amount of S = 50 (Figure 2(a), (c)). For recyclers, when the government subsidy ranges between S = 80 and S = 100, their profits increase, peaking at S = 90, and then gradually decline. This indicates that subsidies beyond S = 90 result in a diminishing cost–benefit ratio and an overall downward profit trend (Figure 2(b)). Finally, irrespective of the subsidy recipient, the construction sales price gradually decreases until the subsidy amount reaches S = 40, turning negative at S = 40. After S = 40, the sales price gradually increases, peaking at S = 50, and then gradually declines (Salmasnia & Shabani, 2023).

The recycling ratio of construction waste becomes larger with subsidies up to S = 40, which indicates enhanced efficiency in resource recovery. However, at extreme levels of waste salvageability (S = 50 and higher), the recycling ratio becomes negative, likely due to over-saturation of the recycling market or logistical challenges in handling excessively high quantities of recyclable materials (Figure 2(c)). The retail price set by manufacturing enterprises shows an initial increase with subsidies (Figure 2(d)), thus reflecting the higher value or cost-pass-through of recycled materials. As salvageability increases, retail prices tend to decrease, thus suggesting that the market dynamics favour lower prices when there is more recycled material available.

The results show that government subsidies not only reduce costs and increase revenues for recycling and manufacturing enterprises but also promote more competitive pricing for recycled materials, enhancing market demand for recycled materials and the subsequent profitability for involved enterprises (Liao & Luo, 2022). A strategy that optimises subsidies based on the salvageability of construction waste and the market response to recycled materials is crucial for maximising recovery efficiency and supply chain profitability. This delicate balance requires a nuanced understanding of the operational thresholds of RSCs.

The dispersion of construction waste per unit area $\beta = [0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, \text{and } 1]$ is used to observe its relationship with and influence on the total profits of recycling and manufacturing enterprises (Figure 3(a) and (b)), recycling ratio of the construction waste (Figure 3(c)), and retail price of new building materials (Figure 3(d)).

Figure 3 comprehensively shows the effect of government subsidies on the RSC of post-earthquake construction waste. When analyzing the total profit of manufacturing enterprises (Figure 3(a)), it can be observed that without subsidies, there is a consistent baseline profit across different values of β. Introducing subsidies, whether the target is recycling or manufacturing enterprises, consistently increases profits but has no better effect than the case without subsidies until β reaches a certain threshold. Specifically, at $\beta = 0.9$, profits are optimised, whereas at $\beta = 1$, there is a dramatic decline, thus providing the optimal range for the subsidies to be impactful.

For recycling enterprises (Figure 3(b)), subsidies also increase profits at all levels of β, with the most significant increase at the higher end of the β range, thus emphasising effectiveness of subsidies in encouraging recycling activities. In terms of the recycling ratio of construction waste, subsidies appear to increase ratios up to a certain point, after which the ratio becomes smaller. This indicates that while subsidies are effective in enhancing recycling efficiency (Figure 3(c)), there may be diminishing returns or adverse effects when they exceed a certain level. The retail price data from manufacturing enterprises suggest (Figure 3(d)) that subsidies lead to an initial decrease in prices, which gradually increases with higher β values. This could be attributed to the reduced need for subsidies as the volume of recyclable material increases, thus reflecting a responsive and adaptive market. In conclusion, government subsidies play a critical role in increasing the efficiency and profitability of RSCs, but their impact is subject to diminishing returns after reaching the optimal level of resource availability and subsidy allocation. The analysis of waste dispersion and salvage volume offers a deeper understanding of the infrastructural and logistical challenges such as limited debris stacking sites that amplify the complexity of implementing efficient recycling processes (Rentizelas & Trivyza, 2022).

The coefficient of the amount of construction waste loss is $\delta = [0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, \text{and } 1]$. Figure 4 plots the total profit of the recycling and manufacturing enterprises (Figure 4(a) and (b)), recycling ratio of the construction waste (Figure 4(c)), and retail price of new building materials (Figure 4(d)).

The implementation of government subsidies significantly influences the economic landscape within the RSC for post-earthquake construction waste. As the coefficient of construction waste loss (δ) increases from 0 to 1, a trend emerges in which both the manufacturing (Figure 4(a)) and recycling enterprises (Figure 4(b)) see substantial growth in total profit when they receive subsidies. Notably, at lower values of δ, the profit increase is moderate; however, as δ approaches 1, the impact of subsidies becomes more profound, which leads to a profit margin that far exceeds the case where there are no subsidies. This finding suggests that government subsidies are a critical catalyst in optimising the profitability of RSC activities, particularly with more construction waste recovered.

At the same time, the ratio of recycling construction waste notably becomes larger with the presence of subsidies (Figure 4(c)), thus reinforcing the efficiency of waste recovery processes. Furthermore, the retail price set by manufacturing enterprises somewhat increases with subsidies (Figure 4(d)), thus suggesting a balanced pass-through of subsidy benefits to end-pricing and potentially reflecting the sustainable value of the materials (Harijani et al., 2023; He & Sun, 2022). However, at extreme values of δ, the reverse is true, which shows the potential inefficiencies or market saturation. This complex relationship of subsidy level, profit margin, and recycling efficiency underscores the need for a nuanced understanding and strategic implementation of subsidy policies to ensure sustainable and profitable post-disaster construction waste management (Cheng et al., 2022; Chileshe et al., 2015).

8. Implications

8.1. Implications for researchers

This study provides a robust framework that researchers can utilise as a baseline for further investigation of

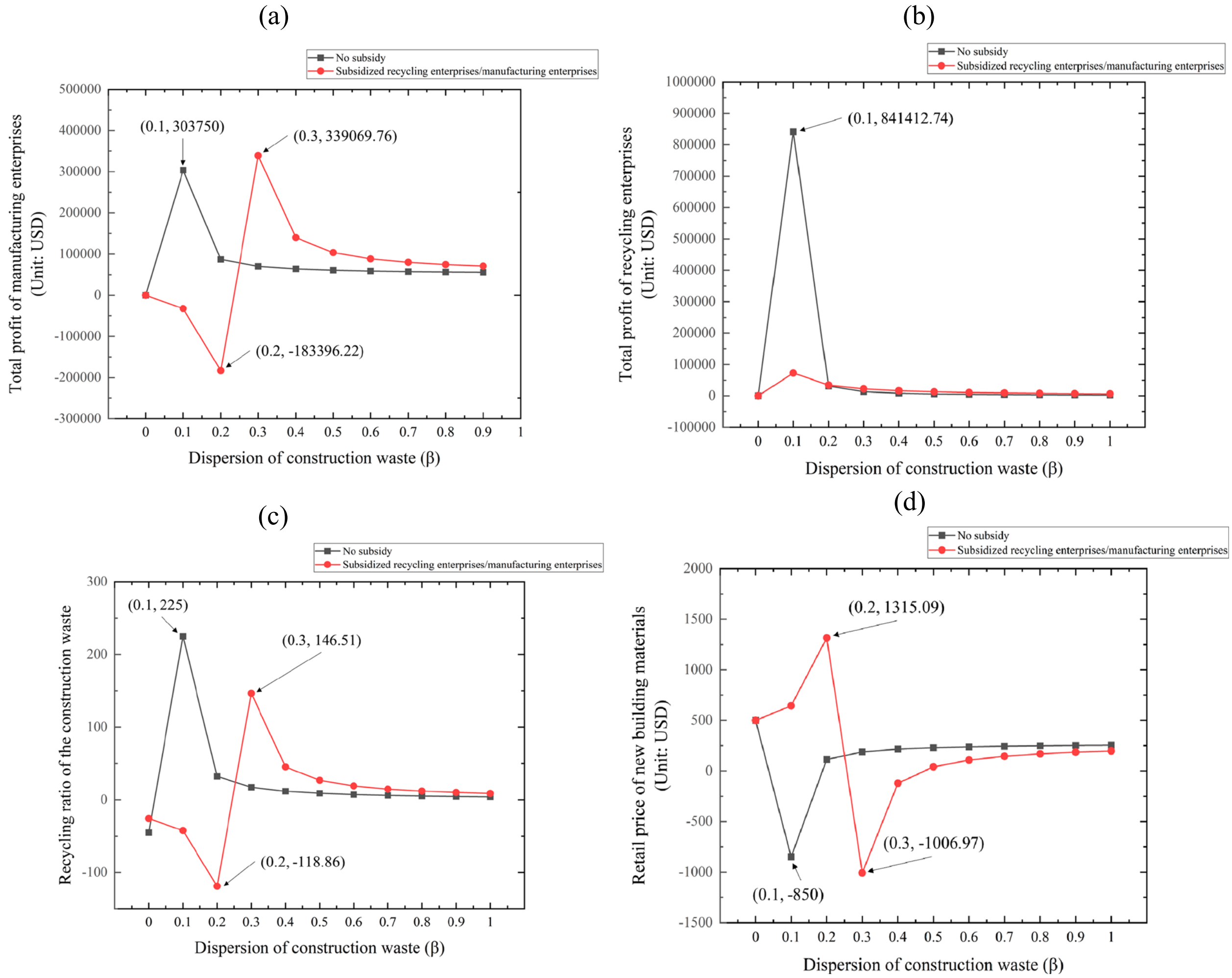

Figure 3. Fluctuation of total quantity of recycled waste with dispersion of construction waste (Unit: USD).

RSC models, particularly in post-disaster scenarios. The consideration of government policies, economic sustainability, and environmental considerations in the RSC model opens up new avenues for academic inquiry (Zarei et al., 2019; Zhu & Liu, 2023). Future studies could explore the comparative effectiveness of various waste management strategies across different geographical locations and disaster types, thus contributing to a more nuanced understanding of RSC dynamics (Valenciano-Salazar et al., 2022; Werkneh, 2022).

Our work introduces innovative methodologies that combines system dynamics with empirical data analysis to offer researchers novel tools for examining complex supply chain mechanisms (Rogerson & Parry, 2020; Sahoo et al., 2023). This methodological approach encourages the adoption and adaptation of advanced analytical techniques in supply chain research, which pave the way to advance studies that can capture the intricacies of supply chain operations in crisis situations (Varriale et al., 2021; Wang & He, 2023).

Note the importance of interdisciplinary research in addressing the multifaceted challenges of post-disaster waste management. Researchers are encouraged to collaborate across fields such as environmental science, urban planning, economics, and engineering to develop comprehensive solutions that address both the immediate needs of disaster-affected areas and the long-term goals of sustainability and resilience (Patil et al., 2021; Pribicevic & Delibasic, 2021).

8.2. Implications for policymakers/government

The findings highlight the critical role of government intervention in facilitating effective waste management practices. Policymakers/governments are advised to develop clear and actionable policies that support the establishment and operation of RSCs, including incentives for recycling and remanufacturing, guidelines for waste transfer pricing, and regulations that ensure environmental protection. Such policies can significantly

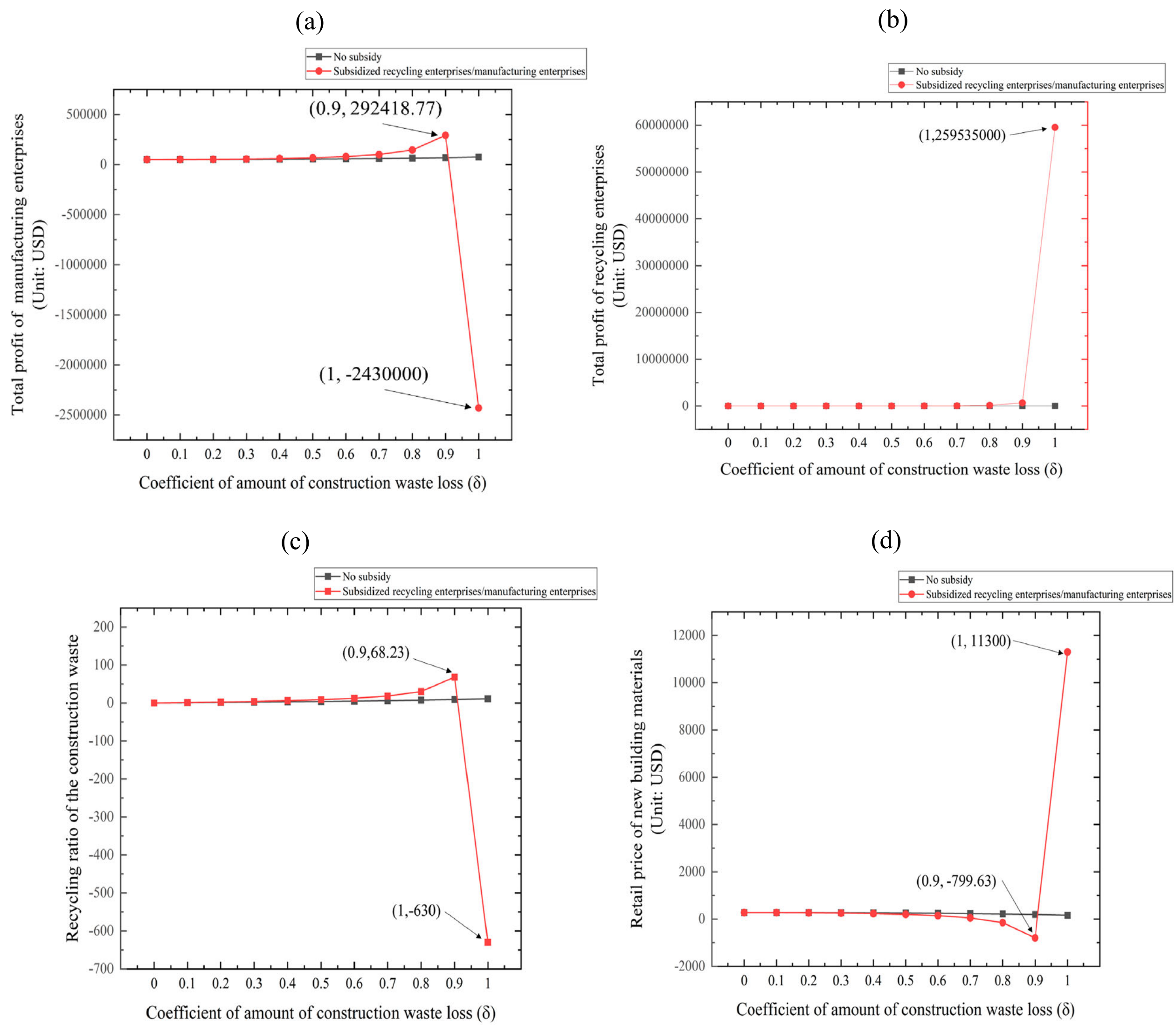

Figure 4. Comparison of RSC model of construction waste recycling with coefficient of amount of construction waste loss (Unit: USD).

enhance the sustainability and efficiency of post-disaster recovery efforts (Zhou & Qi, 2023; Zhu et al., 2018).

This research work advocates for more collaboration between the public and private sectors in managing construction waste in post-earthquake scenarios (Kongar et al., 2017; Marc et al., 2017). Governments are encouraged to initiate partnerships with private enterprises by providing subsidies, tax incentives, or grants that support the recycling industry. This approach can lead to more innovative and financially viable waste management solutions (Cao et al., 2018; De Risi et al., 2022).

Policymakers have a vital role in promoting awareness of the benefits of sustainable waste management practices. Through educational programs and campaigns, governments can increase public understanding and acceptance of recycling initiatives, thereby facilitating smoother implementation of RSC models and enhancing community participation in sustainability efforts (Camacho-Vallejo et al., 2015; Di Filippo et al., 2022).

8.3. Implications for managers

Managers in the recycling and manufacturing sectors can leverage the insights from this study to refine their strategic planning and risk management processes. Understanding the dynamics of RSCs and the impact of governmental policies on waste management allows managers to make informed decisions about resource allocation, investment in recycling technologies, and development of new products using recycled materials (Madani & Rasti-Barzoki, 2017; Shaw & Scully, 2023).

This research emphasises the importance of building collaborative networks within the supply chain to enhance the efficiency of waste management. Managers should establish strong relationships with suppliers, government agencies, and end-users to create a more integrated and responsive RSC. Collaboration can lead to better coordination, reduced costs, and more innovative solutions to waste management challenges (Savaskan et al., 2004; Shaw & Scully, 2023).

This study also serves as a call to action for managers to prioritise sustainability and corporate social responsibility in their operations (Sakai et al., 2020; Salmasnia & Shabani, 2023). By adopting practices that reduce environmental impacts and contribute to the circular economy, companies not only comply with regulatory requirements but also build a positive brand image and customer loyalty. Managers are encouraged to view sustainable waste management not as a regulatory burden but as an opportunity for innovation and growth (Pal, 2024; Pal & Sarkar, 2023).

9. Limitations

The optimal scheme obtained from this game model system can serve as a reference for decision-makers and practitioners in post-disaster areas, as it provides a systematic and effective solution for the coordination and optimisation of RSCs. By considering the constraints and uncertainties of post-earthquake situations and the cooperation between government and enterprises, the optimal scheme can help to improve the efficiency of construction waste recycling, reduce environmental impacts, and promote sustainable development. Therefore, the study has significance in terms of application and promotional value in the field of disaster waste management and circular economy.

In establishing a construction waste recycling supply chain, several factors must be considered. First, the supply chain should be based on local economic conditions and government support to ensure effective operations. Secondly, scheduling of the site visits and initial treatment of construction waste should be carried out accordingly. Finally, recycling processes and means that are scientifically sound should be adopted for effective waste protection. In the future, it is recommended that the focus could shift to the incorporation of insurance mechanisms into a multi-game model or the improvement of construction waste treatment processes and reuses.

The RSC in this context involves various actors, and includes not only a three-party game method but also a four-party game method. Recent studies (Pal, 2024; Wu, 2021; Yi et al., 2016; Zhao & Ma, 2022) have highlighted the importance of considering relationships between consumers and government, as well as consumers and enterprises. As this study focuses on the relationship between government and enterprises, further research is needed to explore the dynamics between consumers and the Chinese government or enterprises.

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