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Supply chain transformation for pursuing carbon-neutrality

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Supply chain transformation for pursuing carbon-neutrality

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Editorial: Supply chain transformation for pursuing carbon-neutrality

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KEYWORDS

green supply chain, carbon neutrality, net zero, supply chain transformation, disruptive technologies, operations management, sustainable development goals

Editorial on the Research Topic
Supply chain transformation for pursuing carbon-neutrality

The progress toward using renewables and increasing energy efficiency is deemed insufficient as global warming is outpacing the positive developments. Taking energy consumption as an example, the overall share of fossil fuels in global primary energy demand has remained constant over the past 25 years. Current initiatives often focus narrowly on specific supply chain activities and may rely on traditional technologies, resulting in suboptimal outcomes. A comprehensive examination of whole supply chains and understanding the trade-offs between different activities is required for a positive overall impact, achieving carbon neutrality, and, eventually, ecological restoration.

Acknowledging the role of manufacturing and construction activities in environmental issues, many studies focused on the supply chain's transformation to establish carbon neutrality in these sectors. Our primary investigations of the supply chain literature showed a growing interest in carbon-related issues. These studies are multidisciplinary with the research methodologies ranging from conceptual and qualitative to quantitative. While *carbon neutrality* has been used since late 2021, *carbon footprint*, *carbon tax*, *carbon trading*, and *low-carbon economy* are among the related concepts that have long been discussed in the academic literature. Adopting disruptive new technologies that support the green transformation of supply chains, like *blockchain*, is one of the recent topics that attracted academic attention. The keyword *"carbon neutrality"* has most frequently co-occurred with *green supply chain*, *sustainability*, *life cycle assessment*, *game theory*, *optimization*, and *blockchain*.

Hierarchical clustering of the most frequently used keywords in the literature is considered to identify the major research themes using a three-step procedure. Considering keywords as vertices and co-occurrences as edges, the shortest steps between all vertices are determined first. The steps required to reach from the source vertex to every other vertex are then calculated. As the final step, the edge(s) with the highest crossings are removed with distinct node clusters being the results. Results are shown in Figure 1. In this figure, the size of the vertices and edges represent their importance with respect to the keyword's occurrence and the keywords' co-occurrences, respectively. Closeness between vertices shows greater correlations.

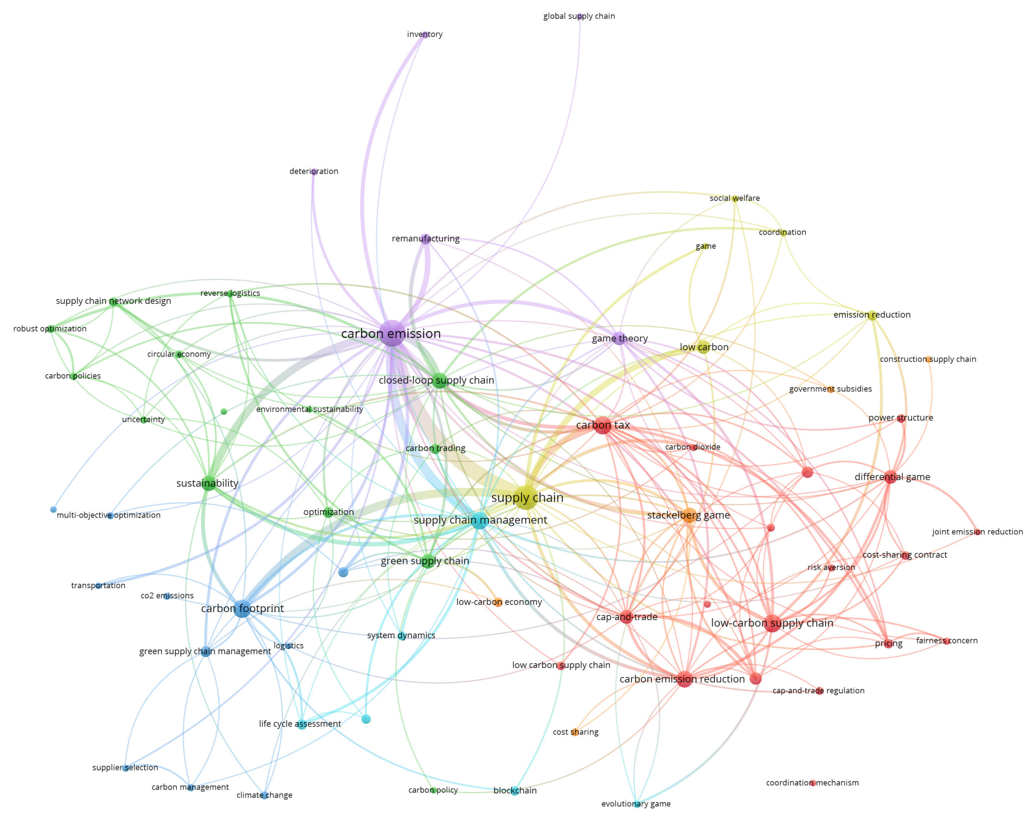

FIGURE 1
Network visualization of the frequently used keywords and their interactions (the figure is generated using *VOSviewer* considering the articles published until the end of 2024).

This investigation revealed that *low carbon supply chain*, *cap-and-trade*, *carbon emission reduction*, and *pricing* formed the most prevalent research theme (represented by red nodes) where Differential and Stackelberg games are among the major applied methodologies. *Closed-loop supply chain*, *circular economy*, *reverse logistics*, and *remanufacturing* are central to the second biggest research cluster (represented by green nodes) with optimization and supply chain network design being the major research methods. The third largest research cluster (represented by blue nodes) has formed around *carbon footprint*, *life cycle assessment*, and *green supply chain management*, which mostly concerns decision-making, like *supplier selection*.

Overall, the main objective of the studies on supply chain transformation has been to reduce the negative impacts of industrial activities on the environment. In addition, net-zero practices have implications for improving social welfare and fostering a low-carbon economy. Exploring the opportunities and challenges of supply chain transformation with a focus on carbon peak and neutrality concepts, both in theory and practice plays an important role in the sustainable development of industries. This exploration inspired our Research Topic. We invited contributions focusing on technological transformation, energy transition, and modernization of manufacturing supply chains to bring together researchers from different backgrounds to contribute to the supply chain transformation for pursuing carbon neutrality. A summary of these contributions is presented below.

"Supply chain control tower and the adoption of intelligent dock booking for improving efficiency" explored the implementation of Intelligent Dock Booking within a Supply Chain Control Tower framework. The proposed system decreases truck waiting times and idle periods, optimizes dock usage, and improves overall transportation efficiency, contributing to reduced fuel consumption and lower carbon emissions (Wyciślak and Pourhejazy).

"The impact of global value chain embedding on the upgrading of China's manufacturing industry" examined the impact of global value chain embedding on the green transformation of China's manufacturing industry. The study highlights the importance of technological upgrading and innovation in the manufacturing sector, which could be extended to clean technologies for carbon neutrality (Fu).

"Coordination contracts and numerical analysis of low-carbon competitive supply chains under the influence of low-carbon goodwill" introduced a novel low-carbon goodwill model that incorporates advertising competition; they highlighted the role of balancing competition and cooperation in low-carbon initiatives (Xie et al.).

"A sustainable NEV manufacturer-retailer system under the Nash bargaining framework considering the impact of the COVID-19 epidemic under the CVaR criterion" developed a novel negotiation mechanism incorporating risk aversion and the Conditional Value-at-Risk (CVaR) criteria. The article provided insights into promoting sustainability in vehicle production and sales (Han and Cheng).

"Extended reality implementation possibilities in direct energy deposition-arc" integrated extended reality (XR) technologies into additive manufacturing as another disruptive new technology. The authors showed that implementing XR in the manufacturing process can potentially reduce material wastage and energy consumption by enabling more accurate design, planning, and execution of manufacturing tasks (Lund et al.).

"Implementing concepts from green logistics in the turkey production supply chain" contributed an optimization model for brooder-finisher assignments in a turkey production network, aiming to minimize transportation distances and associated greenhouse gas emissions. They showed a 50 percent reduction in greenhouse gas emissions associated with turkey transportation (Wilson et al.).

"Power plant units for CO2 neutral energy security in Switzerland" introduced the concept of Power Plant Units (PPUs) for the on-demand delivery of renewable energy and addressing the intermittency issues associated with renewable energy sources. The authors evaluated various renewable energy production and storage technologies, and provided a roadmap for technology adoption in the transition to a carbon-neutral economy (Züttel et al.).

"Closed-loop supply chain decision making and coordination considering channel power structure and information symmetry" explored Corporate Social Responsibility (CSR) and the possibility of manufacturers mis-reporting information about their recycling efforts. Their analysis of recycling rates and CSR levels indirectly addressed emissions reduction strategies by promoting the recycling and remanufacturing of used products (Huo et al.).

"Towards the design of a smart warehouse management system for spare parts management in the oil and gas sector" contributed a framework for implementing digital technologies in spare parts warehousing; their supply chain framework can reduce waste, improve efficiency in spare parts management, and is aligned with circular economy principles by optimizing inventory levels and reducing avoidable material waste (Khan et al.).

Supply chain transformation is a prerequisite for pursuing the Sustainable Development Goals (SDGs). The editors sincerely hope that this Research Topic will attract more researchers to the sustainability discussion and inspire more innovations in pursuing carbon neutrality.

Author contributions

PP: Writing – original draft. SW: Writing – original draft. WS: Writing – review & editing. ÅE: Writing – review & editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supply chain control tower and the adoption of intelligent dock booking for improving efficiency

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Poor coordination at distribution centers is a prime source of supply chain delays and energy waste that can be avoided through real-time planning and enhanced visibility. As a modern logistics topic with implications for supply chain transformation, Intelligent Dock Booking (IDB) coordinates the incoming and outgoing shipments at distribution centers. The research on IDB is at the early development stage. This study contributes to the Supply Chain Control Tower (SCCT) by developing a conceptual model of IDB, identifying its implementation requirements, and exploring its impacts on the supply chain performance. The causal loops and stock/flow diagrams are used to investigate how several efficiency indicators like the number of cancellations, planning time, utilization of space for loading and unloading, and the duration of processing trucks at distribution centers can be improved. Further, real-time data integration, operational preconditions, automated scheduling, dynamic responsiveness, and interdepartmental integration are identified as the key implementation requirements. The findings provide a foundation for implementing IDB systems in SCCTs.

KEYWORDS

logistics 4.0, visibility, transport management, distribution network, automated decision-making

1 Introduction

The competition among major corporations is mostly about their supply chain capabilities. System-wide coordination is essential for companies to operate at their best capacity and stay competitive (Simchi-Levi et al., 2008). The Supply Chain Control Tower (SCCT) works as a coordination and consolidation platform to provide enhanced visibility for the efficient material flow between retailers, warehouses, factories, part manufacturers, and downstream suppliers. The control tower does not own trucks and/or physical assets and acts merely as an intermediary between customers and Transport Service Providers (TSPs). SCCT is capable of integrating technologies, processes, and human expertise that serve as supply chain orchestrators or partners; it improves the cost, quality, reliability, and responsiveness of the companies and is believed to strengthen the competitive strategy (Midkiff, 2021; Sharabati et al., 2022). The control tower has implications for Supply Chain (SC) leadership, transparency, workforce development, and collaboration (Dalporto and Venn, 2020). Such a platform is likely to facilitate the development of intermodal transport (Giusti et al., 2019), which is supported by the European Commission's transport policy (Ramos de Oliveira et al., 2022). SCCT is also expected to improve resilience, which may be achieved directly (Syahchari et al., 2022), or indirectly through improving various supply chain competencies (Islam et al., 2023).

The literature on SCCT is at the early development stages; the existing body of knowledge is mostly about the adoption of the new technology (Smith, 2022). There is a need to analyze the already implemented SCCT systems to explore rooms for possible improvement. Besides, decision support systems that facilitate higher degrees of intelligence in SCCT are very limited (Ye et al., 2022). As a prime example, automating repetitive transport management decisions, like dock booking, should be investigated for a truly autonomous SCCT; a direction that has inspired the present study.

Industry 4.0 emphasizes higher degrees of automation in the SC to accommodate the surging global demand more efficiently. Autonomous technologies and intelligence contribute a lot to the successful development and implementation of autonomous SCs (Liotine, 2019). In this situation, human capital is expected to play a different role in the future of logistics management (Kucukaltan et al., 2022) with their involvement evolving into strategic decision-making (Hofmann and Rüsch, 2017). Repetitive decisions at the operational and tactical levels, which are often time and cost-intensive to be managed by a human, should be automated. Autonomous decision-making in the supply chain has received recent recognition (see Li et al., 2022). Automating transport management decisions in the SCCT context is very limited (Vlachos, 2021).

Dock booking is a prime example of decisions that can be automated; automating dock booking has implications for the effective implementation of SCCT, particularly to diminish human errors and reduce administrative workload by slashing the need for manual information entry (Rodrigue, 2022). Dock booking/reservation studies are limited to a handful of optimization methods. (Miao et al., 2014) developed a metaheuristic algorithm for dock assignment in a cross-dock management system. (Sharma, 2017) developed a mathematical problem for truck dock allocation. (Fallahtafti et al., 2021) proposed a mathematical model for time slot management of loading docks in warehouses. Most recently, (Song et al., 2022), proposed an integrated optimization approach for the simultaneous planning of vehicle routes for the TSP and schedules the dock time slots at the SC facility. (Falsafi et al., 2022) introduced a decision-support model based on truck-dock assignment and transport mode selection to minimize the ripple effect of possible disruptions on the production plans. We also found a case study by Marzialia et al. (2022) that developed new performance indicators for evaluating order picking and loading-dock arrival timeliness.

As we delve into a transformation to Industry 4.0 SCs, it becomes crucial to understand the nuances of adopting intelligent decision systems in SCCT by answering the following questions.

RQ1. What are the requirements for implementing the IDB system?

RQ2. How does the IDB system impact the performance of SCCT?

Leveraging a system dynamics perspective, we employed the Causal Loop Diagrams (CLDs) and Stock and Flow Diagrams (SFDs) to develop a conceptual model that answers these questions. CLDs are used to identify the variables of interest and map their interrelationships within the system. SFDs enabled us to analyze the temporal evolution of these variables, offering insights into their dynamic behavior. This framework provides a grasp of the dock booking complexities and system architecture. The conceptual model is investigated in the supply chain of a major Fast-Moving Consumer Goods (FMCG) company. The proposed criteria and alternatives emanate from comprehensive industry consultations, expert interviews, and preliminary field investigations to study the most important challenges in the adoption of IDB. The blend of academic rigor and real-world insight supported by the author's experience of working in an SCCT environment ensures theoretical robustness and practical relevance.

The remainder of this article is organized into four sections. Section 2 establishes the necessary background. Section 3 elaborates on the transport management system in the case company. Section 4 presents the IDB model, elaborating on the underlying principles. Sections 5 and 6 analyze the potential benefits of the proposed model and highlight its implications for energy efficiency in the supply chain. Finally, Section 7 synthesizes the findings and provides insights on potential directions for future research.

2 Background

2.1 Transport management

Transportation information capabilities—like real-time access to reliable data on cargo status and freight data exchange—improve logistics service level (Lee and Shin, 2008), and operational efficiency, and reduce externalities (Mehmood et al., 2017). Depending on the asymmetry of costs and benefits among logistics partners (Wyciślak, 2022), real-time transport visibility was shown to reduce the average and maximum number of trucks in the distribution centers as well as site sojourn times (Dunke and Nickel, 2020).

Unstructured data sources (Wu and Yang, 2018) and online information technology solutions have been used for the real-time collection of logistics data, like truck arrivals and loading in logistics sites (Dunke and Nickel, 2020). Companies are also adopting new technologies to improve transportation information capabilities beyond the current norms (Callefi et al., 2022). The Internet of Things (IoT), which obtains data through sensors and communication devices, is a prime example of new technology with disruptive implications for transport management and decision-making. Transport visibility and real-time information sharing are some of the major drivers of IoT adoption (Farquharson et al., 2021). IoT-enabled transport systems are being employed to improve last-mile transport of time-sensitive and perishable goods (Wanganoo et al., 2021). Intelligent transport systems are recently equipped with cloud computing performing data analytics for decision support (Tyagi and Sreenath, 2023). For instance, travel time predictions are improved with machine learning applications based on big traffic data (Chen et al., 2023). For a comprehensive review of IoT applications in Supply Chain Management (SCM), we refer interested readers to (Ben-Daya et al., 2019).

SCCT consists of the technology that enables a centralized planning and control platform and integrates data from various sources to manage the flow of information, like orders, shipments, and inventory levels. The control tower links man, machines, and methods through IoT, and uses Artificial Intelligence and cloud platforms for decision aid and/or automated decision-making. End-to-end visibility, decision analytics, and process execution are some of the capabilities of SCCTs[1].

1 https://itsupplychain.com/self-reliant-supply-chains-in-the-business-4-0-environment-an-intelligent-control-tower/

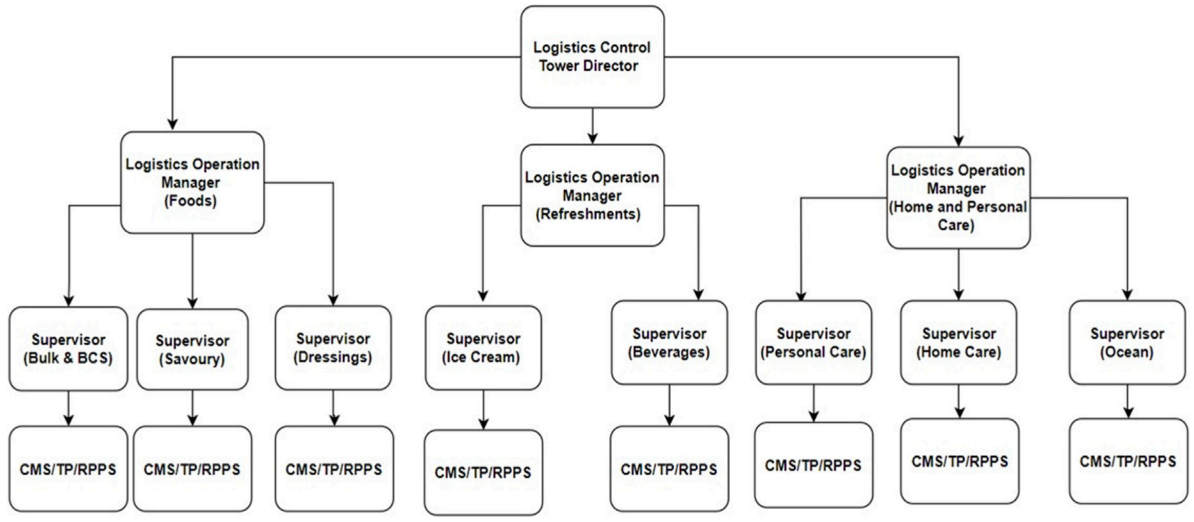

FIGURE 1
The hierarchies in the control tower of the case company.

From the transport management system perspective, an SCCT supports the control, planning, execution, and billing of transport activities (Rölli, 2021). This includes monitoring and managing 1) Transport operations; 2) Transport finances including invoice verification and transport budget controlling; 3) Logistics systems development including support, maintenance, and development of transport management system; 4) Logistics scale-up (i.e., implementation of new transport volumes, logistics efficiency projects), and 5) Logistics procurement including tendering, contract administration, market intelligence services, and pallet supply management.

Urban distribution centers and consolidation strategies have been investigated to examine their implications for improving supply chain efficiency (Morganti and Gonzalez-Feliu, 2015). SCCT as a consolidation service requires further investigation. The present study focuses on the logistics network orchestrated by SCCT.

2.2 Fast-moving consumer goods

The FMCG industry is characterized by high demand for service quality (Mbhele, 2016), a wide variety of products and large assortment size (Joseph et al., 2010), frequent deliveries of product batches (Colicchia et al., 2017), and product with a short life (Pan and Choi, 2016). These characteristics together with the low profit margins in FMCG (Birhanu et al., 2017) make logistics efficiency more imperative than in other sectors. In this situation, the products' long average time in the supply chain is not desired, making this an important factor in different managerial decision-making in FMCG (Pourhejazy et al., 2019).

Taking fresh meat, fruit, and vegetables as an example, the quality of products decreases rapidly and continues to decay until purchased and used by the end consumers. Considering the time-sensitive nature of products with deterioration of quality (Aljohani and Thompson, 2018), the revenue of the entire supply chain depends on the timeliness of logistics operations. In this situation, speed is a key performance indicator in FMCG supply chains (Dewa et al., 2017).

Transport visibility and timeliness are arguably the most important capabilities in the supply chain of FMCG companies. This has made FMCG an industry with the largest demand for third-party logistics (Dev et al., 2016). The intense competition results in low brand loyalty in FMCG (Wu et al., 2019); companies are constantly searching for improvement opportunities to stay competitive. Considering FMCG characteristics, and the implications of supply chain control towers for transport visibility and timeliness, a case from FMCG is presented in the next section to explore the nuances of SCCTs.

3 Transport management in the case company

The studied FMCG company has recently established an SCCT unit to handle orders from SC partners (factories, marketing and sales groups, and multi-country organizations) and other business partners (distribution centers and part manufacturers). Managing the transport operations in the European cluster and the Ocean and Air transport are among the major responsibilities of the SCCT unit; this includes the end-to-end transport operations and logistics between suppliers and factories (raw and pack transport), factories and primary warehouses (primary transport), and secondary warehouses (secondary transport). While the primary transports using the company fleet achieved the economy of scale by bundling shipments on international routes, shorter routes in the secondary transport are outsourced to third-party logistics (3PL) providers.

The operations in the SCCT unit are divided into three main product categories: Foods, Refreshments, and Home and Personal Care. The material and product characteristics, like the short shelf life of food products, the temperature-sensitive nature of

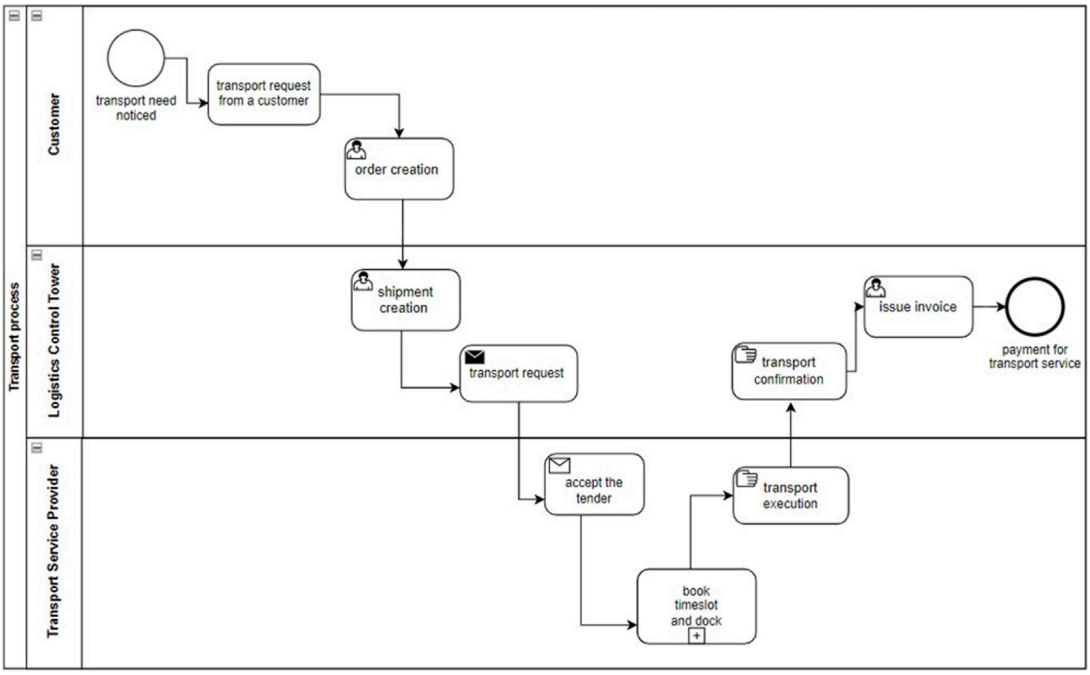

FIGURE 2
Interactions within the transport process.

refreshments, and chemical substances in home and personal care, differentiate these categories. These characteristics enforce certain transportation constraints; for example, home and personal care products cannot be transported with products from other categories due to the contamination risk. Factories, distribution centers, and part manufacturers accommodating the products are assigned to one of the three product categories considering their annual portfolio, transport requests, and key contacts. This approach enables transport planners to combine orders of less-than-full-truck loads from one category to maximize capacity utilization while considering the risk of tainted materials and products.

The SCCT unit is managed by the logistics director. As shown in Figure 1, logistics operation managers are responsible for different product categories. Supervisors manage sub-categories and a separate managerial role is defined for ocean operations. Customer management specialists (CMS), and regional project and process specialists (RPPS) support logistics operation managers and supervisors. Finally, transport planners handle the orders from one of three main product categories; the transport planners are allocated to specific geographical regions to support the combination of orders through maximizing full-truck-load shipments.

The planning department divides the assignments into (a) Raw and packed goods, and (b) Finished goods. The former responsibility consists of (I) ensuring that raw material is available for production and that packed products are available for delivery to customers (II) maintaining the lowest possible material and product levels in factories and distribution centers; (III) purchasing the required material and products. As the second responsibility, finished goods planning must ensure that products are available for delivery to customers, and plan the manufacturing and purchasing activities as well as delivery schedules. The logistics procurement team is responsible for tendering services and contract management, pallet management, pallet supply management, and SCCT market intelligence. In cooperation with the procurement team, the quality department is in charge of investigating claims and reviewing/reporting quality-related performance indicators regularly.

Once a shipment request is initiated, the transport planner should arrange the associated pick-up and delivery. Every factory is handled by one transport planner so that the customer will have only one contact point at the company's end. The customer management specialists get involved only in special circumstances and for driving performance improvements. The transport planner considers shipment priorities (i.e., normal and urgent) as well as resource management factors, like dock ownership, the number of available docks, and the working hours to plan the order fulfillment operations. The transport process is visualized in Figure 2 followed by a detailed description of the major operations.

3.1 Order management

The order fulfillment process begins when the SCCT unit receives a transport request; the order can be in the form of manual, interfaced, Electronic Data Interchange (EDI), or Flatto. The main difference between these order types is their integration with the Transport Management System and the amendment option after integration. A registered order includes the following information: loading and unloading locations and times, number of pallets, gross weight, transport condition, Incoterms, and special requirements, like dangerous goods, and express delivery. Given this information, the SCCT unit assigns immediate requests to the categories and the rest to the bulk/ocean transport. Within the selected category, the orders will be forwarded to specific transport planners considering their geographical responsibility. The transport planner combines orders based on the vendor codes within his/her category. The transport planner should also handle the capacity- and time-management decisions to select the best shipping alternative considering costs, carbon emissions, and customer service time when there is intermodal transportation.

3.2 Shipment initiation

New orders are added to the Transport Management System (TMS) as soon as all required information is entered. The SCCT then takes over the planning of the shipment, aiming to maximize the number of Full Truck Loads. If the transport service is outsourced, the SCCT forwards the request to a contracted TSP. In cases of having no suitable TSP or route available, or if the TSP rejects the load, the SCCT offers the load in the spot market.

3.3 Transport execution

After a TSP confirms they can handle the load, a dock must be reserved for the carrier. This process, which is known as "dock booking", involves selecting an available dock and scheduling a specific time for pickup or delivery at the factories or distribution centers. The term "load execution" refers to the actual process of transporting the goods, which spans from on-time collection to on-time delivery. Throughout this phase, real-time updates on shipment status are shared among all parties involved.

After fulfilling a transport demand, the financial department completes the transport process. For this purpose, SCCT executes a monthly invoicing process for the TSP. SCCT should work with partners from planning, IT, logistics procurement, quality, finance, and development units to complete these processes. The performance of SCCT, therefore, depends on the quality of the master data provided by the European center.

4 Conceptual model

This section uses CLDs to identify and map the interactions between various variables pertinent to dock booking (e.g., working hours, dock availability, shipment priorities). In the CLD diagrams, variables are connected by arrows to specify the direction of their interactions, with positive (+) or negative (−) signs indicating the nature of the relationships. SFDs are used to represent the dynamic behavior of the system over time to understand how changes in one part of the system (e.g., changes in shipment priorities or dock availability) impact the overall situation. In the SFD diagrams, a "stock" represents a quantity that accumulates over time, while a "flow" represents the rate at which the stock changes.

Once a transport task is confirmed, the TSP must book a dock and time slot at the pickup and delivery sites using the transport management system of the focal company. Frequently executed

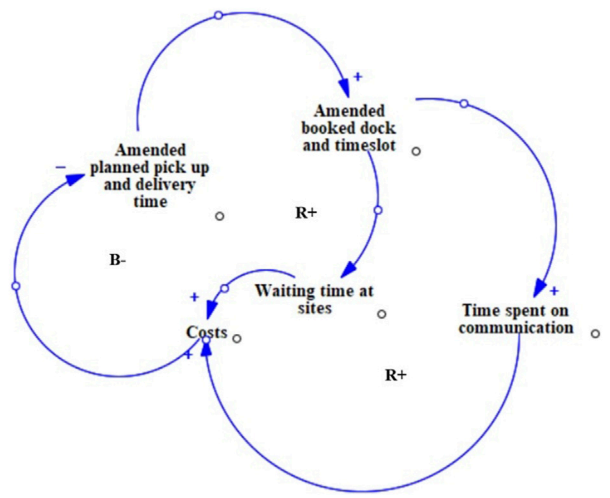

FIGURE 3
Interactions within the transport process.

shipments on short routes between factories and warehouses (known as shuttles) are exempted from dock booking. Besides, factories that work in close-to just-in-time situations do not require a booking.

In the case company, dock booking compliance at distribution centers is about 65 percent, whereas it amounts to 19 percent at the factories. In addition to the pickup arrangement, the planned arrival time also requires a booking while the dispatcher at the site is responsible for informing the driver about the dock number. This process is inefficient considering that the possible shipment delays and simultaneous arrivals may create truck queues and increase the drivers waiting times. Besides, 3PL often uses different platforms for communication; the focal company has to use fragmented solutions to manage dock bookings, which may result in conflicting schedules. This is particularly challenging, considering that the subcontracted shipments account for more than 60% of shipments.

From an operational perspective, the factories frequently change the production schedule because of amendments to customer orders; this drives changes in the planned pick-up and delivery times and amendments to dock bookings and timeslots. The data from the transport management system of the company suggests that 5 percent of requests are rescheduled or canceled while the actual scale of rescheduled appointments is around 45 percent. This is because most of the amendments are not updated on the central transport management system. Such modifications to booked docks and timeslots result in longer waiting times at sites and more communications between the SCCT unit, the TSP, and the site. The causal loop in Figure 3 shows the time accumulation during the communication process where two reinforcing loops accumulate time and one balancing loop compensates for it.

In addition to the time deficiencies, the dock booking process in the transport management system of the SCCT unit does not offer sufficient user experience. The users need approximately 25 clicks to complete a dock booking, which amounts to 200 s for highly experienced users and up to 10 min for moderately experienced

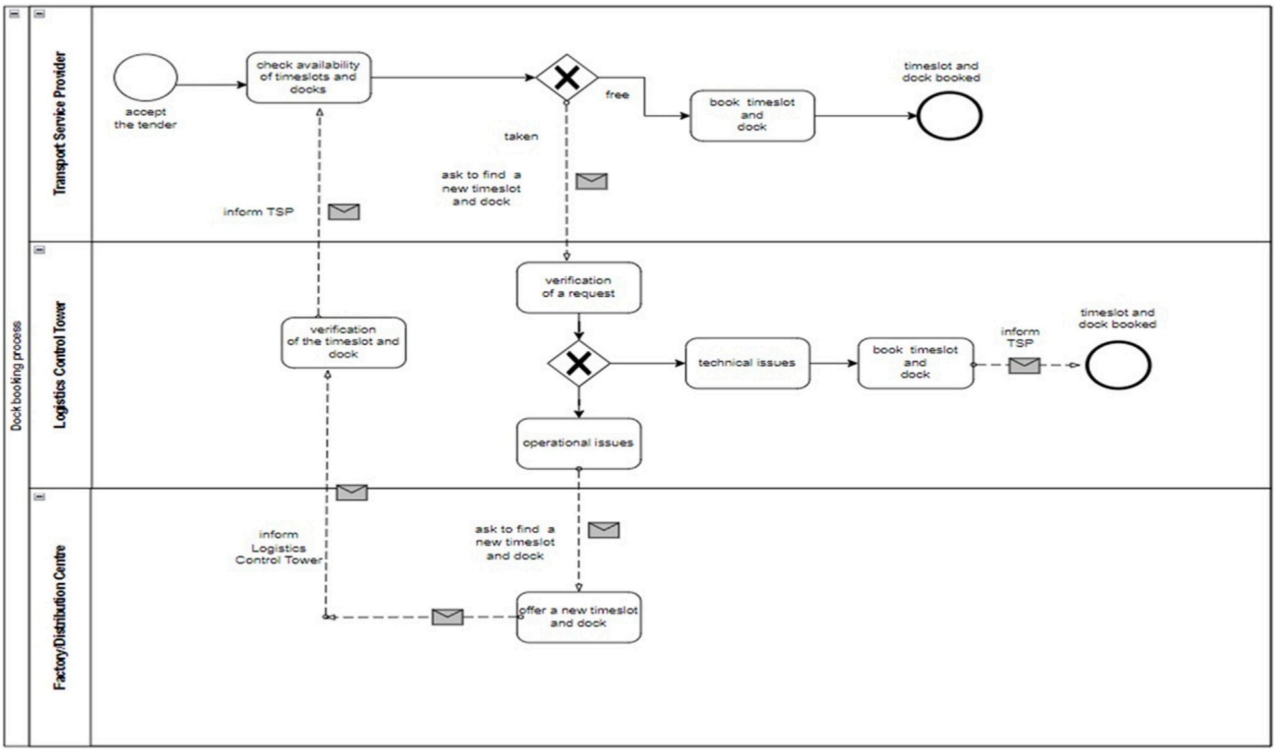

FIGURE 4
The as-is dock booking process.

users. The surveys conducted by the company revealed that 60 percent of TSPs wanted to reduce the hassle of completing the dock booking process shown in Figure 4.

In the current system, the dock booking process begins with checking the availability of time slots and docks. If there are no availabilities, the TSP contacts a customer management specialist or transport planner from the SCCT unit. The outcome should be then communicated with a dispatcher on the site (i.e., factory and distribution center) to check for the new timeslot and dock, and inform the TSP about the possible openings. That is, the customer management specialist (or transport planner) has to communicate with the driver, subcontractor, TSP, and the site. The partners exchange information within this communication loop to update the timeslots and docks. In this situation, communications consume the prevailing part, approximately 73% of planners' time; implementing a central system addresses this issue.

A new scheme suitable for the implementation of the IDB system is investigated. For the sake of simplicity, the operational scope is narrowed to the lanes connecting the factories and distribution centers, the loading of finished goods at the factories, and the unloading of finished goods at distribution centers. The proposed model consists of a procedure for autonomous dock booking based on real-time data on the working hours of the SC facilities, dock availabilities, and shipment priorities (i.e., regular or urgent) to complete the inquiry; the process should fulfill the following assumptions.

Condition 1. If automatically calculated timeslots are within the working hours of the SC facility (e.g., distribution centers and factories), then:

1.1. When there are free timeslots and docks, they must be booked on the same day;
1.2. When there are no free timeslots and docks on the same day, the agent must book the earliest timeslot the next work day.

Condition 2. If automatically calculated timeslots are outside the working hours of the SC facility, then:

2.1. A new time slot at the earliest possible on the same day must be booked;
2.2. When there are no free time slots earlier on the same day, the agent must seek a time slot at the earliest possible on the following working day.

Condition 3. Distribution centers should be given the alternative to accept or decline a new time slot; this is because the new Expected Time of Arrival (ETA) may deviate from the planned arrival time and conflict with other schedules considering that the distribution center is often used by different users (the case company's SCCT unit is not the only customer) and there are no explicitly dedicated docks for certain companies. Besides, it should be possible for the prioritized shipments to replace a normal shipment that is booked already, if necessary.

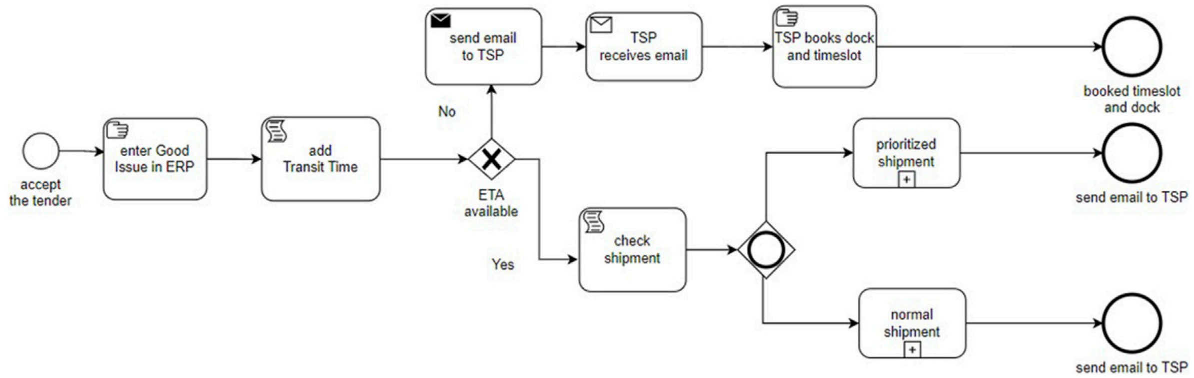

FIGURE 5
The exemplary process of dock booking under the stated conditions.

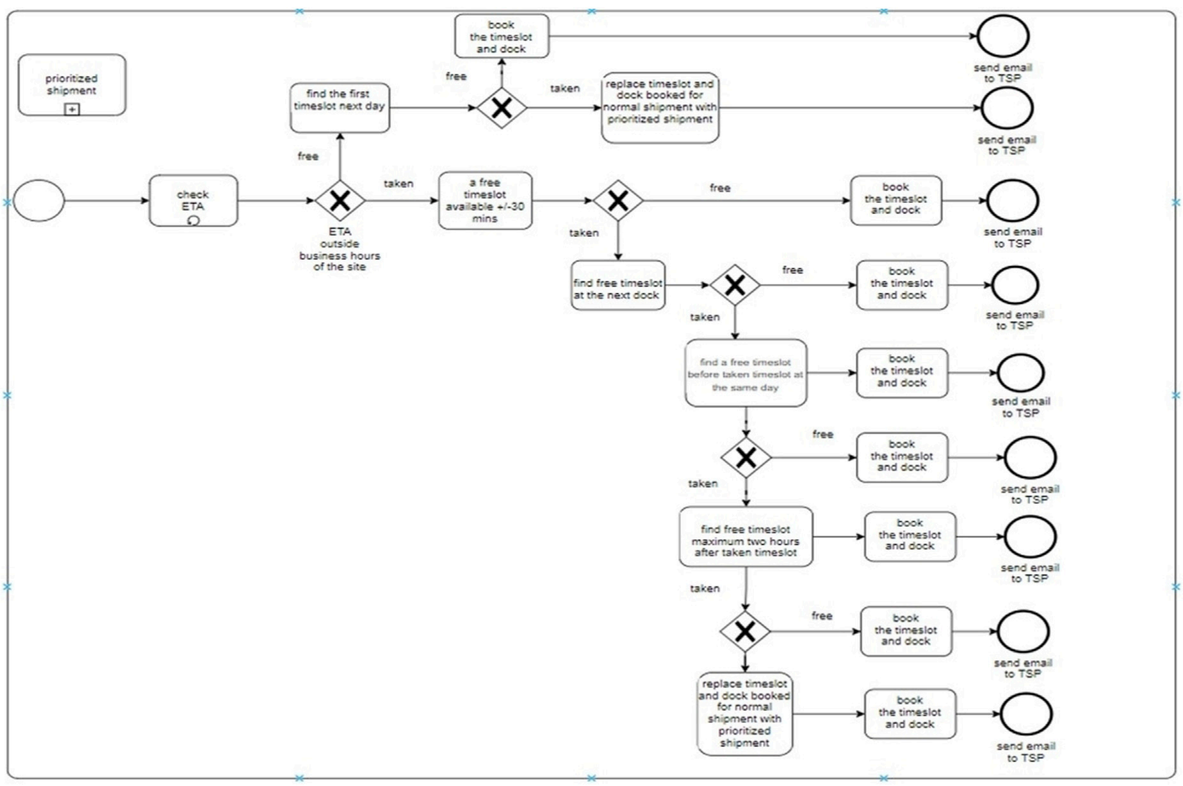

FIGURE 6
The proposed dock booking process.

An exemplary dock booking process considering these conditions is shown in Figure 5. In this process, the site manager can select the time intervals wherein he/she wants to receive a notification on the ETA; the latest update of the ETA triggers amendments to the booked timeslots and docks.

The inquiry for autonomous dock booking begins when the TSP accepts the tender. Once the truck is loaded at the factory, the employee enters the transport status (good issue) into the system. Considering the distance, the agent adds the transit time into the loading time in the ERP platform and checks for the dock availability in the distribution center at the ETA; if available, the agent checks whether the shipment is prioritized or normal and informs the TSP.

The agent checks ETA in several rounds to complete the booking process. If the ETA is not outside the business hours of the site, the earliest free timeslot available on the same day should be booked in the range of ± 30 min. Otherwise, if the ETA is outside of the business hours of the site, the first available timeslot on the next business day is booked. If there are no free time slots available at the

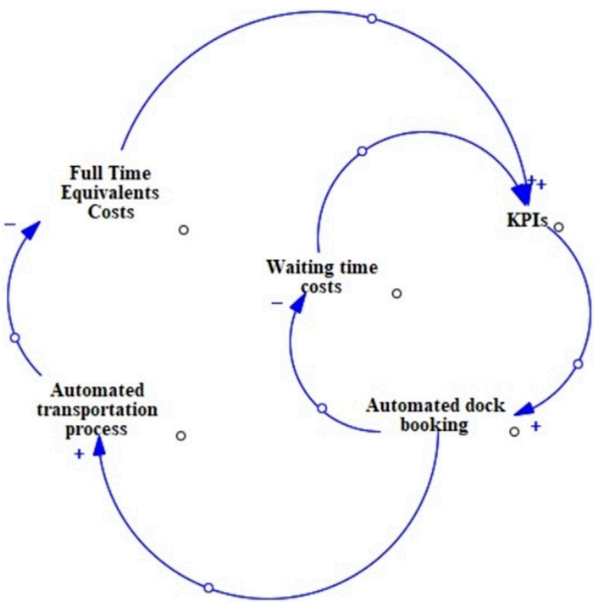

FIGURE 7
The cost-benefit cycles for implementation of the dock booking system.

first checked dock, the agent should check for another available dock on the same day. The agent should then check for the possibility of replacing the existing timeslot and dock booked for normal shipments with the prioritized shipment. The procedure is illustrated in Figure 6. The proposed approach has a focus on reducing communication time through the automation of processes, but will also impact other performance indicators. The next section analyzes the outcomes of adopting the new dock-booking approach.

5 Discussions

The case company has yet to fully benefit from adopting the SCCT platform; the process improvement opportunities are stalled due to manual decision-making and the lack of a central dock booking system. Cost savings and customer service improvements are the most anticipated benefits of implementing a centralized system for real-time data ETA information and IDB. Figure 7 shows the cost-benefit cycle perceived for analyzing the performance of the proposed conceptual model followed by performance analysis of the IDB system in Figure 8 and investigating the operational benefits.

In this model, *stocks* are defined as successful bookings and cost reduction. The former refers to the accumulated number of successful bookings over time. The latter represents the accumulated savings in costs over time. *Flows* include the following.

- Booking updates represent the rate at which new bookings are added (Unit of measure: number of bookings per unit of time).
- Unsuccessful bookings refer to the rate at which bookings are unsuccessful (Unit of measure: number of bookings per unit of time).
- Demurrage cost reduction is the savings in demurrage costs (Unit of measure: monetary value per unit of time).
- Personnel cost reduction represents the savings in personnel costs (Unit of measure: monetary value per unit of time).

The model's variables are listed below.

- Booking failure rate represents the percentage of failed bookings.
- Deviation between the actual time of arrival and ETA.
- Information processing delays are the time it takes to process information.
- Personnel per hour costs.

Average waiting time per truck. On this basis, the following equations represent the state dynamics in the system.

$$Successful\,Bookings(t) = Successful\,Bookings(t-1) + Booking\,Updates(t) - Unsuccessful\,Bookings(t) \quad (1)$$

$$Cost\,Reduction(t) = Cost\,Reduction(t-1) + Demurrage\,Cost\,Reduction(t) + Personnel\,Cost\,Reduction(t) \quad (2)$$

$$Unsuccessful\,Bookings(t) = Booking\,Updates(t) * Booking\,Failure\,Rate(t) \quad (3)$$

$$Personnel\,Cost\,Reduction(t) = Personnel\,per\,Hour\,Costs(t) * (1 - Information\,Processing\,Delays\,Reduction(t)) \quad (4)$$

$$Waiting\,Time(t) = Unsuccessful\,Bookings(t) * Average\,Wait\,Time\,per\,Truck \quad (5)$$

$$Demurrage\,Cost\,Reduction(t) = Waiting\,Time(t) * Demurrage\,Cost\,per\,Hour \quad (6)$$

$$Booking\,Failure\,Rate(t) = 1 / \left(1 + exp\left(-k * \left|Actual\,Time\,of\,Arrival(t) - Expected\,Time\,of\,Arrival(t)\right|\right)\right) \quad (7)$$

Equation 7 shows that a larger deviation from ETA increases the booking failure rate. The exponential term in the equation represents an increasing rate of change and the 1/(1 + exp(-k * (Deviation between Actual Time of Arrival(t) and Expected Time of Arrival(t)))) term ensures that the booking failure rate is bounded between 0 and 1.

From a practical perspective, improvement in information flow is the first tangible outcome of implementing the IDB system in the SCCT unit of the company. This results in both immediate and sequential performance improvements. First, the real-time updates of ETA remove the information processing time on updating the delays, cancellations, and aligning timeslots. The process skips unnecessary communications between the transport planners and the factory/distribution center, resulting in approximately 2^n fewer interactions in the dock booking process. Besides, the new system is less prone to human errors, a factor that increases the percentage of bookings and requests resulting in actual transport. The details of the projected information flow-related outcomes are summarized in Table 1.

The conceptual model in Figure 9 shows the impact of information processing delays on the communication loop between the providers (e.g., subcontractors, freight forwarders, drivers), the

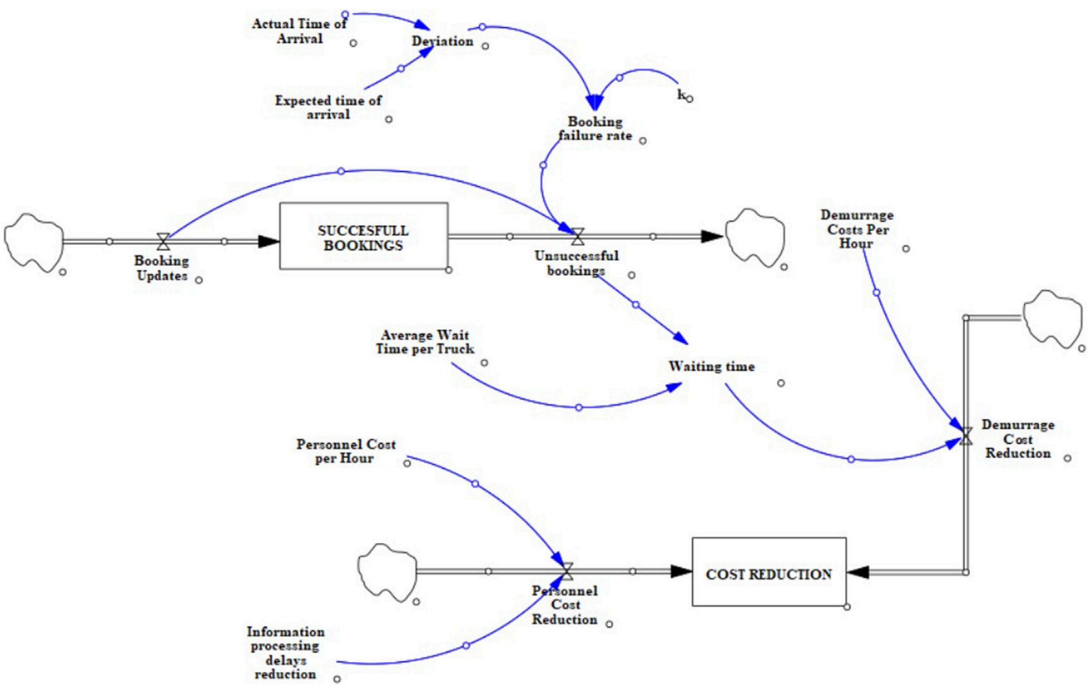

FIGURE 8
Performance model of the dock booking system.

TABLE 1 Information flow improvement after deploying the intelligent dock booking system.

Benefit	Perceived improvement	Barriers
• A decrease in late cancellations and bookings canceled earlier than, for example, 24 h before departure	• Reducing the costs associated with the waiting times (i.e., $\frac{waiting\ time\ costs}{total\ transportation\ costs}$)	• Achieving accurate Expected Time of Arrival
	• An increase in the ratio of bookings and requests that results in actual transport (i.e., $\frac{succesful\ bookings}{all\ bookings}$)	• Tensions between co-created value and governance costs
• A reduction in the planning time (e.g., tracing the shipments, determining the departure delays, updating new timeslot and docks, *etc.*)	• Fewer contact points and reducing the required interactions; reducing the transport execution cost	• Tensions between competition and collaboration
	• Improving service level (i.e., $\frac{the\ number\ of\ detention\ claims}{the\ total\ number\ of\ shipments}$)	• Tensions between co-created value and governance costs
		• Achieving accurate Expected Time of Arrival

SCCT unit, and the SC facility (e.g., factory, distribution center). Increasing the ratio of successful bookings over the resulting delay time (i.e., $(All\ bookings - unsuccesful\ bookings)/Delay\ time$) improves the effectiveness of the dock booking process. That is, reducing delay time and increasing the number of successful bookings to minimize the deficiencies.

Delay in informing the involved parties (i.e., driver, subcontractor, freight forwarder, and the SCCT unit) about the booking changes has a negative impact on the perceived information. Considering that most of the booking updates take place around average delay time, the third-order delay seems more appropriate than a first-order delay. This is because information on ETA can greatly deviate from the actual arrival time in the case of the first order delay.

Improvement in SC's physical flow is the next tangible outcome of implementing the IDB system. In particular, well-informed dock booking is expected to reduce the time trucks spend in an SC facility waiting in loading and unloading queues. This, in turn, results in shorter product time in the SC and reduces operational costs.

To estimate the perceived improvement, the detention claim by the TSPs is compared with the truck check-in/check-out timestamps. IDB reduces the number of trucks in transit considering the difference between trucks' incoming and outcoming rates. This is because the trucks' incoming rate, delay time, and the number of trucks in transit impact the trucks' outcoming rate. Comparing the waiting time with the time between check-in and check-out timestamps, the company confirmed that a 20 percent cost reduction associated with waiting time could be expected. Cost savings can also be achieved with better utilization of dock spaces. From the operations management perspective, more efficient transportation

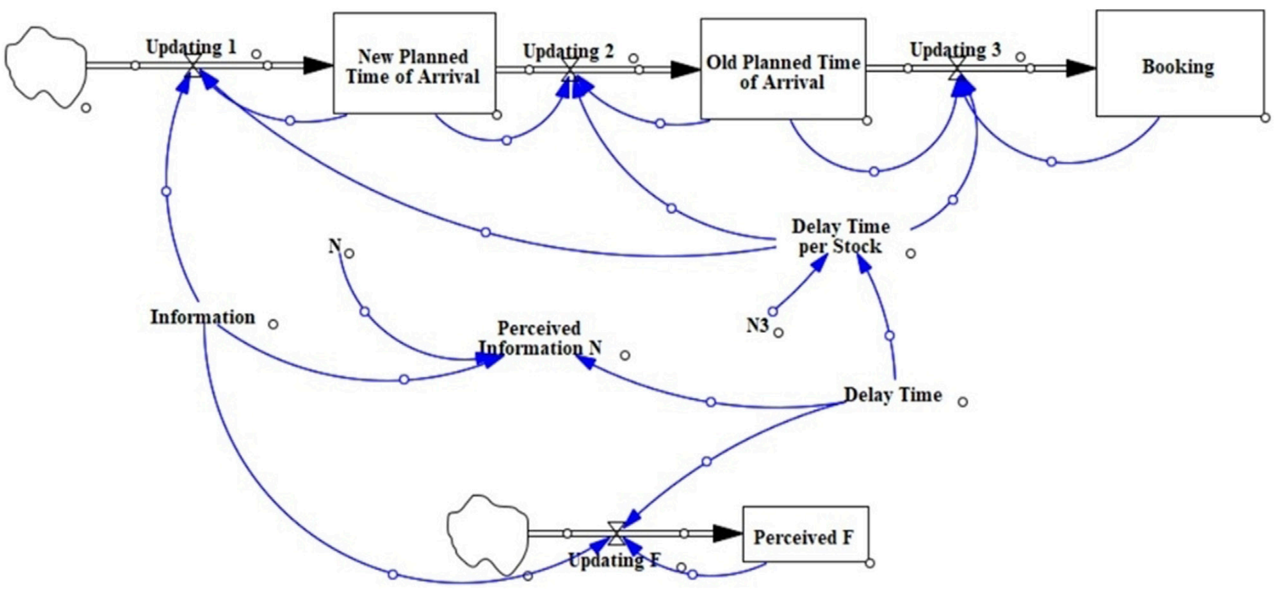

FIGURE 9
Impact analysis of delays.

TABLE 2 Physical flow improvement after deploying the intelligent dock booking system.

Benefit	Perceived improvement	Barriers
• Better utilization of space for loading and unloading	• Reduced facility costs $\frac{\text{costs of warehouse space before the implementation} - \text{costs of warehouse space after the implementation}}{\text{costs of warehouse space before the implementation}}$	• Achieving the repeatedly accurate Expected Time of Arrival
		• Tensions between co-created value and governance costs
• A reduction in the duration of processing trucks in the SC facility	• Reduced processing times $\frac{\text{time of processing the truck before the implementation} - \text{time of processing the truck after the implementation}}{\text{time of processing the truck before the implementation}}$	• Achieving the repeatedly accurate Expected Time of Arrival
	• Reduced inventory costs	• Tensions between co-created value and governance costs
		• Tensions between competition and collaboration

reduces the space needed for material/goods storage in the SC. Table 2 lists the major physical flow improvements.

Overall, the most immediate effects are reduced waiting time at sites (SC time) and decreased demurrage (SC cost). The sequential (delayed) effects consist of the ability to integrate shipment planning, TSP allocations, and internal logistics of factory and distribution centers with the IDB system, which improves SC flexibility. Besides, this integration has implications for SC's quality of fast-moving products.

Asymmetry of benefits may cause tensions between the involved parties; what is considered a value for one party may be perceived as a cost for the others. This causes practical limitations to the implementation of the IDB system. Compliance is a prime example, which impacts the percentage of tracked shipments. From the shipments that could not be tracked, the accuracy of ETA is the major barrier with 40 percent within the range of ± 1 h, 48 percent within the range of ± 2 h, and 59 percent within the range of ± 4 h. However, an accuracy of over 90 percent within the ± 1 h range is required to implement the proposed dock booking solution. This limitation can be overcome by narrowing the scope of deployment to the critical lanes where a higher percentage of tracked shipments provides accurate data to the underlying model, ensuring higher accuracy of ETA.

6 Implications for energy efficiency

Discussions confirmed the transformative nature of IDB in improving efficiency. The shift towards automation, real-time updates, and centralized data management fosters energy efficiency in the following ways.

- Decreased Truck Waiting Times. Energy is wasted when trucks are idle, waiting for their turn to load or unload. The IDB system reduces waiting times, thereby avoiding unnecessary fuel consumption. Besides, improved ETA accuracy improves traffic flow within the facility, resulting in reduced congestion and, consequently, less idling, and fuel wastage.
- Optimal Dock Usage. With a real-time booking system, docks can be used at their maximum capacity, ensuring that resources like electricity and manpower are used efficiently. This is in contrast to scenarios where docks remain empty due to manual scheduling errors or no-shows.
- Optimized Storage. Efficient transportation reduces the need for prolonged material/goods storage, saving energy in facilities that need to maintain specific product conditions, like refrigeration and air conditioning.
- Integration Capabilities. The IDB system allows for cohesive integration across supply chain processes. This results in more predictable and streamlined operations, making it easier to shift some of the activities to the off-peak periods to reduce the load on the electrical grids.
- Reduced Information Processing. The timely and accurate exchange of information enables efficient decision-making, leading to reduced energy consumption in the planning process.

Furthermore, reducing demurrage and personnel costs implies more efficient operations, which typically correlates with higher energy efficiency. Future research may quantify, monitor, and optimize the energy performance improvement by the IDB system in terms of the following performance indicators.

- Idle Time Energy Wastage (kWh or Liters/Gallons): the energy wastage during truck idle times;
- Cooling/Heating Efficiency (kWh per m^3): energy consumed to uphold specific storage conditions;
- Peak Load Energy Consumption (kWh): energy usage during peak hours;
- Carbon Footprint (Metric Tons CO2 Equivalent): the greenhouse gases emitted due to energy consumption;
- Energy Cost Saving (Monetary Value, e.g., $): financial savings through energy efficiency.

7 Conclusion

This article investigated an IDB system with a focus on a supply chain network that is orchestrated by the control tower. A new operational scheme was put forward to analyze and improve the performance of the control tower recently established in a well-known international FMCG company. The desired upgrades in the system were conceptually analyzed where both physical and information flow-related performance indicators are expected to improve and bring about energy efficiency. Besides, reducing unnecessary truck movements, waiting times, and the need for storage can contribute greatly to decreasing energy consumption and help in the company's net-zero goals. The major findings are summarized below.

RQ1. The successful implementation of the IDB system requires a blend of real-time data availability, operational clarity, system autonomy, agility, and a high level of integration. The requirements for implementing the IDB system are:

1. Real-time Data: The IDB system thrives on real-time data availability. SCCT must be able to obtain data and disseminate real-time insights with a focus on operational hours, dock statuses, and shipment priorities.
2. Standard Frameworks: A well-defined operational framework, especially those tied to working hours and distribution center discretion, should be established for decision-making.
3. Automated Scheduling: The IDB system should be able to autonomously map out dock schedules based on real-time data sources.
4. Dynamic Responsiveness: The system must be agile, especially when system variables, such as ETAs are highly unstable. Adjusting dock and timeslot allocations in response to these dynamics is essential.
5. Inter-departmental Collaboration: Smooth and timely interactions between departments, like IT, finance, and quality assurance are essential to ensure the seamless flow of real-time data.

RQ2. A reduction in demurrage costs, space requirements, energy costs, and inventory costs, as well as improved customer service, are the tangible outcomes of automating the dock booking process; the improved aspects of SCCT's performance are:

1. Communication Efficiency: The IDB system reduces communication overhead, allowing key personnel like planners and logisticians to prioritize critical activities.
2. Supply Chain Efficiency: The IDB system decreases truck waiting times, which facilitates a smoother material flow. This results in a potential cost saving of up to 20%.
3. Space Efficiency: Intelligent planning maximizes dock space usage which, in turn, diminishes the demand for additional storage areas; this translates to tangible cost reductions.
4. Operational Efficiency: The agility provided by the IDB system reduces common operational bugs, like scheduling failures, which are the root cause of various wastes/delays.
5. Energy Efficiency: Streamlined operations, diminished superfluous storage, and curbed idle times facilitate a more energy-aware system, reducing energy costs.

This case study acts as a stepping stone for future developments in automating logistics decision-making and administrative operations that can be integrated into an SCCT. There are challenges to implementing the IDB system, such as the need for integrating it with other systems and departments, and the need to train employees on how to use the system. Future studies may address such operational and tactical issues, investigating it from an optimization perspective. To be more specific, system dynamics can be used for strategy development and decision analysis in the dock booking system. Revenue management models can be useful to maximize profitability by regulating acceptance/rejection decisions in a network with both formal and informal truckers and the TSP. Game theory models are needed to help analyze the tensions between different SC partners considering the co-created value and governance costs. Finally, the scope of SCCT can be extended inspired by well-established transportation concepts, like train formation planning (Li et al., 2023) and shunting.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

SW: Conceptualization, Data curation, Formal Analysis, Methodology, Writing–review and editing. PP: Investigation, Project administration, Software, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Publisher's note

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The impact of global value chain embedding on the upgrading of China's manufacturing industry

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In the current international trade characterized by global value chains (GVCs), to improve the trade interests of China's manufacturing industry and change the unfavorable situation of "big but not strong," industrial upgrading is an important issue that needs to be solved urgently. Based on the analysis of the impact of embedding in GVCs on the acquisition of trade benefits, the paper empirically tests the impact of embedding GVCs on manufacture upgrading by using industry segmentation data of China's manufacturing industry from the year 2000 to 2014 in the world input–output database. The research shows that 1) from 2000 to 2014, forward and backward participation increased from 11.2% and 15.2% to 14.6% and 15.9%, respectively; China's manufacturing industry mainly participates in the GVC in a backward way, which significantly improves trade interests; 2) both forward participation and backward participation in the GVC are conducive to the increase of trade benefits and are positive at the 5% level, which has a significant driving effect on the upgrading of the manufacturing industry; and 3) heterogeneity testing shows that capital-intensive, technology-intensive, and high-tech industries gain significant trade benefits, and embedding GVCs is more conducive to upgrading. Therefore, integrating into the GVC at a higher level is the direction to promote the upgrading of China's manufacturing industry.

KEYWORDS

global value chain, China's manufacturing industry, forward participation, backward participation, upgrading

1 Introduction

At present, the international economy is characterized by factor cooperation, trade of increased intermediate goods, and rapid development of outsourcing. A final product is jointly produced by countries according to advantageous factors, forming a vertical specialization mode (Cheng, 2022). Its manifestation is that multinational corporations distribute different production processes in different countries, and the final product has more than two production stages, more than two countries participate in production, forming "international intraproduct specialization" or "factor division" that is commonly known as the global value chain (GVC), which is particularly obvious in the manufacturing industry (Xiang, 2021). Affected by this, the pattern of international division of labor has expanded from interproduct division to intraproduct division, and international trade has developed from product trade to task trade (Chen et al., 2021). For developing countries, this means that export products that originally need to master a full set of production technologies can be integrated into the international division of labor under the background of GVC and only need to master the technology for specific production tasks or links. Therefore, the GVC provides developing countries with a fast track to accelerate the process of industrialization. China is a major manufacturing country and the "world factory." Integrating into the GVC provides a fast channel for the rapid development of the manufacturing industry. Since entering into WTO, China has long relied on the advantage of low labor cost to engage in processing trade, embedded into the GVC dominated by developed countries, engaged in production and assembly with very low added value (Xiang, 2019). For example, when exporting a $200 iPhone, China only earns $3.36 in manual fees, and most of the profits are seized by developed countries (Wen, 2018). Many key parts and core technologies still depend on imports from abroad, the rise of trade protectionism has a great impact on China's industry, considering its large scale, China's manufacturing is still not powerful, and enhancing the added value of exporting products and obtaining more trade benefits is an important direction for the transformation and upgrading of the manufacturing industry.

In recent years, restricted by resources and environment, China's factor cost advantage has gradually weakened, and it has fallen into the dilemma of "race to the bottom" with low-wage countries such as India and Vietnam, and a large number of labor-intensive industries have been transferred to Southeast Asian countries (Gao et al., 2020a). The high-end manufacturing return policy launched by the United States weakens the technology spillover effect of China's export products, intensifies the competition in the manufacturing field, and brings "crowding risk." The double squeeze of "high-end return" in developed countries and "low-end diversion" in developing countries forced China's manufacturing industry to upgrade (Gao et al., 2020b). COVID-19 has brought a great impact, and the global economy has pressed the pause button. In the face of an uncertain economic situation at home and abroad, China has put forward a strategy of "accelerating the formation of a new development pattern with the domestic cycle as the main body and the domestic and international dual cycles promoting each other." While emphasizing the domestic cycle, we should expand the opening at a higher level and integrate into global innovation chain. How to achieve upgrading of the manufacturing industry on the basis of domestic and foreign integrated development is an important issue that needs to be solved urgently (Fu, 2022; Li, 2022). In this context, clarifying the impact mechanisms of the integration of the GVC on manufacturing, upgrading, and testing the role of different impact mechanisms in China's participation in the GVC will provide theoretical support and practical basis for solving the aforementioned problems. The article intends to start with analyzing the impact mechanism of embedded global value chain on the manufacturing industry, use a value-added trade decomposition method to calculate the degree of embedded global value chain, empirically test the relationship between GVC embedding and export domestic added value, and put forward a theoretical and practical basis for the upgrading of the manufacturing industry under the "double cycle" pattern.

Compared with existing research, possible marginal contributions of this paper are as follows: first, from a research perspective, exploring the relationship between integrating into the global production system and industrial upgrading from the perspective of GVC is beneficial for clarifying the mechanism of integrating the GVC on industrial upgrading and providing useful decision-making references for "seizing high position of GVC." Second, from the perspective of research methods, the latest GVC forward and backward participation index constructed by Wang et al. (2017a) is used, and the characteristics of the GVC and the degree of embedding manufacturing GVC are comprehensively characterized. The latest data from the World Input Output Database (WIOD) are used, based on theoretical hypotheses, and econometric tests are conducted on overall and sub-samples. Third, in terms of research content, heterogeneity effects of integrating the GVC are analyzed from the perspectives of factor intensity and technology intensity, providing empirical evidence for preventing "capture by the low-end" and climbing toward high end of the GVC, enriching and expanding policy connotation of theoretical research.

2 Literature review

Trade theory attempts to explain what benefits trade brings to countries, enterprises, or individuals, to make judgments about whether and how to participate in the international division of labor and provide a basis for trade policy (Tang, , 2020). At present, the global industrial chain is accelerating its restructuring, and the impact of integrating into the GVC on developing countries has become a hot research topic (Tian et al., 2022; Wiryawan et al., 2022). Most studies about the upgrading process show that by participating in the GVC, enterprises can achieve industrial upgrading through channels such as participating in the professional division of labor and obtaining technological spillovers (Pahl and Timmer, 2020; VeeramaniDhir, 2022). In recent years, with the development of research methods of value-added trade, studies have increasingly taken export domestic value added (DVA) as a measure of trade interest to examine the impact of participating in the GVC on DVA. The accounting for the degree of GVC embeddedness is based on the decomposition of value-added trade (Koopman et al., 2014). In the process of quantitative analysis of the GVC, the input–output analysis method is mainly used from a macro perspective. Hummels et al. (2001) used the vertical specialization (VS) index to measure the degree of a country's participation in the international division of labor for the first time under the assumption that imports are entirely from abroad (Hummels et al., 2001). Johnson and Noguera (2012) used the Global Trade Analysis Project (GTAP) database to measure the participation of 94 countries in GVC production sharing by value-added export rate (VAX) (Johnson and Noguera, 2012); Wang et al. (2013) and Wang et al. (2017b) further improved and decomposed a country's total trade into DVA and foreign value added and then expanded to the national, bilateral, and sectoral levels. The total export was divided into nine parts and 16 parts, respectively. Based on the complete decomposition of total exports, the GVC participation index (GVC_participation) is constructed to measure the degree of a country's participation in the GVC division of labor (Wang et al., 2013). The former HIY decomposition method may lead to a serious underestimate of the share of foreign value added. The latest input–output decomposition method establishes a complete set of accounting rules from official trade gross value statistics to trade value-added statistics by distinguishing the content of domestic and foreign factors in various production activities and distinguishing content of factors in various domestic and foreign production activities (Wang et al., 2017a; Wang et al., 2017b). The participation of China's manufacturing industry in the GVC showed a dynamic trend from 2000 to 2018. By 2018, the forward and backward participation in China's manufacturing industry had reached 0.148 and 0.162, respectively (Huang and Yang, 2022; Zhang and Li, 2022). Regarding the measurement of manufacture upgrading, one kind of literature is measured by alternative indicators such as export domestic value-added rate (DVAR), export technology complexity (EXPY), revealed comparative advantage (RCA), which is considered as DVAR (domestic value creation part included in export products), EXPY (technical level contained in export products), and RCA (proportion of industrial export share), which can measure a country's position in the GVC and take increasing income, improving technical level or market share as the direction of industrial upgrading (Kee and Tang, 2016; Johnson and Noguera, 2012). The other kind of literature is measured by the upstream degree (UI) index constructed by Antràs and Chor (2018). Judging by measuring distance from the beginning of production to the final product, the lower the upstream index, the more the benefits. The direction of industrial upgrading is defined with the size of the UI index.

To analyze the factors affecting industrial upgrading, the domestic and foreign literature discusses the impact of human capital quality, capital deepening, foreign direct investment (FDI), system quality, infrastructure construction, trade facilitation, and other factors on industrial upgrading (Kummritz et al., 2017; Zhang and Li, 2022). Human capital is indispensable to economic development. The deepening of senior talent and capital is an important factor to promote scientific and technological progress. The technological spillovers and competitive effects brought by FDI are important forces driving the technological progress of enterprises and the renewal of product quality. System quality and business environment are the key areas for the optimization and improvement of China's opening to the outside world. They are crucial to attracting foreign capital and talent and creating a good development environment for enterprises. Domestic and foreign scholars empirically tested the influencing factors of manufacture upgrading through macro- and micro-level data. Xiang (2020) used the panel data of China's manufacturing industry to find that domestic service factor input is conducive to the upgrading of the manufacturing value chain, while the impact of foreign service factor input on manufacture upgrading is negative (long and Wang, 2017). Yu Donghua et al. (2019) selected panel data of China's manufacturing industry from 2001 to 2014 and found that although there are "low-end locking" and "absorption threshold" effects, embedding the GVC is conducive to the transformation and upgrading of China's manufacturing industry (Gao et al., 2019). Kee and Tang (2016) integrated macro and micro data and found that by using domestic raw materials to replace imported raw materials, the domestic added value of export products can be increased and China's industrial upgrading can be achieved (Koopman et al., 2014).

Through literature review, it can be found that different scholars have analyzed the impact of GVC embedding on manufacture upgrading from different angles. The research conclusions of most literature are positive, and some scholars have studied the "capture effect" and "low-end locking" of GVC embedding (Xiao et al., 2019; Xiang, 2020). At present, few studies focus on China to investigate the impact of different participation paths of the GVC on the upgrading of China's manufacturing industry. Therefore, this paper will take export DVA as the measurement index of manufacture upgrading, on the basis of describing the path of China's manufacturing industry, integrated into the GVC, investigate the differential impact of GVC forward participation and backward participation on China's manufacture upgrading, and identify the impact mechanisms of the aforementioned two paths. The structure of the article will be arranged as follows, the second part is theoretical analysis, the third part is the empirical test and explanation, the fourth part is further heterogeneity analysis, and the last part is conclusion and recommendations.

3 Theoretical analysis

At present, there are different definitions of manufacturing upgrading. Gereffi et al. (2001) defined industrial upgrading under the background of global value chain as four types: product upgrading, process upgrading, function upgrading, and chain upgrading (Yu and Tian, 2019). In recent years, with the development of the decomposition method of value-added trade, research studies have increasingly taken export DVA as the index to measure trade interest. Therefore, this paper defines the upgrading of the manufacturing industry as the process of transformation from a low-value-added industry to a high-value-added industry, that is, the process of continuous increase of value added in export and the rise of trade interests. The division of labor in the global value chain makes specialization within the scope of globalization more refined. The added value in the GVC is distributed in various links such as design and R&D, production and manufacturing, marketing, and distribution. With the advantages of resource endowment and human capital, China's manufacturing industry is embedded in the GVC and is changing from low-end processing and assembly to R&D and design and brand marketing, and it is climbing from low value-added links to high value-added links (Yue et al., 2018). China has become the world's largest manufacturing country since 2010, and the total domestic added value of the manufacturing industry has been increasing. Embedding the GVC has a significant impact on China's acquisition of technology, enhancement of innovation, and realization of value chain climbing. The manufacturing industry achieves industrial upgrading through three ways: specialization effect, learning by doing effect, and technological spillover effect.

3.1 Specialization effect

China's manufacturing industry can gain economies of scale by participating in global specialization. The production efficiency of enterprises has been continuously improved due to the fine division of labor, and the production cost has been greatly reduced. The industrial products made in China have occupied the global market with an irresistible price advantage, obtaining a continuous expansion of the total DAV. Direct integration of the GVC reduces the cost of industrial strategy selection of China's manufacturing industry. In the process of undertaking industrial transfer in developed countries, China can learn from the original development mode and path of developed countries, make full use of global resources and markets, and drive the common development of domestic related industries through the introduction of foreign advanced technology, capital, and talents; trade and investment drive the optimization of the industrial structure, solve the problems of insufficient domestic capital goods and poor technology, and quickly achieve industrial development and upgrading on a high basis (Hu et al., 2020).

3.2 Learning by doing effect

Participating in GVC can acquire technical knowledge, accumulate production experience in understanding and solving problems, continuously strengthen production, and improve labor productivity. It has not only trained a large number of skilled workers but also trained a large number of engineers learning foreign advanced technology, and human capital can be optimized. The import of intermediate products has optimized the allocation of resources and laid a foundation for improving the technical content of domestic export intermediate products. Enterprises have upgraded their products through technology follow-up or imitation innovation to enhance the DAV of their products. The learning by doing effect not only optimizes the allocation of resources and human capital but also promotes the upgrading of the industrial structure (Gereffi et al., 2001).

3.3 Technology spillover effect

After embedding the GVC, Chinese enterprises can directly introduce or learn from the advanced technology of foreign enterprises, undertake outsourcing businesses such as communication and electronics industries, import intermediate products containing a large amount of knowledge and technology for processing and production, and have the opportunity to divide labor and cooperate with developed countries to obtain "technology spillover" (Wang, 2019). At the same time, to meet the strict requirements of multinational corporations on product safety, environmental protection, and other product quality and occupy a place in the fierce international market, Chinese manufacturing enterprises need to constantly improve their processes and realize product upgrading through digestion, absorption, reintegration, and innovation. The high standard requirements of multinational corporations force OEM enterprises to improve their technical standards, promote continuous improvement of export product quality standards, and upgrade in the GVC (Yu and Cheng, 2021).

At the same time, we also notice that to maintain their own interests, developed countries will set up barriers and implement blockades in key core technology fields. As a result, developing countries are "locked and captured at the low-end chain," and there is even a risk of "chain breaking," and the long-term introduction of foreign technology will lead to substitution and lack of independent innovation ability of enterprises, forming path dependence for long-term engagement in low-end low profit links. There is a threshold effect in absorbing advanced technology of multinational corporations. Technology spillover will have a positive impact only when the level of economic development and human capital reach a certain threshold (Wang et al., 2021). In short, whether the effect of embedded GVC is good or bad needs to be judged according to different economic environments and development stages and other factors. The following will be tested in the empirical part, and a conclusion will be drawn. Based on the aforementioned analysis, the following assumptions are put forward:

Hypothesis 1. Positive effect of embedding into the GVC is greater than the negative effect, which is conducive to China's manufacturing industry to obtain trade benefits, achieve product upgrading and process upgrading through learning advanced technology and experience, and promote the upgrading of the industrial structure.

Hypothesis 2. Different manufacturing industries have different trade interests embedded in the GVC. China's manufacturing industry, which mainly involves labor-intensive industries in the international division of labor, can improve the technical content of products, increase the DAV of exports, and facilitate industrial upgrading.

4 Main indicators and typical facts

4.1 Measuring the degree of manufacturing embeddedness in global value chains: a decomposition model of value-added trade

Assuming that there are G countries and N industrial sectors in the world, the inter-country input–output table (ICIO) is shown in Table 1.

TABLE 1 Inter-country input–output table.

Input		Intermediate use				Final demand				Total
Output		1	2	. . .	G	1	2	. . .	G	Output
Intermediate	1	Z^{11}	Z^{12}	. . .	Z^{1g}	Y^{11}	Y^{12}	. . .	Y^{1g}	X^1
	2	Z^{21}	Z^{22}	. . .	Z^{2g}	Y^{21}	Y^{22}	. . .	Y^{2g}	X^2
Inputs	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	G	Z^{g1}	Z^{g2}	. . .	Z^{gg}	Y^{g1}	Y^{g2}	. . .	Y^{gg}	X^g
Value added		Va^1	Va^2	. . .	Va^g					
Total input		$(x^1)'$	$(x^2)'$	. . .	$(x^g)'$					

Among them, Z^{sr} is the intermediate input matrix (produced in country S and used in country R), Y^{sr} is the final product vector, Va^s is the added value vector, and X^s is the total output vector. Wang Zhi (2013) decomposed the total value of a country's export trade into 16 parts, including added value and double counting, according to different sources and the final destination of added value of trade, realizing the complete decomposition of export trade. The specific decomposition formula of the total export trade value of country s (or region) to country r (or region) E^{sr} is as follows:

$$\begin{aligned}
E^{sr} = {} & \underbrace{(V^sB^{ss})^T \# Y^{sr}}_{(1)-DVA_FIN} + \underbrace{(V^sL^{ss})^T \# (A^{sr}B^{rr}Y^{rr})}_{(2)-DVA_INT} \\
& + \underbrace{(V^sL^{ss})^T \# \left[A^{sr}\sum_{t\neq s,r}^{G} B^{rt}Y^{tt} + A^{sr}B^{rr}\sum_{t\neq s,r}^{G} Y^{rt} + A^{sr}\sum_{t\neq s,r}^{G} B^{rt}\sum_{u\neq s,t}^{G} Y^{tu}\right]}_{(3)-DVA_INTrex} \\
& + \underbrace{(V^sL^{ss})^T \# \left[A^{sr}B^{rr}Y^{rs} + A^{sr}\sum_{t\neq s,r}^{G} B^{rt}Y^{ts} + A^{sr}B^{rs}Y^{ss}\right]}_{(4)-RDV} \\
& + \underbrace{(V^sL^{ss})^T \# \left(A^{sr}B^{rr}\sum_{t\neq s,}^{G} Y^{st}\right) + \left(V^sL^{ss}\sum_{t\neq s,}^{G} A^{st}B^{ts}\right)^T \# (A^{sr}X^r)}_{(5)-DDC} \\
& + \underbrace{\left[(V^rB^{rs})^T \# Y^{sr} + \left(\sum_{t\neq s,r}^{G} V^tB^{ts}\right)^T \# Y^{sr}\right]}_{(6)-FVA_FIN} \\
& + \underbrace{\left[(V^rB^{rs})^T \# (A^{sr}L^{rr}Y^{rr}) + \left(\sum_{t\neq s,r}^{G} V^tB^{ts}\right)^T \# (A^{sr}L^{rr}Y^{rr})\right]}_{(7)-FVA_INT} \\
& + \underbrace{\left[(V^rB^{rs})^T \# (A^{sr}L^{rr}E^{r*}) + \left(\sum_{t\neq s,r}^{G} V^tB^{ts}\right)^T \# (A^{sr}L^{rr}E^{r*})\right]}_{(8)-FDC} \\
= {} & (DVA_FIN + DVA_INT + DVA_REX) + (RDV) \\
& + (FVA_FIN + FVA_INT) + (DDC + FDC), \\
= {} & DVA + RDV + FVA + PDC. \qquad (1)
\end{aligned}$$

According to the aforementioned decomposition process, the 16 parts of the total export trade are summarized and combined, as shown in Table 2.

The total output X can be divided into two parts: intermediate product AY and final product Y:

$$X = AX + Y = A^DX + Y^D + A^FX + Y^F = A^DX + Y^D + E. \qquad (2)$$

$A^D = \begin{bmatrix} A^{11} & 0 & \dots & 0 \\ 0 & A^{22} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & A^{GG} \end{bmatrix}$ is the diagonal block matrix of domestic input coefficient. A^F is the off-diagonal block matrix of import input coefficient, $A^F = A - A^D$. Y is the production vector of final products and services for domestic consumption. Final export product vector $Y^F = Y - Y^D$. E is the total export vector. Formula (2) can be decomposed as follows:

$$\begin{aligned}
X &= (I - A^D)^{-1}Y^D + (I - A^D)^{-1}E = LY^D + LE \\
&= LY^D + LY^F + LA^FX. \qquad (3)
\end{aligned}$$

Therefore, the domestic added value and final product production can be decomposed into

$$\begin{aligned}
\hat{V}B\hat{Y} &= \hat{V}L\hat{Y}^D + \hat{V}L\hat{Y}^F + \hat{V}LA^FB\hat{Y} \\
&= \hat{V}L\hat{Y}^D + \hat{V}L\hat{Y}^F + \hat{V}LA^FL\hat{Y}^D + \hat{V}LA^F\left(B\hat{Y} - L\hat{Y}^D\right). \qquad (4)
\end{aligned}$$

By summing up the line vectors in Eq. 4, according to the flow direction, the domestic added value at the country/sector level is decomposed into (forward linkage)

$$Va' = \hat{V}BY = \underbrace{\hat{V}LY^D}_{(1)\_V\_D} + \underbrace{\hat{V}LY^F}_{(2)\_V\_RT} + \underbrace{\hat{V}LA^FLY^D}_{(3a)\_V\_GVC\_S} + \underbrace{\hat{V}LA^F\left(BY - LY^D\right)}_{(3b)\_V\_GVC\_C} \qquad (5)$$

By summing up the vectors in Eq. 4, according to the source, the added value of final product production is decomposed into (backward linkage)

$$Y' = VB\hat{Y} = \underbrace{VL\hat{Y}^D}_{(1)\_Y\_D} + \underbrace{VL\hat{Y}^F}_{(2)\_Y\_RT} + \underbrace{VLA^FL\hat{Y}^D}_{(3a)\_Y\_GVC\_S} + \underbrace{VLA^F\left(B\hat{Y} - L\hat{Y}^D\right)}_{(3b)\_Y\_GVC\_C} \qquad (6)$$

Among them, V_D、Y_D does not involve trade; it is the DAV produced and absorbed by the country. V_RT、Y_RT is the DAV included in the final product export. V_GVC_S、Y_GVC_S refers to a simple GVC activity that only crosses the border once and is the DAV included in the export of intermediate products; V_GVC_C、Y_GVC_C refers to complex GVC activities that cross the border more than once, involving indirect trade with third countries.

4.2 Quantitative index construction

On the basis of Eqs. 5 and (6), the forward participation index (PA_f) and the backward participation index (PA_b) are constructed to measure the degree of a country's sector level participation in the GVC:

$$\mathrm{PA\_f} = \frac{\mathrm{V\_GVC}}{\mathrm{Va'}} = \frac{\mathrm{V\_GVC\_S}}{\mathrm{Va'}} + \frac{\mathrm{V\_GVC\_C}}{\mathrm{Va'}}, \qquad (7)$$

$$\mathrm{PA\_b} = \frac{\mathrm{Y\_GVC}}{Y'} = \frac{\mathrm{Y\_GVC\_S}}{Y'} + \frac{\mathrm{Y\_GVC\_C}}{Y'}. \qquad (8)$$

The forward participation index (PA_f) calculates the proportion of added value created by a country to the DAV contained in global exports of intermediate goods. It measures the degree of dependence of other countries on domestic intermediates, and it is the value added calculated from the perspective of production, which is similar to the VS1 index proposed by Hummels et al. (2001), but VS1 is the proportion of the total value in trade. The backward participation index (PA_b) calculates the proportion of intermediate products used by the country from the perspective of added value and measures the country's dependence on other countries' intermediates. The traditional VS and VS1 indicators cannot reflect whether a country participates in simple GVC or complex GVC. In terms of total value, the VS1 indicator may be very high for industries with few direct exports (such as mining), and the

TABLE 2 Conceptual framework of gross trade accounting.

Gross export (goods and services) (E)			
(1)DVA (Domestic value-added absorbed abroad)	(2)FVA (Foreign value added)	(3)PDC (Pure double counting part)	(4)RDV (Returned value added)
DVA_FIN (domestic value added of final exports)	FVA_FIN (foreign value added of final export)	DDC (pure double counting from domestic sources)	
DVA_INT (intermediate exports absorbed by direct importing countries)		FDC (pure double counting from foreign sources)	
DVA_REX (intermediates sent to the first importer and then re-exported to a third country)	FVA_INT (foreign value added of intermediate exports)		

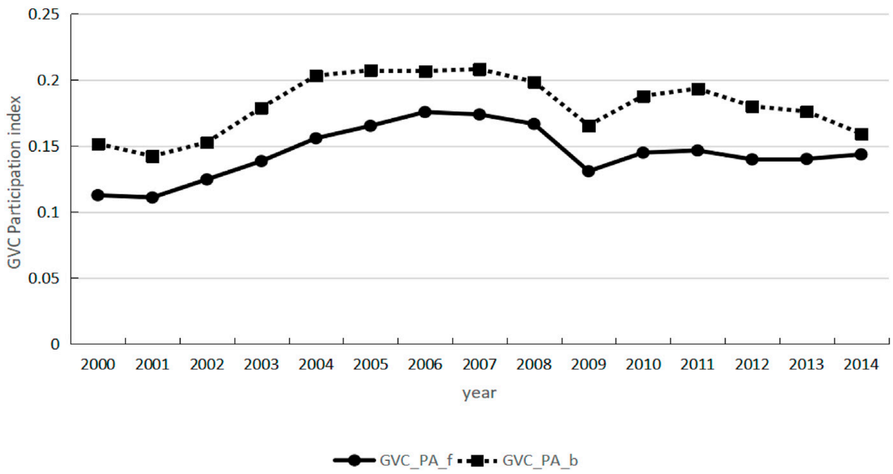

FIGURE 1
Participation of China's manufacturing industry in the GVC from 2000 to 2014. Source: WIOD

improved indicators can better reflect the degree of a country's participation in the GVC.

4.3 Typical facts of Chinese manufacturing embedding the GVC

According to the calculation methods of the forward participation index (PA_f) and the backward participation index (PA_b) mentioned above and using the data of the WIOD 2016 database, Figure 1 measures the participation degree of China's manufacturing industry in the GVC from 2000 to 2014.

As can be seen from Figure 1, China's manufacturing industry mainly participates in the GVC in the way of backward participation, which shows that China's manufacturing industry mainly depends on the supply of imported intermediates in the process of integrating into global production, embeds the processing and assembly link of the GVC with the advantage of cheap labor, and mainly participates in global division of labor in the way of "processing trade." This is also a realistic feature that "processing trade" accounts for half of China's import and export since China's entry into WTO. At the same time, China also exports intermediate products, such as aircraft, auto parts, and other products, and participates in the GVC in a forward-linking way. Data from the World Bank show that China has become the world's most important product supplier and demander, and it is the central node of the GVC, becoming the core hub of the GVC (Zhang and Zhang, 2022).

With the time dynamic evolution track of participation, the forward and backward participation indexes were increasing from 12.5% and 15.6% in 2001 to 18.6% and 19.9% in 2008, respectively, indicating that after China's accession to the WTO, China's participation in the international division of labor continued to deepen, and the manufacturing industry was deeply integrated into the GVC. In 2008, due to the impact of the global financial crisis, there was a brief decline, and the participation index dropped to 13.7% and 16.3%, respectively, in 2009. After the impact of the crisis subsided, it gradually recovered. From 2010 to 2014, the trend of trade protection became increasingly serious, and the trend of anti-globalization spread. The forward and backward participation decreased from 15.1% and 18.2% to 12.5% and 15.1%, respectively. There was a trend of "decoupling" of the GVC and internalization of the global industrial chain demonstrated by Timmer et al. (2016) (Hu et al., 2021). It is worth noting that compared with the decline of backward participation since 2012, the forward participation is rising. China's manufacturing industry is changing from a user of imported intermediate goods to a provider of exported intermediate goods. In the dynamic transformation from "value input" to "value output," which replaces imported foreign added value with DAV, the transformation and upgrading of processing trade has achieved preliminary results.

5 Empirical test and analysis

5.1 Model construction

The aforementioned research shows that different embedding methods, or different sectors of manufacturing industries, participate in the international division of labor and have different effects on the DAV of exports. To test the impact of GVC embedding on the upgrading of the manufacturing industry, the econometric model is set as follows:

$$LnDVA_{it} = \beta_0 + \beta_1 LnPA_{it} + \beta_2 Controls + \gamma_{i+}\mu_{t+}\delta_{it}, \quad (9)$$

where subscript i represents the manufacturing industry sector and t represents the year. The explained variable is export DVA, that is, the total DVA of China's manufacturing export sector, which is an indicator to measure the upgrading of the manufacturing industry; according to the decomposition framework of trade added value by Wang et al. (2013), the larger its value is, the more trade benefits will be obtained from exports. The core explanatory variable PA represents GVC embeddedness, including GVC forward participation (PA_f) and GVC backward participation (PA_b), and the calculation method is derived from the previous section. Controls represent industry control variables, including GVC position (PO), labor productivity (PR), industry capital intensity (K/L), and foreign direct investment (FDI). γ_i, μ_t, and δ_{it} represent industry fixed effects, year fixed effects, and standard error, respectively. Taking into account the differences in the level values of different variables, logarithmic processing was performed during the estimation process.

5.2 Variables and data

The following control variables are selected in this paper:

(1) GVC position index (PO): the position of the manufacturing industry embedded in the GVC. "Upstream index" constructed by Antras et al. (2012) is referred to measure the position of China's manufacturing industry embedded in the GVC. The data come from the RIGVC UIBE database. (2) Labor productivity (PR): measured by *per capita* domestic added value. (3) Industry capital intensity (K/L): measured by the ratio of fixed capital to the number of employees in the manufacturing sector. The data of the aforementioned two variables are from socio-economic accounts of WIOD. (4) Foreign direct investment (FDI): it is measured by the accumulative value of the amount of foreign direct investment actually utilized in the year. The data are from the annual database of the National Bureau of Statistics of China (NBSC), and the descriptive statistical results of each variable are shown in Table 3.

5.3 Empirical test results and analysis

5.3.1 Benchmark model regression

According to the data of the latest version of WIOD (2016), this paper analyzes the impact of GVC embedding on manufacture upgrading by using panel data of 18 sub-industries of China's manufacturing industry from 2000 to 2014. Before the regression test, the panel fixed-effects model (FE) and random-effects model (RE) are used to regress Eq. 8. The results of the Hausman test reject the original hypothesis at the level of 1%, so the econometric model adopts the fixed-effects model for regression. At the same time, to control the possible endogenous problems, by controlling the time fixed effect and sector fixed effect, the endogenous problem caused by missing variables is partially solved. The test results are shown in Table 4.

The regression of column (1) shows that when GVC forward participation is taken as the explanatory variable, its coefficient is 1.655, and the estimated value has passed the significance statistical test at the level of 5%. When other control variables are added to column (2), the result is 0.425, which is still significant at the same level, indicating that GVC forward participation of the manufacturing industry is conducive to the increase of DAV of export and plays a positive role in promoting the upgrading of the manufacturing industry, and the results of columns (3) and (4) also show that GVC backward participation plays a significant positive role in promoting DVA of exports; comparing the values of column (2) and column (4), it can be found that the coefficient of forward participation of 0.425 is greater than that of backward participation of 0.341, and the significant level is higher, indicating that forward participation is more conducive to obtaining trade benefits. The aforementioned two dimensions show that the division of labor embedded in the GVC is conducive to the improvement of DAV of China's manufacturing exports, and the manufacturing industry can obtain the increase of trade benefits by participating in the GVC.

On one hand, China imports intermediate products for assembly and processing. On the other hand, China also exports intermediate products for production by other countries. China's manufacturing industry is already in the hub of double circulation of the GVC. One circulation is the value chain between China and developed countries. China imports intermediate products for assembly and processing from developed countries, and the final products are exported to foreign markets. Another circulation is between China and developing countries. China exports intermediate products and imports final products; that is, China participates in the international division of labor in the way of forward and backward participation. The way of forward participation is that China exports intermediate products for use by other countries. There is more DAV contained in export

TABLE 3 Descriptive statistics of variables.

Variable	Definition	Obs	Mean	Std. dev.	Min	Max
lnDVA	Domestic value added	270	9.654	1.119	6.831	12.112
lnPA_f	GVC forward participation	270	−2.037	0.482	−3.523	−1.250
lnPA_b	GVC backward participation	270	−1.763	0.329	−2.667	−0.891
lnPO	GVC position index	270	1.081	0.238	0.569	1.489
lnK/L	Foreign direct investment	270	4.416	1.536	0.430	7.629
lnFDI	Industry capital intensity	270	15.227	0.186	14.765	15.466
lnPR	Labor productivity	270	4.215	0.753	2.828	6.595

Source: WIOD, RIGVC UIBE, and NBSC.

TABLE 4 Benchmark regression results.

Variable	(1)	(2)	(3)	(4)
lnPA_f	1.655** (0.461)	0.425** (0.122)		
lnPA_b			1.850** (0.593)	0.341* (0.147)
lnPO		0.690* (0.465)		1.190* (0.524)
Ln(K/L)		−0.036* (0.013)		−0.044** (0.015)
lnFDI		0.916*** (0.166)		1.110*** (0.187)
lnPR		1.225*** (0.127)		1.128*** (0.134)
_cons	13.02*** (0.939)	−9.175** (2.389)	12.92*** (1.045)	−12.49*** (2.667)
Time fixed effect	Yes	Yes	Yes	Yes
Sector fixed effect	Yes	Yes	Yes	Yes
N	270	270	270	270
R^2	0.160	0.944	0.127	0.939

The values in parentheses are standard errors, and ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. They are the same for the following tables.

intermediate products. Chinese products continue to be upgraded, technical content is higher and higher, and industrial products rise to the middle and high end of the value chain. Backward participation means that China participates in the division of labor characterized by processing trade. Although the added value at the enterprise level is not high, labor-intensive industries not only solve a large number of employment problems but also obtain large trade benefits in the process of "learning by doing," which is conducive to industrial upgrading. Compared with the two, forward participation is more conducive to upgrading, which is in line with the expectations of economic intuition and verifies theoretical hypothesis 1.

In the regression results of control variables, there is a positive relationship between DVA and the position of global value chain (PO) and labor productivity (PR). The significance test shows that enterprises in the upstream of the GVC and those with higher labor productivity gain higher trade benefits, while their export products contain more DAV. For example, enterprises engaged in design and R&D illustrate this. From the perspective of industry capital intensity (K/L), its coefficient is negative and significant, indicating that the industry capital intensity is high and it obtains less trade benefits. The possible reason is that too much fixed asset investment reduces the acquisition of trade benefits when exporting products. It is worth noting that the regression results of the impact of FDI on export DVA have passed the significance test at the level of 1%, indicating that FDI is an important factor to improve trade interests. It is an important force to promote the integration of China's manufacturing industry into GVC at the beginning of opening up. For example, foreign-funded enterprises represented by Foxconn make full use of China's cheap labor, invest in labor-intensive industries such as electronics and computers, place assembly and processing links in China, export finished products abroad, and integrate GVC in the way of backward participation. The processing trade once occupied half of China's trade, which promoted the rapid growth of China's manufacturing scale and the increase of trade interests. At the same time, relevant studies show that FDI is a "double-edged sword" with positive and negative effects, while stimulating economic growth, it also "captures" Chinese enterprises and lowers the position of GVC division of labor, which is not conducive to industry upgrade.

TABLE 5 Robustness test.

Variable	(1)	(2)	(3)	(4)
lnPA_f	0.542*** (0.125)		2.985* (1.121)	
lnPA_b		0.535** (0.136)		4.692*** (0.966)
lnPO	0.133 (0.398)	0.829 (0.453)	−0.595 (0.712)	−0.106 (0.479)
ln(K/L)	−0.0635*** (0.0151)	−0.0608** (0.0188)	−0.0336** (0.0115)	−0.0266* (0.0115)
lnFDI	1.358*** (0.208)	1.481*** (0.260)	1.142*** (0.172)	1.202*** (0.183)
lnPR	1.143*** (0.128)	1.048*** (0.143)	1.073*** (0.105)	0.862*** (0.120)
_cons	−14.61*** (2.874)	−17.02*** (3.586)	−13.64*** (2.610)	−15.82*** (2.776)
Time fixed effect	Yes	Yes	Yes	Yes
Sector fixed effect	Yes	Yes	Yes	Yes
Kleibergen–Paap rk LM statistic			53.516 [0.0000]	43.846 [0.0000]
Kleibergen–Paap rk Wald F statistic			526.145	2938.451
			{16.38}	{16.38}
N	252	252	270	270
R^2	0.946	0.941	0.942	0.948

Kleibergen–Paap rk LM is used to test the correlation between instrumental variables and endogenous variables. LM statistics and their *p*-values are reported. It is reasonable to reject the original hypothesis. Kleibergen–Paap rk Wald F is used to test whether the tool variable is of weak identification. It reports the F statistic and its critical value at the 10% level. It is reasonable to exceed the critical value.

5.3.2 Robustness test

To ensure reliability of the aforementioned test results, two methods are used for the robustness test. The first method is to overcome the potential endogeneity and prevent two-way causality between DVA and GVC participation; that is, DVA may also affect the degree of GVC embedded in the manufacturing industry. The lag period of GVC forward participation and GVC backward participation is introduced into the equation, the impact of the current period can be excluded to a certain extent, and the regression results are reported in columns (1) and (2) of Table 5; in the second method, VS and VS1 indicators proposed by Hummels are used as alternative indicators of GVC forward participation and GVC backward participation, and empirical results are reported in columns (3) and (4) of Table 5. It can be seen that the estimated coefficients of variables have passed the significance level test to different degrees, and the estimated symbols are consistent with the benchmark regression results, which further shows that the embedded GVC is conducive to the upgrading of the manufacturing industry. The result is robust.

5.4 Further analysis

5.4.1 Factor density heterogeneity analysis

To analyze the differences of trade benefits obtained by manufacturing industries with different factor intensities, (1) the C5~C9, C16, and C22 sectors in the WIOD are classified as labor-intensive manufacturing industries by referring to the division method by Xiang (2016), (2) C10~C15 sectors are classified as capital-intensive manufacturing, and (3) C17~C21 sectors are classified as technology-intensive manufacturing (Zheng and He, 2021). The impact of GVC embedding on manufacture upgrading is tested in groups. The regression results are shown in Table 6.

It can be seen from Table 6 that manufacturing industries with different factor intensities in the forward participation mode have a significant impact at the level of 10% and 5%, respectively. However, for manufacturing industries with different factor intensities in the way of backward participation, only the technology-intensive manufacturing industry is significant at the level of 10%; capital-intensive and labor-intensive industries are not significant, which means that compared with the processing and production of imported intermediate products, intermediate products are exported to obtain more trade benefits. The results of forward participation regression show that with the development of China's manufacturing industry and the continuous improvement of capital- and technology-intensive industries, the technical level of domestic complete machine products has reached an international advanced level and has a large production capacity. The empirical results show that by exporting to foreign countries, significant trade benefits can be obtained. The regression results with backward participation as the main explanatory variable show that China's traditional manufacturing industries, such as footwear and other labor-intensive industries, which are embedded in the GVC by means of processing trade, give full play to the advantage of cheap labor and widely participate in the GVC driven by foreign investment, but the trade benefits obtained from exports are not significant. The main reason is that such industries are at the low end of the GVC and their profits are as thin as a blade. They can only win by relying on scale and quantity advantages, such as handbags, clothing, and footwear produced by Chinese OEM, and high-value-added links such as brand, design, and marketing are in the hands of developed countries. Only by increasing technical content, refining labor-intensive industries, and shifting to the direction of R&D,

TABLE 6 Factor density heterogeneity analysis.

Variable	Labor intensive		Capital intensive		Technology intensive	
	(1)		(2)		(3)	
lnPA_f	0.499* (0.168)		0.414* (0.109)		0.528** (0.0946)	
lnPA_b		0.542 (0.237)		0.268 (0.294)		0.880* (0.280)
lnPO	1.227* (0.501)	1.472 (0.634)	2.439* (0.792)	3.044** (0.677)	0.776 (0.588)	1.729* (0.431)
lnK/L	−0.0192 (0.0113)	−0.0284* (0.00836)	−0.0286 (0.0195)	−0.0312 (0.0193)	−0.0224 (0.0237)	−0.0411 (0.0246)
lnFDI	0.672* (0.186)	0.731** (0.186)	0.827** (0.152)	1.030** (0.215)	0.826 (0.380)	0.890 (0.484)
lnPR	1.104*** (0.153)	1.157*** (0.0685)	1.026*** (0.101)	0.910*** (0.115)	1.639*** (0.164)	1.544*** (0.163)
_cons	−5.072 (2.573)	−6.378* (2.491)	−9.763** (1.871)	−13.38** (3.241)	−9.330 (5.434)	−10.42 (7.189)
Time fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Sector fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
N	105	105	90	90	75	75
R2	0.953	0.952	0.976	0.971	0.959	0.960

TABLE 7 Technology level heterogeneity analysis.

Variable	High tech (1)		Medium-to-high tech (2)		Low-to-medium tech (3)		Low tech (4)	
lnPA_f	2.082** (0.437)		0.359* (0.136)		0.515* (0.143)		0.594* (0.162)	
lnPA_b		2.101*** (0.185)		0.474* (0.181)		0.556* (0.188)		0.477 (0.259)
lnPO	0.753 (0.788)	2.104** (0.474)	0.814 (0.828)	1.447 (0.838)	3.489** (0.736)	4.154** (0.705)	1.551* (0.417)	1.476 (0.620)
lnK/L	0.0283 (0.0421)	−0.00365 (0.0217)	−0.0221 (0.0203)	−0.0342 (0.0172)	−0.0125 (0.0150)	−0.0174 (0.0179)	−0.0297* (0.0108)	−0.0344** (0.00758)
lnFDI	−0.0131 (0.467)	−0.0477 (0.134)	0.721 (0.462)	0.890 (0.414)	0.703* (0.153)	0.806** (0.104)	0.793** (0.139)	0.835** (0.148)
lnPR	1.467** (0.450)	1.775*** (0.140)	1.612*** (0.163)	1.522*** (0.130)	1.011*** (0.0974)	0.853*** (0.0888)	0.914*** (0.113)	1.091*** (0.0927)
_cons	7.074 (6.176)	4.465* (1.771)	−8.572 (7.217)	−11.27 (6.627)	−8.805* (2.113)	−10.49** (2.023)	−6.256* (2.007)	−7.821** (1.904)
Time fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sector fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	15	15	90	90	75	75	90	90
R^2	0.982	0.996	0.960	0.958	0.981	0.979	0.949	0.944

design, and brand marketing can more export added value be obtained.

5.4.2 Technology level heterogeneity analysis

The DVA of exports obtained by manufacturing sectors with different technical levels is also different. The following is a test of trade benefits obtained by manufacturing sectors with different technical levels. According to OECD technical classification standard, the manufacturing industry in WIOD is divided into four categories:(1) among them, the C17 sector is high-tech manufacturing;(2) C11, C12, and C18~C21 sectors are medium- and high-tech manufacturing; (3) C10 and C13~C15 sectors are medium- and low-tech manufacturing; and (4) C5~C9 and C22 sectors are low-tech manufacturing (Hong and Shang, 2019). The grouping regression test results are shown in Table 7.

As can be seen from Table 7, forward participation and backward participation have passed the significance test at the level of 5% and 1%, respectively, in high-tech industries, backward participation is not significant in low-tech industries, and others have passed the significance test at the level of 10%. Whether participating in GVC forward or backward, the higher the technical level, the more significant the regression result, indicating that the higher the technical level of the industry is, the more significant the participation in the GVC to obtain trade benefits. In particular, the backward participation mode of the high-tech industry is significant at the level of 1%, indicating that the “technology spillover” effect of participating in the GVC has brought obvious trade benefits to China, and hypothesis 2 has passed the test. China carries out the processing and assembly of low-end links by importing foreign advanced equipment and high-end technology and acquires new knowledge and skills through technology spillover, which can quickly achieve the upgrading of process flow and products; however, in high-end manufacturing fields such as precision instruments, CNC machine tools and electronic equipment, many key parts and core technologies are still in the hands of developed countries. When China plans to enter the field of “core and commanding heights,” it will challenge the vested interests of developed countries and encounter the dilemma of blockade and capture, and only by strengthening R&D and independent innovation can China break through the dilemma of “low-end locking.”

6 Conclusion and recommendations

By using the panel data of China’s manufacturing industry from 2000 to 2014 in WIOD, this paper calculates the degree of China’s manufacturing industry embedded in the GVC and empirically tests the impact of GVC embedding on the upgrading of the manufacturing industry. The results show that 1) China’s manufacturing industry mainly embeds the GVC in the way of backward participation, which is manifested in the processing trade of imported intermediate products. 2) Embedding GVC is conducive to obtaining trade benefits and upgrading the Chinese manufacturing industry. 3) Capital-intensive industries, technology-intensive industries, and high-tech industries gain significant trade benefits, and embedding the GVC is more conducive to upgrading.

The aforementioned research conclusions have important policy implications for further research on the upgrading of China’s manufacturing industry and achieving high-quality development. In recent years, trade frictions provoked by the United States and the impact of COVID-19 have intensified trade protectionism (Timmer et al., 2016). Under the domestic and foreign dual pressure, it becomes more urgent for China’s manufacturing industry to upgrade. In the context of building a new development pattern of domestic and international double circulation, the experience of integrating into the GVC shows that under the new development pattern, it is necessary to further expand opening up and integrate with the world at a higher level. For example, the signing of RCEP has laid a good foundation for high-level opening up of regional members, and it will promote export growth and the digital transformation and upgrading of China’s manufacturing industry (Xiang, 2016). In view of this, this paper puts forward the following suggestions: first, we should continue to integrate into the GVC, constantly optimize the trade structure, and cultivate new competitive advantages of enterprises in the international markets. The integration of the GVC is a successful experience in the upgrading of the Chinese manufacturing industry. In the future, China needs to continue to open up from a high starting point, siphon foreign advanced production factors into a high-quality business environment, actively undertake high-tech production links with multinational companies, and promote industrial upgrading with the help of technology spillover effects. Second, we should vigorously promote transformation of enterprises toward digitalization, cultivate advanced manufacturing industry clusters, build a new value chain dominated by domestic demand, and drive domestic to climb to the middle and high end of GVC. For example, China’s high-speed rail industry chain has driven supporting industries to expand to foreign markets under domestic market effect, and it promoted the dynamic transformation from a GVC to a global innovation chain. Third, we should formulate upgrading strategies according to the classification of manufacturing industries and encourage and guide foreign capital to invest more in high-tech industries. Traditional labor-intensive manufacturing products need to improve their technological content, strengthen brand building, and upgrade to labor-intensive links in high-tech industrial chains. We also need to cultivate internal motivation for independent innovation of high-tech enterprises, break through external dependence on core technologies and key components, reduce dependence on foreign high-tech products, and strive to become the main body of the global innovation chain.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

QF: writing–original draft and writing–review and editing.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Coordination contracts and numerical analysis of low-carbon competitive supply chains under the influence of low-carbon goodwill

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Introduction: Under the dual opportunities of low-carbon consumption preference and online consumption platforms, vendors' low-carbon advertising incursions provide opportunities for decarbonization and market position enhancement, as well as further research on the value of low-carbon advertising. This study aims to explore the contractual choices of green vendors' online channels participating in low-carbon advertising competition under the low-carbon goodwill effect, and to simulate and evaluate the contractual choices of supply chain members.

Methods: Using differential games, through the innovative application of the traditional low-carbon goodwill model and the introduction of the low-carbon advertising competition intensity coefficient, we design one-way and two-way cost-sharing contracts under low-carbon competition, coordinate the vicious competition in the supply chain, and provide contractual choices for supply chain participants.

Results and discussion: Under the low-carbon advertising competition decision, the manufacturer has an absolute low-carbon market advantage, but the interests of all supply chain members are weakened, and interestingly, the manufacturer, who dominates the market, is the facilitator of the contractual agreement. Second, well-designed pacts can provide manufacturers and traders with more options for low-carbon strategies. Although both one-way and two-way cost-sharing pacts can generate Pareto gains for the supply chain and its members in advertising competition, two-way cost-sharing pacts are superior to one-way pacts in terms of coordination advantages. In addition, an important finding is that greater profit growth can be achieved through contractual cooperation in low-intensity advertising competition. Thus, moderate competition is desirable, while excessive competition can harm the supply chain system. Manufacturers should actively urge retailers to cooperate in order to optimize profits and establish long-term stable partnerships between upstream and downstream firms in green supply chains.

KEYWORDS
green manufacturers, low-carbon goodwill, low-carbon advertising competition, contractual option, differential game

1 Introduction

The year 2022 marks the 50th anniversary of the United Nations Environment Programme (UNEP), which recognizes that current global low-carbon efforts face enormous challenges and that more needs to be achieved by all countries (United Nations Environment Programme, 2022; Yang et al., 2023). At the Stockholm+50 conference in 2022, hundreds of speakers encouraged governments to make serious commitments to global environmental issues (Willetts, 2022). Serious global climate issues are also affecting people's consumer choices, and in 2021, Euromonitor published a report on the "Top 10 Global Consumer Trends," showing that approximately 65% of consumers worldwide are concerned about "climate change" and are placing greater emphasis on environmentally friendly actions (Yi et al., 2022). A large number of enterprises have joined the ranks of low-carbon emission reduction, focusing on low-carbon transformation, helping brands upgrade their green industrial chain and seize the dominant position in green and low-carbon development (Roh et al., 2022). Meanwhile, affected by COVID-19, global e-commerce sales are expected to increase by 38% year-on-year in 2019–2020. Due to the impact of the epidemic on consumption patterns, consumers are gradually shifting from offline consumption to online marketing channels.

Consumers' climate awareness and the impact of the pneumonia epidemic have directly prompted green supply chain enterprises to implement targeted measures (Sarti et al., 2018; Camilleri et al., 2019). Many enterprises and supply chain members have focused on low-carbon transformation to help brands upgrade their green industry chain and seize the first opportunity for green and low-carbon development. For example, IKEA launched its global sustainability strategy "Benefit People, Benefit the Planet" in 2012 and continues to prioritize the harmonious development of people and the environment under this policy. In 2022, Kao ESG released the Kao (China) ESG Vision: Kao (China) ESG Vision: "Walking with Beauty, Living with the Environment." Kao (China) ESG Vision: "Living with Beauty."

Typically, supply chain partners steadily increase their goods' low-carbon goodwill through manufacturing and marketing campaigns to promote customers' purchase behavior (Ghosh and Shah, 2015; Hong and Guo, 2019). Clearly, realizing a low-carbon green supply chain is dependent not only on the degree of decarbonization at the production end but also on the amount of decarbonization at the consuming end. It is a highly plausible scenario for green manufacturers to use direct marketing channels for low-carbon marketing in low-carbon supply chain practices to boost their goods' low-carbon goodwill and market competitiveness.

As a result, whether manufacturers choose to enter the low-carbon advertising competition market is advantageous to them, whether it is conducive to increasing brand low-carbon goodwill, and whether the supply chain under low-carbon competition has the best choice of low-carbon contract have become important issues. Therefore, studying the low-carbon channel advertising competition scenarios of green producers and retailers in the context of a low-carbon economy is critical. The purpose of this research is to analyze the best contractual options and run simulations in the competitive supply chain of low-carbon advertising penetrated by green manufacturers' internet direct marketing channels.

Four models were designed in this study with the aim of answering the following questions:

(1) How do the low-carbon goodwill and low-carbon emission reduction characteristics of green manufacturers change in low-carbon advertising competition between green manufacturers and retailers?
(2) How does the intensity of low-carbon advertising competition affect supply chain members' market demand and supply chain optimization decisions?
(3) Who are the supply chain members with market advantages in low-carbon advertising competition?
(4) Can uni- and bi-directional cost-sharing contracts achieve Pareto improvement or optimization in supply chain coordination under low-carbon advertising competition? Who benefits more as a supply chain member under the contractual co-ordination model? Which coordination contract strategy will supply chain members choose in competition?

Finally, the remainder of the paper is organized as follows: a review of related literature and relevant hypotheses and symbol interpretation are given in Section 2; modeling of supply chain decision-making results under the centralized and decentralized modes of low-carbon advertisement competition is given in Section 3; designing uni- and bi-directional cost-sharing contracts for coordinating vicious competition in the supply chain is discussed in Section 4; simulation analysis for validation is given in Section 5; and finally, some conclusions are drawn in Section 6.

2 Literature review

The relevant literature covers three aspects: the application of low-carbon goodwill, advertising competition in the supply chain, and low-carbon advertising coordination strategies.

2.1 The application of low-carbon goodwill

Consumers define the low-carbon behaviors of supply chain members as low-carbon supply chains are deployed, which will affect their low-carbon purchasing habits. Among these, brand goodwill has the greatest influence on customer behavior. Goodwill was initially presented as a new supply chain tool, culminating in the renowned Nerlove–Arrow model of advertising investment, in which Nerlove and Arrow asserted that advertising is a direct way of promoting goodwill (Nerlove and Arrow, 1962). The traditional goodwill model is still employed in multifactor dynamic variable modeling in supply chain studies. In current research, the typical goodwill model is conducted as a state variable to investigate the impact of consumers' low-carbon preferences on revenue in a low-carbon supply chain, with the goodwill model primarily consisting of two dynamic variables: manufacturers' low-carbon emission reduction efforts and retailers' low-carbon advertising efforts (Zhou and Ye, 2018;

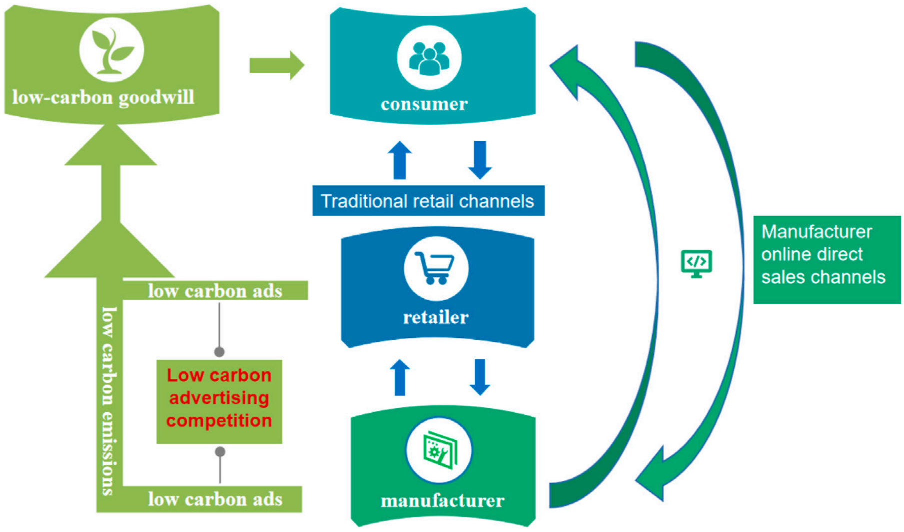

FIGURE 1
Supply chain system description.

TABLE 1 Relevant parameter symbols.

Meaning	Parameter
Influence coefficient of low-carbon advertising on market demand	τ
Low-carbon advertising competition intensity	s
Retail price	p
Wholesale price	w
Manufacturer's emission reduction investment	n(t)
Manufacturer's low-carbon advertising investment	am(t)
Retailer's low-carbon advertising investment	ar(t)
Low-carbon emission reduction level	x(t)
Low-carbon goodwill	g(t)
Profit of the supply chain system	J_S
Manufacturer's profit	J_m
Retailer's profit	J_r
Manufacturer's low-carbon cost	C_m
Retailer's low-carbon cost	C_r
Manufacturer's market demand	$d_m(t)$
Retailer's market demand	$d_r(t)$

Kang et al., 2019; Liu and Xu, 2022). There are numerous other applications for goodwill modeling; for example, Liang and Li. (2020) and Zhang et al. (2021) developed a low-carbon goodwill model for multiple retailers' low-carbon advertising efforts in a dual-channel study to consider the effects of consumer reference to low-carbon effects and product low-carbon goodwill on purchases in a dual-channel supply chain. Furthermore, scholars have used low-carbon goodwill to low-carbon tourist supply networks, such as presenting low-carbon goodwill during crisis situations and utilizing big data to investigate the long-term operation of low-carbon tourism supply chains (Ma et al., 2020; Zhang et al., 2021). Furthermore, goodwill models are utilized to describe risk contingency production efforts in supply chain risk contingency research (Wu et al., 2022a). However, in this work, we will improve the classical goodwill model based on the manufacturer's low-carbon advertising competition context.

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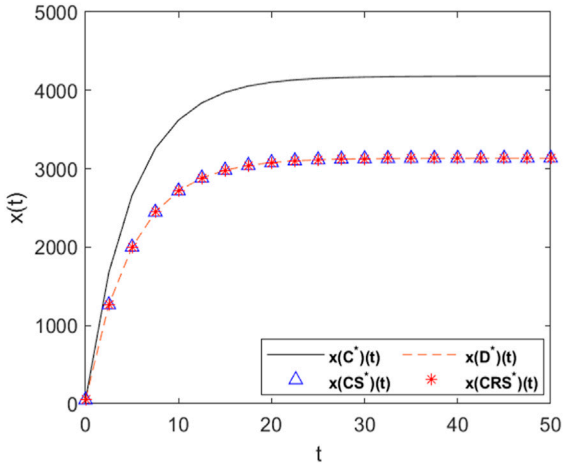

FIGURE 2
Variation in the low-carbon emission reduction level over time.

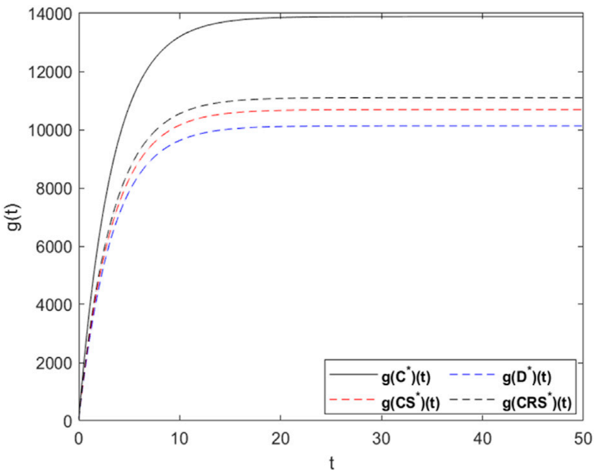

FIGURE 3
Variation in low-carbon goodwill over time.

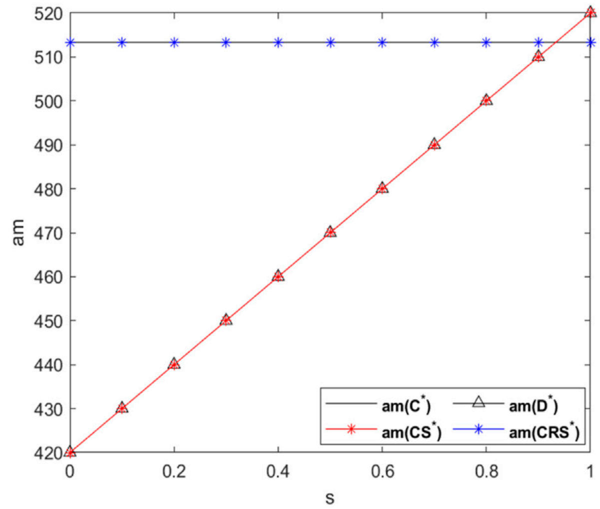

FIGURE 4
Influence of s on manufacturer's low-carbon advertising investment.

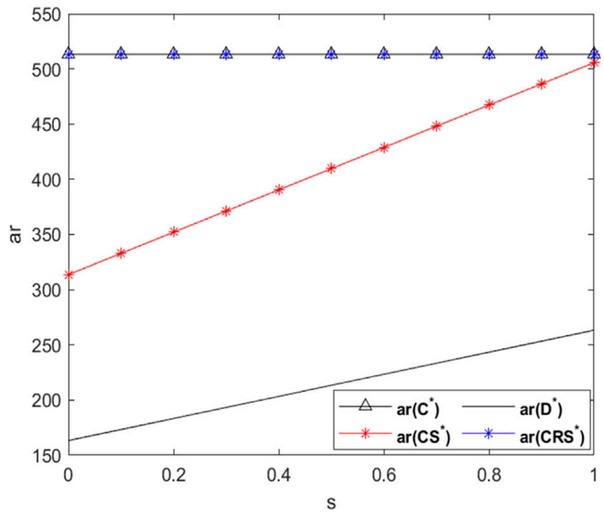

FIGURE 5
Influence of s on retailer's low-carbon advertising investment.

2.2 Advertising competition in the supply chain

In supply chain advertising competition, more research has been conducted on advertising competition between manufacturers and between retailers; for example, Zhang et al. (2020) found that advertising competition between manufacturers may be more beneficial than price competition between retailers for the same product. Chang et al. (2021) and Zhong et al. (2022) considered advertising competition between retailers and examined how retailers should choose control strategies to gain an advantage in competition. Unusually, Wu et al. (2022b) argued that the manufacturer can act as a coordinator between two competing retailers to facilitate the marketing efforts of both. A small number of scholars have also studied the issue of advertising competition between manufacturers and retailers; for example, Karray and Herran., (2021) studied the retailer's shop brand competing with the manufacturer's national brand. Karle et al. (2020) studied the competitive marketplace between third-party platforms and retailers. Zhang et al. (2021) studied the strategic interaction between the manufacturer's brand advertising infringement and the retailer's introduction of PSB and SB.

2.3 Low-carbon advertising coordination strategies

Advertising cooperation is an important tool for coordinating manufacturers' and retailers' decisions. Berger (1973) first defined

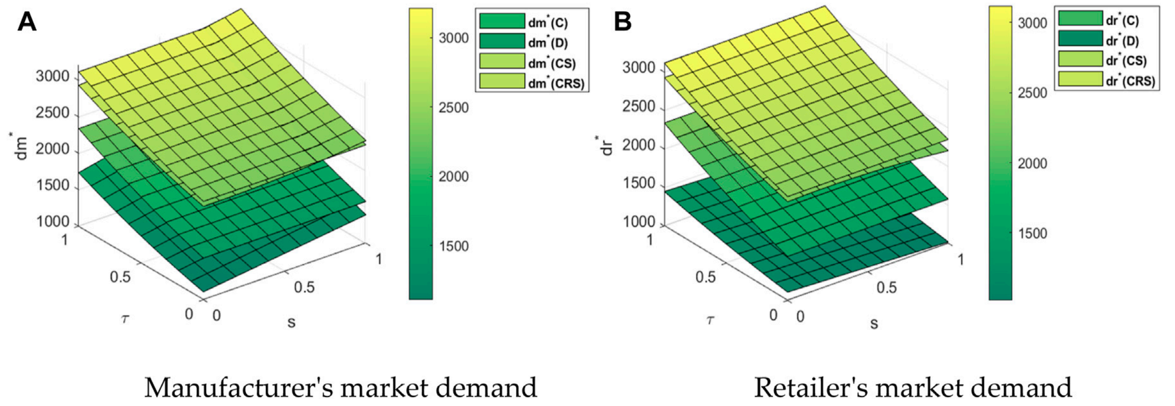

FIGURE 6
Comparison of market demand under four models of low-carbon competition. **(A)** Manufacturer's market demand. **(B)** Retailer's market demand.

an advertising cooperation model with the participation rate as a manufacturer's decision variable. Zhou et al. (2016), Chutani and Sethi, (2018), Yu et al. (2020), and Sarkar et al. (2020) investigated manufacturers' and retailers' dynamic collaborative advertising decisions to optimize low-carbon supply chain management and improve supply chain performance by providing retailers with different levels of advertising support. Xiao et al. (2019) and Xiang and Xu, (2019) studied advertising coordination strategies in a dual-channel supply chain. He et al. (2020) considered three low-carbon suppliers and integrators in the context of corporate social responsibility and three low-carbon cost-sharing strategies for cooperation. Huang (2023) studied low-carbon advertising cooperation strategies between a manufacturer and two retailers, demonstrating the impact of joint promotion on emission reduction and performance.

According to the examination of literature, the creation of low-carbon supply chains has attracted wide attention from researchers both at home and abroad, and research in this area has yielded rich results that are of significant guiding value to company practice. However, with the ongoing growth of the low-carbon supply chain, there are still many gaps, and this paper intends to start from the following points:

(1) From the literature combing, it is found that few scholars have considered the participation of manufacturers' direct sales channels in low-carbon advertising competition, ignoring the positioning of manufacturers' roles in low-carbon supply chains; second, for the composition of low-carbon goodwill, the low-carbon goodwill model under the low-carbon advertisement competition between manufacturers and retailers can be expanded and innovated on the basis of the traditional goodwill model. Therefore, this paper considers the aforementioned two cases at the same time and explores the changing characteristics of low-carbon goodwill and low-carbon emission reduction level under low-carbon advertising competition as well as the coordination contract under low-carbon competition.
(2) In terms of the supply chain contract strategy, while some scholars have conducted study on the cooperation of low-carbon supply chain members, the majority of the scholars have not studied the coordination contract in the context of low-carbon competitiveness. Second, the majority of the compacts are single cost-sharing compacts for low-carbon emission reduction and low-carbon advertisement; however, research on the feasibility of considering bi-directional cost-sharing compacts under low-carbon advertisement competition is insufficient. Therefore, the proposal of this contract stands in a new theoretical perspective and realistic situation perspective.

Therefore, this paper explores the coordination contract of manufacturer's invasion of low-carbon advertising campaigns under the influence of low-carbon goodwill and extends the traditional low-carbon goodwill model to reflect manufacturer's low-carbon participation; second, the low-carbon advertising competition between manufacturers and retailers is taken into account in the establishment of the market demand model, and the low-carbon advertising competition intensity coefficient is introduced. We explore the equilibrium strategy of supply chain members in the competitive situation, investigate the coordination mechanism of advertising competition and cooperation contract, and try to realize a breakthrough in both theoretical innovation and practical applications.

3 Underlying models and assumptions

3.1 Problem assumptions and symbol descriptions

This paper investigates a supply chain system consisting of a manufacturer and a traditional retailer with dual online and offline channels. In the context of the global low-carbon goal, the manufacturer carries out low-carbon production and sells through both the traditional retail channel and the online direct sales channel. During the production process, manufacturers engage in low-carbon emission reduction activities; during the sales process, manufacturers and retailers engage in low-carbon advertising, and there is a competitive relationship between the two in terms of low-

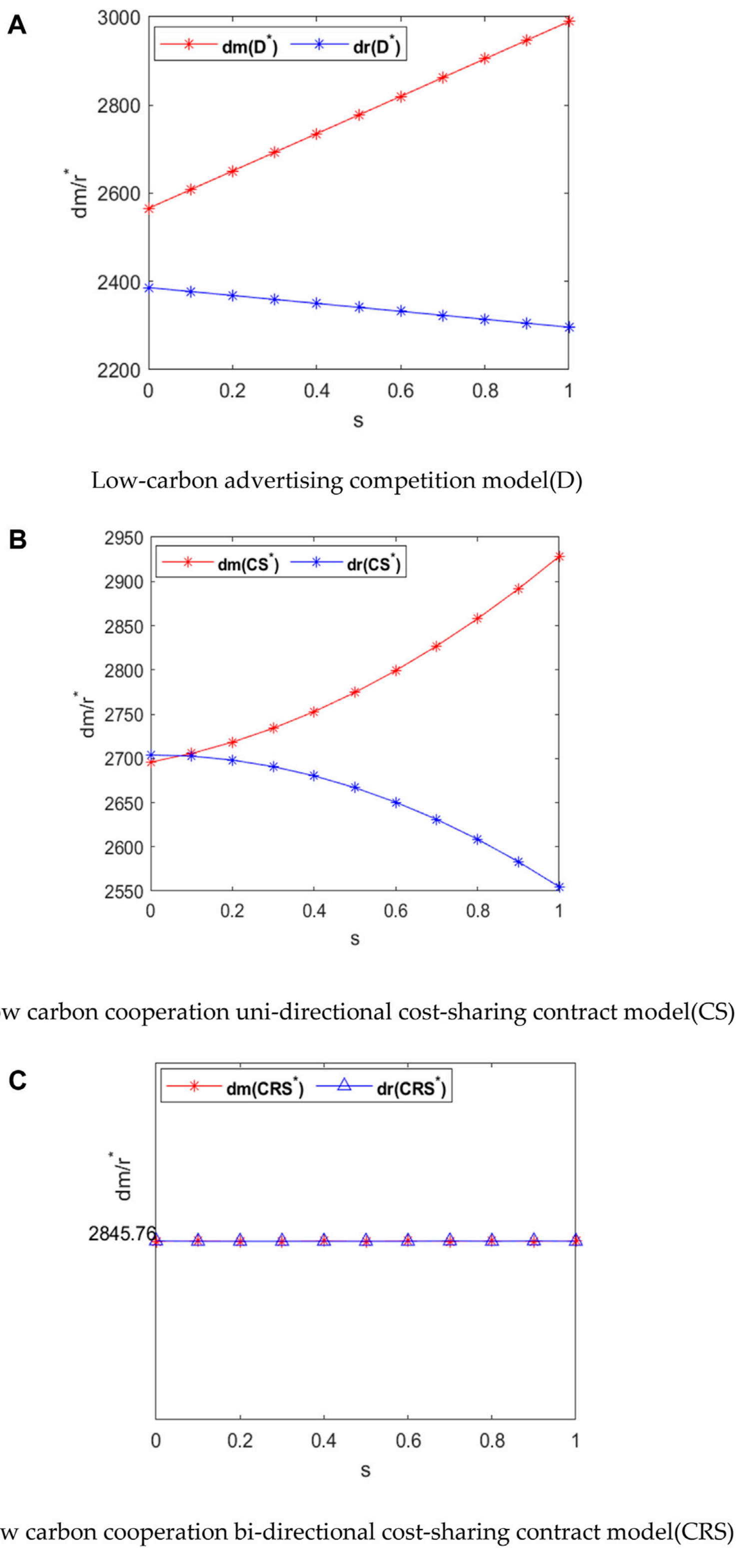

FIGURE 7
Changes in market demand under low-carbon advertising competition. **(A)** Low-carbon advertising competition model (D). **(B)** Low-carbon cooperation uni-directional cost-sharing contract model (CS). **(C)** Low-carbon cooperation bi-directional cost-sharing contract model (CRS).

carbon advertising. As a result, the level of low-carbon goodwill of a product is conferred by the manufacturer's low-carbon emission-reducing production in the production process and the manufacturer's and retailer's low-carbon advertising campaigns in the sales process. The underlying model analysis in this section includes a centralized approach without competition

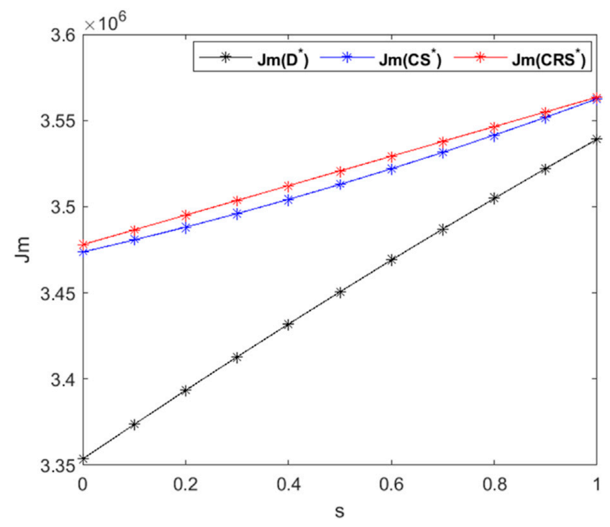

FIGURE 8
Comparison of the manufacturer's profit under contract and competition modes.

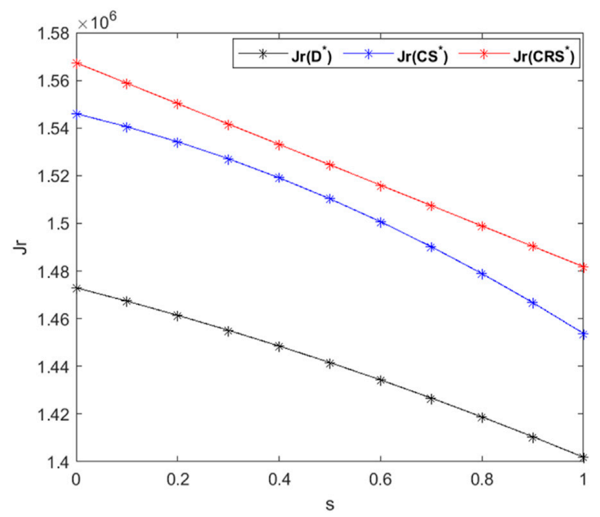

FIGURE 9
Comparison of the retailer's profit under contract and competition modes.

(denoted by superscript C) and a decentralized approach with low-carbon competition (denoted by superscript D). The supply chain system is shown in Figure 1. The main symbols are explained as shown in Table 1.

Assumption 1. In the low-carbon emission reduction production chain, the level of emission reduction achieved by the manufacturer is determined by their investment in emission reduction technology in their manufacturing processes. However, as equipment ages and technology is updated, emission reduction technology will deteriorate. As a result, the dynamic change process of the product's low-carbon emission reduction level in this paper is as follows, referring to the Zhou and Ye (2018) model of product's low-carbon emission reduction level:

$$\dot{x}(t) = \alpha n(t) - \beta x(t), \tag{1}$$

where $x(0) = x_0$; α is the impact coefficient of low-carbon emission reduction input on the low-carbon emission reduction level, α> 0; and β is the natural attenuation rate of the low-carbon emission reduction level, β > 0.

Assumption 2. In addition to the conventional goodwill model based on Nerlove-Arrow (1962), this article refers to the competitive goodwill model of He et al. (2021). Based on the case of the manufacturer's direct sales channel advertising intrusion in this paper, it is defined that the low-carbon goodwill model of this paper consists of the manufacturer's and retailer's low-carbon advertising inputs as well as the manufacturer's level of low-carbon emission reduction together, and the process of the low-carbon goodwill change in this paper is as follows:

$$\dot{g}(t) = \sigma[a_m(t) + a_r(t)] + \theta x(t) - \varepsilon g(t), \tag{2}$$

where $g(0) = g_0$; σ is the impact coefficient of low-carbon advertising investment on low-carbon goodwill; θ is the impact coefficient of the low-carbon emission reduction level on low-carbon goodwill; and ε is the natural decay rate of low-carbon goodwill.

Assumption 3. Referring to Prasad and Sethi (2004) and Zaccour (2008) cost function models, the low-carbon cost of supply chain members is a quadratic function of emission reduction and advertising inputs. Furthermore, in accordance with Giovanni's (2010) study, the manufacturing and retailing costs are normalized to zero to simplify the modeling. In this paper, the low-carbon cost function of supply chain members is expressed as follows:

$$C_m = \frac{1}{2}\kappa_1 n^2(t) + \frac{1}{2}\kappa_2 a_m^2(t), \tag{3}$$

$$C_r = \frac{1}{2}\kappa_3 a_r^2(t), \tag{4}$$

where κ_1, κ_2, and κ_3, respectively, represent the manufacturer's low-carbon emission reduction input cost coefficient, low-carbon advertising input coefficient, and retailer's low-carbon advertising input coefficient, $\kappa_1 > 0, \kappa_2 > 0, \kappa_3 > 0$.

Assumption 4. Referring to Kopalle and Winer (1996), the demand function for low-carbon products is a linear function. In addition, with reference to Chen et al. (2017) and Martín-Herrán and Sigue (2017), pricing is carried out without considering the effect of price changes and assuming that manufacturers adopt a uniform pricing strategy. The prices of both direct sales and traditional retail channels of manufacturers are p. Based on the aforementioned assumptions, the demand function in this paper is as follows:

$$d_m(t) = b_1 + \eta x(t) + \gamma g(t) + s[a_m(t) - a_r(t)] + \tau a_m(t), \tag{5}$$

$$d_r(t) = b_2 + \eta x(t) + \gamma g(t) + s[a_r(t) - a_m(t)] + \tau a_r(t), \tag{6}$$

where η is the impact coefficient of the emission reduction level on market demand, $\eta > 0$; γ is the impact coefficient of low-carbon goodwill

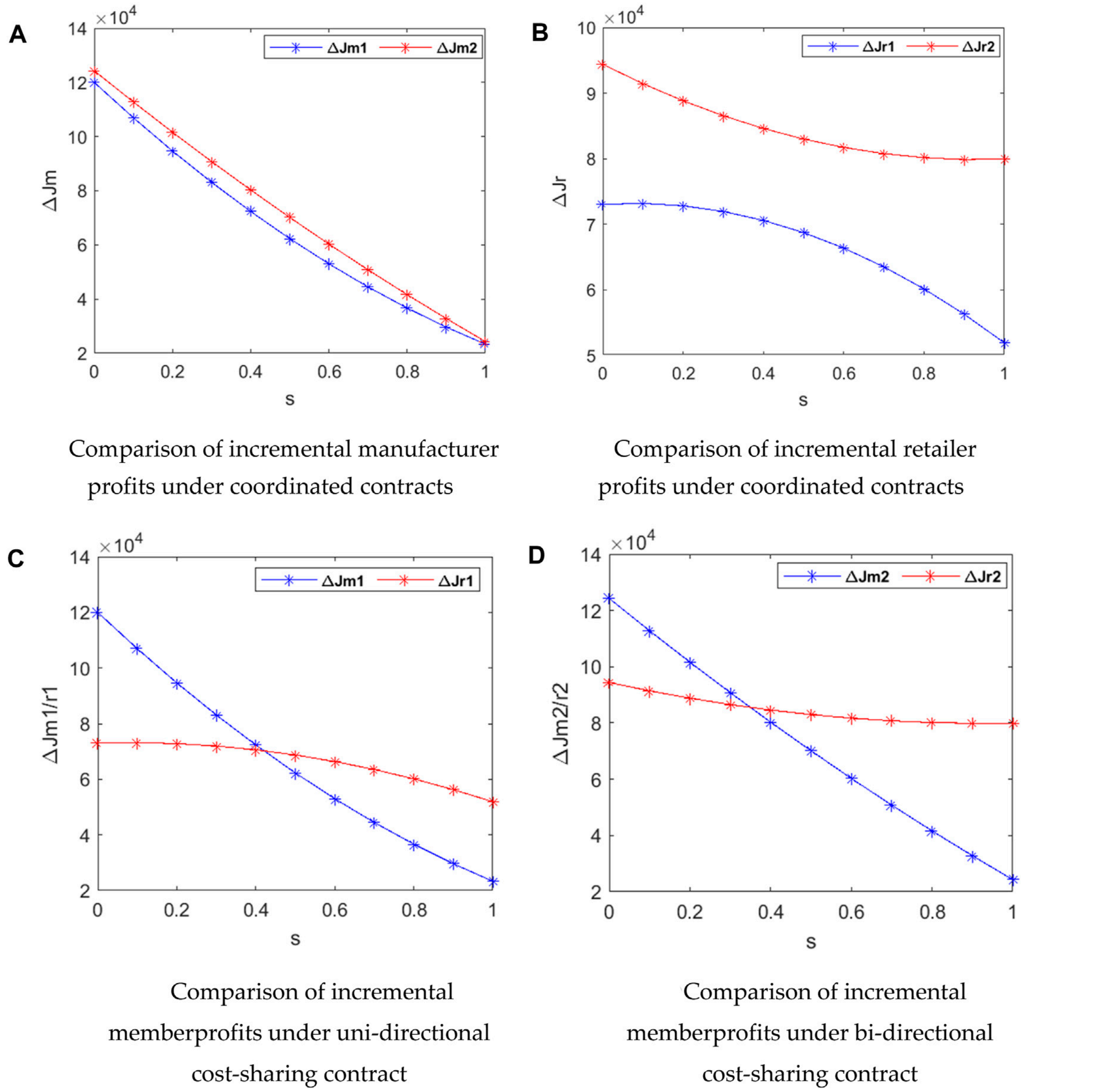

FIGURE 10
Comparison of profit increments of supply chain members under two coordination contracts. **(A)** Comparison of incremental manufacturer profits under coordinated contracts. **(B)** Comparison of incremental retailer profits under coordinated contracts. **(C)** Comparison of incremental member profits under uni-directional cost-sharing contracts. **(D)** Comparison of incremental member profits under bi-directional cost-sharing contracts.

on market demand, $\gamma > 0$; s is the competition intensity coefficient of low-carbon advertising between the manufacturer and retailer, $s > 0$; τ is the impact coefficient of low-carbon advertising on market demand, $\tau > 0$; and b_1 and b_2 are, respectively, the potential inherent market demand of direct sales channels and traditional retail channels.

Assumption 5. In an unlimited time range, manufacturers and retailers present the same discount rate ρ,$\rho > 0$. The objective function of manufacturers and retailers indicates that the goal of manufacturers and retailers is to maximize profits in an infinite time interval. The long-term profit function expression of manufacturers, retailers, and supply chain systems are as follows:

$$J_m = \int_0^\infty e^{-\rho t}\left[p d_m(t) + w d_r(t) - \frac{1}{2}\kappa_1 n^2(t) - \frac{1}{2}\kappa_2 a_m^2(t)\right]dt, \tag{7}$$

$$J_r = \int_0^\infty e^{-\rho t}\left[(p - w) d_r(t) - \frac{1}{2}\kappa_3 {a_r}^2(t)\right]dt, \tag{8}$$

$$J_s = \int_0^\infty e^{-\rho t}\left[p(d_m(t) + d_r(t)) - \frac{1}{2}\kappa_1 n^2(t) - \frac{1}{2}\kappa_2 a_m^2(t) - \frac{1}{2}\kappa_3 a_2^r(t)\right]dt. \tag{9}$$

3.2 Centralized decision model (C)

In the centralized decision model, the manufacturer and retailer make decisions with the objective of maximizing the profit of the supply chain. Therefore, the objective function of the low-carbon supply chain system in centralized decision-making is as follows:

$$J_s^C\left(g^C(t), x^C(t)\right) = \max_{n^C, a_m^C, a_r^C} \int_0^\infty e^{-\rho t}\left[p\left(d_m^C + d_r^C\right)\right) - \frac{1}{2}\kappa_1 n^{C^2} - \frac{1}{2}\kappa_2 a_m^{c^2} - \frac{1}{2}\kappa_3 a_r^{c^2}\Big)\Big] dt. \tag{10}$$

Proposition 1. The equilibrium results of the differential game under the centralized decision-making model are as follows:

$$\begin{cases} n^{C*} = \dfrac{2\alpha p[\eta(\rho+\varepsilon)+\theta\gamma]}{\kappa_1(\rho+\varepsilon)(\rho+\beta)} \\ a_m^{C*} = \dfrac{p\tau(\rho+\varepsilon)+2p\sigma\gamma}{\kappa_2(\rho+\varepsilon)} \\ a_r^{C*} = \dfrac{p\tau(\rho+\varepsilon)+2p\sigma\gamma}{\kappa_3(\rho+\varepsilon)}, \end{cases} \tag{11}$$

$$\begin{cases} x^{C*}(t) = x_\infty^{C*} + (x_0 - x_\infty^{C*})e^{-\beta t} \\ g^{C*}(t) = g_\infty^{C*} + (g_0 - g_\infty^{C*})e^{-\varepsilon t}, \end{cases} \tag{12}$$

$$\begin{cases} x_\infty^{C*} = \dfrac{2\alpha^2 p[\eta(\rho+\varepsilon)+\theta\gamma]}{\beta\kappa_1(\rho+\varepsilon)(\rho+\beta)} \\ g_\infty^{C*} = \dfrac{\sigma p\tau(\rho+\varepsilon)+2p\sigma^2\gamma}{\varepsilon\kappa_2(\rho+\varepsilon)} + \dfrac{\sigma p\tau(\rho+\varepsilon)+2p\sigma^2\gamma}{\varepsilon\kappa_3(\rho+\varepsilon)} \\ \qquad + \dfrac{2\theta\alpha^2 p[\eta(\rho+\varepsilon)+\theta\gamma]}{\varepsilon\beta\kappa_1(\rho+\varepsilon)(\rho+\beta)}, \end{cases} \tag{13}$$

$$J_s^{C*} = \frac{p[b_1+b_2+\tau(a_m^{C*}+a_r^{C*})]}{\rho} + \frac{2\eta C_1 p}{\rho+\beta} + \frac{2\eta x_\infty^{C*} p}{\rho} + \frac{2\gamma C_2 p}{\rho+\varepsilon} + \frac{2\gamma g_\infty^{C*} p}{\rho} - \frac{\kappa_1 n^{C*^2}}{2\rho} - \frac{\kappa_2 a_m^{C*^2}}{2\rho} - \frac{\kappa_3 a_r^{C*^2}}{2\rho}, \tag{14}$$

where $C_1 = x_0 - x_\infty^{C*}, C_2 = g_0 - g_\infty^{C*}$.

Corollary 1.

$$\frac{\partial n^{C*}}{\partial \eta} > 0, \frac{\partial n^{C*}}{\partial \gamma} > 0, \frac{\partial n^{C*}}{\partial \alpha} > 0, \frac{\partial n^{C*}}{\partial \beta} < 0, \frac{\partial n^{C*}}{\partial \kappa_1} < 0; \frac{\partial a_m^{C*}}{\partial \tau} > 0, \frac{\partial a_m^{C*}}{\partial \gamma} > 0, \frac{\partial a_m^{C*}}{\partial \sigma} > 0, \frac{\partial a_m^{C*}}{\partial \kappa_2} < 0;$$
$$\frac{\partial a_r^{C*}}{\partial \tau} > 0, \frac{\partial a_r^{C*}}{\partial \gamma} > 0, \frac{\partial a_r^{C*}}{\partial \sigma} > 0, \frac{\partial a_r^{C*}}{\partial \kappa_3} < 0.$$

Corollary 1 suggests that when consumers have higher brand preferences (γ), supply chain c members will invest more in emission reduction and advertising. Meanwhile, consumers' low-carbon preference (η) has a positive effect on emission reduction investment, but manufacturers' and retailers' advertising investment does not depend on this factor, including price (p) and the coefficient of the impact of low-carbon advertising on goodwill and market demand (σ, τ). In addition, the recession rate β, discount factor ρ, and cost parameters κ_1, κ_2, andκ_3 have a negative effect on the corresponding low-carbon efforts.

3.3 Low-carbon advertising competition model (D)

Under the centralized decision model, it is difficult for members in the actual supply chain system to reach a unanimous goal, and low-carbon competition among members is common; thus, in the low-carbon advertising competition decision, both manufacturers and retailers take their own interests as decision goals. Manufacturers and retailers are on equal footing under this ruling, and they play a Nash differential game. The game sequence is such that both the manufacturer and the store set their own choice variables in order to maximize their own earnings. Then, under the decentralized decision of competition without contract, the goal function is as follows:

$$\begin{cases} J_m^D\left(g^D(t), x^D(t)\right) = \max\limits_{n^D, a_m^D} \int_0^\infty e^{-\rho t}\left[pd_m^D + wd_r^D\right) - \frac{1}{2}\kappa_1 n^{D^2} - \frac{1}{2}\kappa_2 a_m^{D^2}\Big] dt \\ J_r^D\left(g^D(t), x^D(t)\right) = \max\limits_{a_r^D} \int_0^\infty e^{-\rho t}\left[(p-w)d_r^D\right) - \frac{1}{2}\kappa_3 a_r^{D^2}\Big] dt. \end{cases} \tag{15}$$

Proposition 2. The equilibrium results of the differential game under the low-carbon advertising competition model are as follows:

$$\begin{cases} n^{D*} = \dfrac{\alpha(p+w)[\eta(\rho+\varepsilon)+\theta\gamma]}{k_1(\rho+\varepsilon)(\rho+\beta)} \\ a_m^{D*} = \dfrac{(\rho+\varepsilon)[p(s+\tau)-ws]+(p+w)\sigma\gamma}{k_2(\rho+\varepsilon)} \\ a_r^{D*} = \dfrac{(p-w)[(\rho+\varepsilon)(s+\tau)+\sigma\gamma]}{k_3(\rho+\varepsilon)}, \end{cases} \tag{16}$$

$$\begin{cases} x^{D*}(t) = x_\infty^{D*} + (x_0 - x_\infty^{D*})e^{-\beta t} \\ g^{D*}(t) = g_\infty^{D*} + (g_0 - g_\infty^{D*})e^{-\varepsilon t} \end{cases} \tag{17}$$

$$\begin{cases} x_\infty^{D*} = \dfrac{\alpha^2(p+w)[\eta(\rho+\varepsilon)+\theta\gamma]}{\beta\kappa_1(\rho+\varepsilon)(\rho+\beta)} \\ g_\infty^{D*} = \dfrac{\sigma(\rho+\varepsilon)[p(s+\tau)-ws]+(p+w)\sigma^2\gamma}{\varepsilon\kappa_2(\rho+\varepsilon)} \\ \qquad + \dfrac{\sigma(p-w)[(\rho+\varepsilon)(s+\tau)+\sigma\gamma]}{\varepsilon\kappa_3(\rho+\varepsilon)} \\ \qquad + \dfrac{\alpha^2\theta(p+w)[\eta(\rho+\varepsilon)+\theta\gamma]}{\varepsilon\beta\kappa_1(\rho+\varepsilon)(\rho+\beta)}, \end{cases} \tag{18}$$

$$\begin{cases} J_m^{D*} = \dfrac{pb_1+wb_2}{\rho} + \dfrac{p[s(a_m^{D*}-a_r^{D*})+\tau a_m^{D*}]}{\rho} + \dfrac{w[s(a_r^{D*}-a_m^{D*})+\tau a_r^{D*}]}{\rho} + \dfrac{\eta D_1(p+w)}{\rho+\beta} \\ \qquad + \dfrac{\eta x_\infty^{D*}(p+w)}{\rho} + \dfrac{\gamma D_2(p+w)}{\rho+\varepsilon} + \dfrac{\gamma g_\infty^{D*}(p+w)}{\rho} - \dfrac{\kappa_1 n^{D*2}}{2\rho} - \dfrac{\kappa_2 a_m^{D*^2}}{2\rho}, \\ J_r^{D*} = \dfrac{(p-w)[b_2+s(a_r^{D*}-a_m^{D*})+\tau a_r^{D*}]}{\rho} + \dfrac{\eta D_1(p-w)}{\rho+\beta} + \dfrac{\eta x_\infty^{D*}(p-w)}{\rho} \\ \qquad + \dfrac{\gamma D_2(p-w)}{\rho+\varepsilon} + \dfrac{\gamma g_\infty^{D*}(p-w)}{\rho} - \dfrac{\kappa_3 a_m^{D*^2}}{2\rho}, \end{cases} \tag{19}$$

where $D_1 = x_0 - x_\infty^{D*}, D_2 = g_0 - g_\infty^{D*}$.

Corollary 2.

$$\frac{\partial n^{D*}}{\partial \eta} > 0, \frac{\partial n^{D*}}{\partial \gamma} > 0, \frac{\partial n^{D*}}{\partial \alpha} > 0, \frac{\partial n^{D*}}{\partial \beta} < 0, \frac{\partial n^{D*}}{\partial \kappa_1} < 0; \frac{\partial a_m^{D*}}{\partial s} > 0, \frac{\partial a_m^{D*}}{\partial \tau} > 0, \frac{\partial a_m^{D*}}{\partial \gamma} > 0, \frac{\partial a_m^{D*}}{\partial \sigma} > 0, \frac{\partial a_m^{D*}}{\partial \kappa_2} < 0;$$
$$\frac{\partial a_r^{D*}}{\partial s} > 0, \frac{\partial a_r^{D*}}{\partial \tau} > 0, \frac{\partial a_r^{D*}}{\partial \gamma} > 0, \frac{\partial a_r^{D*}}{\partial \sigma} > 0, \frac{\partial a_r^{D*}}{\partial \kappa_3} < 0.$$

According to Corollary 2, in the low-carbon advertising competition model, the intensity of low-carbon advertising competition between the manufacturer and retailer has a positive effect on low-carbon advertising investment, and obviously, the more intense the advertising competition between the manufacturer

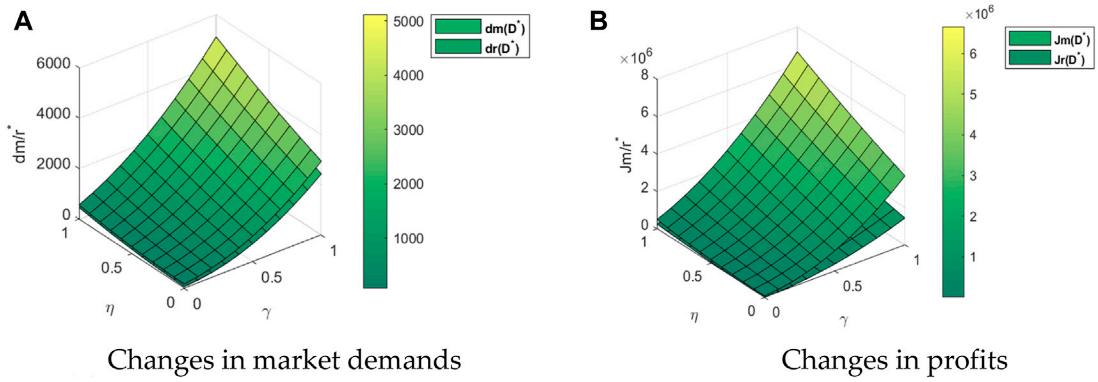

FIGURE 11
Impact of γ and η coefficients on market demand and profits. **(A)** Changes in market demands. **(B)** Changes in profits.

and retailer, the more they are stimulated to invest in advertising. The effects of other influencing factors on the equilibrium strategy are consistent with Corollary 1.

Corollary 3. A comparison of low-carbon decisions of supply chain members under centralized and competitive models is as follows:

(1)$n^{C*} > n^{D*}$; (2) when $0 < s < \frac{\sigma\gamma}{\rho+\varepsilon'}$ then $a_m^{C*} > a_m^{D*}$; when $s \geq \frac{\sigma\gamma}{\rho+\varepsilon'}$ then $a_m^{D*} > a_m^{C*}$; and (3) $a_r^{C*} > a_r^{D*}$.

According to Corollary 3, the level of emission reduction and low-carbon reduction achieved by the manufacturer in the competitive decision is lower than that in the centralized decision; retailer's low-carbon advertising and promotion investment is lower than that in the centralized decision. However, when the level of advertising competition is low, manufacturer's advertising investment in the centralized decision is greater than that in the competitive decision; when advertising rivalry is fierce, the competitive decision's advertising investment will be bigger than that of the centralized decision. It indicates that when there is intense competition in low-carbon advertising, the manufacturer is more willing to invest in advertising costs, and according to the competition model, the more the manufacturer invest in low-carbon advertising, the greater the positive impact on profits and market demand.

4 Design of the cost-sharing contractual model

According to the underlying models, centralized decision-making can help the low-carbon supply chain achieve higher returns. However, in the actual low-carbon supply chain operation process, members are usually independent individuals, and decentralized decision-making with the goal of maximizing their own profits is the most common choice; however, it is difficult to achieve good returns in decision-making with the goal of maximizing decision-making. As a result, achieving the sustainable development of low-carbon competitive supply chains necessitates the full cooperation of both upstream and downstream supply chains. In this section, we will investigate the coordination strategy for the sustainable development of low-carbon competitive supply chains by designing two types of cost-sharing contract mechanisms.

4.1 Low-carbon cooperation uni-directional cost-sharing contract model (CS)

In the uni-directional cost-sharing contract model, considering the absolute advantage of the manufacturer in the low-carbon competitive market and the sustainable development of the supply chain system, the manufacturer is designed to share a certain amount of low-carbon advertising costs for the retailer, so as to promote the retailer's market motivation, with a sharing ratio of ξ ($0 \leq \xi \leq 1$). The manufacturer and the retailer form a Stackelberg differential game, assuming that the manufacturer acts as a leader and the retailer acts as a follower in this decision, and the specific order of the game is as follows: the manufacturer determines the optimal emission reduction. Finally, the retailer determines the optimal low-carbon advertising effort. Then, the objective functions of the manufacturer and the retailer under the uni-directional cost-sharing contract decision are as follows:

$$\begin{cases} J_m^{CS}(g^{CS}(t), x^{CS}(t)) \\ \quad = \max\limits_{n^{CS}, a_m^{CS}, \xi} \int_0^\infty e^{-\rho t}\left[pd_m^{CS} + wd_r^{CS} - \frac{1}{2}\kappa_1 n^{CS^2} - \frac{1}{2}\kappa_2 a_m^{CS^2} - \frac{1}{2}\kappa_3 \xi a_r^{CS^2}\right]dt, \\ J_r^{CS}(g^{CS}(t), x^{CS}(t)) \\ \quad = \max\limits_{a_r^{CS}} \int_0^\infty e^{-\rho t}\left[(p-w)d_r^{CS} - \frac{1}{2}\kappa_3(1-\xi)a_r^{CS^2}\right]dt. \end{cases} \tag{20}$$

Proposition 3. The equilibrium results of the differential game under the uni-directional cost-sharing contract model are as follows:

$$\begin{cases} n^{CS*} = \dfrac{\alpha(p+w)[\eta(\rho+\varepsilon)+\theta\gamma]}{\kappa_1(\rho+\varepsilon)(\rho+\beta)} \\ a_m^{CS*} = \dfrac{(\rho+\varepsilon)[p(s+\tau)-ws]+(p+w)\sigma\gamma}{\kappa_2(\rho+\varepsilon)} \\ a_r^{CS*} = \dfrac{(p-w)[(\rho+\varepsilon)(s+\tau)+\sigma\gamma]}{\left(1-\xi^{CS*}\right)\kappa_3(\rho+\varepsilon)}, \end{cases} \tag{21}$$

$$\xi^{CS*} = \frac{(3ws+3w\tau-3ps-p\tau)(\rho+\varepsilon)+p\sigma\gamma+3w\sigma\gamma}{(ws+w\tau-ps+p\tau)(\rho+\varepsilon)+3p\sigma\gamma+w\sigma\gamma} \tag{22}$$

$$\begin{cases} x^{CS*}(t) = x_\infty^{CS*} + (x_0 - x_\infty^{CS-S*})e^{-\beta t} \\ g^{CS*}(t) = g_\infty^{CS*} + (g_0 - g_\infty^{CS*})e^{-\varepsilon t}, \end{cases} \tag{23}$$

$$\begin{cases} x_\infty^{CS*} = \dfrac{\alpha^2(p+w)[\eta(\rho+\varepsilon)+\theta\gamma]}{\beta\kappa_1(\rho+\varepsilon)(\rho+\beta)}, \\ g_\infty^{CS*} = \dfrac{\sigma(\rho+\varepsilon)[p(k+\tau)-wk]+(p+w)\sigma^2\gamma}{\varepsilon\kappa_2(\rho+\varepsilon)} \\ \quad + \dfrac{\alpha^2\theta(p+w)[\eta(\rho+\varepsilon)+\theta\gamma]}{\varepsilon\beta\kappa_1(\rho+\varepsilon)(\rho+\beta)} \\ \quad + \dfrac{\sigma(\rho+\varepsilon)(p-w)(k+\tau)+(p-w)\sigma^2\gamma}{\varepsilon\left(1-\xi^{CS*}\right)\kappa_3(\rho+\varepsilon)}, \end{cases} \tag{24}$$

$$\begin{cases} J_m^{CS*} = \dfrac{pa_1+wa_2}{\rho} + \dfrac{p[s(a_m^{CS*}-a_r^{CS*})+\tau a_m^{CS*}]}{\rho} + \dfrac{w[s(a_r^{CS*}-a_m^{CS*})+\tau a_r^{CS*}]}{\rho} + \dfrac{\eta U_1(p+w)}{\rho+\beta} + \\ \quad \dfrac{\eta x_\infty^{CS*}(p+w)}{\rho} + \dfrac{\gamma U_2(p+w)}{\rho+\varepsilon} + \dfrac{\gamma g_\infty^{CS*}(p+w)}{\rho} - \dfrac{\kappa_1 n^{CS*2}}{2\rho} - \dfrac{\kappa_2 a_m^{CS*2}}{2\rho} - \dfrac{\xi^{CS*}\kappa_r a_r^{CS*2}}{2\rho} \\ J_r^{CS*} = \dfrac{(p-w)[a_2+s(a_r^{CS*}-a_m^{CS*})+\tau a_r^{CS*}]}{\rho} + \dfrac{\eta U_1(p-w)}{\rho+\beta} + \dfrac{\eta x_\infty^{CS*}(p-w)}{\rho} + \dfrac{\gamma U_2(p-w)}{\rho+\varepsilon} \\ \quad + \dfrac{\gamma g_\infty^{CS*}(p-w)}{\rho} - \dfrac{\left(1-\xi^{CS*}\right)\kappa_3 a_r^{CS*2}}{2\rho}, \end{cases} \tag{25}$$

where $U_1 = x_0 - x_\infty^{CS*}, U_2 = g_0 - g_\infty^{CS*}$.

Corollary 4. A comparison of low-carbon decisions of supply chain members under centralized, competitive, and uni-directional cost-sharing contract models is as follows:

(1)$n^{C*} > n^{CS*} = n^{D*}$; (2) when $0 < s < \frac{\sigma\gamma}{\rho+\varepsilon}$, then $a_m^{C*} > a_m^{CS*} = a_m^{D*}$; when $s \geq \frac{\sigma\gamma}{\rho+\varepsilon}$, then $a_m^{CS*} = a_m^{D*} > a_m^{C*}$; and (3) $a_r^{C*} > a_r^{CS*} > a_r^{D*}$.

According to Corollary 4, the retailer's low-carbon advertising input in the uni-directional cost-sharing contract is larger than that in the competitive decision-making model and smaller than that in the centralized decision-making model. It can be seen that the uni-directional cost-sharing contract can promote retailers' low-carbon advertising inputs. However, when the degree of advertising competition is low, the manufacturer's advertising input in the centralized decision is greater than that in the uni-directional cost-sharing contract, and the advertising input in the uni-directional cost-sharing contract is equal to that in the competitive decision. When advertising competition is high, advertising inputs under the uni-directional cost-sharing contract and the competitive decision are equal and greater than those under the centralized decision. It is illustrated that due to the manufacturer's market advantage in low-carbon competition, the manufacturer will not reduce the competitive trend of low-carbon advertising due to the cost-sharing contract because the low-carbon advertising inputs can bring more benefits to it compared to the low-carbon emission reduction inputs. In the following section, a bi-directional cost-sharing contract is introduced to further enhance the coordination contract.

4.2 Low-carbon cooperation bi-directional cost-sharing contract model (CRS)

This subsection builds on the uni-directional cost-sharing contract to create a bi-directional cost-sharing contract. Under the bi-directional cost-sharing contract, low-carbon advertising inputs are shared with each other in the interest of the entire coalition. In this case, the advertising cost-sharing rate shared by the manufacturer for the retailer is λ $(0 \leq \lambda \leq 1)$, and the advertising cost-sharing rate shared by the retailer for the manufacturer is μ $(0 \leq \mu \leq 1)$. In the model and results of the advertising cooperative cost-sharing contract, the superscript is CRS, and the objective functions of the manufacturer and the retailer are expressed as follows:

$$\begin{cases} J_m^{CRS}(g^{CRS}(t), x^{CRS}(t)) = \max\limits_{n^{CRS}, a_m^{CRS}, \lambda} \displaystyle\int_0^\infty e^{-\rho t} \\ \left[pd_m^{CRS} + wd_r^{CRS} - \dfrac{1}{2}\kappa_1 n^{CRS^2} - \dfrac{1}{2}(1-\mu)\kappa_2 a_m^{CRS^2} - \dfrac{1}{2}\lambda\kappa_3 a_r^{CRS^2}\right]dt \\ J_r^{CRS}(g^{CRS}(t), x^{CRS}(t)) = \max\limits_{a_r^{CRS}, \mu} \displaystyle\int_0^\infty e^{-\rho t} \\ \left[(p-w)d_r^{CRS} - \dfrac{1}{2}(1-\lambda)\kappa_3 a_r^{CRS^2} - \dfrac{1}{2}\mu\kappa_2 a_m^{CRS^2}\right]dt. \end{cases} \tag{26}$$

Proposition 4. The equilibrium results of the differential game under the bi-directional cost-sharing contract model are as follows:

$$\begin{cases} \mu^{CRS*} = \dfrac{(p-w)(\sigma\gamma - s\rho - s\varepsilon)}{p\tau(\rho+\varepsilon)+2p\sigma\gamma} \\ \lambda^{CRS*} = \dfrac{(p+w)\sigma\gamma + (ws+w\tau-ps)(\rho+\varepsilon)}{p\tau(\rho+\varepsilon)+2p\sigma\gamma}, \end{cases} \tag{27}$$

$$\begin{cases} n^{CRS*} = \dfrac{\alpha(p+w)[\eta(\rho+\varepsilon)+\theta\gamma]}{\kappa_1(\rho+\varepsilon)(\rho+\beta)} \\ a_m^{CRS*} = \dfrac{(\rho+\varepsilon)[p(s+\tau)-ws]+(p+w)\sigma\gamma}{(1-\mu^{CRS*})\kappa_2(\rho+\varepsilon)} \\ a_r^{CRS*} = \dfrac{(\rho+\varepsilon)(p-w)(s+\tau)+(p-w)\sigma\gamma}{\left(1-\lambda^{CRS*}\right)\kappa_3(\rho+\varepsilon)}, \end{cases} \tag{28}$$

$$\begin{cases} x^{CRS*}(t) = x_\infty^{CRS*} + (x_0 - x_\infty^{CRS*})e^{-\beta t} \\ g^{CRS*}(t) = g_\infty^{CRS*} + (g_0 - g_\infty^{CRS*})e^{-\varepsilon t}, \end{cases} \tag{29}$$

$$\begin{cases} x_\infty^{CRS*} = \dfrac{\alpha^2(p+w)[\eta(\rho+\varepsilon)+\theta\gamma]}{\beta\kappa_1(\rho+\varepsilon)(\rho+\beta)}, \\ g_\infty^{CRS*} = \dfrac{\alpha^2\theta(p+w)[\eta(\rho+\varepsilon)+\theta\gamma]}{\varepsilon\beta\kappa_1(\rho+\varepsilon)(\rho+\beta)} \\ \quad + \dfrac{\sigma(\rho+\varepsilon)[p(s+\tau)-ws]+(p+w)\sigma^2\gamma}{\varepsilon(1-\mu)\kappa_2(\rho+\varepsilon)} \\ \quad + \dfrac{\sigma(\rho+\varepsilon)(p-w)(s+\tau)+(p-w)\sigma^2\gamma}{\varepsilon(1-\lambda)\kappa_3(\rho+\varepsilon)}, \end{cases} \tag{30}$$

$$\begin{cases} J_m^{CRS*} = \frac{pb_1 + wb_2}{\rho} + \frac{p[s(a_m^{CRS*} - a_r^{CRS*}) + \tau a_r^{CRS*}]}{\rho} + \frac{w[s(a_r^{CRS*} - a_m^{CRS*}) + \tau a_r^{CRS*}]}{\rho} + \frac{\eta R_1 (p+w)}{\rho+\beta} \\ + \frac{\eta x_\infty^{CRS*} (p+w)}{\rho} + \frac{\gamma R_2 (p+w)}{\rho+\varepsilon} + \frac{\gamma g_\infty^{CRS*} (p+w)}{\rho} - \frac{\kappa_1 n^{CRS*2}}{2\rho} - \frac{(1-\mu)\kappa_2 a_m^{CRS*^2}}{2\rho} - \frac{\lambda\kappa_3 a_r^{CRS*^2}}{2\rho} \\ J_r^{CRS*} = \frac{(p-w)[b_2 + s(a_r^{CRS*} - a_m^{CRS*}) + \tau a_r^{CRS*}]}{\rho} + \frac{\eta R_1 (p-w)}{\rho+\beta} + \frac{\eta x_\infty^{CRS*} (p-w)}{\rho} + \frac{\gamma R_2 (p-w)}{\rho+\varepsilon} \\ + \frac{\gamma g_\infty^{CRS*} (p-w)}{\rho} - \frac{\mu\kappa_2 a_m^{CRS*^2}}{2\rho} - \frac{(1-\lambda)\kappa_3 a_r^{CRS*2}}{2\rho}, \end{cases} \tag{31}$$

where $R_1 = x_0 - x_\infty^{CRS*}, R_2 = g_0 - g_\infty^{CRS*}$.

The profit comparison of supply chain members and systems under competitive versus cost-sharing decisions is complex and cannot be explained by deductive analytical formulas. Therefore, this paper will show part of it in the arithmetic analysis.

Corollary 5. A comparison of the low-carbon decisions of supply chain members under centralized, competitive, uni-directional cost-sharing, and bi-directional cost-sharing contract models is as follows:

(1)$n^{C*} > n^{CRS*} = n^{CS*} = n^{D*}$; (2) when $0 < s < \frac{\sigma\gamma}{\rho+\varepsilon}$, then $a_m^{C*} = a_m^{CRS*} > a_m^{CS*} = a_m^{D*}$; when $S \geq \frac{\sigma\gamma}{\rho+\varepsilon}$, then $a_m^{CS*} = a_m^{D*} > a_m^{CRS*} = a_m^{C*}$; and (3) $a_r^{C*} = a_r^{CRS*} > a_r^{CS*} > a_r^{D*}$.

According to Corollary 5, the manufacturer's low-carbon abatement efforts are not improved in either the bi-directional cost-sharing contract or the uni-directional cost-sharing contract because the manufacturer's share of abatement costs is not considered in the cost-sharing contract. The retailer's low-carbon advertising input in the bi-directional cost-sharing contract is equal to that in the centralized decision-making, which proves that the bi-directional cost-sharing contract promotes the retailer's low-carbon advertising input better than the uni-directional cost-sharing contract, reflecting the effectiveness of the bi-directional cost-sharing contract. At the same time, under certain conditions, the manufacturer's low-carbon advertising input can also reach the same level of centralized decision-making under the bi-directional cost-sharing contract.

5 Numerical analysis

Through the mathematical calculation of the model in the previous two sections, this section will further validate the supply chain decision-making under low-carbon competition and the coordination effect of the two types of contracts by analyzing numerical examples, mainly investigating the effects of the key parameter coefficients, s and τ, on the theoretical results under different decision-making models, as well as the comparisons of the profits and incremental changes under various decision-making models. The visualization results of numerical simulation are given to provide some management insights into the sustainable development of low-carbon supply chain. The parameter settings refer to Li and Xu, (2022) and Yang et al. (2021). The parameter value is set to $\rho = 0.3$, t = 1, θ = 0.6, β = 0.2, α = 0.8, η = 0.7, s = 0.4, γ = 0.5, σ = 0.6, Ɛ = 0.3, b1 = b2 = 20, p = 200, w = 100, $\kappa_1 = \kappa_2 = \kappa_2 = 1$, $x_0 = 0$, $g_0 = 0$, $\Delta Jm_1 = J_m^{CS*} - J_m^{D*}$, and $\Delta Jr_1 = J_r^{CS*} - J_r^{D*}, \Delta Jm_2 = J_m^{CRS*} - J_m^{D*}, \Delta Jr_2 = J_r^{CRS*} - J_r^{D*}$.

5.1 Change characteristics of the low-carbon emission reduction level and low-carbon goodwill

The results in Figures 2, 3 show that the emission reduction level trajectory and the low-carbon goodwill trajectory are monotonic, cumulative state variables, and both the emission reduction level trajectory and the low-carbon goodwill trajectory converge to a steady state as they approach infinity. Second, the low-carbon goodwill and emission reduction levels in the centralized decision model are higher than those in the low-carbon advertising competition model, which indicates that the low-carbon emission reduction levels and low-carbon goodwill levels of the supply chain are compromised in the low-carbon competition scenario. Meanwhile, the low-carbon goodwill levels in the uni- and bi-directional cost-sharing contract are higher than those in the low-carbon advertising competition model, which indicates the effectiveness of the contract.

5.2 Changes in low-carbon advertising investment under competition

The results in Figures 4, 5 show that the advertising inputs of manufacturers and retailers increase with the degree of competition in the low-carbon advertising competition model and the decision of uni-directional cost-sharing contract. Uni-directional cost-sharing contracts can boost retailers' low-carbon advertising efforts. Under the bi-directional cost-sharing contract decision, the vicious competition between the two parties in the low-carbon advertising input can be eliminated, and the low-carbon advertising input decision is equal to the centralized decision under the bi-directional cost-sharing contract. Meanwhile, the numerical analysis also further supports the conclusion of Corollary 5.

5.3 Changes in market demand under competition

According to Figures 6A, B, it can be seen that both manufacturers and retailers are able to realize the increase in market demand in uni-directional and bi-directional cost-sharing contracts. According to the results in Figure 7, the low-carbon advertising competition model (a) increases the market demand of the manufacturer while decreasing the market demand of the retailer, and the manufacturer has an absolute market advantage in the low-carbon advertising competition. Under a uni-directional cost-sharing contract, both the manufacturer's and retailer's market demand increases, and in the case of low-advertising competition intensity (b), the retailer briefly establishes market dominance, but the manufacturer regains full market dominance when advertising competition intensity increases. Finally, the bi-directional cost-sharing contract (c) generates more stable and higher market demand for both the manufacturer and the retailer than the low-carbon advertising competition model, demonstrating the coordinated effect of the bi-directional cost-sharing contract.

5.4 Changes in profits under competition

Figures 8, 9 illustrate how uni-directional and bi-directional cost-sharing contracts can be used to harmonize competitive low-carbon advertising conflicts among supply chain participants, increase the profitability of supply chain members, and achieve Pareto improvements ($J_m^{CRS*} > J_m^{CS*} > J_m^{D*}, J_r^{CRS*} > J_r^{CS*} > J_r^{D*}$). Here, both uni-directional and bi-directional cost-sharing contracts improve the profitability of manufacturers and retailers. However, compared to the uni-directional cost-sharing contract, manufacturers' and retailers' profits increase more under the coordination of the bi-directional cost-sharing contract, and the bi-directional cost-sharing contract would be a better choice of coordination contract. At the same time, it can be found that manufacturers' and retailers' profit increases are opposite in the contractual model, with manufacturers' profits increasing with low-carbon competition and retailers' on the contrary. Because of this trend, manufacturers and retailers will have different preferences for the strategic choice of contract.

The results in Figures 10A, B show that the incremental profits of both the manufacturer and the retailer are greater than zero under both contractual coordination models and that the incremental profits of both the manufacturer and the retailer are greater than those of the uni-directional cost-sharing contract under the bi-directional cost-sharing contract, which implies that the bi-directional cost-sharing contract is more favorable and leads to contractual cooperation between the two parties. In addition, from the analysis of Figures 10C, D, the manufacturer and retailer can gain more by reaching a contract in low-intensity competition; therefore, manufacturers who like competition need to be reminded that they should not be greedy for competition in low-carbon advertising competition. Appropriate, healthy competition is a good medicine to promote the market, but excessive competition will bring about a greater chain reaction, and manufacturers should actively encourage the retailers to cooperate together in order to realize cooperation in low-intensity advertising competition. Retailers should actively encourage retailers to cooperate together in order to maximize the profit of cooperation and realize the long-term and stable cooperative relationship between upstream and downstream enterprises in the green supply chain, which is conducive to the long-term and stable development of the green supply chain.

5.5 The impact of low-carbon preferences (η) and brand preferences (γ) on markets and profits under competition

According to Figure 11, in the competitive market, the demand and profit of manufacturers and retailers increase with the coefficients of low-carbon preference (η) and brand preference (γ), where the effect of brand preference is greater than that of low-carbon preference, and thus there is a scenario in which manufacturers compete greedily in low-carbon advertising competition; at the same time, in the scenario of decentralized low-carbon advertising competition, the demand and profit of manufacturers are greater than those of retailers, and it also shows that the manufacturers have an advantageous decision-making position in the low-carbon competition.

6 Conclusion

Under pressing global environmental issues, all businesses are obliged to work together to make the global transition to a low-carbon economy. In this study, a dynamic supply chain system consisting of a dual channel of green producers and merchants is constructed based on the investigation of the coordination contract of the low-carbon advertising competitive supply chain under the influence of low-carbon goodwill. Differential game theory is utilized to solve the low-carbon goodwill, market demand, and optimal value functions of producers and retailers for each of the four choice models. The impact of the competitive intensity of low-carbon advertisements on market demand and supply chain members' profits is discussed using equilibrium strategy analysis and numerical examples, and the coordination effects of uni-directional and bi-directional cost-sharing contracts under low-carbon competitive conditions are further examined, and the following interesting conclusions are obtained: 1) under the low-carbon advertising invasion of the manufacturer's direct marketing channel, the stronger advertising competition intensity between the manufacturer and retailer will stimulate both parties to invest more in low-carbon advertising efforts, and at the same time, it can lead to higher low-carbon goodwill of branded products, but such vicious competition is not beneficial to the supply chain members and the system, and both manufacturer's and retailer's profits will be damaged by the competition in the decentralized competition model. Meanwhile, brand preference and low-carbon preference have positive effects on market demand and the profit of manufacturers and retailers in the decentralized competition model. Therefore, in a healthy low-carbon competition, low-carbon supply chain members reaching a low-carbon cooperation contract is the best strategy to maintain a sustainable supply chain system. 2) In the decentralized model, the manufacturer's market demand increases with the increase in advertising competition intensity, and the retailer's market demand decreases with it, which indicates that the retailer does not possess the market advantage in the case of the manufacturer's direct sales channel invasion of low-carbon advertising competition; there is a renunciation behavior, and the manufacturer has an absolute market advantage in advertising competition. Furthermore, the strength of this low-carbon advertising competition will be an important factor in the coordination of the manufacturer's and the retailer's strategic choices in the later stage of the process factors. At the same time, under the coordination of uni-directional cost-sharing contracts and bi-directional cost-sharing contracts, the channel market demand conflict in the supply chain can be gradually reduced and eventually improved to achieve stable win–win market demand. 3) Under the decision-making model of uni-directional and bi-directional cost-sharing contracts, the supply chain system can realize Pareto gains. The study shows that in the context of low-carbon advertising competition, both green manufacturers and retailers have the willingness to cooperate, and the allocation of advertising costs between manufacturers and retailers can stimulate both parties to invest in low-carbon advertising, gradually reduce the conflict of channel market demand in the supply chain, and ultimately realize perfection, which makes contractual decision-making more profitable than that of the supply chain members in the context of low-carbon advertising competition. Meanwhile, a bi-directional cost-sharing contract is superior to a uni-directional cost-sharing contract. 4) In terms of the coordination effect of contracts, the study found that entering into a contract under low-advertising competition intensity is more favorable to the profit growth of supply chain members, while entering into a contract under low-advertising competition intensity is more favorable to the profit of manufacturers and entering into a contract under strong competition is more favorable to the profit of retailers. Therefore, savvy green manufacturers should increase their cost share to promote cooperation with retailers under low-competition conditions. In practice, therefore, green manufacturers should proactively seize the opportunity of low-carbon competition by adjusting their low-carbon advertising cost share to retailers in order to promote advertising cooperation between the two parties and obtain optimal profit gains.

Through the research in this paper, the main contributions and management discussions are as follows:

(1) In the implementation of low-carbon economy, both manufacturers and retailers play important roles in the production and marketing of low-carbon products. For example, manufacturers break the constraints of traditional channels, open up online channels, and participate in low-carbon advertisements to further enhance the low-carbon goodwill of their products, which in turn promotes the sales of low-carbon products. This not only changes the passive role of manufacturers in the traditional supply chain to participate in low-carbon advertising cost sharing but also provides different decision-making references for manufacturers on how to position themselves in the low-carbon role in the supply chain. At the same time, it is also an in-depth exploration of the value of low-carbon advertising, as well as a further application and innovation of the traditional low-carbon goodwill model.
(2) Due to the impact of the epidemic and the rapid development of Internet, many manufacturers choose to open online direct sales channels to increase their market share as well as profits. Therefore, the focus on the low-carbon advertising competition scenario between manufacturers and retailers is of great practical value. It is worth reminding through the study that manufacturers should not only focus on their own benefits no matter which invasion strategy they adopt to gain access to the low-carbon competitive market but also actively carry out vertical cooperation while maintaining orderly and healthy competition, and low-carbon contractual cooperation under the healthy competition can enable both supply chain members to realize the optimal benefits. Therefore, supply chain members should strengthen the awareness of "win–win cooperation," pay attention to the interests of supply chain partners while paying attention to their own benefits, treat partners as part of their own enterprises, and make "win–win" maximization only when the interests of partners are equal to their own interests.
(3) The traditional supply chain marketing model is difficult to promote the transformation of enterprises to green consumer-oriented production methods, resulting in a large loss of market demand, which not only harms the profit margin of enterprises themselves but also hinders the development process of greening the whole society. Therefore, in the face of consumers' low-carbon consumption preference, forging the low-carbon competitive advantage of green manufacturing industry in the process of implementing carbon compliance and carbon neutral target tasks, comprehensively analyzing the supply chain coordination strategy under low-carbon advertisement competition not only provides low-carbon strategy options for supply chain members but also provides a theoretical basis for the sustainable development of low-carbon supply chain.

In this paper, we analyze dynamic optimization strategies and design coordination contracts for the low-carbon advertising intrusion supply chain of a green manufacturer in a low-carbon environment, without taking into account the influence of government subsidies and carbon emission policies on supply chain members' decisions. As a result, in future research, we can include policy limitations to create a more comprehensive supply chain coordination contract that is worth studying.

The model proof process in Section 4 is similar to that in Section 3.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

D-rX: methodology, software, and writing–original draft. QQ: data curation, investigation, project administration, and writing-review and editing. J-mX: funding acquisition, supervision, and writing–review and editing. X-jH: project administration, and writing–review and editing. M-tJ: conceptualization, formal analysis, investigation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1260667/full#supplementary-material

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A sustainable NEV manufacturer-retailer system under the Nash bargaining framework: considering the impact of the COVID-19 epidemic under the CVaR criterion

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Suppose a new energy vehicle (NEV) manufacturer-retailer system where the wholesale price and the order quantity are determined through a negotiation procedure. Considering the impact of the COVID-19 epidemic, the manufacturer and the retailer are both assumed to be risk averse with Conditional Value-at-Risk (CVaR) as their performance measure. With the uniform distribution assumption, we derive the equilibrium solutions as well as the players' profit shares in the Stackelberg game and Nash bargaining framework. We quantitatively address the impacts of the players' confidence levels and government subsidy on the equilibrium order quantity, wholesale price and profit allocation in both negotiation frameworks. We find that, in both negotiation frameworks and considering the impact of the COVID-19 epidemic, a more risk-averse (i.e., with lower confidence level in CVaR model) manufacturer or retailer tends to occupy a higher profit share. On the other hand, a higher government subsidy aiming at offsetting the epidemic's impact leads to a higher profit share for the manufacturer and a lower one for the retailer. A quantitive comparison of the equilibriums in the two negotiation frameworks indicates that more NEVs are ordered by the retailer and a higher system profit is generated in the Nash bargaining framework than the Stackelberg game. Thus, we analytically prove that the Nash bargaining framework is superior to the Stackelberg game for the NEV manufacturer-retailer system in terms of both quantity and profit with consideration of the epidemic impact. In addition, a series of numerical experiments is carried out to illustrate the effects of some significant parameters on the equilibrium order quantity and the system profit allocation in different negotiation frameworks. These numerical experiments also further demonstrate the superiority of the Nash bargaining framework for either NEV player—no matter how the epidemic trend and the government subsidy vary—and provide a quantitative scope for the retailer's bargaining power to sustainably maintain the win-win cooperation between the NEV manufacturer and retailer in the superior Nash bargaining framework within the epidemic environment. From the perspective of policy, the government should increase subsidy within the epidemic environment to offset the negative effect and can degenerate subsidy when the epidemic dissipates. Furthermore, as the subsidy degenerates, both model results and numerical experiments show that the manufacturer suffers a more unfavorable effect, so the government can preferentially support the manufacturer by adjusting the subsidy to a higher level to alter players' relative powers and profit shares.

KEYWORDS

new energy vehicle (NEV), COVID-19 epidemic, conditional value-at-risk (CVaR), Stackelberg game, Nash bargaining

1 Introduction

Automobile exhaust is considered one of the main sources of carbon dioxide (CO_2) contributing to the greenhouse effect (Achtnicht, 2012). According to the report by the European Environment Agency (EEA), CO_2 generated by the transport sector has increased from 1990 to 2006 and accounted for 23% of the total CO_2 in the air in 2006 (European Environment Agency EEA, 2009; China Association of Automobile Manufactures CAAM, 2018). On the other hand, the incredible increase of automobile consumption meanwhile has resulted in a petroleum shortage. The desire to promote the sustainable development of society, energy conservation, and emission reduction has attracted a great deal of attention from governments all around the world. As an industry emerging to cope with environmental deterioration and energy challenges, new energy vehicles (NEVs) have obtained substantial support from many countries. In China, the sustainable development of NEVs is extremely meaningful for improving air quality and adjusting the energy structure as well as for promoting the reform and transformation of the automotive industry.

Benefiting from the government's policy and the technology research and development, the NEV production and sales have experienced a rapid increase in recent years. However, at present, most NEV managerial studies consist in qualitative research on policies or empirical research on consumers' purchase intentions. Although supply chain management has been a hot issue for many years and some researchers have focused on supply chain issues in different situations (see Das Roy and Sana, 2021; Sana, 2022a; Sana et al., 2018 for example,), the NEV supply chain has its peculiarities, and quantitative research on it is rare. On the other hand, we know that the negotiation mechanism is commonly used between manufacturers and retailers to determine contract parameters such as price and quantity. The issue on how to sustainably maintain an NEV manufacturer-retailer system under a favorable negotiation mechanism is a research gap. Supposing an NEV manufacturer-retailer system (hereafter we use he/his to stand for manufacturer/manufacturers and she/her for retailer/retailers), we aim to explore the negotiation mechanism between the two players with full consideration of the peculiarities of the NEV industry, such as the extremely high production cost and the inclusion of the government subsidy. We assume that the manufacturer offers the retailer a wholesale price contract based on subsidy sharing (SS-WP); thus, the two players negotiate with each other about the wholesale price and the order quantity. The negotiation mechanism is modeled on the Stackelberg game and the Nash bargaining framework (NBF); in the following, a comparison between them is provided to identify the superior framework.

Usually, research on the negotiation mechanism considers players as risk neutral. However, that is not very practical in the context of NEV commerce. With the marketization process of NEVs, consumers' diversified demands are increasing. Meanwhile, government policies relating to NEVs are constantly adjusted; for example, the subsidy is decreasing continuously nowadays. In addition, because it is an emerging industry, NEV market demand is very uncertain. As the player directly facing consumers and market demand, the retailer needs to bear great risk when making decisions on order quantity. Therefore, the NEV retailer tends to behave as a risk-averse decision maker rather than a risk-neutral one. On the other hand, the profit of a manufacturer in general industries only depends on the retailer's order quantity and has nothing to do with the uncertain demand. Accordingly, we can assume these manufacturers are risk neutral. However, some empirical studies have indicated that some manufacturers also tend to be risk averse rather than risk neutral, for example, Fisher and Raman (1996) and Katok and Wu (2009). In the NEV industry, since the government subsidy is based on the realized sales quantity, the subsidy amount the NEV manufacturer obtains is also related to the uncertain demand. In other words, the NEV manufacturer shares the demand risk, and his risk attitude, in turn, affects the negotiation results. Consequently, we assume the NEV manufacturer also behaves in a risk-averse manner. Moreover, considering the shock of the COVID-19 epidemic, the NEV manufacturer or retailer could be more risk averse, which is reflected in a higher degree of risk aversion.

Several studies, such as Eeckhoudt et al. (1995), Agrawal and Seshadri (2000), Chen et al. (2007), and Shen et al. (2016), have involved the risk-averse decision maker using the newsvendor model by the traditional expected-utility method. All these studies imply that the optimal order (or production) quantity is reduced by risk aversion and decreases proportionally to degree of risk aversion without considering shortage penalty. Besides the expected-utility method, three other major approaches have been widely used in operations management to characterize risk aversion: mean-variance (MV) analysis (Markowitz, 1959), Value-at-Risk (VaR) (Jorion, 1997), and Conditional Value-at-Risk (CVaR; see Rockafellar and Uryasev, 2000; Rockafellar and Uryasev, 2002). Mean-variance analysis is an approach to model risk aversion that satisfies a class of decision makers with the concave quadratic utility function (see Buzacott et al., 2011; Chen et al., 2001 for reviews). However, Ma et al. (2012) explained that the MV approach is inadequate because it equally quantifies desirable upside outcomes and undesirable downside outcomes. In the VaR evaluation, the decision maker is allowed to specify a confidence level (say, η with $\eta \in$) for attaining a certain level of wealth, and we need to maximize the η-quantile of the profit function (Jorion, 1997). Because the VaR measure also has some limitations, such as non-subadditivity and nonconvexity, Rockafellar and Uryasev (2000), Rockafellar and Uryasev (2002) defined a new measure of risk, CVaR. The CVaR criterion, which measures the average profit falling below the η-quantile level (or VaR), has better computational characteristics than VaR (Artz et al., 1999). Hence, recently more studies have investigated the risk-averse newsvendor problem in the CVaR framework (e.g., Ahmed et al. (2007); Gotoh and Takano (2007); Choi and Ruszczyński (2008); Chen et al. (2009). Due to the desirable mathematical characteristics of CVaR, we have adopted CVaR as the risk-averse decision makers' performance measurement in our model.

In this paper, we investigated the negotiation mechanism in an NEV manufacturer-retailer system where both players are risk averse considering the impact of the COVID-19 epidemic. It was presupposed that the two players negotiate regarding the wholesale price and the order quantity with the objective of maximizing their risky performances, as measured by the CVaR criterion, in the Stackelberg game or the NBF framework. With the uniform distribution assumption, we derived the equilibrium solutions as well as the two players' profit shares in the two negotiation frameworks. We found that, in both negotiation frameworks, the two players' risk attitudes play a similar role in affecting the players' profit shares. The manufacturer or the retailer tends to obtain a higher profit share when he/she becomes more risk averse. The effect of the government subsidy is also similar in both negotiation frameworks. As the subsidy increases to offset the impact of the COVID-19 epidemic, the retailer's profit share decreases while the manufacturer's increases. Besides, in the NBF framework, the bargaining power contrast also markedly affects the players' profit shares. Greater bargaining power always leads to a higher profit share and a higher absolute profit for either player. By comparing the Stackelberg game with the NBF framework, we analytically proved that the NBF equilibrium brings about a larger NEV order quantity and a higher system profit. Thus, we concluded that the NBF framework is superior to the Stackelberg game for the NEV manufacturer-retailer system in terms of both quantity and profit. Comparing the effects of some significant parameters in the two negotiation frameworks through numerical experiments further testified to the superiority of the NBF framework for either NEV player no matter how the epidemic trend and the government subsidy vary. It provides a necessary condition for the bargaining power contrast to sustainably maintain the NEV manufacturer-retailer system in the superior NBF framework. Our proposed model enriches research on the negotiation mechanism between the NEV manufacturer and retailer by incorporating the risk aversion effect with the CVaR approach considering the COVID-19 epidemic effect and quantitatively analyze the impacts of the players' confidence levels and government subsidy on the equilibrium order quantity, wholesale price and profit allocation. By a quantitive comparison of the equilibrium order quantity and profit allocation in the two negotiation frameworks, we analytically prove that the NBF framework is effective, feasible, and superior in promoting NEV sales and enhancing each player's profit when compared to the Stackelberg game. In addition, both model results and numerical experiments show that the manufacturer suffers a more unfavorable effect from the subsidy degeneration, so the government can preferentially support the manufacturer by adjusting the subsidy to a higher level to alter players' relative powers and profit shares. The findings may provide guiding principles for the sustainable win-win cooperation between the NEV manufacturer and retailer, which can be beneficial to promote the sustainable development of NEV commerce against the backdrop of the epidemic effect.

The rest of this paper is organized as follows. We review literature related to our work in Section 2. Section 3 solves the Stackelberg model with the manufacturer as the leader and analyzes the players' profit shares in this case. In Section 4, we derive the equilibrium solutions and the players' profit shares in the NBF framework and compare the results to those in the Stackelberg game. We carry out numerical experiments and report additional observations and implications in Section 5. In Section 6, we conclude this paper and present some managerial insights according to the findings.

2 Literature review

As an essential issue in the operations management field, the newsvendor model is the foundation of our study (see Khouja (1999) and Qin et al. (2011) for reviews). The newsvendor model has recently been adopted in different scenes to deal with some modern problems (see Sana, 2020; Sana, 2022b; Sana, 2022c for examples) and is also regarded as a common method to characterize the risk aversion effect in supply chain management. Among the studies on the risk-averse newsvendor model, those using the CVaR criterion are more closely related to our work. For example, two early studies by Gotoh and Takano (2007) and Chen et al. (2009) investigated the risk-averse newsvendor problem under the CVaR criterion with the objective of minimizing CVaR in regard to loss and maximizing CVaR in regard to profit; both studies demonstrated that risk aversion can reduce the newsvendor's order quantity. Due to the desirable mathematical characteristics of CVaR, many researchers have adopted it to model complex problems regarding risk-averse newsvendors. The related literature includes (Cheng et al., 2009; Xu, 2010; Xu and Li, 2010; Wu et al., 2014; Luo et al., 2015; Xue et al., 2015; Xu et al., 2016), and others. For example, Xu (2010) has used CVaR to investigate the effects of parameter changes, Wu et al. (2014) employed it to characterize the optimal quantity and pricing decisions of a risk-averse newsvendor under both quantity and price competition, and Xu et al. (2016) utilized it to formulate a risk-averse newsvendor's opportunity loss. The appearance of a vast amount of literature on the application of CVaR in the inventory problem indicates the accuracy and effectiveness of the CVaR approach. Even though the above-named studies focused on different problems, all of them have verified that a risk-averse newsvendor's order quantity is reduced by risk aversion and decreases with respect to the degree of risk aversion. These studies incorporating risk aversion with CVaR in different settings further make up the basis for analyzing the negotiation mechanism in a supply chain containing risk-averse players within the COVID-19 epidemic environment.

The previously mentioned literature only focused on the retailer's risk aversion effect and considered the manufacturer to be risk neutral. However, empirical studies have indicated that the manufacturer also tends to be risk averse rather than risk neutral. For example, Fisher and Raman (1996) found that the manager of a ski-wear factory usually decides to produce less than the theoretical quantity in the risk-neutral case. Katok and Wu (2009) conducted experimental research on supply chain contracts and showed that the wholesale price set by the manufacturer systematically deviates from the theoretical value with the risk-neutral assumption. To our best knowledge, very few studies have addressed the negotiation problem considering both players as risk averse. Gang et al. (2011) considered the supplier and the manufacturer as risk-averse decision makers to investigate the quality investment and price decision in a supply chain. They showed that, compared to a risk-neutral supply chain, a risk-averse supply chain may have lower, same, and higher product quality, depending on the supply chain strategy. For an NEV manufacturer-retailer system in which the manufacturer also undertakes some of the demand risk, it is more practical to involve the effect of the manufacturer's risk attitude. In this paper, considering the COVID-19 epidemic effect, both the NEV manufacturer and retailer have been characterized as risk-averse players to explore the effects of their risk attitudes on the negotiation mechanism.

Negotiation is a common mechanism to determine the contract parameters in a supply chain. Mieghem (1999), one of the first researchers to consider the bargaining problem in supply chains, investigated negotiations on incomplete contracts, where some of the contract parameters are left unspecified ex-ante and the surplus is divided based on the players' ex-post bargaining power. Some other researchers have analyzed the bargaining problem in a supply chain under different model assumptions. For example, Ertogral and Wu (2001) proposed bargaining models in one-buyer/one-supplier and one-buyer/multiple-suppliers cases and studied the contract negotiation process. Nagarajan and Sosic (2008) surveyed papers on applications of cooperative bargaining models to supply chain management and provided some future research directions. Plambeck et al. (2007a), Plambeck and Taylor (2007b) addressed the effects of renegotiation on contracts in different settings. Song and Gao (2018) established a game model for a green supply chain with a revenue-sharing contract and determined that the bargaining revenue-sharing contract can make the supply chain's total profit higher than the retailer-led revenue-sharing contract. These studies showed the equilibrium solutions and supply chain profit allocations or the players' preferences with different negotiation mechanisms under different contracts.

As respective representatives of noncooperative and cooperative games, the Stackelberg game and NBF framework are more frequently used in the supply chain area. The Stackelberg model is considered a classic noncooperative game, and related literature includes (Bernstein and Marx, 2006; Chen et al., 2012; Wu, 2013; Hua et al., 2017), among others. Bernstein and Marx (2006) adopted the Stackelberg game to address the effect of a retailer's bargaining power, modeled using the ability to set reservation profit levels, on the supply chain profit allocation. Chen et al. (2012) examined the manufacturer's pricing strategies and the coordination schemes in a dual-channel supply chain under the Stackelberg game with the manufacturer as the leader. Wu (2013) analyzed the effects of buyback policy on retail price, order quantity, and wholesale price in a duopoly competing supply chain under two channel policies: vertical integration and manufacturer's Stackelberg. Hua et al. (2017) established a Stackelberg game model to identify the optimal pricing and advertising strategies for both players in a two-echelon reverse supply chain of household unwanted medications.

As a representative of cooperative game models, the NBF problem also has attracted much attention. Hua et al. (2006) investigated the negotiation mechanism between a manufacturer and a retailer and provided the NBF equilibrium regarding the wholesale price and order quantity. Gurnani and Shi (2006) derived the NBF solution in the supply chain where the supplier is unreliable in delivery and discussed the effect of using a down-payment or nondelivery penalty in the contract for the two cases of buyer overtrust or undertrust. Nagarajan and Bassok (2008) used the NBF framework to model the multilateral negotiations between an assembler and various suppliers and examined the profit allocation in the supply chain. Ye et al. (2018) examined a mixed contract with an asymmetric NBF model and proved that such a contract is feasible to achieve an efficient biofuel supply chain. Although these studies have provided optimization approaches under the Stackelberg game or the NBF framework for various supply chains, all of them held to the risk-neutral assumption rather than considering the risk aversion effect.

Recently, some research studies incorporating risk aversion in the supply chain bargaining model have arisen. Ma et al. (2012) extended the study by Hua et al. (2006) and showed that a NBF equilibrium also exists in the two-echelon supply chain when the retailer is risk averse and tries to maximize her CVaR about profit. Li et al. (2014) explored a NBF problem in a dual-channel supply chain where the risk-neutral manufacturer and the risk-averse retailer negotiate with each other and explored the effect of the retailer's risk aversion degree on the retail price and the profit allocation. He et al. (2017) considered a supply chain consisting of one risk-neutral manufacturer and one risk-averse supplier with CVaR measurement and proposed a risk diversification contract that has a Pareto improvement and can allocate supply chain profit appropriately under the NBF framework. However, most papers with risk-averse assumptions considered only one of the players as risk averse. As mentioned previously, it is not appropriate to ignore the risk aversion effect of either player in an NEV manufacturer-retailer system, especially considering the COVID-19 epidemic effect.

As an emerging industry, NEVs garner much attention from many governments. Research on NEVs has focused on battery technology and has also emphasized marketing and consumer behavior. Bapna et al. (2002) suggested that governments should improve charging facilities to decrease NEV usage costs for consumers; Wang et al. (2017) used a multiple linear regression method to identify four key factors that promote NEV sales; Zhang and Bai (2017) proposed a policy-dependency mapping method to analyze 175 NEV government policies at various levels with multiple purposes. These qualitative studies have shown that several policies can promote the advancement of NEV commerce, such as strengthening research and development, establishing specific subsidies and tax policies, improving charging facilities, and so on. Some quantitative studies have addressed the NEV supply chain or NEV commerce. For example, Luo et al. (2014) quantitatively investigated the NEV supply chain under a government's price-discount incentive scheme that involves a price discount rate and a subsidy ceiling. They derived the most effective discount rate and subsidy ceiling that maximizes NEV sales as well as most effectively improves the manufacturer's incentive for NEV production. Liu et al. (2017) built an evolutionary game model between auto manufacturers and governments and discovered that the evolutionary game presents as stable when governments implement a dynamic taxation strategy or a dynamic subsidy strategy. The simulation of China's NEV industry indicates that a policy of dynamic taxations and static subsidies is effective for NEV industry development. Shao et al. (2017) addressed the NEV market under two different structures (monopoly and duopoly) and formulated a utility model composed of consumers who make utility-maximizing choices and manufacturers who set optimal pricing. They showed that the government prefers to implement a subsidy incentive scheme rather than a price discount incentive scheme, and, under the subsidy incentive scheme, the NEV market in the monopoly setting has a smaller environmental impact than that in the duopoly setting. In particular, two other papers have included in their considerations a behavioral element, loss aversion, to explore the NEV optimal production strategy under risk. Zhang (2014) considered both consumer trade-offs and government subsidies together with decision makers' loss aversion to evaluate relevant influences on the NEV optimal production strategy and indicated that subsidies can help to increase the production quantity and offset the loss aversion effect. Gu et al. (2017) investigated a loss-averse NEV manufacturer's optimal production decision considering battery recycling and proved that battery recycling can offset the negative effects of loss aversion on the optimal production quantity and expected utility. Concerning another behavioral element, risk aversion, Han and Xu (2018) designed a sales rebate/penalty contract based on subsidy sharing (SS-SRP) to coordinate a two-echelon NEV supply chain consisting of a risk-neutral manufacturer and a risk-averse retailer and evaluated the coordination efficiency. However, studies on NEV supply chains considering risk aversion are still quite scarce. Furthermore, the bargaining problem in an NEV manufacturer-retailer system considering the risk aversion effect has not yet been investigated.

The COVID-19 epidemic (National Health Commission, 2022) has had a tremendous impact on all walks of life and the overall national economy. Although the current situation of the epidemic in China continues to improve, due to the complex and severe situation of the overseas epidemic, the epidemic impact may persist for a long time. Since the outbreak of the COVID-19 epidemic, each national government put forward a series of policies to resist the epidemic impact, and many scholars investigated the effectiveness of these policies. For example, Ahmed et al. (2023) and Khan et al. (2021) adopted ARDL approach or the PMG-ARDL model to analyze the government policy response to COVID-19 epidemic and indicated that government economic support, debt/contract relief, stringency, and health and containment measures play a significant role in the fight against COVID-19 epidemic. In China, some scholars conducted researches on the impact of the COVID-19 epidemic on China's national economy and social production and life, such as Xue and Sha (2020), Li (2020), Zheng et al. (2020). Huang (2020) analyzed the impact of the epidemic on the automobile industry, while (Chen, 2020; Wang, 2020a; Wang, 2020b; Liu, 2020) and others paid attention to the impact the NEV industry in particular suffered. Regarding the epidemic impact on the NEV industry, the above studies mostly briefly analyzed from a qualitative perspective. There are almost no relevant quantitative analyses and model research approaches, and, in particular, research on the impact of the epidemic from the perspective of behavioral theory is mostly lacking.

Deviating from the previously mentioned studies, we consider the COVID-19 epidemic effect and risk aversion with the CVaR criterion, propose quantitative models with the Stackelberg game and the NBF framework, and focus on the profit allocation between the NEV manufacturer and retailer with full consideration of the peculiarities of NEV commerce. We adopted a quantitative approach to deal with the supply chain issue in NEV industry, assuming both the NEV manufacturer and retailer are risk-averse agents, considering the COVID-19 epidemic effect with the CVaR criterion, comparing different negotiation frameworks and providing a superior mechanism, these are the main contributions of this article. By exploring the negotiation mechanism under different frameworks, we hope to provide some insights into implications for the sustainable win-win cooperation between the NEV manufacturer and retailer under the superior NBF framework, which may help to promote NEV marketization within the COVID-19 epidemic environment.

3 Stackelberg game

For a two-echelon NEV supply chain, coordination is an ideal state (see Han and Xu, 2018). Although it meets the incentive compatibility constraint of the slave party, it does not necessarily meet the participation constraint of the master party and the slave party. In this case, each player in the supply chain usually determines the contract parameters and profit allocation through a specific negotiation mechanism. Suppose an NEV manufacturer-retailer system that faces a stochastic market demand x with a probability density function (*p.d.f.*) of $f(x)$ and a cumulative distribution function (*c.d.f.*) of $F(x)$. The NEV manufacturer and retailer are both risk averse with CVaR as their risk performance measurement. The manufacturer's and retailer's confidence levels are denoted as η_m and η_r, respectively. The lower η_m and η_r are, the more risk averse the manufacturer and retailer are. The epidemic effect is involved in the risk aversion degree. When the epidemic situation is severe/optimistic, the manufacturer's and retailer's respective risk aversion degrees are higher/lower, i.e., the confidence levels are lower/higher. Moreover, as the retailer faces the market demand directly and bears the inventory risk, we assume that $0 < \eta_r < \eta_m \le 1$.

Referring to the model by Zhang (2014), suppose NEVs are produced at a unit cost of c and sold to consumers at an exogenous price p. At the end of the selling season, the unsatisfied demand will be lost, and the leftover inventory will be disposed of at a unit salvage value s. Assume that $c > p > s$. Such an assumption conforms to the practice in the NEV industry because the NEV production cost is extremely high (especially the battery cost), even higher than the retail price. Since the NEV manufacturer and retailer cannot afford the high production cost independently, NEVs are subsidized by both national and local governments. We denoted the per-unit government subsidy as Y and assumed that $+Y > c$, which ensures that the NEV manufacturer-retailer system can obtain positive profit from the perspective of the system with the government's financial support. In addition, according to common practice in NEV commerce, we assumed that Y is shared by the manufacturer and the retailer by the proportion β: $(1-\beta)$ $(0 \le \beta \le 1)$.

We assumed that the manufacturer offers an SS-WP contract to the retailer (see Han and Xu, 2018) and that the two players negotiate with each other about the order quantity q and the wholesale price w. Denote q_i^* and w_i^*, where $i = s, n$, as the equilibrium optimal order quantity and wholesale price, respectively, under the Stackelberg game and the NBF framework. With the CVaR as the objective functions, we used the calculus method to derive optimal solutions under the Stackelberg game and the NBF framework respectively, used a partial derivative approach to conduct a factor analysis, used comparative analysis to identify the superior negotiation framework, and then employed numerical experiments to extend and clarify the mathematical results. We started our analysis with the CVaR formulations of the retailer and the manufacturer.

3.1 The CVaR expressions of the retailer and the manufacturer

The retailer's and manufacturer's profits, denoted as $\pi_r(q,w)$ and $\pi_m(q,w)$, can be expressed, respectively, as follows.

$$\begin{aligned}\pi_r(q,w) &= [p+(1-\beta)Y]\min(q,x) - wq + s(q-x)^+\\ &= [p+(1-\beta)Y-w]\min(q,x) - (w-s)(q-x)^+\\ &= [p+(1-\beta)Y-w][q-(q-x)^+] - (w-s)(q-x)^+\\ &= [p+(1-\beta)Y-w]q - [p+(1-\beta)Y-s](q-x)^+\end{aligned} \tag{3.1}$$

$$\pi_m(q,w) = (w-c)q + \beta Y\lfloor q-(q-x)^+\rfloor = (w+\beta Y-c)q - \beta Y(q-x)^+ \tag{3.2}$$

For calculation convenience, we have adopted the definition of CVaR by Rockafellar and Uryasev (2000), Rockafellar and Uryasev (2002) and referred to the risk-averse newsvendor model under CVaR criterion proposed by Chen et al. (2009), and the CVaR expressions for the retailer and the manufacturer, denoted as $CVaR(\pi_r(q,w))$ and $CVaR(\pi_m(q,w))$, are provided as follows, respectively.

$$CVaR(\pi_r(q,w)) = \max_{v_r\in R} \rightleftharpoons \left\{v_r + \frac{1}{\eta_r}E[\min(\pi_r(q,w)-v_r,0)]\right\} = \max_{v_r\in R} \rightleftharpoons \left\{v_r - \frac{1}{\eta_r}E[v_r-\pi_r(q,w)]^+\right\} \tag{3.3}$$

$$CVaR(\pi_m(q,w)) = \max_{v_m\in R} \rightleftharpoons \left\{v_m + \frac{1}{\eta_m}E[\min(\pi_m(q,w)-v_m,0)]\right\} = \max_{v_m\in R} \rightleftharpoons \left\{v_m - \frac{1}{\eta_m}E[v_m-\pi_m(q,w)]^+\right\} \tag{3.4}$$

where E is the expectation operator, $(\cdot)^+ = \max\{\cdot,0\}$, and v_r and v_m are profit thresholds denoted in the real number set R (Chen et al., 2009). Based on these definitions and results, we provide the following theorem to show the CVaR expressions for the retailer and the manufacturer.

Theorem 3.1. *The CVaR expressions for the retailer and the manufacturer can be formulated, respectively, as follows.*

$$CVaR(\pi_r(q,w)) = \begin{cases}[p+(1-\beta)Y-w]q - \dfrac{p+(1-\beta)Y-s}{\eta_r}\displaystyle\int_0^q F(x)dx & q\le F^{-1}(\eta_r)\\ [p+(1-\beta)Y-s]F^{-1}(\eta_r) - (w-s)q - \dfrac{p+(1-\beta)Y-s}{\eta_r}\displaystyle\int_0^{F^{-1}(\eta_r)} F(x)dx & q> F^{-1}(\eta_r)\end{cases} \tag{3.5}$$

$$CVaR(\pi_m(q,w)) = \begin{cases}(w+\beta Y-c)q - \dfrac{\beta Y}{\eta_m}\displaystyle\int_0^q F(x)dx & q\le F^{-1}(\eta_m)\\ (w-c)q + \beta YF^{-1}(\eta_m) - \dfrac{\beta Y}{\eta_m}\displaystyle\int_0^{F^{-1}(\eta_m)} F(x)dx & q> F^{-1}(\eta_m)\end{cases} \tag{3.6}$$

Proof. Refer to Supplementary Appendix SA1.

Theorem 3.1 explicitly provides the CVaR expressions for the risk-averse NEV retailer and manufacturer under the SS-WP contract. With all variables given, if the retailer's ordering quantity is q and the wholesale price is w, the retailer's and manufacturer's risky performances measured by CVaR can be calculated using Eq. 3.5 and Eq. 3.6, respectively.

The NEV retailer's CVaR measurement just extends the expression shown by Chen et al. (2009) by introducing the government subsidy Y with the assumption that the retail price p is exogenous. In regard to the NEV manufacturer's CVaR measurement shown by Eq. 3.6, we can see that $CVaR(\pi_m(q,w))$ is calculated by the retailer's payment wq minus the production cost $-cq$ and plus the profit obtained from the government subsidy Y. The portion $(w-c)q$ is a riskless part that depends only on the wholesale price and the retailer's order quantity while having nothing to do with the realized demand or the manufacturer's risk attitude. The payoff related to the government subsidy is influenced by the realized demand and thus is considered a risky part. Such a risky payoff is affected by the manufacturer's risk attitude. When $q\le F^{-1}(\eta_m)$, i.e., $\eta_m \ge F(q)$, indicating that the manufacturer's risk aversion degree is low, the risky payoff can be expressed as $\beta Yq - \frac{\beta Y}{\eta_m}\int_0^q F(x)dx$, which is decided by the manufacturer's risk attitude as well as the retailer's order quantity. When $q> F^{-1}(\eta_m)$, i.e., $\eta_m < F(q)$, indicating that the manufacturer's risk aversion degree is high, the risky payoff can be expressed as $\beta YF^{-1}(\eta_m) - \frac{\beta Y}{\eta_m}\int_0^{F^{-1}(\eta_m)} F(x)dx$, which depends only on the manufacturer's risk attitude while having no relation to the retailer's order quantity.

3.2 Stackelberg equilibrium

Under the Stackelberg game with the manufacturer as the leader, given the SS-WP contract, the retailer firstly decides her optimal order quantity with the objective of maximizing her CVaR. In anticipation of the retailer's order quantity, the manufacturer then decides the optimal wholesale price for himself to maximize his CVaR. For calculating convenience, we assumed that the demand is subject to a uniform distribution on $[0, B]$. According to the CVaR expressions given in Theorem 3.1, we derived the Stackelberg equilibrium, shown in the following theorem.

Theorem 3.2. *The Stackelberg equilibrium between the NEV manufacturer and retailer is* (q_s^*, w_s^*), *where*

$$q_s^* = \frac{B\eta_r\eta_m(p+Y-c)}{2\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y} \tag{3.7}$$

$$w_s^* = \frac{\eta_m[p+(1-\beta)Y-s][p+(1-2\beta)Y+c]+\eta_r\beta Y[p+(1-\beta)Y]}{2\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y} \tag{3.8}$$

Proof. Recall Eq. 3.5, when $q \le F^{-1}(\eta_r)$, and take the first-order derivative of $CVaR(\pi_r(q,w))$ with respect to q:

$$\frac{\partial CVaR(\pi_r(q,w))}{\partial q} = [p+(1-\beta)Y-w] - \frac{p+(1-\beta)Y-s}{\eta_r}F(q)$$

Then, taking the second-order derivative of $CVaR(\pi_r(q,w))$ with respect to q, we obtain

$$\frac{\partial^2 CVaR(\pi_r(q,w))}{\partial q^2} = -\frac{p+(1-\beta)Y-s}{\eta_r}f(q) < 0$$

This means that $CVaR(\pi_r(q,w))$ is concave with respect to q; so, let $\frac{\partial CVaR(\pi_r(q,w))}{\partial q} = 0$, and we obtain

$$q_s^* = F^{-1}\left(\frac{\eta_r[p+(1-\beta)Y-w]}{p+(1-\beta)Y-s}\right) = \frac{B\eta_r[p+(1-\beta)Y-w]}{p+(1-\beta)Y-s} \tag{3.9}$$

When $q > F^{-1}(\eta_r)$, take the first-order derivative of $CVaR(\pi_r(q,w))$ with respect to q, and we obtain

$$\frac{\partial CVaR(\pi_r(q,w))}{\partial q} = -(w-s) < 0$$

So $CVaR(\pi_r(q,w))$ is decreasing with respect to q when $q > F^{-1}(\eta_r)$.

Combining the above two cases, a unique optimal order quantity $q_s^* \in$ exists, shown by Eq. 3.9.

Predicting the retailer's order quantity q_s^*, the manufacturer intends to determine an optimal wholesale price with the objective of maximizing his CVaR.

Note that $q_s^* \le F^{-1}(\eta_r) < F^{-1}(\eta_m)$, according to Eq. 3.6; so there is

$$CVaR(\pi_m(q_s^*,w)) = (w+\beta Y-c)q_s^* - \frac{\beta Y}{\eta_m}\int_0^{q_s^*} F(x)dx$$

Take the first-order derivative of $CVaR(\pi_m(q_s^*,w))$ with respect to w:

$$\begin{aligned}\frac{\partial CVaR(\pi_m(q_s^*,w))}{\partial w} &= q_s^* + (w+\beta Y-c)\frac{\partial q_s^*}{\partial w} - \frac{\beta Y}{\eta_m}\frac{\partial q_s^*}{\partial w}F(q_s^*)\\ &= \frac{B\eta_r[p+(1-\beta)Y-w]}{p+(1-\beta)Y-s} - (w+\beta Y-c)\frac{B\eta_r}{[p+(1-\beta)Y-s]} + \frac{\beta Y}{\eta_m}\frac{B\eta_r}{[p+(1-\beta)Y-s]}\frac{\eta_r[p+(1-\beta)Y-w]}{p+(1-\beta)Y-s}\\ &= \frac{B\eta_r}{p+(1-\beta)Y-s}\left\{[p+(1-2\beta)Y-2w+c] + \frac{\eta_r\beta Y[p+(1-\beta)Y-w]}{\eta_m[p+(1-\beta)Y-s]}\right\}\end{aligned}$$

Then take the second-order derivative of $CVaR(\pi_m(q_s^*,w))$ with respect to w, and we obtain

$$\frac{\partial^2 CVaR(\pi_m(q_s^*,w))}{\partial w^2} = \frac{B\eta_r}{p+(1-\beta)Y-s}\left\{-2-\frac{\eta_r\beta Y}{\eta_m[p+(1-\beta)Y-s]}\right\} < 0$$

This means that $CVaR(\pi_m(q_s^*,w))$ is concave with respect to w; so let $\frac{\partial CVaR(\pi_m(q_s^*,w))}{\partial w} = 0$, and we obtain the optimal wholesale price for the manufacturer w_s^*, shown by Eq. 3.8. Substitute Eq. 3.8 into Eq. 3.9, and the equilibrium optimal order quantity is obtained and expressed as Eq. 3.7.

In the NEV manufacturer-retailer system, when the manufacturer and the retailer are both risk averse with the CVaR criterion and negotiate with each other under the Stackelberg game, the equilibrium consists in the retailer ordering q_s^* NEVs at a wholesale price w_s^*. Under such an equilibrium, the subsidy-sharing proportion between the manufacturer and the retailer decides the system profit allocation by markedly affecting the equilibrium wholesale price w_s^*. And we can prove that the Stackelberg game can always achieve a situation where both players obtain positive profit no matter how much the manufacturer's subsidy-sharing proportion β is.

Corollary 3.1. *Under the Stackelberg game, both the manufacturer and the retailer can always obtain positive profit no matter how the government subsidy is shared.*

Proof. In order to ensure that both the manufacturer and the retailer can obtain positive profit under the Stackelberg equilibrium, the necessary condition is $c - \beta Y < w_s^* < p + (1-\beta)Y$. Recalling Eq. 3.8 there is

$$c - \beta Y < \frac{\eta_m [p + (1-\beta)Y - s][p + (1-2\beta)Y + c] + \eta_r \beta Y [p + (1-\beta)Y]}{2\eta_m [p + (1-\beta)Y - s] + \eta_r \beta Y} < p + (1-\beta)Y$$

$$\Rightarrow \begin{cases} (c-\beta Y)\{2\eta_m [p + (1-\beta)Y - s] + \eta_r \beta Y\} < \eta_m [p + (1-\beta)Y - s][p + (1-2\beta)Y + c] + \eta_r \beta Y [p + (1-\beta)Y] \\ \eta_m [p + (1-\beta)Y - s][p + (1-2\beta)Y + c] + \eta_r \beta Y [p + (1-\beta)Y] < [p + (1-\beta)Y]\{2\eta_m [p + (1-\beta)Y - s] + \eta_r \beta Y\} \end{cases}$$

$$\Rightarrow \begin{cases} \eta_m [p + (1-\beta)Y - s] + \eta_r \beta Y > 0 \\ p + Y - c > 0 \end{cases}$$

It is easily found that the above inequalities hold unconditionally for arbitrary β on $[0, 1]$.

Corollary 3.1 shows the availability of the Stackelberg game. No matter how the manufacturer and the retailer share the government subsidy, the equilibrium can guarantee that both players will obtain at least a positive profit and further remain motivated to participate in the business. The subsidy-sharing proportion between the two players directly affects the system profit allocation. We further analyzed this issue in the next subsection.

By observing Eq. 3.7 and Eq. 3.8, we can see that, with the assumption $0 < \eta_r < \eta_m \le 1$, the Stackelberg equilibrium is influenced by both players' risk attitudes. The reason is that the manufacturer decides the equilibrium wholesale price based on the retailer's order decision, which is related to the retailer's risk attitude and his own risk attitude as well. The effects of two players' confidence levels on the Stackelberg equilibrium are provided in the following proposition.

Proposition 3.1. *Under the Stackelberg game, the equilibrium order quantity increases with respect to either the manufacturer's or retailer's confidence level; the equilibrium wholesale price increases in connection with the retailer's confidence level yet decreases in connection with the manufacturer's.*

Proof. Recalling Eq. 3.7, we convert the expression of q_s^* as follows.

$$q_s^* = \frac{B\eta_r \eta_m (p + Y - c)}{2\eta_m [p + (1-\beta)Y - s] + \eta_r \beta Y} = \frac{B\eta_m (p + Y - c)}{2\eta_m [p + (1-\beta)Y - s]/\eta_r + \beta Y} = \frac{B\eta_r (p + Y - c)}{2[p + (1-\beta)Y - s] + \eta_r \beta Y/\eta_m}$$

We can easily find that q_s^* increases in η_r or η_m.

According to Eq. 3.8, taking the first-order derivative of w_s^* with respect to η_r, we obtain

$$\frac{\partial w_s^*}{\partial \eta_r} = \frac{\beta Y [p + (1-\beta)Y]\{2\eta_m [p + (1-\beta)Y - s] + \eta_r \beta Y\} - \beta Y \{\eta_m [p + (1-\beta)Y - s][p + (1-2\beta)Y + c] + \eta_r \beta Y [p + (1-\beta)Y]\}}{\{2\eta_m [p + (1-\beta)Y - s] + \eta_r \beta Y\}^2}$$

$$= \frac{\eta_m \beta Y (p + Y - c)[p + (1-\beta)Y - s]}{\{2\eta_m [p + (1-\beta)Y - s] + \eta_r \beta Y\}^2} > 0$$

Therefore, w_s^* increases in η_r.

Then take the first-order derivative of w_s^* with respect to η_m, and we obtain

$$\frac{\partial w_s^*}{\partial \eta_m} = \frac{[p + (1-\beta)Y - s][p + (1-2\beta)Y + c]\{2\eta_m [p + (1-\beta)Y - s] + \eta_r \beta Y\} - 2[p + (1-\beta)Y - s]\{\eta_m [p + (1-\beta)Y - s][p + (1-2\beta)Y + c] + \eta_r \beta Y [p + (1-\beta)Y]\}}{\{2\eta_m [p + (1-\beta)Y - s] + \eta_r \beta Y\}^2}$$

$$= -\frac{\eta_r \beta Y [p + (1-\beta)Y - s](p + Y - c)}{\{2\eta_m [p + (1-\beta)Y - s] + \eta_r \beta Y\}^2} < 0$$

Therefore, w_s^* decreases in η_m.

A lower confidence level indicates a higher risk aversion degree. Proposition 3.1 reveals that, under the Stackelberg game, the equilibrium order quantity decreases in connection with the either the manufacturer's or the retailer's risk aversion degree. Previous literature has concluded that a more risk-averse retailer tends to order less when the manufacturer is assumed to be risk neutral. When the NEV manufacturer is also considered a risk-averse decision maker, the Stackelberg equilibrium order quantity is further reduced as the manufacturer or the retailer becomes more risk averse. On the other hand, the equilibrium wholesale price decreases in connection with the retailer's risk aversion degree yet increases in connection with the manufacturer's. When the retailer/manufacturer becomes more risk averse, the wholesale price should be adjusted to attract the more conservative retailer/manufacturer to participate in the business. The epidemic exacerbates the retailer's risk aversion degree and thus decreases the equilibrium order quantity as well as the equilibrium wholesale price; simultaneously, it heightens the manufacturer's risk aversion degree and thus decreases the equilibrium order quantity and increases the equilibrium wholesale price.

3.3 Profit allocation under the Stackelberg game

The previous subsection provides the equilibrium under the Stackelberg game and the impacts of players' risk attitudes. However, we are more interested in the system profit allocation and what elements it is related to. To investigate this, we first defined the retailer's profit share as

$$\rho_r = \frac{E\pi_r(q,w)}{E\pi(q,w)} = \frac{E\pi_r(q,w)}{E\pi_r(q,w) + E\pi_m(q,w)} \tag{3.10}$$

where $E\pi_r(q,w)$, $E\pi_m(q,w)$, and $E\pi(q,w)$ stand for the expected profits of the retailer, the manufacturer, and the entire system, respectively. Thus, the retailer's profit share under the Stackelberg game ρ_{rs} can be obtained, as shown in the following theorem.

Theorem 3.3. *Under the Stackelberg equilibrium, the retailer's profit share is:*

$$\rho_{rs} = \frac{(2-\eta_r)\eta_m[p+(1-\beta)Y-s]}{4\eta_m[p+(1-\beta)Y-s] + 2\eta_r\beta Y - \eta_r\eta_m(p+Y-s)} \tag{3.11}$$

Proof. Under the Stackelberg equilibrium, (q_s^*, w_s^*), $E\pi_r(q_s^*, w_s^*)$, and $E\pi_m(q_s^*, w_s^*)$ can be obtained by ordering $\eta_r = 1$ and $\eta_m = 1$ in the expressions of $CVaR(\pi_r(q_s^*, w_s^*))$ and $CVaR(\pi_m(q_s^*, w_s^*))$. Therefore, we have

$$\begin{aligned} E\pi_r(q_s^*, w_s^*) &= [p+(1-\beta)Y-w_s^*]q_s^* - [p+(1-\beta)Y-s]\int_0^{q_s^*}F(x)dx \\ &= [p+(1-\beta)Y-w_s^*]q_s^* - \frac{p+(1-\beta)Y-s}{2B}q_s^*2 \end{aligned} \tag{3.12}$$

$$E\pi_m(q_s^*, w_s^*) = (w_s^*+\beta Y-c)q_s^* - \beta Y\int_0^{q_s^*}F(x)dx = (w_s^*+\beta Y-c)q_s^* - \frac{\beta Y}{2B}q_s^*2 \tag{3.13}$$

Moreover, the supply chain's total expected profit can be obtained.

$$\begin{aligned} E\pi(q_s^*, w_s^*) &= E\pi_r(q_s^*, w_s^*) + E\pi_m(q_s^*, w_s^*) \\ &= (p+Y-c)q_s^* - (p+Y-s)\int_0^{q_s^*}F(x)dx \\ &= (p+Y-c)q_s^* - \frac{p+Y-s}{2B}q_s^*2 \end{aligned} \tag{3.14}$$

Recalling Eq. 3.7 and Eq. 3.8, we obtain

$$\begin{aligned} E\pi(q_s^*, w_s^*) &= (p+Y-c)q_s^* - \frac{p+Y-s}{2B}q_s^*2 \\ &= (p+Y-c)q_s^* - \frac{p+Y-s}{2B}\frac{B\eta_r\eta_m(p+Y-c)}{2\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y}q_s^* \\ &= (p+Y-c)q_s^* - \frac{\eta_r\eta_m(p+Y-c)(p+Y-s)}{4\eta_m[p+(1-\beta)Y-s]+2\eta_r\beta Y}q_s^* \\ E\pi_r(q_s^*, w_s^*) &= [p+(1-\beta)Y-w_s^*]q_s^* - \frac{p+(1-\beta)Y-s}{2B}q_s^*2 \\ &= [p+(1-\beta)Y-w_s^*]q_s^* - \frac{\eta_r[p+(1-\beta)Y-w_s^*]}{2}q_s^* \\ &= [p+(1-\beta)Y-w_s^*]\left(1-\frac{\eta_r}{2}\right)q_s^* \\ &= \frac{(2-\eta_r)\eta_m[p+(1-\beta)Y-s](p+Y-c)}{4\eta_m[p+(1-\beta)Y-s]+2\eta_r\beta Y}q_s^* \end{aligned}$$

Finally, ρ_{rs} can be calculated through Eq. 3.10.

$$\begin{aligned} \rho_{rs} &= \frac{E\pi_r(q_s^*, w_s^*)}{E\pi(q_s^*, w_s^*)} \\ &= \frac{\frac{(2-\eta_r)\eta_m[p+(1-\beta)Y-s](p+Y-c)}{4\eta_m[p+(1-\beta)Y-s]+2\eta_r\beta Y}q_s^*}{(p+Y-c)q_s^* - \frac{\eta_r\eta_m(p+Y-c)(p+Y-s)}{4\eta_m[p+(1-\beta)Y-s]+2\eta_r\beta Y}q_s^*} \\ &= \frac{(2-\eta_r)\eta_m[p+(1-\beta)Y-s]}{4\eta_m[p+(1-\beta)Y-s]+2\eta_r\beta Y-\eta_r\eta_m(p+Y-s)} \end{aligned}$$

Under the Stackelberg equilibrium with the manufacturer as the leader, the retailer and the manufacturer share the system profit by the proportion ρ_{rs}: $(1-\rho_{rs})$, where ρ_{rs} is given by Eq. 3.11. We can find in Eq. 3.11 that ρ_{rs} depends on both the manufacturer's and the retailer's confidence levels when other variables are determined. That is to say, the players' profit shares are affected by both players' risk attitudes. The following proposition focuses on this issue.

Proposition 3.2. *Under the Stackelberg equilibrium, the retailer's profit share decreases in relation to her confidence level and increases in relation to the manufacturer's.*

Proof. Recalling Eq. 3.11, we take the first-order derivative of ρ_{rs} with respect to η_r and obtain

$$\frac{\partial \rho_{rs}}{\partial \eta_r} = \frac{-4\eta_m\eta_m[p+(1-\beta)Y-s][p+(1-\beta)Y-s]-2\eta_m[p+(1-\beta)Y-s][2\beta Y-\eta_m(p+Y-s)]}{\{4\eta_m[p+(1-\beta)Y-s]+2\eta_r\beta Y-\eta_r\eta_m(p+Y-s)\}^2}$$
$$= -\frac{\eta_m[p+(1-\beta)Y-s][4\beta Y(1-\eta_m)+2\eta_m(p+Y-s)]}{\{4\eta_m[p+(1-\beta)Y-s]+2\eta_r\beta Y-\eta_r\eta_m(p+Y-s)\}^2} < 0$$

Therefore, ρ_{rs} decreases in η_r.

We convert the expression of ρ_{rs} as follows.

$$\rho_{rs} = \frac{(2-\eta_r)\eta_m[p+(1-\beta)Y-s]}{4\eta_m[p+(1-\beta)Y-s]+2\eta_r\beta Y-\eta_r\eta_m(p+Y-s)}$$
$$= \frac{(2-\eta_r)[p+(1-\beta)Y-s]}{4[p+(1-\beta)Y-s]+2\eta_r\beta Y/\eta_m-\eta_r(p+Y-s)}$$

We can easily find that ρ_{rs} increases in η_m.

Proposition 3.2 explains how the manufacturer's and retailer's respective risk attitudes affect the players' profit shares under the Stackelberg equilibrium. The retailer obtains a larger profit share when she becomes more risk averse or when the manufacturer becomes less risk averse. Such a conclusion is also symmetrically applicable for the manufacturer. In other words, a more risk-averse player tends to occupy a larger profit share. The risk aversion degree of the player who is more sensitive to the epidemic could be enlarged more and thus achieve a larger profit share increase. However, a more risk-averse player results in a lower order quantity and further a lower profit for the entire system. Therefore, the effect of the risk aversion degree on a player's absolute profit is not very clear, and we further addressed this issue later by numerical experiments.

As one of the peculiarities in NEV commerce, the government subsidy is another point we should pay close attention to. The impact of the subsidy on the players' profit shares in the NEV manufacturer-retailer system under the Stackelberg equilibrium is provided as follows.

Proposition 3.3. *Under the Stackelberg equilibrium, the retailer's profit share decreases in relation to the government subsidy.*

Proof. Recalling Eq. 3.11, we convert the expression of ρ_{rs} as follows.

$$\rho_{rs} = \frac{(2-\eta_r)\eta_m[p+(1-\beta)Y-s]}{4\eta_m[p+(1-\beta)Y-s]+2\eta_r\beta Y-\eta_r\eta_m(p+Y-s)} = \frac{(2-\eta_r)\eta_m}{4\eta_m+\frac{2\eta_r\beta Y-\eta_r\eta_m(p+Y-s)}{p+(1-\beta)Y-s}}$$

Denote

$$P = \frac{2\eta_r\beta Y-\eta_r\eta_m(p+Y-s)}{p+(1-\beta)Y-s}$$

Take the first-order derivative of P with respect to Y, and we obtain

$$\frac{\partial P}{\partial Y} = \frac{(2\eta_r\beta-\eta_r\eta_m)[p+(1-\beta)Y-s]-(1-\beta)[2\eta_r\beta Y-\eta_r\eta_m(p+Y-s)]}{[p+(1-\beta)Y-s]^2}$$
$$= \frac{\eta_r\beta(2-\eta_m)(p-s)}{[p+(1-\beta)Y-s]^2} > 0$$

Therefore, P increases in Y and $\rho_{rs} = (2-\eta_r)\eta_m/(4\eta_m+P)$ decreases in Y.

Besides affecting the two players' risk attitudes, the government subsidy also has a noticeable impact on the players' profit shares in the NEV manufacturer-retailer system. When the government subsidy is augmented, the retailer's profit share is reduced while the manufacturer's is enlarged. Since the change in the subsidy amount can alter the players' profit shares, the government can choose to support the NEV manufacturer/retailer more by adjusting the subsidy amount. However, a larger government subsidy always leads to a higher profit for the entire system. Therefore, the effect of the government subsidy on a player's absolute profit also needs further discussion by numerical experiments.

4 Nash bargaining

In the NBF framework, the manufacturer and the retailer negotiate with each other about the order quantity and the wholesale price in order to enlarge the payoff pie and split it according to the bargaining power contrast between the two players. Suppose that the retailer's bargaining power is ω $(0 \le \omega \le 1)$. Then $(1-\omega)$ represents the manufacturer's bargaining power. Other notations are the same as for the Stackelberg model. In addition, we assumed that the manufacturer's and retailer's respective reserved payoffs measured by CVaR are deterministic and set as zero for calculating convenience. Rockafellar and Uryasev (2002) explained why this assumption is reasonable and indicated that this setting does not change the equilibrium qualitative properties. Thus, the NBF problem can be formulated as follows.

$$\max_{q>0, c-\beta Y<w<p+(1-\beta)Y} CVaR(\pi_r(q,w))^{\omega}\cdot CVaR(\pi_m(q,w))^{1-\omega} \tag{4.1}$$

4.1 Nash bargaining equilibrium

According to the CVaR expressions given in Theorem 3.1, we can derive the NBF equilibrium in an NEV manufacturer-retailer system by solving Eq. 4.1. The results are provided in the following theorem.

Theorem 4.1. *The NBF equilibrium between the NEV manufacturer and retailer is* (q_n^*, w_n^*), *where*

$$q_n^* = F^{-1}\left(\frac{\eta_r\eta_m(p+Y-c)}{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y}\right) \tag{4.2}$$

$$w_n^* = [(1-\omega)p+(1-\beta-\omega)Y+\omega c] - \frac{\{(1-\omega)\eta_m[p+(1-\beta)Y-s]-\omega\eta_r\beta Y\}\int_0^{q_n^*}F(x)dx}{\eta_r\eta_m q_n^*} \tag{4.3}$$

Proof. Recalling Eq. 3.5, take the first-order derivatives of $CVaR(\pi_r(q,w))$ with respect to q and w, respectively:

$$\frac{\partial CVaR(\pi_r(q,w))}{\partial q} = \begin{cases} [p+(1-\beta)Y-w] - \dfrac{p+(1-\beta)Y-s}{\eta_r}F(q) & q\le F^{-1}(\eta_r) \\ -(w-s) & q>F^{-1}(\eta_r) \end{cases}$$

$$\frac{\partial CVaR(\pi_r(q,w))}{\partial w} = -q$$

Similarly, recalling Eq. 3.6, take the first-order derivatives of $CVaR(\pi_m(q,w))$ with respect to q and w, respectively:

$$\frac{\partial CVaR(\pi_m(q,w))}{\partial q} = \begin{cases} (w+\beta Y-c) - \dfrac{\beta Y}{\eta_m}F(q) & q\le F^{-1}(\eta_m) \\ (w-c) & q>F^{-1}(\eta_m) \end{cases}$$

$$\frac{\partial CVaR(\pi_m(q,w))}{\partial w} = q$$

To solve Eq. 4.1, the necessary conditions are:

$$\begin{cases} \omega\dfrac{\partial CVaR(\pi_r(q,w))}{\partial q}CVaR(\pi_m(q,w)) + (1-\omega)\dfrac{\partial CVaR(\pi_m(q,w))}{\partial q}CVaR(\pi_r(q,w)) = 0 \\ \omega\dfrac{\partial CVaR(\pi_r(q,w))}{\partial w}CVaR(\pi_m(q,w)) + (1-\omega)\dfrac{\partial CVaR(\pi_m(q,w))}{\partial w}CVaR(\pi_r(q,w)) = 0 \end{cases} \tag{4.4}$$

According to the scale of q, noting the assumption $\eta_r < \eta_m$, we have three cases for further discussion.

(1) When $q \le F^{-1}(\eta_r) < F^{-1}(\eta_m)$, Eq. 4.4 can be converted to:

$$\begin{cases} \omega\left\{[p+(1-\beta)Y-w] - \dfrac{p+(1-\beta)Y-s}{\eta_r}F(q)\right\}\left\{(w+\beta Y-c)q - \dfrac{\beta Y}{\eta_m}\displaystyle\int_0^q F(x)dx\right\} \\ +(1-\omega)\left\{(w+\beta Y-c) - \dfrac{\beta Y}{\eta_m}F(q)\right\}\left\{[p+(1-\beta)Y-w]q - \dfrac{p+(1-\beta)Y-s}{\eta_r}\displaystyle\int_0^q F(x)dx\right\} = 0 \\ -q\omega\left\{(w+\beta Y-c)q - \dfrac{\beta Y}{\eta_m}\displaystyle\int_0^q F(x)dx\right\} + q(1-\omega)\left\{[p+(1-\beta)Y-w]q - \dfrac{p+(1-\beta)Y-s}{\eta_r}\displaystyle\int_0^q F(x)dx\right\} = 0 \end{cases}$$

It can be further simplified:

$$\begin{cases} (p+Y-c)-\left[\dfrac{p+(1-\beta)Y-s}{\eta_r}+\dfrac{\beta Y}{\eta_m}\right]F(q_r)=0 \\ \{[p+(1-\beta)Y-w]-\omega(p+Y-c)\}q_r-\left\{\dfrac{(1-\omega)[p+(1-\beta)Y-s]}{\eta_r}-\dfrac{\omega\beta Y}{\eta_m}\right\}\int_0^{q_r}F(x)dx=0 \end{cases}$$

By solving this equation set, we can obtain the NBF equilibrium (q_n^*, w_n^*) where q_n^* and w_n^* are given by Eq. 4.2 and Eq. 4.3. At the equilibrium point, we can testify that the Hessian Matrix of the objective function in Eq. 4.1 is negative definite, thus (q_n^*, w_n^*) is a stable equilibrium.

(2) When $F^{-1}(\eta_r) < q < F^{-1}(\eta_m)$, Eq. 4.4 can be converted to:

$$\begin{cases} -\omega(w-s)\left\{(w+\beta Y-c)q-\dfrac{\beta Y}{\eta_m}\int_0^q F(x)dx\right\} \\ +(1-\omega)\left\{(w+\beta Y-c)-\dfrac{\beta Y}{\eta_m}F(q)\right\}\left\{[p+(1-\beta)Y-s]F^{-1}(\eta_r)-(w-s)q-\dfrac{p+(1-\beta)Y-s}{\eta_r}\int_0^{F^{-1}(\eta_r)}F(x)dx\right\}=0 \\ -q\omega\left\{(w+\beta Y-c)q-\dfrac{\beta Y}{\eta_m}\int_0^q F(x)dx\right\}+q(1-\omega)\left\{[p+(1-\beta)Y-s]F^{-1}(\eta_r)-(w-s)q-\dfrac{p+(1-\beta)Y-s}{\eta_r}\int_0^{F^{-1}(\eta_r)}F(x)dx\right\}=0 \end{cases}$$

It can be further simplified:

$$\begin{cases} (\beta Y-c+s)-\dfrac{\beta Y}{\eta_m}F(q)=0 & a \\ [p+(1-\beta)Y-s]F^{-1}(\eta_r)-(2w+\beta Y-c-s)q-\dfrac{p+(1-\beta)Y-s}{\eta_r}\int_0^{F^{-1}(\eta_r)}F(x)dx+\dfrac{\beta Y}{\eta_m}\int_0^q F(x)dx=0 & b \end{cases} \tag{4.5}$$

Take the first-order derivatives of two sides in Eq. 4.5 with respect to q, respectively:

$$-(2w+\beta Y-c-s)+\frac{\beta Y}{\eta_m}F(q)=0 \tag{4.6}$$

Combining Eq. 4.6 and Eq. 4.5, we obtain $w = s$. That is obviously contradictory to the model assumption. Thus, there is no equilibrium in this case.

(3) When $q \geq F^{-1}(\eta_m) > F^{-1}(\eta_n)$, the equilibrium also does not exist. The proof is similar to the second case and thus omitted here.

In the NEV manufacturer-retailer system, when the manufacturer and the retailer are both risk averse with the CVaR criterion and negotiate with each other under the NBF framework, the equilibrium consists in the retailer ordering q_n^* NEVs at a wholesale price w_n^*. From Eq. 4.2 and Eq. 4.3, we can observe that the equilibrium order quantity depends on the two players' risk attitudes while having nothing to do with the bargaining power contrast between them. The equilibrium wholesale price is related to the two players' risk attitudes as well as the bargaining power contrast. In order to further analyze the effects of both players' risk attitudes and bargaining power, we considered the special case with a uniform distribution assumption. Consistent with the Stackelberg model, suppose that the demand is subject to a uniform distribution on $[0, B]$. Then q_n^* and w_n^* can be expressed as follows.

$$q_n^* = F^{-1}\left(\frac{\eta_r\eta_m(p+Y-c)}{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y}\right)=\frac{B\eta_r\eta_m(p+Y-c)}{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y} \tag{4.7}$$

$$\begin{aligned} w_n^* &= [(1-\omega)p+(1-\beta-\omega)Y+\omega c]-\frac{\{(1-\omega)\eta_m[p+(1-\beta)Y-s]-\omega\eta_r\beta Y\}\int_0^{q_n^*}F(x)dx}{\eta_r\eta_m q_n^*} \\ &= [(1-\omega)p+(1-\beta-\omega)Y+\omega c]-\frac{(p+Y-c)\{(1-\omega)\eta_m[p+(1-\beta)Y-s]-\omega\eta_r\beta Y\}}{2\{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y\}} \end{aligned} \tag{4.8}$$

Based on the above results, we provide the following proposition to explain the relationships between the NBF equilibrium and the two players' confidence levels.

Proposition 4.1. *Under the NBF framework, the equilibrium order quantity increases in connection with either the manufacturer's or retailer's confidence level; the equilibrium wholesale price increases in relation to the retailer's confidence level yet decreases in relation to the manufacturer's.*

Proof. Recalling Eq. 4.2, we convert the expression of q_n^* as follows.

$$q_n^* = \frac{B\eta_r\eta_m(p+Y-c)}{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y} = \frac{B\eta_m(p+Y-c)}{\eta_m[p+(1-\beta)Y-s]/\eta_r+\beta Y} = \frac{B\eta_r(p+Y-c)}{[p+(1-\beta)Y-s]+\eta_r\beta Y/\eta_m}$$

We can easily find that q_n^* increases in η_r or η_m.

According to Eq.(4.3), taking the first-order derivative of w_n^* with respect to η_r, we obtain

$$\begin{aligned}\frac{\partial w_n^*}{\partial \eta_r} &= -\frac{-2\omega\beta Y(p+Y-c)\{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y\} - 2\beta Y(p+Y-c)\{(1-\omega)\eta_m[p+(1-\beta)Y-s]-\omega\eta_r\beta Y\}}{4\{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y\}^2}\\ &= \frac{\eta_m\beta Y(p+Y-c)[p+(1-\beta)Y-s]}{2\{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y\}^2} > 0\end{aligned}$$

Therefore, w_n^* increases in η_r.

Then take the first-order derivative of w_n^* with respect to η_m, and we obtain

$$\begin{aligned}\frac{\partial w_n^*}{\partial \eta_m} &= -\frac{2(1-\omega)(p+Y-c)[p+(1-\beta)Y-s]\{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y\} - 2[p+(1-\beta)Y-s](p+Y-c)\{(1-\omega)\eta_m[p+(1-\beta)Y-s]-\omega\eta_r\beta Y\}}{4\{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y\}^2}\\ &= -\frac{\eta_r\beta Y(p+Y-c)[p+(1-\beta)Y-s]}{2\{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y\}^2} < 0\end{aligned}$$

Therefore, w_n^* decreases in η_m.

As mentioned previously, a lower confidence level indicates a higher risk aversion degree. Proposition 4.1 reveals that the effects of the two players' risk attitudes and the epidemic on the equilibrium under the NBF framework are similar to those under the Stackelberg game. The NBF equilibrium order quantity also decreases in connection with either the manufacturer's or the retailer's risk aversion degree. When both the NEV manufacturer and retailer are considered risk-averse decision makers, the NBF equilibrium order quantity is doubly reduced and decreases as the manufacturer or the retailer become more risk averse. The NBF equilibrium wholesale price also decreases in connection with the retailer's risk aversion degree while increasing in relation to the manufacturer's. The reason is the same as that under the Stackelberg game: when the retailer/manufacturer becomes more risk averse, the wholesale price should be increased/decreased to attract the more conservative retailer/manufacturer to participate in the business.

Under the cooperative NBF framework, the manufacturer and the retailer have a joint aim to increase the supply chain's total payoff. Consequently, the equilibrium order quantity is derived by maximizing the objective function in Eq. 4.1 and is not related to the bargaining power contrast. The other equilibrium solution, the wholesale price, depends on the two players' bargaining powers.

Proposition 4.2. *Under the NBF framework, the equilibrium wholesale price decreases in connection with the retailer's bargaining power.*

Proof. According to Eq. 4.3, taking the first-order derivative of w_n^* with respect to ω, we obtain

$$\frac{\partial w_n^*}{\partial \omega} = -(p+Y-c) - \frac{(p+Y-c)\{-\eta_m[p+(1-\beta)Y-s]-\eta_r\beta Y\}}{2\{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y\}} = -\frac{p+Y-c}{2} < 0$$

Therefore, w_n^* decreases in ω.

This result is intuitive, because the retailer will have a more advantageous position in the bargaining procedure and ask for a lower wholesale price to strive for a higher profit if her bargaining power increases. Similarly, when the retailer's bargaining power is lowered, meaning the manufacturer's bargaining power increases, the equilibrium wholesale price will be higher, and the manufacturer will profit from that. That is why an NEV player always tries his/her best to increase his/her bargaining power by promoting his/her competitiveness in the aspects of scale, effectiveness, reputation, market shares, and so on.

4.2 Profit allocation under the Nash bargaining framework

Similar to the Stackelberg case, we attempted to examine the effects of the players' risk attitudes, the government subsidy, and the bargaining power contrast on the players' profit shares in the NEV manufacturer-retailer system under the NBF framework. To this end, we first calculated the retailer's profit share under the NBF equilibrium ρ_{rn} according to Eq. 3.10, shown in the following theorem.

Theorem 4.2. *Under the NBF equilibrium, the retailer's profit share is:*

$$\rho_{rn} = \frac{(1+\omega-\eta_r)\eta_m[p+(1-\beta)Y-s]+\omega\eta_r\beta Y}{2\{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y\} - \eta_r\eta_m(p+Y-s)} \tag{4.9}$$

Proof. Under the NBF equilibrium (q_n^*, w_n^*), the expected profits for the retailer, the manufacturer, and the entire system, respectively, denoted as $E\pi_r(q_n^*, w_n^*)$, $E\pi_m(q_n^*, w_n^*)$, and $E\pi(q_n^*, w_n^*)$, can be obtained by replacing (q_s^*, w_s^*) with (q_n^*, w_n^*) in Eq. 3.12, Eq. 3.13, and Eq. 3.14. Therefore, we have

$$E\pi_r(q_n^*, w_n^*) = [p + (1-\beta)Y - w_n^*]q_n^* - \frac{p + (1-\beta)Y - s}{2B}q_n^*2 \tag{4.10}$$

$$E\pi_m(q_n^*, w_n^*) = (w_n^* + \beta Y - c)q_n^* - \frac{\beta Y}{2B}q_n^*2 \tag{4.11}$$

$$E\pi(q_n^*, w_n^*) = (p + Y - c)q_n^* - \frac{p + Y - s}{2B}q_n^*2 \tag{4.12}$$

Recalling Eq. 4.7 and Eq. 4.8, we obtain

$$\begin{aligned} E\pi(q_n^*, w_n^*) &= (p + Y - c)q_n^* - \frac{p + Y - s}{2B}q_n^*2 \\ &= (p + Y - c)q_n^* - \frac{p + Y - s}{2B}\frac{B\eta_r\eta_m(p + Y - c)}{\eta_m[p + (1-\beta)Y - s] + \eta_r\beta Y}q_n^* \\ &= (p + Y - c)q_n^* - \frac{\eta_r\eta_m(p + Y - c)(p + Y - s)}{2\{\eta_m[p + (1-\beta)Y - s] + \eta_r\beta Y\}}q_n^* \end{aligned}$$

$$\begin{aligned} E\pi_r(q_n^*, w_n^*) &= [p + (1-\beta)Y - w_n^*]q_n^* - \frac{p + (1-\beta)Y - s}{2B}q_n^*2 \\ &= \left[\omega(p + Y - c) + \frac{(p + Y - c)\{(1-\omega)\eta_m[p + (1-\beta)Y - s] - \omega\beta\eta_r Y\}}{2\{\eta_m[p + (1-\beta)Y - s] + \eta_r\beta Y\}} - \frac{\eta_r\eta_m(p + Y - c)[p + (1-\beta)Y - s]}{2\{\eta_m[p + (1-\beta)Y - s] + \eta_r\beta Y\}}\right]q_n^* \\ &= \frac{(p + Y - c)\{(1 + \omega - \eta_r)\eta_m[p + (1-\beta)Y - s] + \omega\eta_r\beta Y\}}{2\{\eta_m[p + (1-\beta)Y - s] + \eta_r\beta Y\}}q_n^* \end{aligned}$$

Finally, ρ_{rn} can be calculated with Eq. 3.10.

$$\begin{aligned} \rho_{rn} &= \frac{E\pi_r(q_n^*, w_n^*)}{E\pi(q_n^*, w_n^*)} \\ &= \frac{\dfrac{(p + Y - c)\{(1 + \omega - \eta_r)\eta_m[p + (1-\beta)Y - s] + \omega\eta_r\beta Y\}}{2\{\eta_m[p + (1-\beta)Y - s] + \eta_r\beta Y\}}q_n^*}{(p + Y - c)q_n^* - \dfrac{\eta_r\eta_m(p + Y - c)(p + Y - s)}{2\{\eta_m[p + (1-\beta)Y - s] + \eta_r\beta Y\}}q_n^*} \\ &= \frac{(1 + \omega - \eta_r)\eta_m[p + (1-\beta)Y - s] + \omega\eta_r\beta Y}{2\{\eta_m[p + (1-\beta)Y - s] + \eta_r\beta Y\} - \eta_r\eta_m(p + Y - s)} \end{aligned}$$

Under the NBF equilibrium, the retailer takes over ρ_{rn} proportion of the system profit, while the remaining $(1 - \rho_{rn})$ proportion belongs to the manufacturer, where ρ_{rn} is given by Theorem 4.2. Similar to the Stackelberg model, Eq. 4.9 shows that, under the NBF framework, the players' profit shares are also influenced by both players' confidence levels when other variables are determined. We provide the following proposition to address this issue.

Proposition 4.3. *Under the NBF equilibrium, the retailer's profit share decreases in connection with her confidence level and increases in connection with the manufacturer's.*

Proof. Recalling Eq. 4.9, take the first-order derivative of ρ_{rn} with respect to η_r, and we obtain

$$\begin{aligned} \frac{\partial\rho_{rn}}{\partial\eta_r} &= \frac{\{-\eta_m[p + (1-\beta)Y - s] + \omega\beta Y\}\{2\{\eta_m[p + (1-\beta)Y - s] + \eta_r\beta Y\} - \eta_r\eta_m(p + Y - s)\} - \{(1 + \omega - \eta_r)\eta_m[p + (1-\beta)Y - s] + \omega\eta_r\beta Y\}\{2\beta Y - \eta_m(p + Y - s)\}}{\{2\{\eta_m[p + (1-\beta)Y - s] + \eta_r\beta Y\} - \eta_r\eta_m(p + Y - s)\}^2} \\ &= \frac{-2\beta Y\eta_m(1-\eta_m)[p + (1-\beta)Y - s] - \eta_m^2(1-\omega)(p + Y - s)[p + (1-\beta)Y - s]}{\{2\{\eta_m[p + (1-\beta)Y - s] + \eta_r\beta Y\} - \eta_r\eta_m(p + Y - s)\}^2} < 0 \end{aligned}$$

Therefore, ρ_{rn} decreases in η_r.

Similarly, take the first-order derivative of ρ_{rn} with respect to η_m, and we obtain

$$\frac{\partial \rho_{rn}}{\partial \eta_m} = \frac{\begin{array}{c}(1+\omega-\eta_r)[p+(1-\beta)Y-s]\{2\{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y\}-\eta_r\eta_m(p+Y-s)\}\\ -\{(1+\omega-\eta_r)\eta_m[p+(1-\beta)Y-s]+\omega\eta_r\beta Y\}\{2[p+(1-\beta)Y-s]-\eta_r(p+Y-s)\}\end{array}}{\{2\{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y\}-\eta_r\eta_m(p+Y-s)\}^2}$$
$$= \frac{2\eta_r\beta Y(1-\eta_r)[p+(1-\beta)Y-s]+\omega\eta_r^2\beta Y(p+Y-s)}{\{2\{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y\}-\eta_r\eta_m(p+Y-s)\}^2}>0$$

Therefore, ρ_{rn} increases in η_m.

The conclusion about the effects of the two players' risk attitudes and the epidemic on the players' shares is the same as that under the Stackelberg game: under the NBF equilibrium, the retailer's profit share increases in connection with her risk aversion degree yet decreases in connection with the manufacturer's. Such a conclusion is also symmetrically applicable for the manufacturer; the epidemic also heightens either player's risk aversion degree and, thus, increases his/her profit share. We can conclude that, whether the two risk-averse players participate in the Stackelberg game or the NBF procedure, a more risk-averse player always occupies a larger profit share. Also, we further conducted numerical experiments to clarify the effect of the risk aversion degree on a player's absolute profit under the NBF framework—to be discussed at a later point.

Similar to Proposition 3.3, we also examined the effect of the government subsidy on the players' profit shares under the NBF framework. The relationship between the subsidy and the retailer's profit share under the NBF equilibrium is provided as follows.

Proposition 4.4. *Under the NBF equilibrium, the retailer's profit share decreases in connection with the government subsidy.*

Proof. Recalling Eq. 4.9, take the first-order derivative of ρ_{rn} with respect to Y, and we obtain

$$\frac{\partial \rho_{rn}}{\partial Y} = \frac{\begin{array}{c}\{(1+\omega-\eta_r)\eta_m(1-\beta)+\omega\eta_r\beta\}\{2\{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y\}-\eta_r\eta_m(p+Y-s)\}\\ -\{(1+\omega-\eta_r)\eta_m[p+(1-\beta)Y-s]+\omega\eta_r\beta Y\}\{2\{\eta_m(1-\beta)+\eta_r\beta\}-\eta_r\eta_m\}\end{array}}{\{2\{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y\}-\eta_r\eta_m(p+Y-s)\}^2}$$
$$= \frac{\beta\eta_r\eta_m(p-s)[-(2-\eta_m)(1-\eta_r)+(\eta_m-\eta_r)\omega]}{\{2\{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y\}-\eta_r\eta_m(p+Y-s)\}^2}$$

Note that when $0<\eta_r<\eta_m\le 1$ and $\omega\le 1$, there is

$$-(2-\eta_m)(1-\eta_r)+(\eta_m-\eta_r)\omega \le -(2-\eta_m)(1-\eta_r)+(\eta_m-\eta_r) = -(1-\eta_m)(2-\eta_r)\le 0$$

Therefore, $\partial\rho_{rn}/\partial Y<0$ and ρ_{rn} decreases in Y.

Proposition 4.4 shows that the effect of the government subsidy on the players' profit shares is also the same as that under the Stackelberg game: under the NBF equilibrium, a higher subsidy also increases the retailer's profit share yet decreases the manufacturer's. We therefore conclude that the government subsidy can alter the players' profit shares under either the Stackelberg game or the NBF framework. The government can choose to preferentially support the NEV manufacturer/retailer by offering a higher/lower subsidy. Also, we further analyzed the effect of the government subsidy on a player's absolute profit under the NBF framework through numerical experiments.

Besides the players' risk attitudes and the government subsidy, the bargaining power contrast also affects the players' profit shares under the NBF framework. The following proposition focuses on this issue.

Proposition 4.5. *Under the NBF equilibrium, the retailer's profit share increases with respect to her bargaining power.*

Proof. Recalling Eq. 4.9, *take* the first-order derivative of ρ_{rn} with respect to ω, and we obtain

$$\frac{\partial \rho_{rn}}{\partial \omega} = \frac{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y}{2\{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y\}-\eta_r\eta_m(p+Y-s)}>0$$

Therefore, ρ_{rn} increases in ω.

A player with a higher bargaining power will have a more advantageous position in the bargaining procedure and obtain a larger profit share. According to Eq. 4.7 and Eq. 4.12, the bargaining power contrast does not affect the equilibrium order quantity nor the supply chain's total profit. Thus, the bargaining power contrast can change the players' profit shares by altering the equilibrium wholesale price. Moreover, a larger profit share indicates a higher profit since the system profit keeps constant with respect to the bargaining power contrast.

Additionally, it is worth emphasizing that $\omega = 1/2$ is a special case indicating that the retailer and the manufacturer have equal bargaining power. In this case, the above results hold unconditionally.

4.3 A comparison between Stackelberg game and Nash bargaining

We have derived the equilibrium solutions about the order quantity and the wholesale price under both the Stackelberg game and the NBF framework. This subsection compares the results of these two models.

Theorem 4.3. *Under the NBF equilibrium, the equilibrium order quantity and the supply chain's total profit dominate those under the Stackelberg game, i.e.,* $q_n^* > q_s^*$ *and* $E\pi(q_n^*, w_n^*) > E\pi(q_s^*, w_s^*)$.

Proof. According to Eq. 3.7 and Eq. 4.7, we can easily find that

$$q_n^* = \frac{B\eta_r\eta_m(p+Y-c)}{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y} > \frac{B\eta_r\eta_m(p+Y-c)}{2\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y} = q_s^*$$

The integrated supply chain's centralized optimal order quantity is

$$q^* = \frac{B(p+Y-c)}{(p+Y-s)}$$

According to Proposition 4.1, q_n^* increases in η_r or η_m; so, we have

$$q^* = \frac{B(p+Y-c)}{(p+Y-s)} \geq \frac{B\eta_r\eta_m(p+Y-c)}{\eta_m[p+(1-\beta)Y-s]+\eta_r\beta Y} = q_n^* > q_s^*$$

Though the supply chain's total profit $E\pi(q, w)$ increases in q on, $(0, q^*]$ it has nothing to do with the wholesale price. Therefore, we obtain $E\pi(q_n^*, w_n^*) > E\pi(q_s^*, w_s^*)$.

Compared to the Stackelberg game, the NBF framework brings about a larger order quantity as well as a higher system profit. Under the cooperative NBF framework, the retailer and the manufacturer collaborate to achieve equilibrium to maximize the supply chain's total payoff and then split it according to their bargaining powers. Under the uncooperative Stackelberg game, the two players respectively make decisions to maximize their individual payoffs without consideration of the supply chain's total payoff. The manufacturer and the retailer negotiate about the equilibrium by competing with each other, which is unbeneficial for the entire system. Consequently, with systematic consideration, the NEV manufacturer and retailer should participate in the NBF procedure rather than the Stackelberg game. Within the epidemic environment, both players are considered risk averse; therefore, the NBF framework is advantageous for promoting NEV production/sale quantity and enhancing the supply chain's overall profit. We provide further analysis later by numerical experiments to show how to ensure both players' profits higher so that both prefer the NBF framework.

5 Numerical experiments

So far, we have derived the equilibriums as well as the corresponding profit shares under the Stackelberg game and the NBF framework and analyzed the effects of some relevant elements, such as players' risk attitudes, the government subsidy, and the bargaining power. In this section, we have carried out numerical experiments to further clarify the effects of these significant elements on the equilibrium order quantity and the profit allocation under different negotiation frameworks. Comparisons of the results under the two negotiation frameworks illustrate the superiority of the NBF model more intuitively. These findings may provide guidelines for sustainably maintaining the NEV manufacturer-retailer system by balancing the profit allocation between the retailer and the manufacturer under different negotiation frameworks.

Related parameters are theoretically assumed as follows: the NEV market demand is subject to a uniform distribution on $[0, 1000]$, the per-unit retail price is $p = 80000$, the per-unit production cost is $c = 100000$, the per-unit salvage value is $s = 40000$, and the manufacturer's subsidy-sharing proportion is $\beta = 0.2$.

Based on the above numerical assumptions, we first illustrated the effects of some parameters on the equilibrium order quantities under the Stackelberg game and the NBF framework. Given $Y = 40000$ and $\eta_m = 0.9$, Figure 1 describes that the equilibrium order quantities under both negotiation frameworks increase according to the retailer's confidence level η_r. Given $Y = 40000$ and $\eta_r = 0.8$, Figure 2 displays that the equilibrium order quantities under both negotiation frameworks slightly increase according to the manufacturer's confidence level η_m. The confidence level of either the NEV manufacturer or retailer goes lower considering the impact of the COVID-19 epidemic, thus the equilibrium order quantities under both negotiation frameworks are reduced and the retailer's risk attitude brings about a lager influence. Given $\eta_r = 0.8$ and $\eta_m = 0.9$, Figure 3 shows that the equilibrium order quantities under both negotiation frameworks increase according to the government subsidy Y. It is indicated that the government subsidy increasing can improve the equilibrium order quantities under both negotiation frameworks so as to offset the negative impact raised by the COVID-19 epidemic. In addition, these three figures all demonstrate that the equilibrium order quantity under the NBF framework is always larger than that under the Stackelberg game. Thus, it is verified that the superior NBF framework can promote NEV sales no matter how the relevant parameters vary. Moreover, we can also observe that the promoting effect of the NBF framework compared to the Stackelberg game is augmented when the government subsidy increases or when either player becomes less risk averse. We can conclude that when the COVID-19 epidemic eliminates or the government subsidy degeneration is delayed, the superiority of the NBF framework is extended compared to the Stackelberg game.

As mentioned before, since players' risk attitudes, the epidemic, and the government subsidy affect the equilibrium order quantity and further affect the supply chain's total profit, the players' profit shares cannot directly reflect the system profit allocation. Next, we conducted numerical experiments to address the effects of some significant parameters on the profit allocation under the Stackelberg game and the NBF framework respectively. Under the Stackelberg equilibrium provided in Theorem 3.2, the profits of the retailer, the manufacturer, and the

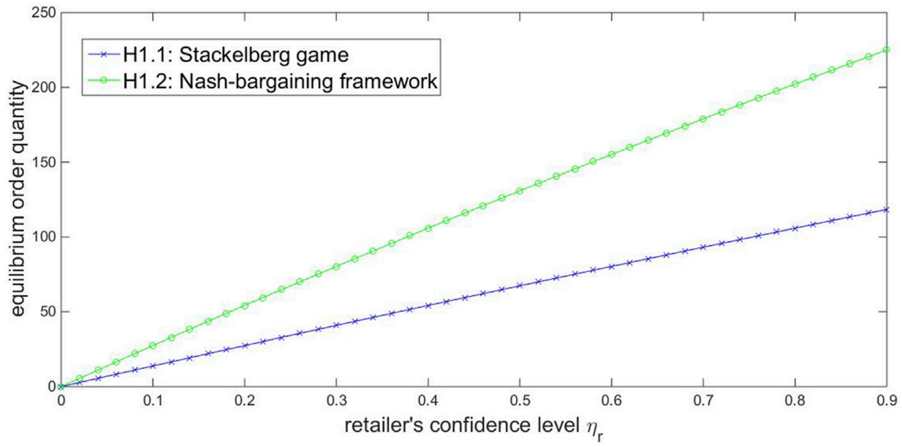

FIGURE 1
Impact of η_r on the order quantity (Y = 40000; η_m = 0.9).

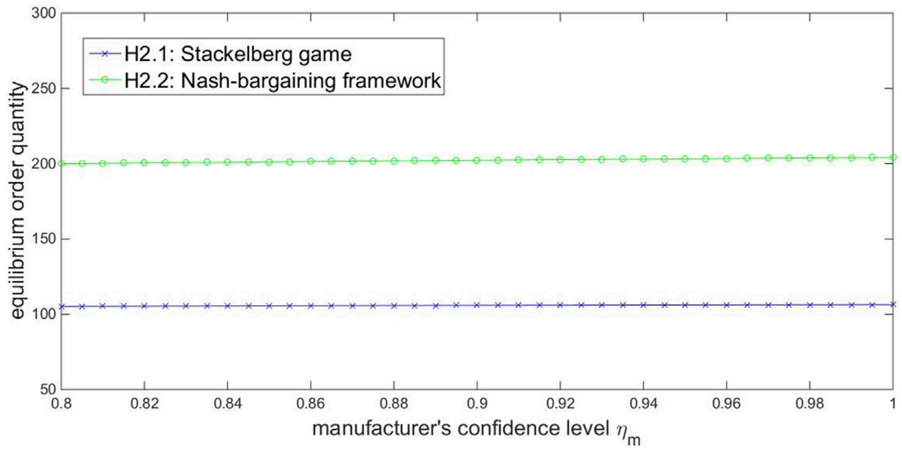

FIGURE 2
Impact of η_m on the order quantity (Y = 40000; η_r = 0.8).

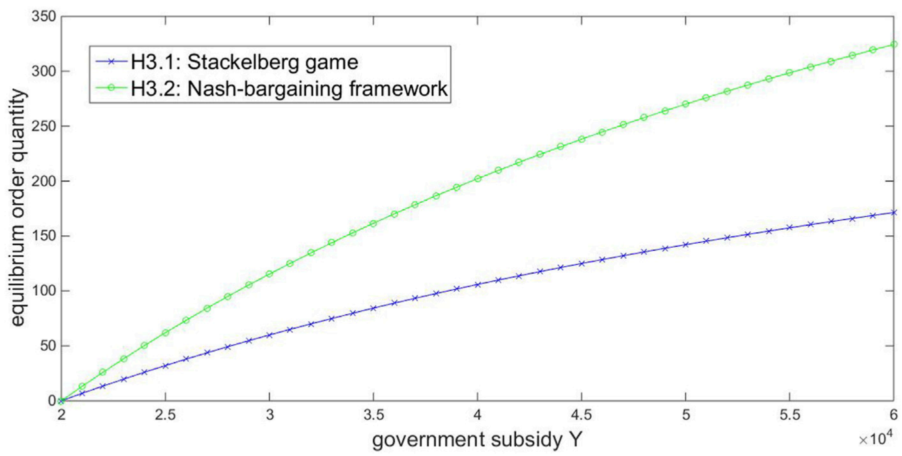

FIGURE 3
Impact of Y on the order quantity (η_r = 0.8; η_m = 0.9).

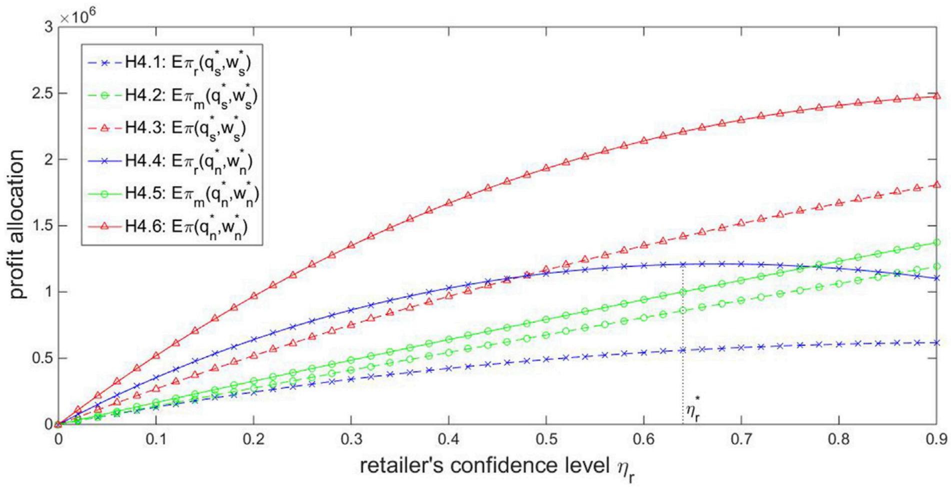

FIGURE 4
Impact of η_r on the profit allocation (Y = 40000; η_m = 0.9; ω = 0.4).

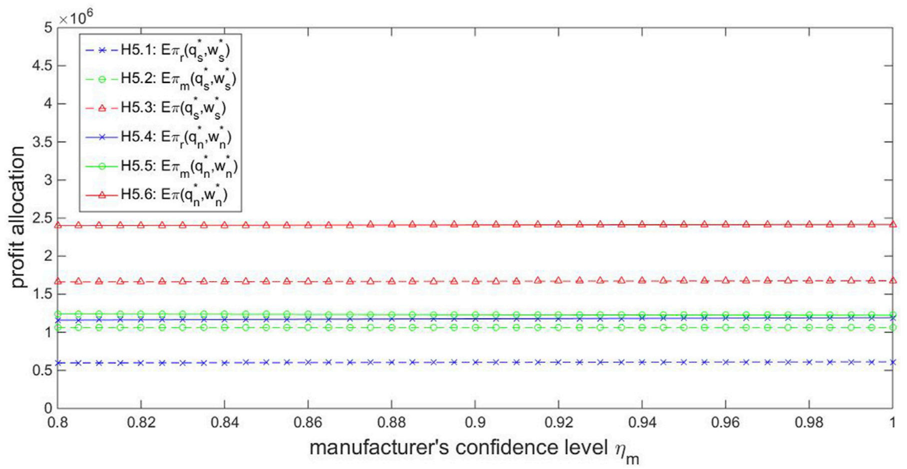

FIGURE 5
Impact of η_m on the profit allocation (Y = 40000; η_r = 0.8; ω = 0.4).

entire system can be calculated by Eq. 3. 12, Eq. 3.13, and Eq. 3.14, respectively. The profits of the retailer, the manufacturer, and the entire system under the NBF equilibrium provided in Theorem 4.1 can be calculated by Eq. 4.10, Eq. 4.11, and Eq. 4.12, respectively.

Based on these results, we next tried to compare the effect of the retailer's risk attitude on the system profit allocation under different negotiation frameworks. Given Y = 40000, η_m = 0.9, and ω = 0.4, we can see in Figure 4 that the profits of the retailer, the manufacturer, and the entire system under the Stackelberg game all increase according to the retailer's confidence level η_r. Recalling Proposition 3.1, a retailer's higher confidence level enlarges the equilibrium order quantity and further leads to a higher profit for the entire system, according to the proof of Theorem 4.3. Proposition 3.2 indicates that a higher η_r reduces the retailer's profit share while increasing the manufacturer's. Thus, as η_r increases, the manufacturer's profit will be augmented because both the supply chain's total profit and the manufacturer's profit share increase simultaneously. For the retailer, when η_r increases, although her profit share is reduced, she gains more from the system profit increase. Thus, the retailer's profit also increases in η_r, but the growth rate is lower than the manufacturer's. Figure 4 also shows that both the manufacturer's and the entire system's profits under the NBF framework increase in connection with the retailer's confidence level η_r. Recalling Proposition 4.1, a retailer's higher confidence level enlarges the equilibrium order quantity and further leads to a higher profit for the entire system according to the proof of Theorem 4.3. Proposition 4.3 indicates that a higher η_r reduces the retailer's profit share while increasing the manufacturer's. Thus, as η_r increases, the manufacturer's profit will be enhanced because both the supply chain's total profit and the manufacturer's profit share increase simultaneously. For the retailer, the effect of η_r under the NBF framework is very different from

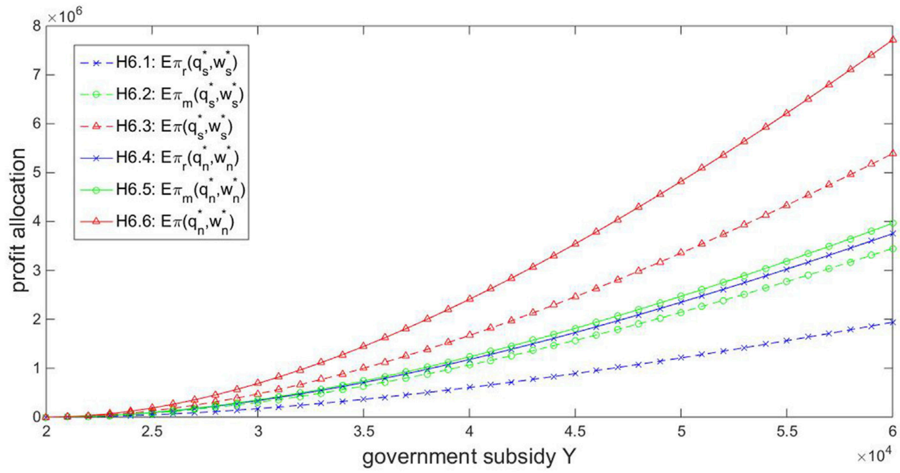

FIGURE 6
Impact of Y on the profit allocation (η_r = 0.8; η_m = 0.9; ω = 0.4).

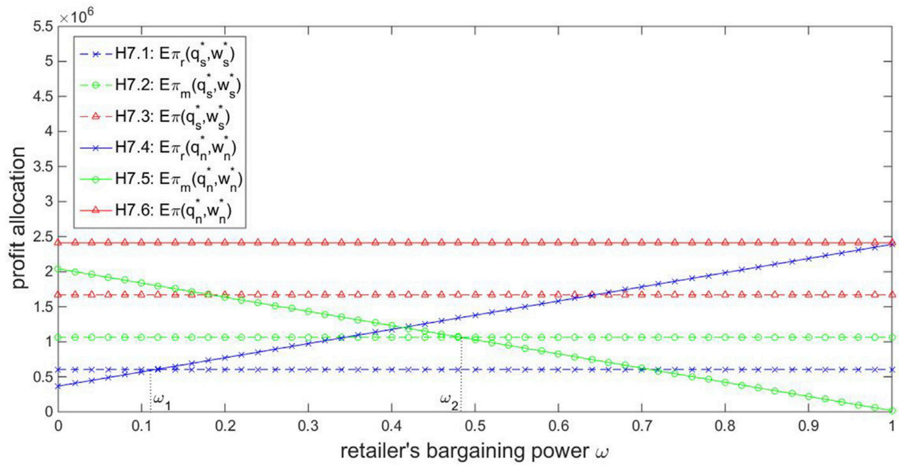

FIGURE 7
Impact of ω on the profit allocation (Y = 40000; η_r = 0.8; η_m = 0.9).

that under the Stackelberg game. Under the NBF equilibrium, if the manufacturer's confidence level is determined, an optimal confidence level exists for the retailer to maximize her profit (η_r^* marked in Figure 4). If $\eta_r < \eta_r^*$, when η_r increases, although the retailer's profit share is reduced, she benefits more from the system profit increase and her profit also increases. If $\eta_r > \eta_r^*$, when η_r increases, the retailer's profit share is reduced, and she cannot gain sufficiently from the system profit increase, and therefore her profit decreases.

Then we paid attention to the effect of the manufacturer's risk attitude. Given Y = 40000, η_r = 0.8, and ω = 0.4, Figure 5 shows how the profits of the retailer, the manufacturer, and the entire system vary in connection with the manufacturer's confidence level η_m under different negotiation frameworks. We can observe that the change of η_m brings about a very slight influence on the profit allocation under either the Stackelberg game or the NBF framework. Recalling the reasonable model assumption $0 < \eta_r < \eta_m \leq 1$, note that the manufacturer's confidence level is usually so high that each player's profit under either negotiation framework is almost unaffected.

As a major characteristic of the NEV industry, the government subsidy plays an important role in the system profit allocation. Given η_r = 0.8, η_m = 0.9, and ω = 0.4, Figure 6 shows the effect of Y on the profit allocation under the Stackelberg game and the NBF framework. We can see that the effects of Y on the profit allocation under the different negotiation frameworks are almost identical. An increase of Y enhances the profits of the retailer, the manufacturer, and the entire system simultaneously. As a profit source outside the supply chain, the government subsidy always benefits both players and the entire system. Proposition 3.3 and Proposition 4.4 indicate that a higher Y reduces the retailer's profit share while increasing the manufacturer's under both negotiation frameworks. Thus, as Y increases, the manufacturer's profit will be augmented because the supply chain's total profit and the manufacturer's profit share increase simultaneously. For the retailer, when Y increases, although her profit share is reduced, she benefits more from the system profit increase. Thus, the retailer's profit also increases in Y, but the growth rate is lower than the manufacturer's.

In practice, the government subsidy is decreasing continuously nowadays. Figure 6 shows that both players' profits will be reduced as the subsidy diminishes. Since a lower Y reduces the manufacturer's profit share while increasing the retailer's, we can know that the manufacturer will suffer more from the decreasing subsidy. We summarize such a conclusion as follows.

Observation 6.1. *As the government subsidy decreases, both the manufacturer's and the retailer's profits are reduced. However, the manufacturer is more severely affected by the decreasing subsidy.*

The diminishing subsidy shocks the manufacturer more seriously, and the epidemic further exacerbates this negative effect. Within the epidemic environment, China has delayed the NEV subsidy decrease, which has been more beneficial for the manufacturer. In addition, the government could support the NEV manufacturer in other aspects to enhance his bargaining power, or the manufacturer could share more of the subsidy, consequently, to help the manufacturer offset the subsidy decrease and the epidemic effect.

We can observe two important common points in Figures 4–6. One is that, under the Stackelberg equilibrium, the manufacturer always obtains a higher profit than the retailer. This is because the manufacturer acts as a leader while the retailer is a follower in the Stackelberg game. Based on the expectation about the retailer's order quantity, the manufacturer can make the final decision about the wholesale price to maximize his CVaR performance. Thus, the manufacturer has an advantageous position and occupies a larger part of the system profit. The other common point in Figures 4–6 is that the retailer's, the manufacturer's and the entire system's profits under the NBF framework are all higher than those under the Stackelberg game no matter how the relevant parameters vary. Thus, the superiority of the NBF framework for both NEV players is further verified. The noncooperative competition between the manufacturer and the retailer in the Stackelberg game is unbeneficial for their own profits and the entire system, while the cooperative NBF framework benefits both players as well as the entire system.

In regard to the effect of the bargaining power on the profit allocation under the NBF framework, Proposition 4.5 and related discussions pointed out that the players' bargaining power contrast decides their profits obtained by affecting their profit shares. For further analysis, given $Y = 40000$, $\eta_r = 0.8$, and $\eta_m = 0.9$, we provide Figure 7 to illustrate how the retailer's, the manufacturer's, and the entire system's profits vary in connection with the retailer's bargaining power ω. As the comparison object, the profit allocation under the Stackelberg game, which has nothing to do with ω, is also involved. We can observe in Figure 7 that, under the NBF framework, with the increase of ω, the retailer's profit is enlarged while the manufacturer's profit is reduced, and the total profit of the supply chain stays invariant. Obviously, a higher degree of bargaining power brings about a higher profit for either player. However, if ω is lower than a certain level ω_1 (marked in Figure 7), the retailer will obtain a lower profit under the NBF framework than the Stackelberg game and thus prefer to participate in the Stackelberg game. On the other hand, if ω exceeds a certain level ω_2 (also marked in Figure 7), the manufacturer will obtain a lower profit under the NBF framework than the Stackelberg game and thus prefer to participate in the Stackelberg game. In other words, ω should fall within a certain scope (ω_1, ω_2) to ensure both players obtain higher profits under the NBF framework than the Stackelberg game and therefore choose to participate in the NBF procedure. Otherwise, either the manufacturer or the retailer will choose to participate in the Stackelberg game, which hurts the other player's and the entire system's profits. We summarized such an observation as follows, offering a principle on the bargaining power contrast between the two players to sustainably maintain the NEV manufacturer-retailer system under the superior NBF framework.

Observation 6.2. *In order to sustainably maintain the NEV manufacturer-retailer system under the superior NBF framework, the retailer's bargaining power should fall within the scope* (ω_1, ω_2).

6 Concluding remarks

In this paper, we investigated the negotiation problem in an NEV manufacturer-retailer system with the Stackelberg model and the NBF framework. Considering the impact of the COVID-19 epidemic, supposing that the NEV manufacturer and retailer are both risk-averse decision makers with the CVaR criterion, we derived the respective equilibriums about the order quantity and the wholesale price under different negotiation frameworks. We then evaluated the two players' profit shares and identified some elements affecting the profit allocation. With numerical experiments, we further compared the effects of these elements on the equilibrium order quantity and the system profit allocation under the two negotiation frameworks.

Under the Stackelberg equilibrium with the manufacturer as the leader, for either player, the increase of his/her risk aversion degree can lead to a higher profit share for him/her. That means the players' risk attitudes can change their relative powers. With the consideration of the epidemic, a more sensitive player's risk aversion degree is enlarged more, which, in turn, leads to a larger profit share increase for that player. However, because the decrease of either player's risk aversion degree creates a higher profit for the entire system, the corresponding numerical experiments showed that both players can finally obtain higher profits when either of them becomes less risk averse (the effect of the manufacturer's risk aversion degree is very slight). As an outside element, the government subsidy ensures that both players obtain positive profits no matter how it is shared between the players. Moreover, the subsidy can also affect the players' relative powers. A subsidy increase results in a higher profit share for the manufacturer and a lower share for the retailer. However, since the subsidy increase brings about a higher profit for the entire system, the corresponding numerical experiment shows that both players can benefit from the subsidy increase.

Under the NBF equilibrium, just like in the Stackelberg case, the increase of a player's risk aversion degree can lead to a higher profit share for him/her. The players' risk attitudes can also change their relative powers under the NBF framework, while the effect of the epidemic remains the same as in the Stackelberg game. However, because the increase of either player's risk aversion degree results in a lower profit for the entire system, a more risk-averse player perhaps cannot obtain a higher profit even though his/her profit share is enhanced. Actually, the corresponding numerical experiment demonstrated that when the manufacturer's confidence level is determined, an optimal confidence level exists for the retailer to maximize her profit. When the retailer's confidence level is determined, the manufacturer's risk attitude plays an insignificant role in affecting the profit allocation. When both players' risk attitudes are determined, the profit allocation depends on the bargaining power contrast between them. Greater bargaining power signifies a higher profit share and a larger profit for either player. The effect of the government subsidy on the profit allocation under the NBF equilibrium is the same as that under the Stackelberg case. The increase of the subsidy results in a higher profit share and a larger profit for the manufacturer. The retailer can also benefit from the subsidy increase, though her profit share is reduced. Considering the role of the government subsidy in the system profit allocation, the government can preferentially support the manufacturer/retailer by adjusting the subsidy to a higher/lower level to alter players' relative powers and profit shares. Within the epidemic environment, the manufacturer will suffer a more unfavorable effect from the subsidy degeneration that is happening nowadays and needs more government support.

Comparing the equilibrium solutions under the Stackelberg game and the NBF framework, we find that the retailer will order more NEVs and the manufacturer-retailer system will obtain a higher profit in the NBF case. With the overall consideration of the system, no matter how relevant parameters and the epidemic situation vary, the NBF framework is always beneficial for promoting NEV sales and enhancing system profit. Thus, we can conclude that the NBF framework is superior to the Stackelberg game for the NEV manufacturer-retailer system in terms of both quantity of sales and profit. Numerical experiments further demonstrated that the NBF framework is superior for either NEV player no matter how the players' risk attitudes and the government subsidy vary. The corresponding numerical experiment indicated that, only if the bargaining power contrast between players is restricted in a certain scope, both players can obtain higher profits under the NBF framework compared to the Stackelberg game. The findings may provide guidelines to maintain the sustainability of the NEV manufacturer-retailer system under the superior NBF framework within the epidemic environment.

By incorporating the risk aversion effect with the CVaR criterion, our investigation enriches the research on the negotiation mechanism in an NEV manufacturer-retailer system. By exploring the effects of some significant elements on the equilibrium order quantity and the system profit allocation under different negotiation frameworks, we have proved the superiority of the NBF framework and offered some guiding principles for the NEV win-win cooperation between the manufacturer and the retailer, which may help to promote the sustainable development of NEV commerce within the epidemic environment.

From the perspective of the NEV industry practice, the following policy suggestions or countermeasures are put forward. ①The risk aversion degree of either the NEV manufacturer or retailer has been increased by the shock of the COVID-19 epidemic, thus the government subsidy degeneration should be appropriately delayed and the policy stability should be maintained. ②The subsidy degeneration can be continued when the COVID-19 epidemic dissipates, but subsidy policies should be adapted to local conditions, and local government subsidy can be used to improve the market vitality in certain areas which are severely affected by the COVID-19 epidemic. ③The subsidy sharing proportion should be appropriately tilted to the manufacturer, which helps to alleviate the larger pressure on the manufacturer raised by the subsidy degeneration and the COVID-19 epidemic and stimulate the vitality of the entire NEV market, but at the same time, the overall balance of the manufacturer-retailer system must be taken into account.

Although the COVID-19 epidemic has gradually subsided, the proposed NEV negotiation model under the CVaR criterion and corresponding results still have reference significance for the equilibrium and profit allocation between the risk-averse NEV retailer and manufacturer under special situations in the future. However, many questions remain unanswered. For example, we use the confidence level in the CVaR model to explain the epidemic effect, which yielded that the epidemic effect is not very conspicuous. In future work, our research direction is to involve an epidemic correction factor and extend the model to a case in which the market demand is influenced by an endogenous price or the retailer's sales effort. Additionally, based on the investigation on the NEV single-channel supply chain in this paper, we are also interested in the negotiation mechanism of an NEV dual-channel supply chain (traditional retail channel and online channel). China's NEV market has developed rapidly in recent years, but after the subsidy decline, the negotiation equilibrium and profit allocation between the NEV retailer and manufacturer will change accordingly, which is also worth further exploration.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

SH: Formal Analysis, Funding acquisition, Investigation, Methodology, Writing–original draft. YC: Data curation, Software, Validation, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2023.1286381/full#supplementary-material

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Nomenclature

For the readers' convenience, we provide a nomenclature to show the notations throughout this paper.

Notations	Meanings
c	per-unit production cost
p	per-unit retail price
s	per-unit salvage value
w	per-unit wholesale price
q	retailer's order quantity
Y	per-unit government subsidy
β	NEV manufacturer's subsidy-sharing proportion
x	market demand
$f(x)$	probability density function of demand
$F(x)$	cumulative distribution function of demand
η_r	retailer's confidence level
η_m	manufacturer's confidence level
w_i^*	equilibrium wholesale price, $i = s$ (for Stackelberg case), n (for Nash case)
q_i^*	equilibrium order quantity, $i = s$ (for Stackelberg case), n (for Nash case)
ρ_{ri}	retailer's profit share, $i = s$ (for Stackelberg case), n (for Nash case)
ω	NEV retailer's bargaining power in Nash bargaining framework
π_r	retailer's profit
π_m	manufacturer's profit
π	manufacturer-retailer system's profit
E	expectation operator
R	real number set
B	upper bound of the demand's uniform distribution

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Extended reality implementation possibilities in direct energy deposition-arc

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The state-of-the-art cleaner smart manufacturing process in the metal industry is the direct energy deposition-arc (DED-arc) process, which has emerged as an energy-efficient method for producing complex geometry metallic constructions. Process flexibility, material-consumption efficiency and high performance have drawn attention amongst both academics and industry, as DED-arc presents an ecologically viable alternative to traditional manufacturing techniques. Concurrently, the parallel emergence of extended reality (XR) technology has unveiled multiple novel possibilities for enhancing the sustainable development of DED-arc processing toward cleaner manufacturing. However, an evident knowledge gap exists concerning the integration of XR into the DED-arc process chain. This research aims to solve this problem by systematically exploring the potential of implementing XR technology within the DED-arc framework. Therefore, this study identifies through a literature review the technological difficulties and prospects associated with merging XR and DED-arc. Subsequently, a series of practical experiments are executed, presenting various applications of XR within the DED-arc process chain. The current research makes several noteworthy contributions to the practical understanding of how XR can be integrated into the DED-arc manufacturing process. Technological challenges are discussed, while the potential benefits of XR adoption in the DED-arc process chain are illuminated in practical applications.

KEYWORDS

direct energy deposition-arc, additive manufacturing, DED, virtual reality, augmented reality, extended reality, mixed reality, DED-arc

1 Introduction

The global aim for the development of a more clean and sustainable manufacturing process has recently shifted a significant amount of enthusiasm toward the direct energy deposition-arc (DED-arc, also sometimes referred to as wire arc additive manufacturing or WAAM). Generally, the DED-arc process combines the advanced manufacturing possibilities of additive manufacturing (AM) with the productivity and flexibility of robotic welding, thus, offering many significant and novel opportunities to reduce environmental impact over to traditional manufacturing methods (Liu et al., 2020; Cunha et al., 2021; Raut and Taiwade, 2021). The advanced manufacturing possibilities of DED-arc are typically considered as the ability to build near-net-shape parts with complex geometry and layer-by-layer, as well as using a wide variety of metallic materials. This gives a significant improvement to the energy-efficiency and sustainability of manufacturing, through avoiding redundant material usage, ability to produce optimized structures as well as reduction of emissions of processing

(Shah et al., 2023). Furthermore, the general economic advantages of DED-arc over traditional manufacturing methods, such as casting, machining and forging, can be viewed as savings in raw material, reduction of requirements for special tooling and increased productivity. The sum of these factors is especially beneficial when low or single-batch production is considered, as the lead time can be significantly shorter meanwhile the energy-efficiency is significantly better than with traditional manufacturing methods.

On the other hand, when compared to other AM methods, DED-arc is considered to offer economic, safety and practical advantages, such as increased productivity, improved additive material utilization rate, relatively inexpensive equipment cost, capability to manufacture large-scale parts, exclusion of handling additive powder material and exclusion of laser-processing related safety aspects (Williams et al., 2016; Liu et al., 2020; Cunha et al., 2021; Raut and Taiwade, 2021; Barath Kumar and Manikandan, 2022). Naturally, as DED-arc is an emerging manufacturing process, there still exist well-known challenges in almost every step in the process chain of DED-arc. However, numerous studies and literary reviews on subjects, such as DED-arc hardware, arc processes, process planning, process control, and quality assurance, indicate that the fundamentals are well covered in the academic literature (Williams et al., 2016; Cunningham et al., 2018; Chaturvedi et al., 2021; Raut and Taiwade, 2021; Treutler and Wesling, 2021). Therefore, it is reasonable to express that DED-arc-technology is mature enough for DED-arc-research to take the next evolution step toward more sustainable and cleaner smart manufacturing.

Unquestionably, DED-arc has emerged to be the major enabling manufacturing technology towards the fourth industrial revolution, and its smart manufacturing opportunities have attracted the interest of both the manufacturing industry and the academic world (Cunningham et al., 2018; Chaturvedi et al., 2021; Liu et al., 2021; Treutler and Wesling, 2021). As mentioned above, the focus of research has shifted from process fundamentals towards the context of Industry 4.0/5.0 and smart manufacturing implementation possibilities on DED-arc (Bueno et al., 2020; Butt, 2020; Dev et al., 2020; Azarian et al., 2021; Feldhausen et al., 2022; Li et al., 2022; He et al., 2023; Kunchala et al., 2023). DED-arc enables the possibility of smart manufacturing, which can be simply defined as Internet-connected process machinery that allows monitoring and control during processing (Bueno et al., 2020; Butt, 2020; Dev et al., 2020; Azarian et al., 2021; Feldhausen et al., 2022; Li et al., 2022). Smart manufacturing can help to reduce the environmental impact of DED-arc, as it can improve production efficiency, material consumption and energy consumption (Hosseini et al., 2021; Wang et al., 2022; Shah et al., 2023). The framework of sustainable and clean smart manufacturing relies heavily on tasks such as manufacturing design and planning, which serve as input data for DED-arc processing. However, feedback from processing and process quality data is often required to optimize the set input process parameters. Feedback is achieved using process monitoring and process control (Bueno et al., 2020; DebRoy et al., 2021; Feldhausen et al., 2022; Li et al., 2022; Reisch et al., 2022). On the other hand, (Hosseini et al., 2021) have demonstrated that process simulation can efficiently reduce the environmental impact of setting up the optimal process parameters in DED-arc, thus minimizing the need for pre-processing tests.

In a thorough current state-of-art review of DED-arc research by He et al. (2023), the virtualization of DED-arc is strongly recognized as one of the next states of DED-arc research challenges. Virtualization realizes the projection of data from the physical DED-arc environment to its digital twin, also known as the virtual DED-arc environment. Ideally, a virtualized DED-arc system would enable operators to remotely monitor and possibly control the DED-arc process (He et al., 2023; Mu et al., 2023). Furthermore, the virtual environment enables process planning and validation of robot programs before advancing to production, which reduces time spent on online-programming and testing in the physical DED-arc environment and increases productivity as the set-up time can be decreased (Schuh et al., 2021; Mu et al., 2023). Moreover, virtual process validation is a more sustainable method as it does not produce any material waste and the energy consumption is insignificant compared to physical process testing and validation. However, little is known about the challenges and possibilities in the virtualization of DED-arc, although analogies to robotic welding and other additive manufacturing processes and DED processes can be drawn, the scientific understanding of the subject is still insufficient.

In recent years, extended reality (XR) technologies have emerged to enable new immersive, interactive and sometimes unique visualization possibilities to be utilized in digital twins and virtual manufacturing for tasks, such as training, simulation, process planning, process monitoring and quality assurance (Cai et al., 2020; Gong et al., 2021; Schuh et al., 2021; Osho et al., 2022; Reisch et al., 2022; Mu et al., 2023). The combination term extended reality is used to generally describe the often quite similarly functioning virtual technologies, which are virtual reality (VR), augmented reality (AR) and mixed reality (MR) (Gong et al., 2021). Studies related to the framework of manufacturing have shown that XR-technology has multiple potential applications for sustainable product development, manufacturing design, assembly, operator training and work instructions, process monitoring, process control and quality assurance and management (Ceruti et al., 2017; Cai et al., 2020; Gong et al., 2021; Schuh et al., 2021; Baroroh and Chu, 2022; Osho et al., 2022; Reisch et al., 2022; Mu et al., 2023).

Given the potential novel possibilities in DED-arc by exploiting XR, it is necessary to go through the recent developments in both subjects, XR and DED-arc. Considering these subjects, the number of papers published has grown rapidly in the recent decade, as can be seen from Figure 1. However, based on the combined search query 'TITLE-ABS-KEY("virtual" OR "augmented" OR "extended" or "mixed" AND "reality" OR "VR" OR "AR" OR "XR" OR "MR") AND "WAAM" OR "wire arc additive manufacturing" OR "DED-arc" OR "direct energy deposition-arc"' made in the Scopus database, it can be concluded that scientific knowledge in this framework is still insufficient as only a few publications on the subject exists.

There exists a lack of knowledge on possibilities and utilization of XR in DED-arc, which is crucial for further development of a clean and sustainable smart manufacturing framework for DED-arc. Therefore, to overcome the lack of knowledge on implementation possibilities of XR in DED-arc, this research assesses a study to find the characteristics of DED-arc production, and further, evaluate the possibilities and challenges of implementation of XR technology to the DED-arc process chain. First, a review of recent studies is presented to answer the questions of which process steps of DED-arc XR technologies can be implemented and what challenges exist in implementation. Then a practical study is conducted, in which multiple concrete XR applications are introduced within the DED-arc process chain and the findings are discussed reflecting on literature and practical experimentation.

In this research, the focus is on robotic DED-arc production using the metal active gas (MAG)-process and XR technology.

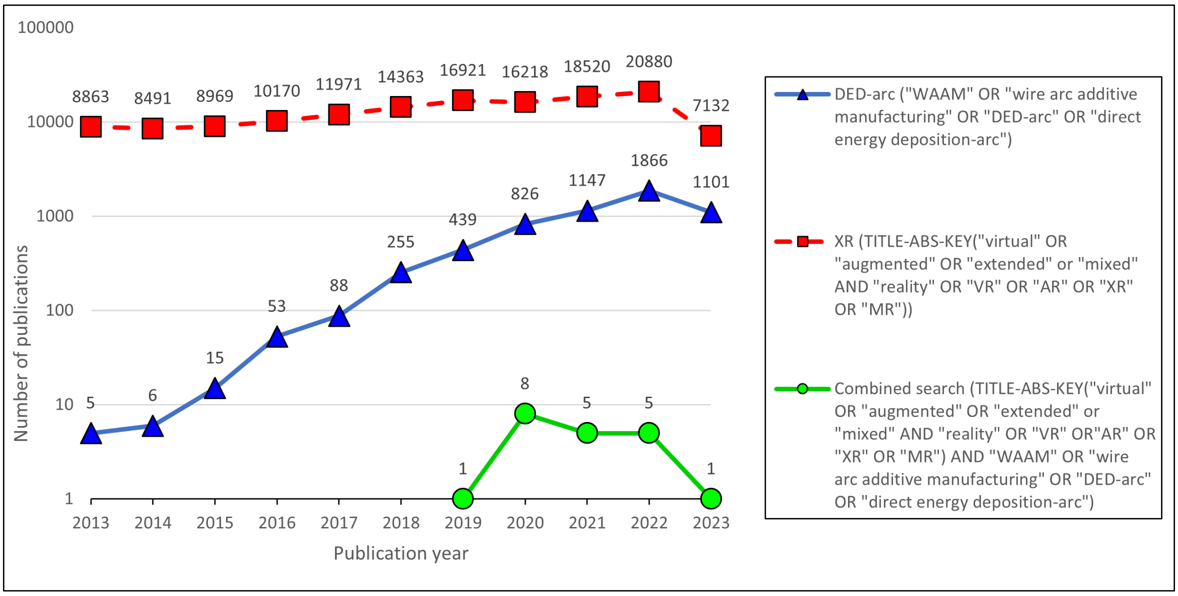

FIGURE 1
Search results for DED-arc, XR and their combined search in Scopus database for time interval 2013 to 2023.

Therefore, subjects relating to other DED or AM processes are considered out of scope, unless the focus of the study is on XR technology. Other categories out of scope are the DED-arc process optimization, process simulation and metallurgical quality-related aspects. Finally, the exact technical and software architecture realization is considered out of scope as well. Therefore, the results of this study will form the basis for further development of XR-applications for DED-arc and contribution to the development cleaner and more sustainable smart manufacturing framework.

2 Materials and methods

The research methodology of this study combines theoretical and empirical research methods and forms a multimethod cross-sectional original study. The first method applied was a state-of-the-art review of academic literature considering DED-arc and XR-related studies. The objective was to determine the characteristics and the process chain of DED-arc, and then define the applications of XR in the manufacturing field. Further, the findings in the literature were used to specify and discuss how XR can be implemented within the DED-arc process chain. The second method applied, carried out a practical experiment to determine design inputs of geometrical properties. As a third method, six DED-arc XR applications were schematically developed, and their implementation possibilities were discussed and reflected in the results from practical tests and literature findings. The research process and expected outcomes are illustrated in Figure 2.

2.1 Literature review

In this study, a total of 37 academic articles regarding the DED-arc and XR have been selected and discussed. The search query used to find the articles on Scopus, and Google Scholar databases was 'TITLE-ABS-KEY("virtual" OR "augmented" OR "extended" or "mixed" AND "reality" OR "VR" OR "AR" OR "XR" OR "MR") AND "WAAM" OR "wire arc additive manufacturing" OR "DED-arc" OR "direct energy deposition-arc"'. The selected articles are used to define the characteristics of DED-arc and XR and then discuss the implementation possibilities and the potential challenges of implementation.

2.2 The product design and slicing

The geometry of the test specimen in the practical experiment was a cylindrical shell. The outer diameter of the cylinder was 80 mm, and the nominal height of the cylinder was 22 layers high and the nominal wall thickness was the size of a single weld bead. The nominal layer height was set to 1.5 mm and the tool path was programmed to follow the middle of the cylindrical shell. As the workpiece was sufficiently simple the "sliced features" were modelled into the workpiece and no external slicing functions were applied, as shown in Figure 3A. A macroscopic test sample was taken from the finished workpiece to accurately measure the thickness and the layer height and to verify the initial geometric design values. Based on the analysis of the macro test sample, a second workpiece concept with more complex geometry was designed, in which the verified weld width and layer height parameters were applied during path planning and slicing operations, see Figure 3B. Finally, the results of those operations were utilized in XR application concepts.

2.3 Experimental setup and materials

The test equipment, software, DED-arc process parameters and procedure specifications are presented in Table 1. The process parameters were determined by utilizing the laboratory welding expert's expertise and based on preliminary testing prior to carrying out the actual DED-arc experiment. To avoid the cumulation of geometrical errors into the same point in the workpiece, the starting and ending points of

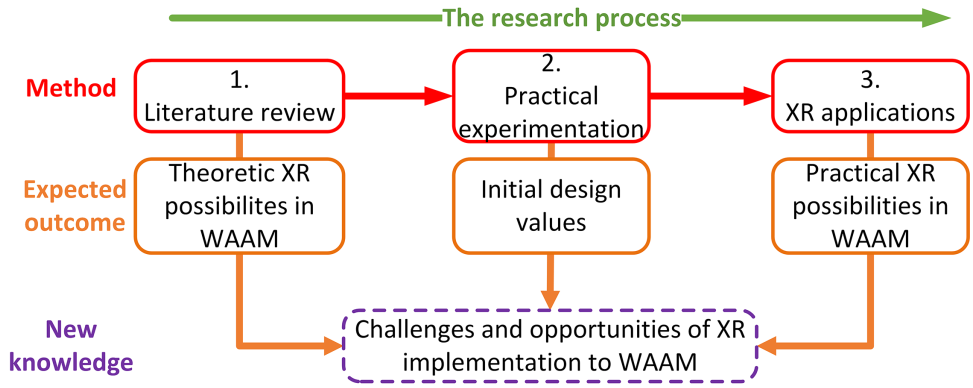

FIGURE 2
The research process of the study. Three main methods are used to gather novel scientific knowledge on XR and DED-arc.

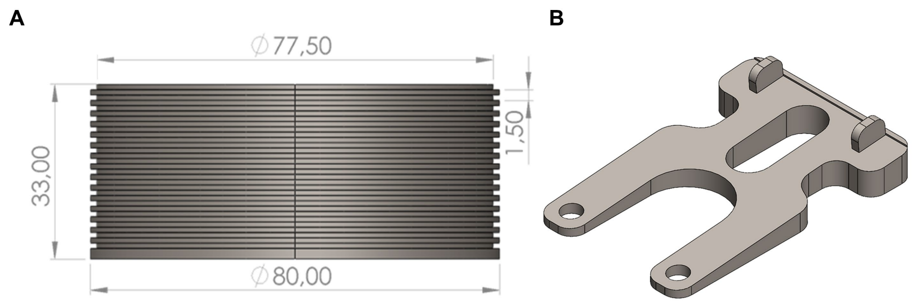

FIGURE 3
(A) Schematic of the main dimension of the test specimen and **(B)** second workpiece in which XR-functions were tested.

processing were incremented in each layer. The tool trajectory and path-related parameters were programmed in the robot offline-programming software Visual Components Delfoi Robotics 4.5 and the fine-tuning of the robot program was executed in another offline-programming software ABB RobotStudio 2022, which was also used to play and control the online execution of the robot program. The process parameters were set up through the robot controller interface prior to processing.

2.4 XR development architecture and methods

The virtual model of the robotic DED-arc cell was modelled into both different robotic offline programming and simulation software used in this study. These two software were used to develop the models of the proposed XR-solutions and then transfer the models to the XR hardware readable file format. Additionally, Blender software was also used to transform models to XR readable file format. XR hardware used were Meta/Oculus Quest 2, mobile phone using the Android operating system, and Microsoft HoloLens 2. Proposed VR applications were used in ABB Robotstudio with an addon Arc Welding powerpack 22022.3 and 3D printing powerpack 2022.3.1 and Visual component experience software 1.7. The ABB RobotStudio required Oculus software to be able to connect the VR hardware to the RobotStudio and the Visual components experience required the Oculus software as well, but also Steam and Steam VR software to be able to connect the VR hardware to the Visual components experience. AR applications were used in RobotStudio AR Viewer software and MR applications in Microsoft 3D Viewer and Microsoft Dynamics 365 Guides. Depending on the software used, the virtual models were transferred, using "save as" or "export to" functions, to a suitable file format. The formats used for XR were .step, .stl, .vcmx, .glb, .rsstnv and .3mf. The principle of how the physical DED-arc environment was integrated into XR is shown in Figure 4.

3 Overview of challenges and possibilities of implementation of XR in DED-arc

In this chapter, the principle of XR is introduced and its applications within the context of manufacturing are reviewed. Next, the principle of DED-arc and its key equipment are defined. Finally, the distinct phases of the DED-arc process chain are analyzed to find the intersecting application points where the XR-technology could be integrated. The state-of-the-art review made in this chapter assesses the question of what the key process steps of DED-arc are, where XR could be implemented and what are the challenges that the implementation may possess.

TABLE 1 The list of equipment, materials, and processing parameters used to conduct testing.

Test equipment and software	
Type	Value and description
DED-arc processing	Industrial robot ABB IRB 1600
DED-arc power source	Fronius TransPuls Synergic 5,000
Robot controller	IRC5
Workpiece positioner	Fixed workbench
Computer	Desktop computer
Temperature sensor	Micro-Epsilon infrared thermal measurement sensor thermoMETER CT-M3
Robot programming method	Offline programming
Offline-programming software	Visual Components Delfoi Robotics 4.5, ABB RobotStudio 2022

Process parameters and procedure specifications	
Parameter	Value and description
Shielding gas mixture	Ar + 8% $CO2$ + 0,03% NO
Additive material/Filler wire	EN ISO 16834-A: G 69 4 M Mn3Nl1CrMo grade S690, Commercial name: OK AristoRod 69
Wire thickness	1 mm
Wire feed speed	5 m/min
Torch travel speed	20 mm/s
Process	Pulse MAG
Average current	107 A
Average voltage	21.5 V
Pulse frequency	0.6 Hz
Contact tip distance	16 mm
Tool alignment	Perpendicular to surface
Number of layers/passes	22
Interlayer/pass temperature	<100°C
Path planning	Increment of both process starting point and ending point by 5 mm in each layer
Substrate material	S355 grade structural steel
Substrate dimensions	200 × 250 × 20 mm
Substrate preparation	Cutting by a saw, surface grinding prior to processing & clamping on to the workbench

3.1 Extended reality state of art and applications in the manufacturing industry

XR either replicates reality by simulation of real processes or extends the realms of possibility by adding virtual content, both of which can be experienced in a fully virtual environment or an environment mixing reality and virtuality. XR is divided into three different sub-technologies which are VR, AR, and MR. Typical characteristic features of XR are immersion in virtual objects, visual and voice elements and interaction with virtual objects. Depending on the XR technology the immersion and interaction are experienced and realized with different hardware technology.

VR typically uses HMD to visualize the virtual 3D world and its content, and either hand gestures or hand controllers are used to interact with the virtual objects and interfaces. AR typically uses a mobile device's computing and its camera to capture a real-time image view of the physical environment and overlay the virtual object to the captured view of the physical environment. The real-time interaction in AR is then realized on the interface on the touch screen of the mobile device. Mixed reality uses HMD to visualize virtual objects in a physical environment and the user can interact with a virtual object by grabbing them with the user's hands, which creates an immersion as if the virtual objects would be like the real objects.

Each XR technology has its scope of application in which they are best fit. Generally, VR is better suitable for offline tasks such as designing, teaching and simulation and AR and MR are better suitable for online tasks such as monitoring and control (Gong et al., 2021). Nevertheless, XR technologies have similarities which makes it possible to have identical functions even though realized with different XR-hardware and therefore the XR technologies are sometimes difficult to distinguish from each other. Therefore, the umbrella term XR is used for the rest of the paper when discussing the potential implementation possibilities for the DED-arc system, unless defining the used XR-technology is seen as necessary for clarity reasons. The number of available research studies concerning the use of XR in DED-arc applications was found to be insufficient, which has also been noted in a few research reviews (He et al., 2023; Mu et al., 2023), and therefore the framework was set to concern the use of XR in the whole manufacturing field.

Several studies have used AR to scan markers, such as QR-code, and then utilize the marker to execute an action. Markers can be used to recognize the correct location of a virtual object or to anchor the object to the marker. Other uses of markers have been the identification of a physical object and reading its information, i.e., reading machine status (Butt, 2020; Cai et al., 2020; de la Peña Zarzuelo et al., 2020). AR has been used to create an interface between the additive manufacturing machine and the user which enabled the control of the machine and the manufacturing process, the selection of a job and online motion control (Butt, 2020). In Szczepanski et al. (2021) AR has been used to create an invisible border for a mobile robot, similarly, an invisible border could be utilized for collision avoidance in a robotic DED-arc system. Other uses of AR found in studies have been visualizing instructions during assembly procedure and inspection of the product quality by comparing the virtual AR object to a manufactured part (Gong et al., 2021; Regassa Hunde and Debebe Woldeyohannes, 2022).

Several researchers have studied VR applications in manufacturing and have found that during product development VR can be implemented as a tool for novel decision-making as well as teaching and training (Regassa Hunde and Debebe Woldeyohannes, 2022). VR is very advantageous in visualization and therefore it has been applied in several studies to layout planning. The VR user can have an immersive and realistic experience through VR simulation, which is often difficult to achieve only from looking at a desktop or laptop screen and therefore benefits the decision-making during layout planning. Furthermore, it is sufficiently effortless to play and simulate different scenarios, which helps in finding the optimal layout and DED-arc robot cell solution (Gong et al., 2021). An especially beneficial feature of VR and MR is the possibility to simulate human

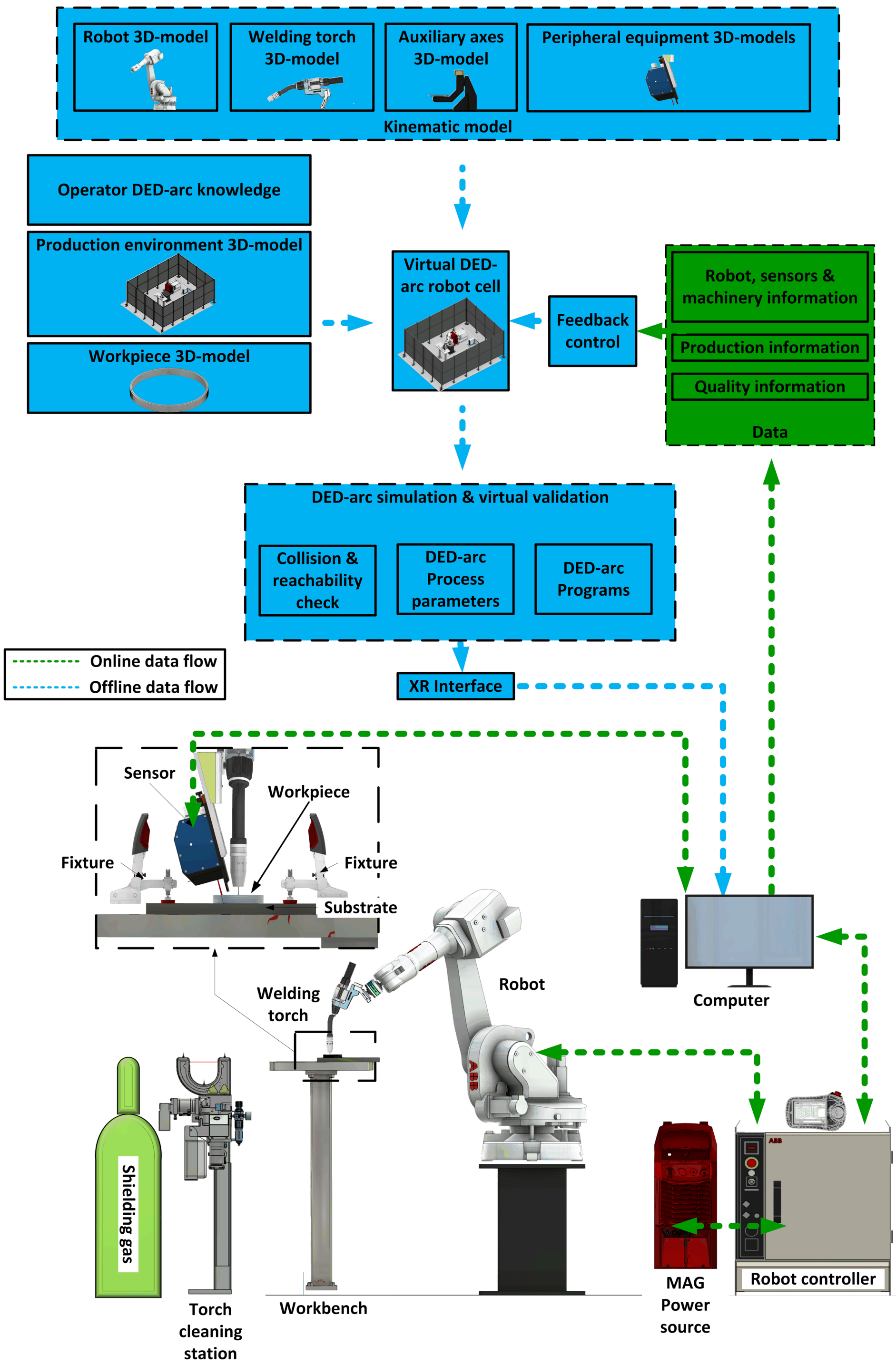

FIGURE 4
The schematic of essential DED-arc station components, data flow in the station and integration to XR.

operator-related tasks and evaluate the performance of the operator, which has been relatively difficult due to challenges related to the reproduction of the real manufacturing environment. XR technologies are free of the limits of reality, therefore there does not exist resource limitations. Robots and other manufacturing machinery can be used without the need of stopping production. Manual operations carried out by the operator are easily trackable and measurable, i.e., for training and human error monitoring purposes (Gong et al., 2021; Baroroh and Chu, 2022). Recreating a realistic virtual environment for simulation can be an arduous task, however in Gong et al. (2021) it was noticed that the VR simulation environment does not need to be completely detailed and realistic as long as the simulated task remains realistic.

Similarly to other XR-technologies, the MR applications found in the studies have been applied to manufacturing design stages such as layout design and simulation, but also to process monitoring and quality inspection (Butt, 2020; Gong et al., 2021; Baroroh and Chu, 2022). In Butt (2020) and Ceruti et al. (2017) researchers reported that the MR has been used to control the robotic arm in wire printing, real-time monitoring in each layer of 3D-printing and then aligning the monitored image data to visualize the reconstructed 3D-model and comparing it to the virtual model over the real model. For DED-arc real-time monitoring, process control and quality visualizing through XR could provide novel methods for quality assurance of DED-arc.

3.2 DED-arc characteristic, process chain, and XR implementation possibilities

The general principle of DED-arc is to deposit filler wire layer-by-layer to form a workpiece. The deposition of filler wire is practiced on top of a substrate, which can be part of the existing workpiece assembly or a single piece of its own. The arc process is used to melt filler wire and shielding gas is used to stabilize the arc and protect the molten material. When the molten weld pool cools down it solidifies, and the cooling rate determines many of the material and mechanical properties of the DED-arc workpiece. Other remarkable factors that affect material properties are the substrate's mechanical, material and chemical properties and substrate thickness, the chemical composition and mechanical properties of filler wire and shielding gas composition.

The DED-arc system using the MAG-process has many analogies to the robotic welding system using the MAG-process (Liu et al., 2021). The arc is generated and controlled using a power source, the filler wire is fed using a wire feeder and the welding torch directs the arc, filler wire and shielding gas to the workpiece. The movement, position and orientation of the welding torch are actuated by the six-axis articulated robot, also known as an industrial robot. The robotic system is controlled by a robot controller. Communication can be established through an ethernet connection between the robot controller and the desktop computer. The above-mentioned setup and equipment form the basics of functions and characteristics of MAG-based DED-arc and the key components of the robotic DED-arc system. However, considering DED-arc-specific challenges in the adaptation of XR-technology, the focus must be extended from the DED-arc-process to the whole DED-arc-process chain to find all the possibilities.

In general, the main steps of the DED-arc process chain can be considered as follows, product development, manufacturing design, pre-DED-arc processes, DED-arc process, post-DED-arc processes and quality assurance (Cunningham et al., 2018; Liu et al., 2020, 2021; Mu et al., 2023). The DED-arc process chain has many distinctive features for each step of the process chain and an overview of them is presented in Figure 5 (Williams et al., 2016; Cunningham et al., 2018; Liu et al., 2020; DebRoy et al., 2021; Liu et al., 2021; Raut and Taiwade, 2021; Mu et al., 2023). Therefore, it is evident that the DED-arc process chain possesses multiple phases that could offer a development platform for XR-applications. Thus, a detailed look at each main process chain step is given.

3.2.1 DED-arc product development

Similarly, to other AM processes, DED-arc provides an opportunity to develop new types of customized design solutions for structures, constructions and components, which desirably offer material savings, optimized products for end usage and increased automatized manufacturability. Typical design requirements of the structure consider its mechanical properties such as ductility, stiffness, strength and fatigue, many of which are strictly related to the material selection, as well as the geometry of the structure. A characteristic of DED-arc is that the optimization of designed cross-sections and geometries can be quite effortlessly achieved, as the material can be added there where it is required and left out where it is not needed. Therefore, the importance of material selection and simulation of material behavior in design concepts will be highlighted factors in DED-arc product development. Naturally, optimization leads to more lightweight products, decreased manufacturing time and therefore more energy-efficient, sustainable and viable DED-arc manufacturing (Gardner, 2023). However, those elements are insignificant if the selected material cannot withstand the circumstances in the end application or cannot be processed with DED-arc. For behalf of DED-arc, selected material must have, in addition to its mechanical properties, also a suitable chemical composition, therefore affecting the weldability or "DED-arcability," which is typically evaluated with different carbon equivalents, a unit of cracking susceptibility and other formulas and diagrams. Generally, when the material has good weldability, it is less prone to defects and cracks, which is important in DED-arc. Therefore, as stated by Gardner (2023) the importance of cooperation between design and manufacturing becomes a major subject, as the knowledge of process input (process, parameters, path planning, etc.) and outputs (bead geometry, distortions, stresses, quality, etc.) have much more effect in the designing inputs than in traditional development procedure.

The characteristic of the development process is to use CAD tools, which means that all the outputs are in digital file format and therefore in one way or another transferable to XR use (Gong et al., 2021; Regassa Hunde and Debebe Woldeyohannes, 2022). Considering the use of XR in the product development of DED-arc, the main applications can be found in the simulation and visualization which both can be utilized in decision-making during the design process. According to Regassa Hunde and Debebe Woldeyohannes (2022) XR enables the possibility to play interactive simulations and immersive visualizations, which are helpful in situations where the concept design must be mimicked in real-world scenarios, as through with traditional CAD environment (computer display) the sense of reality can be difficult to achieve. For example, a VR environment can be used to test virtual design concepts in interactive simulations of end application use or assembly and AR and MR can be utilized to visualize the concept in the real world and at the actual location of the application (Regassa Hunde and Debebe Woldeyohannes, 2022). However, it is difficult to imagine a specialized XR application in the product development of DED-arc that cannot be generalized to traditional product development, which is a positive thought.

3.2.2 DED-arc production planning

Requirements for manufacturing are primarily set by the production machinery and equipment, selected quality level and selected material, which the latter two are decided in the product development step and affect the selection of process parameters. When designing the DED-arc production environment the XR-technology can be implemented in the layout design process, as

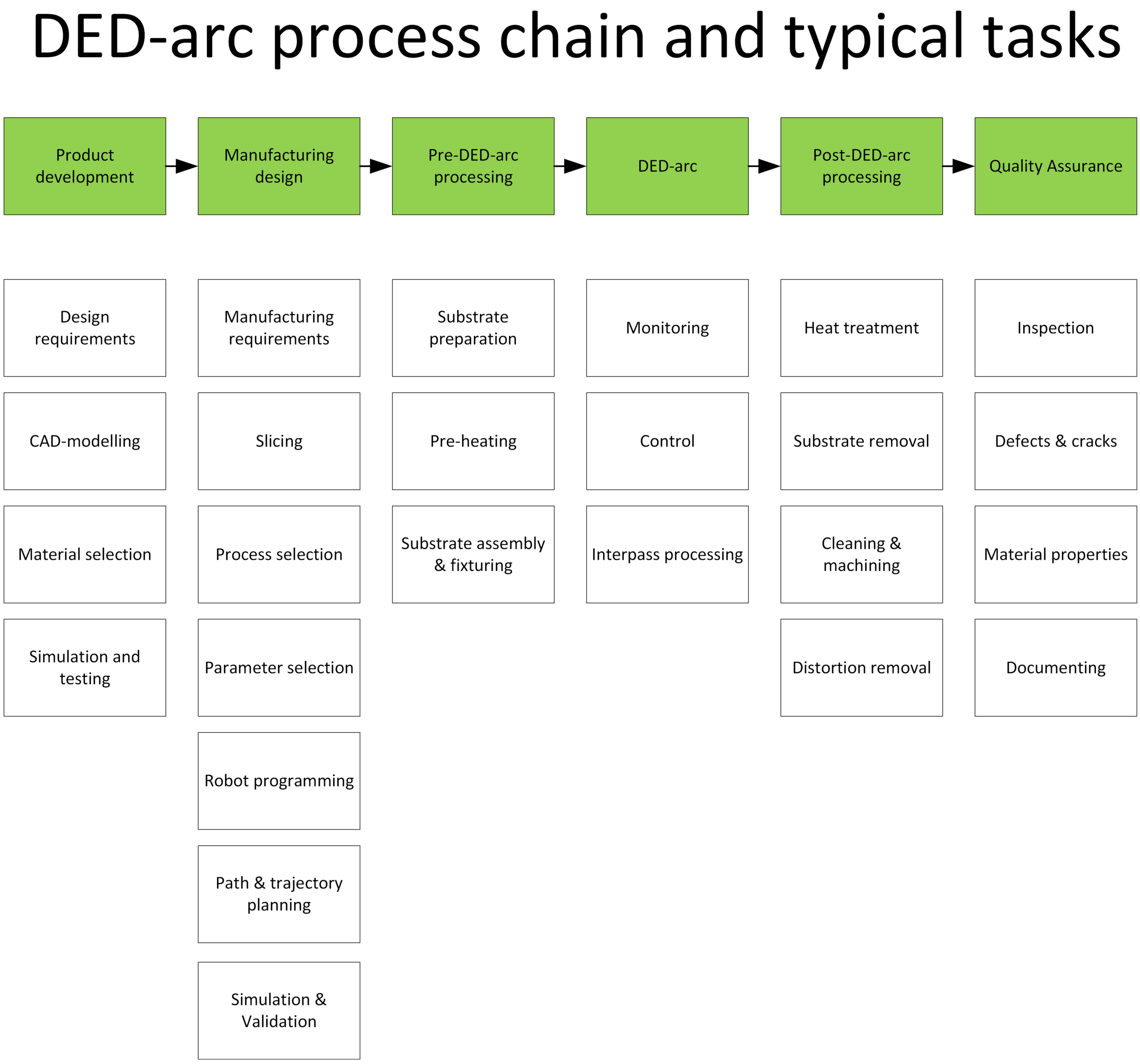

FIGURE 5
Overview of DED-arc process chain.

shown in logistics and assembly process-related XR studies such as Gong et al. (2021) and Baroroh and Chu (2022), in which it can be used for gathering requirements for the layout, tools for helping decision-making and comparing the functionality of different equipment combinations or layout solutions. As the DED-arc system is similar to a robotic welding cell, the modelling of the layout of the production environment is quite a straightforward procedure and can be done with CAM tools such as robot offline programming and simulation software. Generally, the elements of the production layout are robot cells, tool and auxiliary equipment, fixtures, jigs and workpieces, all of which are in a virtual format and therefore accessible and usable with XR-technology. The virtual model of the production environment should include all the essential peripheral devices and objects that are in the work envelope of the robot or can cause risk of collision or safety issues. The virtual model of the robot cell should contain the welding robot and auxiliary axes, as well as the workpiece positioner, other robots and tool change/cleaning/calibration unit.

Using XR, the modeled layout solutions can be visualized and immersed in real size, which helps to realize design flaws of the layout and gather requirements for further improving the layout, therefore XR also helps in the decision-making of selecting the optimal layout solution. One of the key advances of XR is the possibility to simulate the operator tasks, which has traditionally been only possible to execute in the physical world either in the production environment or replication of the production environment, which is costly and often difficult to construct. With XR, testing operator tasks in different layout solutions can be achieved quite effortlessly, which again would be difficult in the real environment. Another key advance of XR is that the virtual layout or parts of it can be projected into the real world enabling the visualization of the layout solution in its planned environment. XR-technology enables more realistic and immersive testing and validation of the DED-arc system as the user can experience the virtual production environment in real size and even interact with its components. Moreover, with MR or AR, the virtual production environment can be projected in the physical world location such as in the planned manufacturing facility (Gong et al., 2021; Baroroh and Chu, 2022).

Slicing the CAD-model sets the theoretical layer height in DED-arc. The known challenges of slicing are as follows determining the layer height, slicing pattern and multiplane slicing. For DED-arc it is characteristic that the bead height is not constant, which sets the difficulty of predetermining the layer height and scientists have suggested many solutions to solve the problem (Cunningham et al., 2018; Liu et al., 2020; Feldhausen et al., 2022). It is quite difficult to see how the application of XR could be implemented for slicing other than visualization of the slicing pattern and therefore, help in decision making.

Arc process selection is an important step in DED-arc production planning as each arc processes have its field of application in which they are best suitable. Arc processes used in robotized DED-arc do not differ from welding processes used in robotic welding, therefore the arc process selection for DED-arc is made between MAG, MIG, TIG, Plasma and SAW (Cunningham et al., 2018; Lin et al., 2021; Liu et al., 2021; Barath Kumar and Manikandan, 2022). Considering the MAG process of DED-arc a process modification is often required to achieve desired quality requirements. The most common and almost state-of-the-art MAG process modification has been the cold metal transfer (CMT), which allows low heat input based on single droplet material transfer resulting in a narrow width and low height of the weld bead. Another commonly used MAG variant is the pulsed arc. Other possible MAG variants are multi-wire configurations such as twin-or tandem-MAG (Cunningham et al., 2018; Lin et al., 2021; Liu et al., 2021; Raut and Taiwade, 2021; Barath Kumar and Manikandan, 2022). A possible XR application could be in the decision-making during the selection of the arc process when the arc process equipment, mainly the welding torch, of the robotic system is compared between processes, other than that it is quite difficult to imagine other applications of XR for arc process selection.

Parameter selection of DED-arc consists of setting the arc process parameters such as current, voltage and torch travel speed, which mainly determines the heat input and therefore affects the cooling time. However, in practice the current and voltage values follow the synergic curve of the power source and the selection of wire feed rate determines the current and voltage values. Other DED-arc process parameters are filler wire and shielding gas-related. Filler wire chemical composition, wire type (flux-cored or solid) and wire thickness. Shielding gas mixture and gas flow rate. Finally, there are the welding torches' trajectory-related parameters such as torch angle, travel angle/rake angle and the contact tip distance, which are determined during robot programming (Cunningham et al., 2018; Liu et al., 2020; Lin et al., 2021; Liu et al., 2021; Raut and Taiwade, 2021; Treutler and Wesling, 2021; Barath Kumar and Manikandan, 2022; Li et al., 2022). For DED-arc it is characteristic that these parameters need both online and offline adjustment. Online control is done during processing and offline control is done during the interlayer stage (He et al., 2023). Considering the XR applications for process parameter selection one main implementation possibility might be the visualization of DED-arc modelling and simulation results in XR. Several studies have used the finite element method (FEM) to model DED-arc, and they have tried to predict the forming weld bead shape, distortions, heat flow, etc. (Barath Kumar and Manikandan, 2022; Gardner, 2023). Results of these simulations could be visualized in XR to, e.g., help decision-making of process parameter selection, designing the required fixturing and defining the structural integrity of the product. The analogy could be drawn to welding simulators that utilize VR technology to recreate the work environment in which the welding parameters can be adjusted and the adjustment affects the weldability, weld geometry and the resulting weld quality could be estimated.

Path planning is one of the key steps of DED-arc production planning. The DED-arc processing paths can be established in multiple ways and finding an optimal path is often a difficult task. Typically, path planning is a multi-variable choice between optimizing mechanical properties, productivity, quality and minimization of distortions while simultaneously ensuring proper filling. Researchers have studied path-planning strategies and presented many solutions with their pros and cons (Cunningham et al., 2018; Liu et al., 2020; Xia et al., 2020; Lin et al., 2021; Liu et al., 2021; Raut and Taiwade, 2021; Treutler and Wesling, 2021; Barath Kumar and Manikandan, 2022; Feldhausen et al., 2022; Li et al., 2022). Path planning of DED-arc is typically done either during slicing or during robot programming. XR could be utilized in visualizing and projecting the process paths as well as via paths, which could be helpful in collision avoidance and testing of the robot paths prior to advancing to production.

Robot programming of DED-arc requires an offline programming method as the DED-arc programs tend to have large amounts of program statements, which would be a too tedious task for online programming (Feldhausen et al., 2022). However, some automation method is required for offline programming of DED-arc and generally, robot paths are generated from the G-code, which was generated during the slicing step. Typically, the G-code does not consider the trajectory of the tool nor the kinematics of the robot and therefore the G-code generated robot program may require some manual tweaking to set the suitable welding torch trajectories and to avoid robot singularities, joint limit errors and collisions (Feldhausen et al., 2022). The offline programming environment allows the simulation and virtual validation of DED-arc programs before postprocessing them to the robot controller. However, the offline programming environment can also be accessed through XR. Therefore, the XR-technology can be used to visualize the robot's movements during simulation and adjustments to the robot program can be applied using XR-offline programming tools. XR-tools help to visualize the welding torch trajectories and the effect of torch trajectory adjustments, which could be helpful in virtual validation of difficult process path sections such as corners or tight spaces and in avoiding collisions.

Modelling of DED-arc has been a widely covered research topic and the general focus has been on process modelling or material property modelling. Process modelling considers the bead geometry, bead and path overlapping, layer height and thermal conduction. Material property modelling considers the metallurgy, distortions, material properties and fatigue (Chaturvedi et al., 2021; DebRoy et al., 2021; Barath Kumar and Manikandan, 2022). The XR implementation use could be seen in the visualization of the DED-arc modelling and simulation results, which could help the user to understand the results and their effects, e.g., in case of distortions the results could be implemented to find the optimal position for fixtures and jigs.

3.2.3 Pre-processing, processing, and post-processing in DED-arc

DED-arc processing can be divided into three stages, pre-processing, processing and post-processing. The pre-processing stages include the preparation of the substrate and its preheating, as well as assembling the substrate and fixturing it to the workbench or workpiece positioner and cleaning the surface of the substrate. Other considered tasks are online testing of the robot program, preparing and maintaining process equipment such as changing or setting up filler wire and shielding gas, and contact tip, and checking power source settings and robot controller settings (Cunningham et al., 2018; Liu et al., 2020, 2021; Mu et al., 2023). In many studies (Bellalouna, 2021; Gong et al., 2021; Regassa Hunde and Debebe Woldeyohannes, 2022), XR has been used in operator training in assembly tasks and therefore XR could be implemented to create work instructions for the pre-DED-arc tasks such as substrate and fixture assembly. Another use of XR could be seen in the tedious task of testing of robot program. The virtual model of the robot could be projected into reality using XR-technology and the virtual robot program could be tested to see if the virtual robot collides with any real object in the workspace.

DED-arc processing considers process monitoring and process control-related tasks (Cunha et al., 2021; Mu et al., 2023). Monitoring of the DED-arc process is achieved using sensors. Generally, process parameters (current and voltage) are monitored through the power source or from the robot controller (torch travel velocity). However, controlling of DED-arc process often requires additional sensing, such as optical or thermal sensing and researchers have even used spectral or acoustic sensing to monitor and control DED-arc (Cunha et al., 2021; Mu et al., 2023). Due to the layer-by-layer nature of DED-arc, the process controlling can occur both online and offline, meaning the control can occur during processing or interlayers. Thus, researchers have developed many online and offline DED-arc controlling methods, which are discussed in detail in Cunningham et al. (2018) and He et al. (2023). In general, the online process control focuses on controlling the molten weld pool and the offline process control focuses on optimizing process parameters or reacting to detected defects, imperfections and geometrical errors monitored during the processing of the previous layer. Considering XR the online process monitoring, XR could be a possible implementation to visualize the in-process state and imperfection locations detected during processing, as has been done in Reisch et al. (2022) to a digital twin. However, the online process controlling with XR could prove to be too difficult or inaccurate. Although, some researchers have developed XR online controlling methods for other am systems and have jogged a robot in the wire printing process or used a haptic feedback control to “manual weld” with a robot, still, it is difficult to see other than online process parameter control occurring over XR in DED-arc (Butt, 2020; Mu et al., 2023). However, for offline process control, XR could offer some possible use applications, such as visualizing the location of detected defects or imperfections or geometrical errors and XR-based robot programming tools to make necessary adjustments to robot programs, process parameters and tool path and trajectory to try to fix the detected faults of the previous layer.

After DED-arc processing some post-processing tasks are typically required. As DED-arc processing is performed on top of the substrate it is often necessary to remove the substrate by some method. To fulfill quality, tolerance, standard or other set requirements a heat treatment may be necessary as well as machining, polishing or cleaning. Numerous heating and cooling cycles will easily cause residual stresses and distortions in the workpiece which may be obligatory to remove (Cunningham et al., 2018; DebRoy et al., 2021). XR could be implemented in DED-arc post-processing as an operator training tool and a way to give visualized work instructions to the operator. For example, the removal of distortions and residual stresses may require heating of some local area from the workpiece and FEM-based modelling information could be visualized through XR which would inform the operator where to apply the heat. Some other applications of XR in post-processing could be superimposing the virtual and therefore ideal workpiece model over the real workpiece and the operator would see if some parts of the workpieces’ dimensions exceed the tolerance limits and therefore would require machining/grinding. Above mentioned XR-tools could provide a productivity increase to time-consuming post-processing tasks.

3.2.4 DED-arc quality assurance and management

The quality assurance in DED-arc considers tasks such as inspection, testing and documenting. Inspection considers the visual quality as well as the non-destructive methods to find defects and imperfections such as cracks, porosity, delamination and geometrical errors (Xia et al., 2020; DebRoy et al., 2021; Li et al., 2022). Inspection in DED-arc can occur during processing and interlayer with the use of monitoring sensors, which enables the use of XR-technology as the monitored data can be visualized in XR (DebRoy et al., 2021; Mu et al., 2023). Therefore, enabling online or offline quality management through process control, as discussed in the previous chapter above. XR-technology enables novel methods to document the visualized inspection data, as the found quality deviation can be superimposed onto the real workpiece or the location of quality deviation can be shown in the visualization of the robot path as has been shown in Reisch et al. (2022). Testing of DED-arc workpieces is often required to find out the mechanical and material properties and the testing result can be visualized in XR, for example, the macrostructure of the workpiece. Most of the quality tests are destructive, meaning that the test results cannot be conducted for the workpiece being under testing or production. Instead, the results can be feedback to product development and manufacturing design stages of the DED-arc process chain, where they can be used to optimize process parameters or in decision-making for further development.

To clarify the results of the literature findings of this sub-chapter, a summarization of found XR functions under the assumed main DED-arc process chain step is presented in Figure 6. However, as most of the XR functions can also fit under another process chain category, a color code is shown to mark other presumed or possible implementation steps. These results therefore need to be interpreted with caution, as the summarization is not exclusive and other configurations are possible.

3.3 Challenges of implementation of XR to DED-arc

Despite the possibilities offered by the XR technology, some challenges exist that have been discussed in various studies, such as

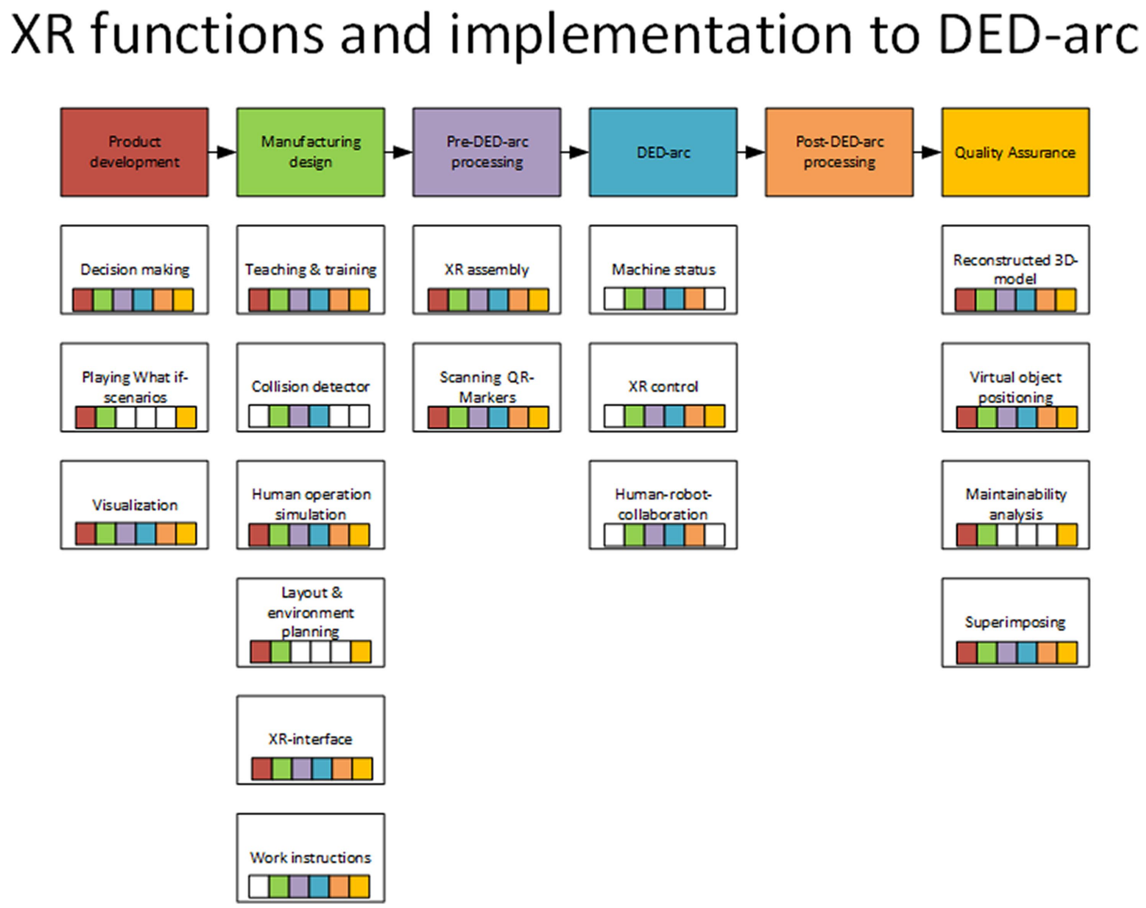

FIGURE 6
Visualization of found XR functions and their possible implementation to the DED-arc process chain.

Butt (2020), Gong et al. (2021), Osho et al. (2022), and Wankhede and Vinodh (2022). Most of these challenges can be categorized as hardware-related, technology-related and usability-related features and challenges. Hardware-related challenges may limit the practical usability of XR, such as working range, working flexibility and work ergonomics. Researchers noticed in Gong et al. (2021) that hand-held XR devices reduce the operator's flexibility as the operator cannot have both hands free, thus limiting the tasks the operator is able to perform while utilizing XR. However, if the hand-held XR device is to be mounted on a fixed location it may have a negative effect on the operator's work ergonomics. Other hardware-related challenges are for example reduction of reachability due to a wired connection, connection errors to a wireless network, limited computing capacity and selection of correct XR hardware for the task (Gong et al., 2021).

Technology-related challenges constrict the possibilities of XR and degrade the user experience. Factors creating technology-related challenges are such as data compatibility and data conversion issues whose resolving can be time-consuming. Numerous studies have reported that conversion of CAD data to the XR-supported format leads to loss of CAD-data, e.g., kinematic relations information, irrelevant data in CAD-objects, and decrease of CAD-objects rendering quality due to optimization into XR use. Especially the decreased rendering quality has been experienced to degrade the user experience (Gong et al., 2021; Regassa Hunde and Debebe Woldeyohannes, 2022). One common novel technology-related challenge is that ready-made software solutions might not exist, and they must be developed by themselves, which naturally slows down adaption to XR technology. Another challenge will be the integration of XR technologies into existing DED-arc systems (Wankhede and Vinodh, 2022).

Usability-related challenges lead to a degraded user experience of the XR tool and in the worst case may cause misuse of the XR tool, these challenges can be difficult to read or misinterpret instructions of the XR tool, unfamiliar user interaction methods of the XR, missing "common sense" in software development, narrow field of view and visual guiding indicators or virtual buttons are outside of the user's perspective (Gong et al., 2021).

4 Results and discussion

This section presents the schematic illustrations of implementation possibilities of XR applications to different stages of DED-arc, which were established using the available equipment and software described in the methods sections of this study above. As the nature of the results is qualitative, the discussions regarding the results are also presented in this section.

4.1 Product development

The DED-arc process chain begins with the product development phase where often preliminary practical experimentation information is required to investigate geometrical properties for example layer height and bead width, as well as mechanical properties and metallurgical properties. Such information can then be utilized in designing near-net-shape structures and products with desired properties for their designated application.

In the current study, the interest was to investigate the geometrical properties to be used as initial values for DED-arc product development. The cross-section macro image of the experimental DED-arc specimen produced in this study can be found in Figure 7. The specimen had a total of 22 layers and the outcome was 33.29 mm. Therefore, the average layer height was defined as 1.51 mm, which verified that an initial design value of 1.5 mm could be used. The width of the specimen was 4.5 mm on its thinnest section.

The results of experimental layer height and bead width were used as initial design parameters for another workpiece. The CAD-model of the second workpiece was sliced with different path patterns and then the sliced workpieces were visually compared in XR, as shown in Figure 8. In XR it is possible to interactively inspect the designed and sliced workpiece for example for decision-making purposes as in Figure 8B or visualize the workpiece in a real environment as in Figure 8C. These results match those observed in earlier studies (Gong et al., 2021; Regassa Hunde and Debebe Woldeyohannes, 2022). Additionally, the information from the macro and micro images of the experimental workpieces consisting of different heat inputs and welding process parameters can be utilized in the design process of DED-arc products. The surface roughness and other visual properties can be embedded in virtual models where the structural integrity, material properties and for example, fatigue life can be evaluated with the visual appearance of the product. Such information, such as shape distortions, metallurgical images, interpass angles and toe radius, could be visualized in the XR environment.

4.2 Manufacturing design and pre-processing

In manufacturing design, the XR technologies can be utilized in multiple applications. In this paper, the implementation possibilities were found in operator training, robot programming and layout design. The preparation operations required before DED-arc processing can be trained and simulated in a VR environment as seen in Figure 9. The assembly and fixturing of substrate are essential work tasks in DED-arc and appropriate execution of these tasks is required for acceptable processing quality. Operator training in VR helps shorten the learning curve of the tasks required for assembling and fixturing the substrate. The correct location of the substrate and fixturing devices can be highlighted, which ensures that the operator learns which type of objects to pick from the material storage and place onto the workbench. In Figure 9 a schematic illustration of the simple assembly and fixturing process of a substrate plate on a robot cell is shown both in VR and reality. However as was not shown in Figure 9, some more detailed instructions could be easily given in VR, as illustrations or in text-based form. For example, instructions for cleaning the surface of the substrate with solvent or with a grinder, or those tasks could be included in the training simulation as well.

One other benefit of VR-based training is that it can be done remotely and not in the actual workstation, which means that the production process will not be disturbed by the training of the operator. However, it should be ensured that the VR training environment resembles the actual work environment. Similar observations have been made in previous studies on the utilization of XR in other manufacturing processes and industrial fields (de la Peña Zarzuelo et al., 2020; Gong et al., 2021; Baroroh and Chu, 2022).

VR is not the only XR technology that can be used to train preparation operations in DED-arc, as can be seen in Figure 10 where different types of MR instructions and guiding methods are presented for the purpose of setting up the robotic DED-arc cell for automatic production. The MR work instructions included virtual elements such as videos of an example execution of work tasks, text-based

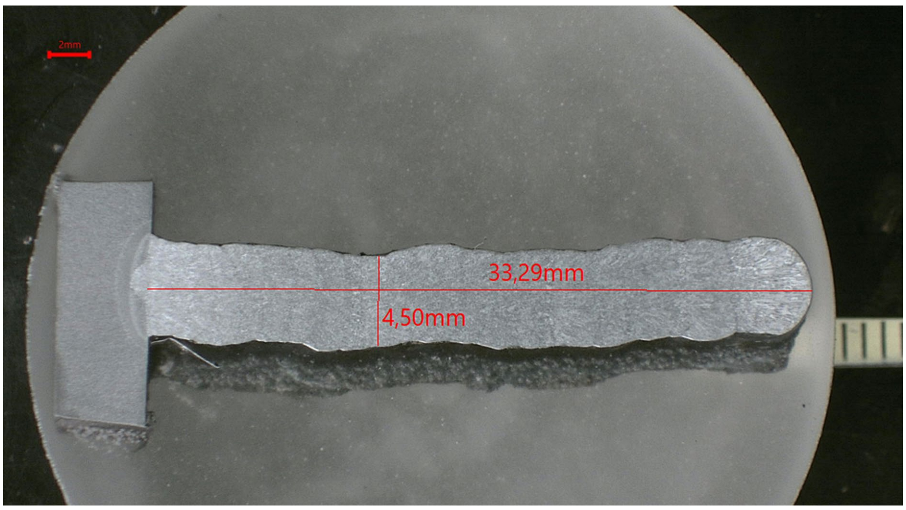

FIGURE 7
Macro image of the test specimen.

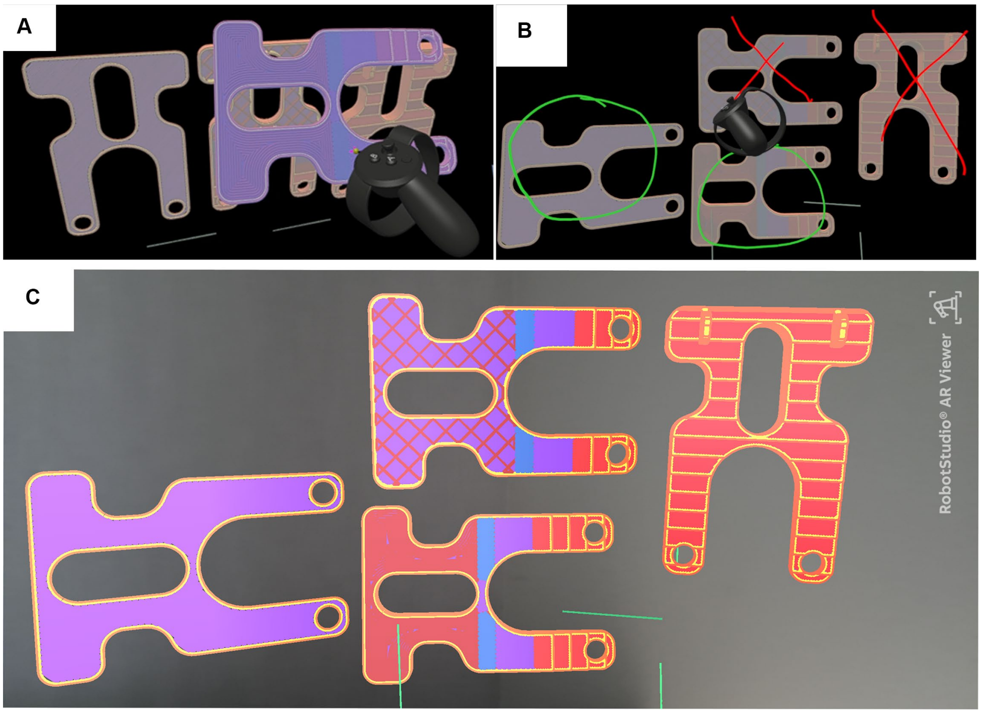

FIGURE 8
Utilizing XR in visualizing, interacting and comparing sliced path patterns, **(A)** interacting with sliced geometry by grabbing the virtual workpiece with VR controller, **(B)** decision-making example, where rejected slicing path patterns are marked with red x and accepted with a green circle and **(C)** AR visualization of sliced path patterns.

instructions, exemplary figures, arrow symbols and number guidance as well as virtual models of the substrate and the industrial robot. Virtual elements were anchored in a fixed location using the QR (quick response)-code in the robot pedestal, as can be seen in Figure 10B. Symbol instructions were used to guide tasks such as turning on a welding power source and robot controller as well as locating the equipment in the robot cell environment. Numbering was used if some work tasks were required to be performed in a certain sequence, for example when turning on the automatic mode of the robot controller as in Figure 10C. The virtual model of the substrate was used to guide where to place the real substrate and similarly, the virtual model of the robot was used to show the supposed position of the robot in its starting point of the DED-arc program, as shown in Figures 10D,E. In Figure 10F the physical robot was run into the starting point to validate if the program was starting as intended.

By utilizing MR, it was possible to create on-site work instructions for the preparation operations of DED-arc processing. The instructions can be used in the training of the operator and even during the actual setting-up of the production process where the instructions can help to reduce human errors, as a reminder of the required work tasks. Overall, the MR instructions were quite clear, illustrative and immersive. However, some problems were observed during the test execution of the work instruction. As Figure 11 shows, the virtual substrate was not in the exact intended location, thus highlighting the importance of careful placement of virtual objects when creating instructions with virtual models. Moreover, the perspective and point of view may cause that in one viewing angle, the virtual model seems to be in the correct position, but when looking from another direction it may reveal that the virtual object has an offset from the ideal position. One more possible option is that QR-code-based calibration had caused some errors on the virtual substrates' location. However, as the work instruction included an example video it was possible to conclude the correct position of the substrate during the test run. In Cai et al. (2020) similar small inaccuracies in QR-code-based calibration were observed, which were caused due to distortion of camera image, misdetection of marker and poor lighting in the environment. These findings highlight the importance of clear and understandable instruction-making to avoid the possibility of misunderstanding.

The accuracy of the position of the virtual robot was noticeably better than the accuracy of virtual substrates', as can be seen from Figure 10F above and Figure 12. Still, it can be seen that the superimposed virtual model has some local mismatches when compared to the physical robot and changing the point of view affects the superimposed model. Interestingly the welding torch was quite accurately in the correct position and the errors were mostly seen in the robot arm. Further, the MR technology could be used to visualize the robot's pose in critical positions of the robot program and therefore verify for example that any collisions would not occur during the execution of the program. Being able to visualize virtually where the robot will move in the next statement would benefit the testing of the new robot program. Typically, a new program may still contain some programming errors, especially in interval movements from one statement to another, where it is easy to cause a collision, e.g., between a robot and a fixture.

The VR environment can also be utilized to visualize the robot tool trajectories and tool paths created by the DED-arc programming tools, which turn the G-code of a sliced CAD workpiece into an actual robot

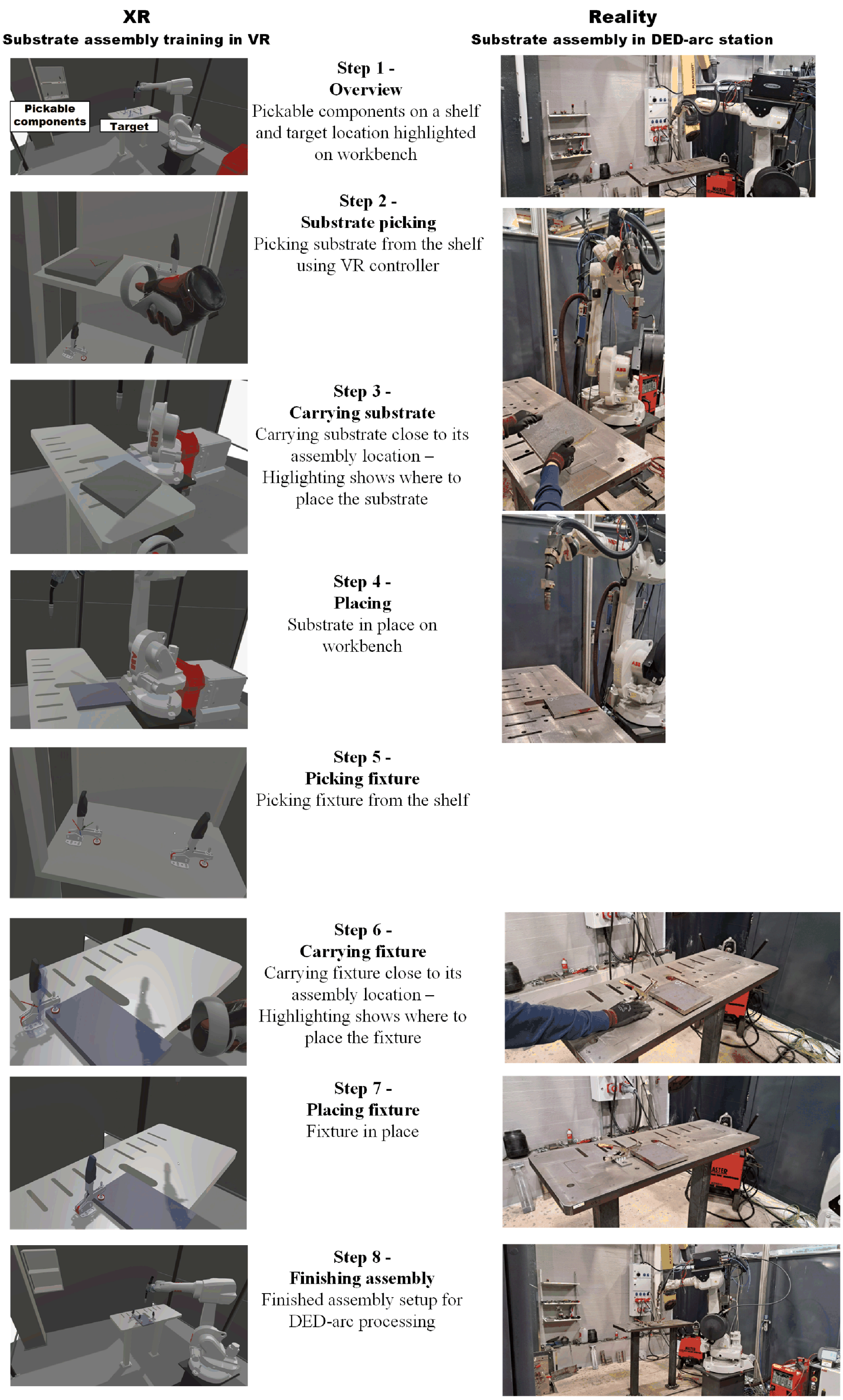

FIGURE 9
Training of substrate assembly and fixturing in VR and illustration of essential steps in reality.

program. Examples of tool trajectory and tool path visualization are shown in Figures 13A,B. Odd and even layers can be visualized with different colors to help distinguish the layers from each other. The visualization of the DED-arc robot program allows the programmer to validate the program in a more intuitive approach than looking at the computer screen, where the perception of problematic tool trajectories

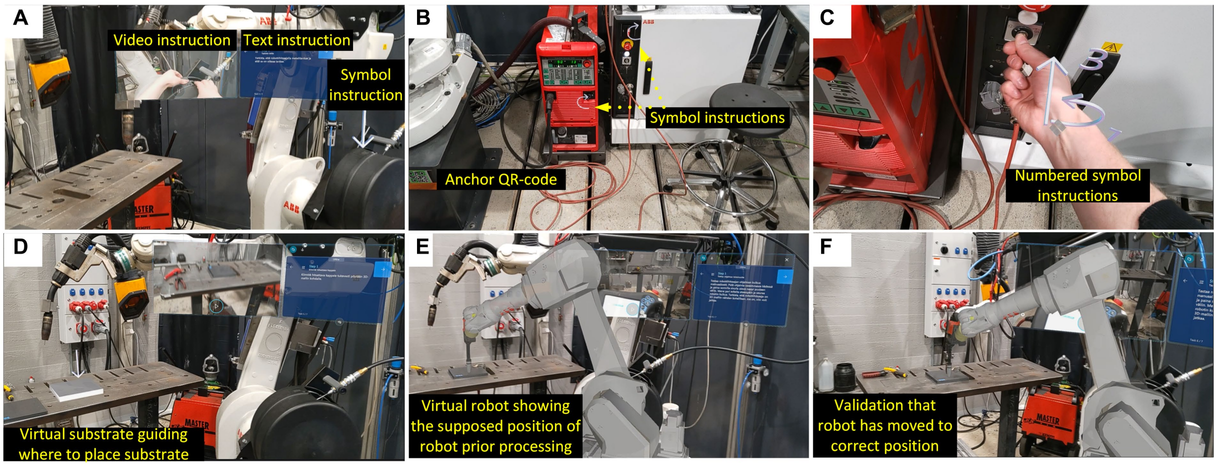

FIGURE 10
MR instructions to guide an operator in pre-DED-arc processes.

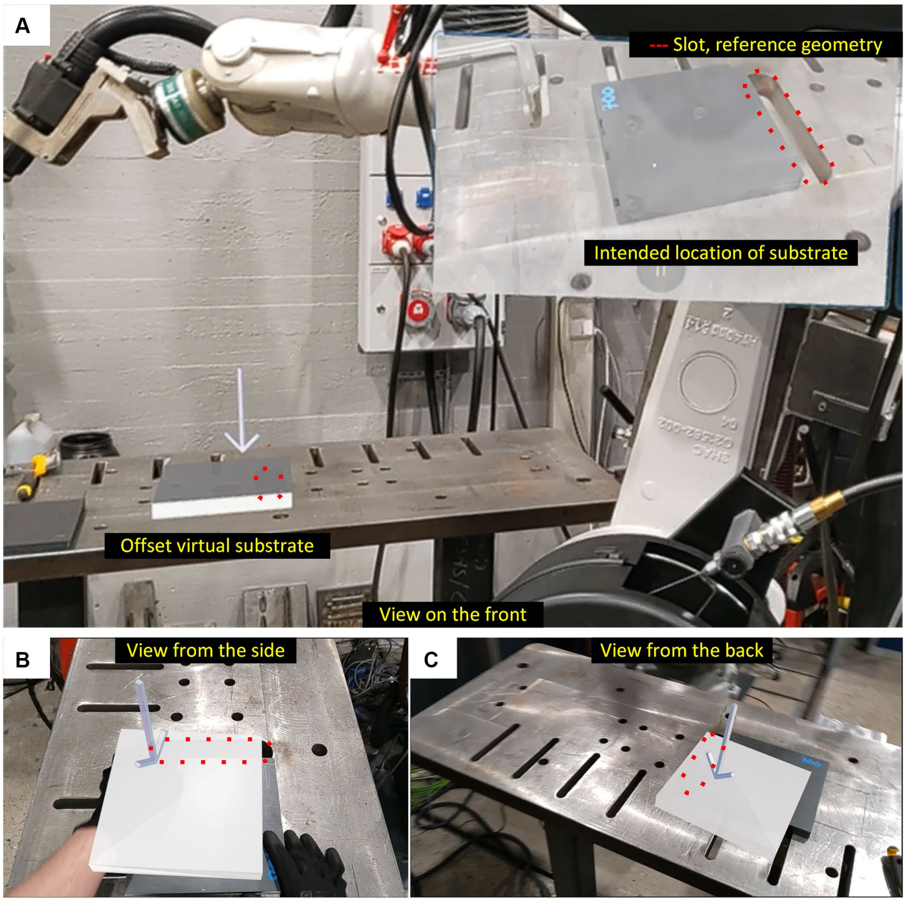

FIGURE 11
Illustration of misplacement of the virtual substrate.

considering the processing can be sometimes limited, thus leading to the need for online modifications of a robot program. In-built VR tools allow the programmer to interact with the virtual robot and its program, which allows tasks such as editing the program, adding or removing statements from the program and measuring the environment as illustrated in Figures 13C,D,E. These above-mentioned tools naturally also exist in the offline programming side of the software, but their availability during the programmer being in VR, streamlines the whole

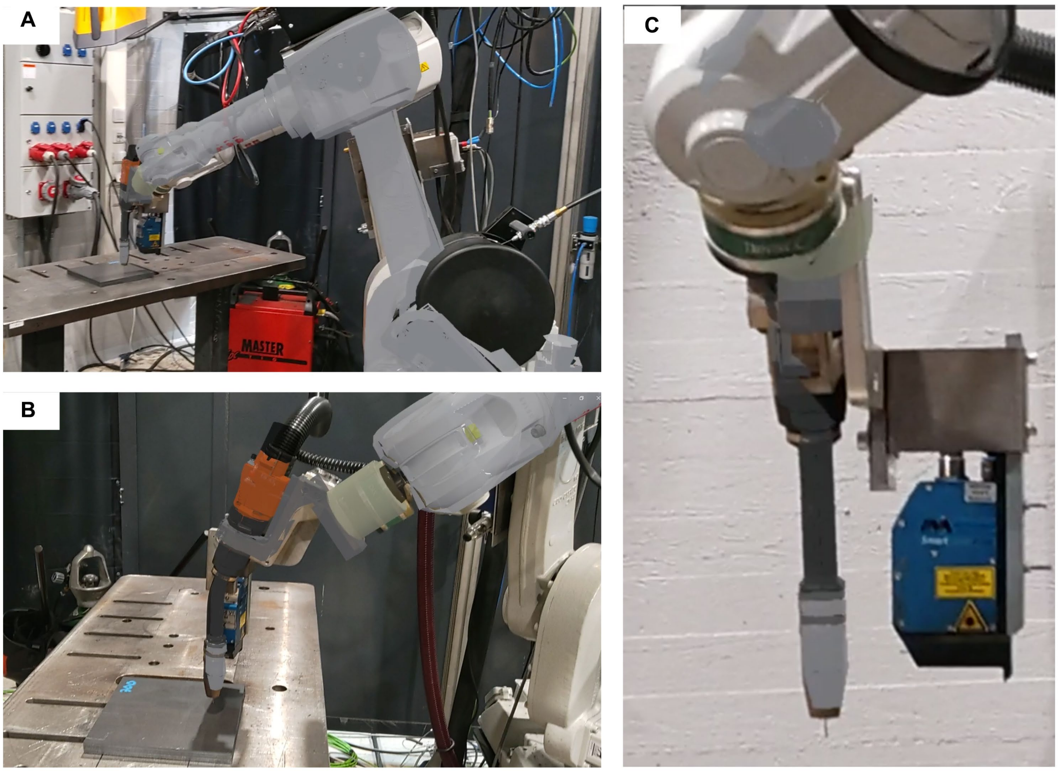

FIGURE 12
Virtual robot model superimposed onto a real robot in MR. **(A)** overview, **(B)** side view, and **(C)** close view.

offline programming process as the programmer can make the necessary edits to the robot program during VR use, thus, the programmer does not need to remove the VR gear to edit the programs.

XR can be utilized in layout planning of a robotic DED-arc cell, as shown in Figure 14, where interactive simulation of the reachability of a robot is tested when a new workpiece positioner is brought to the virtual robot cell layout. Such layout, as in Figures 14B,D, could be used to have two simultaneously run DED-arc processing tasks. The processing task on a stationary workbench would suit simpler one-plane processed workpieces and the processing task on a workpiece positioner would suit more complex workpieces. A VR-based immersive and interactive layout simulation can easily show any layout design faults and mishaps, for example, that there is enough room for the robot operator to be able to work ergonomically in the cell. As in the Figure 14 case, the auxiliary equipment (power source and robot controller) in initial layout A, would have been in the way of the workpiece positioner. Earlier studies have shown that layout planning in logistics design and material flow has its existing applications in XR, however for DED-arc, XR-based layout planning was not found in the literature (Baroroh and Chu, 2022; Regassa Hunde and Debebe Woldeyohannes, 2022).

4.3 DED-arc process monitoring and quality assurance

The utilization of sensor technologies, such as optical sensors and process parameter data from the power source, enables the possibility of feeding the measured data into XR devices either in real-time or in the interlayer. Such XR-based monitoring enables novel methods for robot operators in the decision-making of process control. For example, in online interlayer process control, the operator is able to see all the monitored process data and geometrical data in the XR-view and then respond if any anomalies are detected. One way of visualizing anomalies in the virtual workpiece has been presented in Reisch et al. (2022). Traditionally, the same monitored data would be viewed from the computer screen, which typically is not positioned so that it can be accessed simultaneously when adjusting the online program of a robot. Therefore, the XR-visualized monitoring information could improve the robot operator's work efficiency as well as awareness of process conditions.

In the quality assurance phase, the XR technologies can be used to visualize the visual quality of each additive layer, a 3D-scanned virtual version of the finished DED-arc product, metallurgical information, DED-arc process data used and the positions of the robot along its program. The virtual CAD-model of the workpiece can be superimposed onto the manufactured workpiece and their differences could be evaluated. Ideally, in the occurrence of a quality defect, the position of a robot and its welding torch in a detected anomaly could be recorded and as well the location of the defect could be superimposed either in the real workpiece or in its virtual counterpart. Further, the monitored process parameter values at the location of the defect can be stored. Together the torch position and the process parameter values at the location of the defect can be utilized in the analysis of understanding the reasons why the defect occurred. Further, the macroscopic and microscopic data could

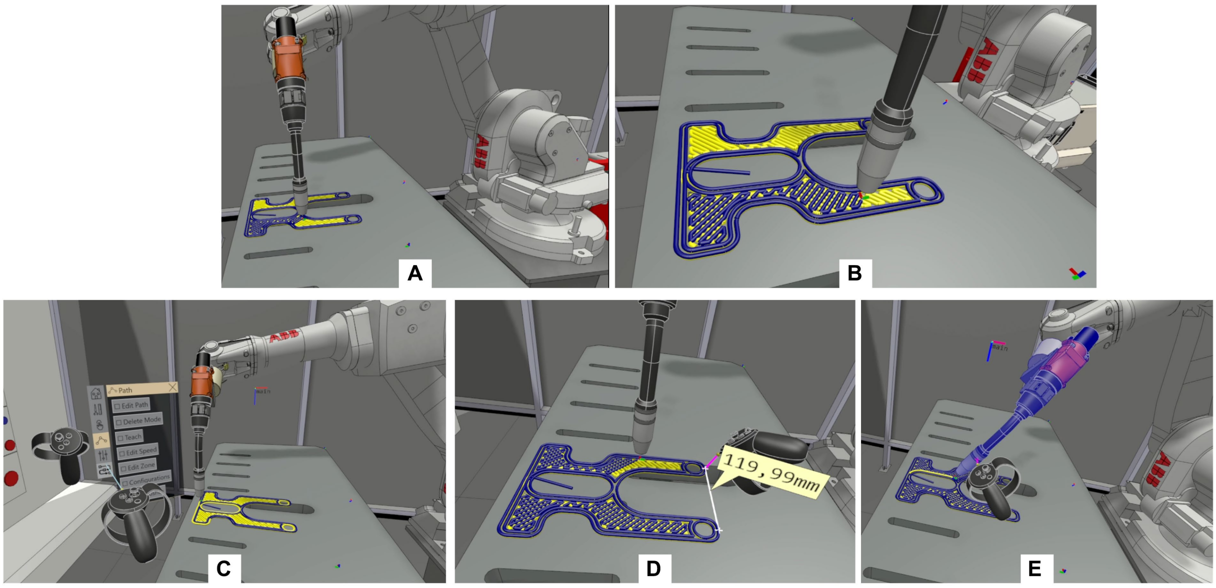

FIGURE 13
Virtual reality DED-arc robot program simulation visualization **(A,B)**, interactive program editing and simulation interaction tools **(C)**, utilization of interactive measurement tool **(D)** and interactive adjustment to tool trajectory **(E)**.

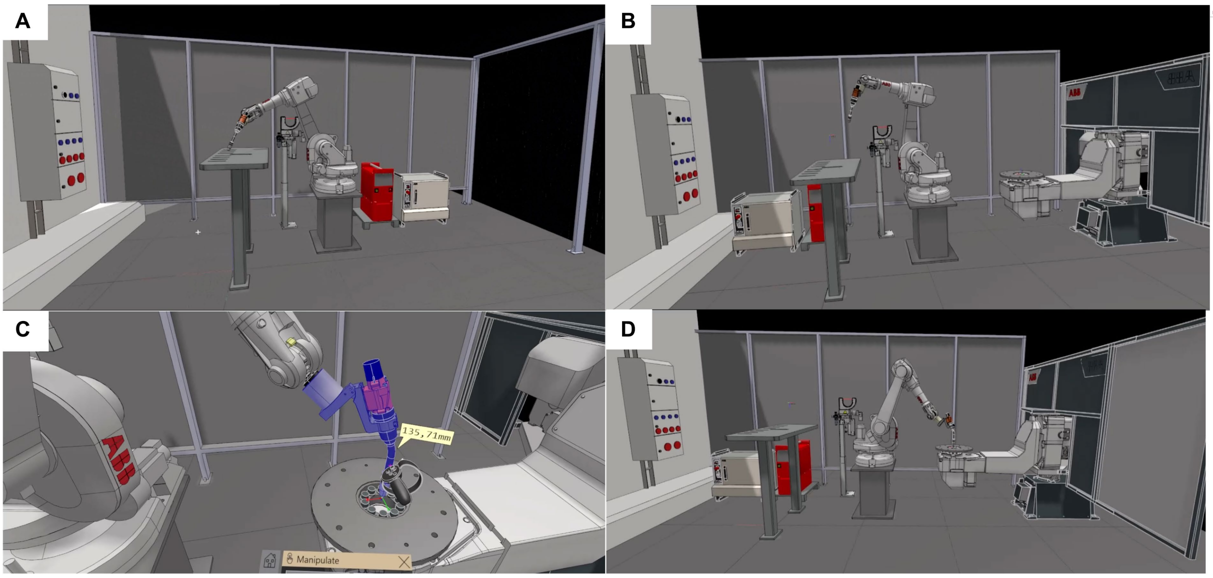

FIGURE 14
Utilization of VR in layout planning of DED-arc cell, **(A)** initial layout, **(B)** new layout with workpiece positioner **(C)** interactive simulation of new layout and **(D)** verification that the robot is able to reach workpiece positioner for DED-arc processing.

be linked for example to the virtual workpiece which would extend the possibilities of utilizing XR in DED-arc quality assurance.

It was observed that the production data can be visualized well with holographic lenses. However, although the CAD model was placed on top of the DED-arc object, the comparison between the real object and the CAD model was found to be challenging. An easier way to visualize the differences between the model and the actual product would be the use of a 3D measuring laser scanner and analysis software. However, if QR-code-based marking had been used, it would most likely have enabled to superimpose of the virtual model onto the actual product much more accurately than the manual placement method used.

4.4 Cleaner production opportunities of XR in DED

The results of this study show several future applications for the development of a clean and sustainable smart manufacturing framework for DED-arc. It can thus be suggested that XR enables multiple novel decision-making opportunities for DED-manufacturing planning, through interactive and immersive visualization, thus hopefully eliminating the "try and error" approach from manufacturing. The present results are significant in at least two major respects.

The XR-enabled decision-making and playing simulation scenarios allow manufacturing planning without disturbing the ongoing DED-arc processing, therefore improving the sustainable development of DED-arc production. Furthermore, XR allows for virtual verification of planned constructions, without building a prototype and then robotic DED-arc allows manufacturing the construction with simple equipment, without building a massive manufacturing complex.

The other aspect is that XR-enabled guidance information can reduce the operator-made errors, and ultimately, interactively estimate the effect of operator-made choices on processing quality, which reduces the probability of process defects and failures, and thus improves the energy efficiency and eliminates the material waste of processing. An example of above mentioned interactive XR-guidance could be a scenario where the operator tries to control bead width and layer height, and the XR-guidance could suggest suitable process parameter values to achieve the desired geometry.

XR-enables remote co-operation in DED-arc, which allows novel types of sustainable development methods, as a group of experts from different fields can interact, visualize and receive immersion from one another regard of the location they are. For example, one expert can give improvement suggestions to process paths as a form of iterated robot program, while another teaches and guides in setting up process equipment and parameters using virtual elements and the third one operates in the physical robotic DED-arc cell.

5 Conclusion

With the continuous development of novel, cleaner and sustainable DED-arc technology, it is evident that digital technology solutions will be strongly within this improvement framework, and extended reality will cover many of the future research and development areas. The purpose of the current study was to determine what possibilities there exist in implementing XR-technology to different steps of the DED-arc process chain and to discuss challenges related to implementation.

The DED-arc process chain and its characteristic steps were defined in this paper. Similarly, the principles of XR-technologies and their features were determined. Then a review of the literature was carried out to find existing XR applications in the DED-arc process. This research has found that a major knowledge gap exists in the research area relating to utilizing XR in DED-arc, although both subjects have been under intensive investigation in recent years. Therefore, XR use cases were searched from other manufacturing fields. The results of this literature investigation have shown that multiple XR utilization possibilities could be implemented in product development, manufacturing design, pre-processing, processing, post-processing and quality assurance of DED-arc.

The results of the experimental part of this research show multiple exemplary practical applications of how XR can be utilized in DED-arc and present the challenges that were noticed. Thus, this research extends our knowledge of opportunities in applying XR into DED-arc and lays the foundation for further research and development. Further, as far as the author's best knowledge, the results are the first time that XR implementation in the DED-arc process chain has been covered extensively.

From a broader perspective, the results contribute to the framework of smart manufacturing research by verifying that the applicability of XR can be extended to DED-arc with similar methods as developed in other manufacturing fields. Further, the results show multiple cleaner methods for manufacturing design, which reduces the need for physical process testing and material waste. Naturally, due to the exemplary and idealistic nature of the results, some limitations exist and therefore future research is required to deepen the knowledge of the utilization of XR in DED-arc. An especially interesting further research topic would be the online process monitoring and quality assurance methods of XR in DED-arc.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

HL: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. SP: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. TS: Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Implementing concepts from green logistics in the turkey production supply chain

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Introduction: The global turkey market represents a sector of increasing growth in the previous decade, and projections for the next decade reflect the probable continuation of this growth. Industry trends also indicate the globalization of turkey meat production, as the loci of production has continually shifted from one dominated by the United States to one with an increasing number of production units globally. In contrast with other popular meat products, comparatively fewer resources have been devoted to academic research concerning the growth, production, distribution, and sale of turkey and turkey products. This lack of research is particularly notable in the area of supply chain management and environmental sustainability. Given the increasing volume of turkey production and lower volume of academic interest, it stands to reason that there remain many opportunities for improvement across the value chain in this industry.

Methods: In this paper, we take a "green logistics" approach and use data provided by one of the largest turkey producers in the United States to formulate a mixed-integer program aimed at minimizing the environmental impact of turkey products in a segment of the product supply chain.

Results: Implementation of the resulting brooder-finisher farm assignments developed by the model would yield an average 50% decrease (184 metric ton) in greenhouse gas emissions at the operation under investigation while also addressing other areas of significant vulnerability for the industry (production costs, biosecurity risk, and animal wellbeing).

Discussion: As consolidated turkey meat production systems continue to expand globally, we argue that a similar approach could readily be deployed by these growing and emerging production systems.

KEYWORDS

optimization, mixed-integer programming, green logistics, agriculture, poultry, turkey

1 Introduction

In the last two decades, a significant volume of research has arisen with the objective of reducing the greenhouse gas (GHG) emissions across the global value chain. While many models and frameworks have been developed, more work is needed in detailing practical changes that firms might readily deploy in their continual effort toward minimizing emissions (Bratt et al., 2021). Concurrent with these research endeavors surrounding green logistics, which may be defined as "the systematic measurement, analysis, and ultimately, mitigation of the environmental impact of logistics activities," a gradual transformation has occurred in the global turkey market (Blanco and Sheffi, 2017). While global turkey production volume has increased gradually over the last decade, the loci of production and consumption has continually shifted from a market dominated by the United States

(US) toward a market that has an increasing number of global producers and consumers (Kálmán and Szollosi, 2023). This transition presents a unique opportunity to implement "green" supply chain solutions as additional production units continue to emerge.

An outline of the paper may be summarized as follows: firstly, after providing additional context surrounding the global turkey market (Section 2.1) and the turkey market's challenges (Section 2.2), we aim to describe the supply chain associated with the production of turkey products (Section 2.3). Secondly, after providing some additional context related to green logistics (Section 2.4), we formulate a mixed-integer programming (MIP) model with the goal of minimizing the GHG emissions associated with a segment of the turkey production supply chain (Section 3). Thirdly, using data provided by one of the largest turkey producers in the United States (US), which we refer to as "the Company," we apply the MIP model and compare the resulting green logistics model with historical data (Section 4.1). Finally, we discuss the limitations of this green logistics model and the significance of the findings for other large turkey manufacturers (Sections 4.2 and 5).

The output generated by the MIP model described herein develops optimal brooder-finisher assignments[1] in a turkey growth and production network. We argue that implementation of this model at any large turkey manufacturer would result in an organization of their supply chain in such a way that would respond to the preeminent challenges faced by the turkey industry, including a reduced Global Warming Potential (GWP, the kg of CO_2-equivalents generated per kg of goods manufactured) of turkey products, increased biosecurity, and increased animal wellbeing. Previous research in the turkey industry directed at improving these parameters has focused heavily on optimizing feed efficiency,[2] modifying feed composition or farm worker behavior, and manipulating a variety of environmental factors (stocking density, temperature, light/chemical exposure, etc.).[3] However, there remains a notable gap in the foregoing academic research in the area of *supply chain* solutions for the turkey industry. Moreover, even a description of the supply chain processes analyzed in this paper has previously been confined to popular press articles and industry manuals, and not as an object of academic investigation. Thus, this paper finds its primary contribution in the successful application of a well-studied solution methodology (the Vehicle Routing Problem) to a "new" industry and, in doing so, provides a framework that other turkey manufacturers might readily adopt.

2 Background

The recorded history of the turkey spans some 500 years, with the bird having served as an important staple to the Native American diet for thousands of years prior. Archaeological evidence suggests that several Native American groups had domesticated the bird before European arrival in the Americas, and records indicate that the bird was then domesticated in Europe shortly thereafter (Brant, 1998; Peres and Ledford, 2016). In the most recent century, turkey has remained a commodity that enjoys significant seasonality due to its association with Thanksgiving and Christmas holidays. Additionally, owing to a favorable nutritional profile, adaptability to various climactic conditions, lack of religious constraints, and increased globalization, turkey products have become increasingly popular throughout the year and around the world (Henrikson et al., 2018; Famous et al., 2019; Khatko and Shirokova, 2022).

2.1 The global turkey market

Concurrent with advancements in genetics, feed science, and animal husbandry, the global turkey market has become increasingly productive, saturated, and competitive (Herendy et al., 2003). In 1962, turkey production in the US comprised nearly 61.1% of global output; in 2022, US production consisted of only 40.8% of global output (FAO, 2024). In the last 15 years, US production has remained relatively constant at 2.7 (+/−0.2) million metric tons while global production has increased from 5.5 million tons in 2007 to 6.2 million tons in 2021 (IndexBox, 2024; USDA, 2024b). Additional countries which hold significant share in the global turkey market and have seen a decline in production and market share in recent years include France (38% decrease in production between 2011 and 2021, 6.8% global market share in 2021), Germany (12.3% decrease, 6.3% share), Brazil (48% decrease, 2.8% share), and the United Kingdom (29% decrease, 2.3% share; FAO, 2024).

As the US, Brazil, and many western European countries have seen either stable or declining production, a variety of other players have emerged on or strengthened their position in the global market. Between 2011 and 2021, Russia increased production the most with an increase of 350,000 tons (Kálmán and Szollosi, 2023). This represents a 615% increase from 2011 and a 6.5% share of global production in 2021. Other nations increasing their production over the same time period include Poland (55% increase, 6.7% share), Spain (64% increase, 5.0% share), Morocco (52% increase, 4.1% share), and Tunisia (78% increase, 2.4% share; FAO, 2024). Nations which represent a notable (1–5%) share of the market and have demonstrated consistent production in the last 10 years include Argentina, Australia, Canada, Hungary, Italy, and Israel (FAO, 2024).

Top importing countries include Mexico, Germany, and Benin while top exporting countries include the US, Poland, and Germany (Kálmán and Szollosi, 2023). Global per capita consumption has remained relatively constant at ∼0.75 kg/capita-year for the last decade (∼5% of global poultry consumption); Israel held the greatest per capita consumption at 9.56 kg/capita-year in 2021, with Qatar, the US, Germany, and the Bahamas having the next greatest per capita consumption rates (Kálmán and Szollosi, 2023).

Continuous increases in turkey production and consumption are expected in the next 5–10 years. Roiter et al. (2021) project a 10–12% increase in finished turkey product consumption in Russia by 2030, as increasing turkey production represents an important aspect of Russia's long-term food security strategy (Zimnyakov

1 See Section 2.3 for a detailed description of the turkey production process, including definitions of the terms "brooder" and "finisher."

2 Feed efficiency is a measure of how much saleable product is produced per unit of feed consumed.

3 See Section 2.4 for a more thorough treatment of this topic.

and Dmitrieva, 2018; Askerov et al., 2021). In comparison, EU production is expected to continue to decline due to increasing domestic and environmental costs while US production is projected to remain relatively stable as in the previous decade (OECD/FAO, 2022; IBIS, 2024). Global turkey consumption of 6.7 million tons is projected for 2025, an 8% increase from 2021 (Hristakieva, 2021). More broadly, global meat consumption is projected to reach 377 tons by 2031, a 48% increase from a 255 ton 2019–2021 baseline; the greatest share of this growth (42.7%) is expected to come from increases in poultry consumption, particularly in developing countries (OECD/FAO, 2022). This livestock expansion is expected to be fueled by an increased consolidation of production units, indicating a continuous shift from small, local farms toward those resembling integrated growth and manufacturing systems as described in Section 2.3 of this paper (OECD/FAO, 2022).

We conclude this section by emphasizing the following points: (1) global turkey meat production has increased steadily over the last decade and is expected to continue to increase over the next decade, (2) this increased production has been and is expected to continue to be fueled by a disproportionately large increase in new production units in developing nations which offset the decline in production units seen in many developed nations, and (3) these new production units will likely resemble the integrated systems such as the one shown in Figure 1. As a result, the turkey supply chain will become increasingly homogenized, representing an opportunity for global manufacturers to more readily implement "greener" supply chain solutions such as the one described in Section 3 of this paper.

2.2 Challenges facing the turkey market

Despite the historical and expected continual growth of the turkey market, there remain many challenges manufacturers face when beginning, maintaining, and expanding production. Aside from the economic challenges associated with meeting increased global demand, manufacturers must contend with social challenges including pressure from consumer concerns over animal wellbeing, challenges related to biosecurity, and challenges related to environmental sustainability.

2.2.1 Social

As the technology and practices utilized in large-scale meat production have changed in the last several decades, a significant body of literature has arisen characterizing consumer attitudes, preferences, and understanding relating to animal welfare. Notwithstanding limited knowledge surrounding the animal husbandry systems utilized by large producers, consumers consistently rate animal welfare as important to them (Verbeke and Viaene, 2000; Frewer et al., 2005; Fleming et al., 2020). Tonsor et al. (2009) demonstrated that media coverage in the US related to animal husbandry and welfare increased between 1982 to 2008, and that there was a statistically significant relationship between negative coverage and decreased demand. The majority of consumers in developed countries receive substantial information about food products from television, the popular press, and social media, thus, large producers suffering from negative media coverage related to poor animal welfare practices face a significant risk of lost revenue (Kalaitzandonakes et al., 2004; Coleman et al., 2022). Few articles discuss public perception of turkey welfare and production processes, however, Bir et al. (2019) found that, for turkey, poor nutrition and illness rank as the top concerns amongst US consumers.

Given the link between public perception and demand, manufacturers clearly have an incentive to maintain a high level of wellbeing for their turkey flocks. Supplementing this incentive is the fact that less diseased, less stressed, more energetic, and better-fed flocks result in fewer mortalities, greater feed efficiency, and greater yield for the manufacturer (Erasmus, 2018). As such, optimizing flock performance via improved animal welfare is an area of significant interest for academia and industry alike. The effects of hot and cold exposure, chemical exposure, stocking density, lighting, antibiotic use, feed composition, and various transportation strategies are all topics of high and prolonged interest (Sherwin et al., 1999; Erasmus, 2017; Wein et al., 2017; Cândido et al., 2018). The relationship between travel distance and mortality rates (for the Company) is explained further in Section 4.1.2 of this paper. Transport represents one of the most stressful events in poultry husbandry and, as such, any supply chain solution or modification must consider the potential impact on animal wellbeing (Marchewka et al., 2013).

2.2.2 Biosecurity

A significant threat to meeting the large and increasing demand on the global turkey meat supply is presented by communicable disease outbreaks, particularly Exotic Newcastle Disease (END, also called Paramoxyvirus) and Highly Pathogenic Avian Influenza (HPAI; Frame, 2010; WOAH, 2024). Due to a natural susceptibility to respiratory infections, both END and HPAI pose significantly greater risks to turkey populations than other forms of poultry (Russell et al., 1989). In one study, Aldous et al. (2010) found turkey to be over 200 times more susceptible than chicken to two recent strains of HPAI. Given the ease of transmission, high prevalence, high mortality rate, and the often-low efficacy of inoculation for these pathogens, the implications of an uncontrolled and widespread outbreak are severe. Consequently, the US Department of Agriculture, EU, and Russian Ministry of Agriculture (as a few case examples) have developed sizeable regulatory frameworks, research programs, monitoring networks, and emergency response procedures aimed at curtailing the risk (Code of Federal Regulations, 2006; Cardona et al., 2018; European Food Safety Authority, 2021; Vorotnikov, 2024).

Preventative measures taken to reduce the risks of infectious disease include proper facility siting (away from water, other livestock), pest control, limiting access to farms, personal protective equipment requirements for farm workers, sanitization procedures (for farm equipment and personnel, replacing litter between flocks), allowing "down time" between flocks, farm climate control, removal of dead livestock, and frequent flock surveillance (USDA, 2013; van Staaveren et al., 2020; Islam et al., 2024). In their assessment evaluating the risk of HPAI infection throughout the turkey-growing process, Cardona et al. (2018) identify

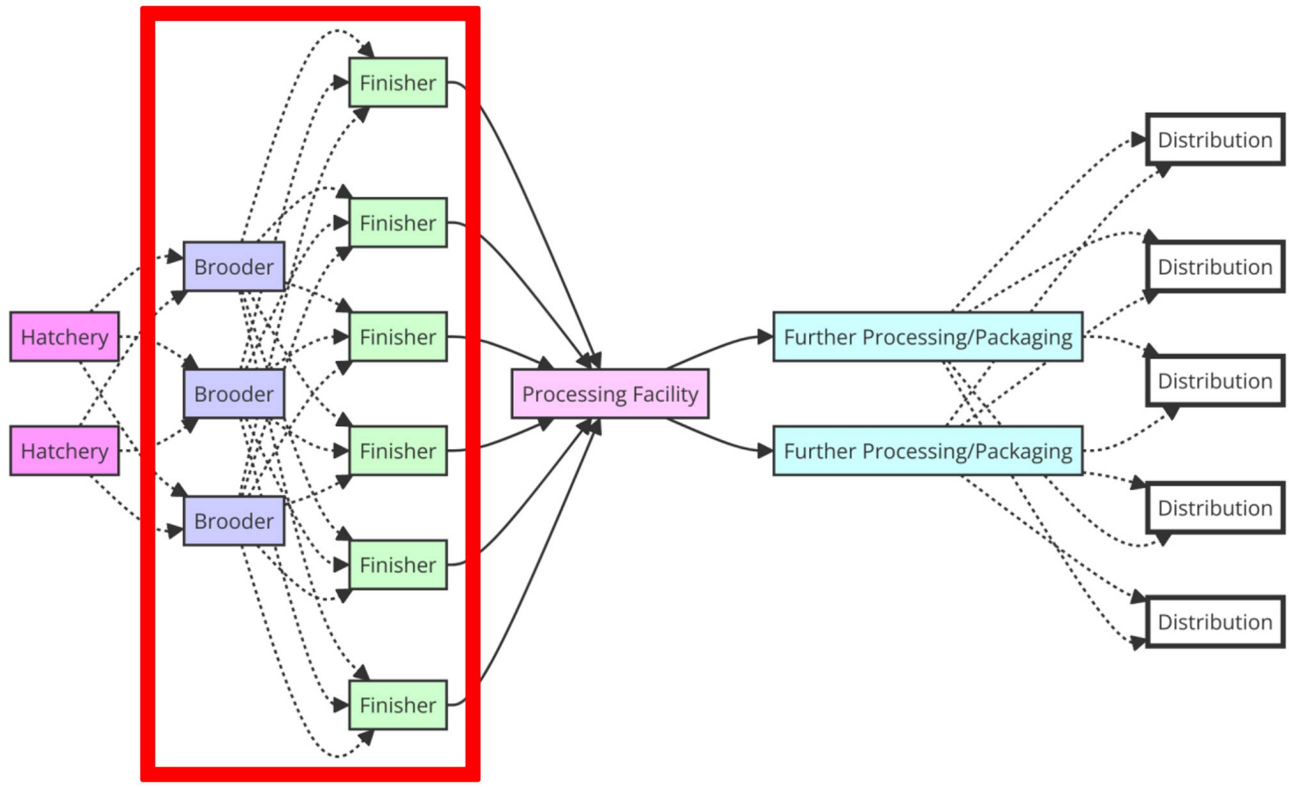

FIGURE 1
Depiction of the turkey product supply chain. The segment of the supply chain analyzed in this paper is highlighted in red.

transportation and load-out of birds as the segment of the process which poses the greatest risk to spreading infection. Thus, any satisfactory supply chain change or solution must contend with potential impacts on biosecurity.

2.2.3 Environmental sustainability

Agricultural production accounts for 19–29% of global anthropogenic GHG emissions, a significant proportion of which (up to 80%) may be attributed to meat production (Fiala, 2008; Vermeulen et al., 2012; Barthelmie, 2022). As noted in Section 2.1 of this paper, global meat consumption is expected to increase 48% (122 tons) by 2031, with the largest share of this change coming from increased poultry consumption. Accordingly, reducing the GWP of poultry products represents a critical component of improving the sustainability of the world's food supply. Numerous Life Cycle Assessments (LCAs) have been conducted estimating the environmental sustainability of chicken, and authors have calculated GWP values ranging from 1.06 kg CO_2-e to 9.98 kg CO_2-e with a mean of 4.12 kg CO_2-e (de Vries and de Boer, 2010; Clune et al., 2017; Costantini et al., 2021). Comparatively fewer LCAs for turkey are available for analysis, however, Leinonen et al. (2016) and Kheiralipour et al. (2017) estimated the GWP for turkey at 3.63 kg CO_2-e and 4.57 kg CO_2-e, respectively. In a 2023 LCA commissioned by the Turkey Farmers of Canada, the agri-food analysis firm Groupe AGÉCO calculated the GWP for turkey at 3.50 kg CO_2-e, with 77% of these emissions coming from the growing of the bird. The largest contributing factors to emissions, both in turkey growing and in the overall product life cycle, are attributable to feed (∼35% total emissions), energy for farm upkeep (∼17% total emissions), and *transportation* (∼12% total emissions; MacKimmie, 2023).

Many groups advocate for sweeping dietary changes as an effective method of curbing climate change (Yue et al., 2017; United Nations, 2024). In comparison with beef (average GWP: 28.73 kg CO_2-e) and other ruminant meat, turkey presents a promising alternative (Clune et al., 2017). Hallström et al. (2015) calculated that replacing ruminant meat with monogastric meat (chicken, pork, turkey, etc.) would result in a 20–35% decline in GHG emissions from dietary sources. Nonetheless, turkey holds a significantly higher GWP than most plant-based sources (with GWPs ranging from 0.20–1.50 kg CO_2-e; Clune et al., 2017). Given the increasing rates of turkey consumption, turkey's high relative GWP when compared to plant-based sources, and the sizeable contribution of transportation to turkey's GWP, implementing sustainable supply chain solutions remains an imperative for the turkey industry.

2.3 The turkey supply chain

As further context for the MIP model and ensuing discussion, this section aims at characterizing the turkey supply chain, with a special emphasis on steps two to three of the process described below. A brief overview of the supply chain in its entirety may be described as follows (also depicted in Figure 1)[4]:

1. Incubation of eggs at a hatchery.
2. Delivery of 1-day-old chicks to farms termed "brooders" in the industry. These farms are specially outfitted to care for birds in their first 4–6 weeks of life.
3. Upon sufficient maturation of the juvenile turkeys (also called "poults"), the livestock is transported from the brooder to a farm referred to as a "finisher" farm. At the finishers, birds are raised to full maturity, which could be expected to take a further 15 weeks.
4. Upon reaching full maturity, grown turkeys are then sent from the finisher to the processing facility where they are harvested.
5. Following the harvesting of the animal, the assortment of products gathered from the bird are then sent to other facilities for further processing and packaging, as differing products (thigh meat, breast meat, offal, etc.) may be allocated to different commodities (sausage, hot dogs, sandwich meat, pet food, etc.). As an alternative to this step, some larger manufacturers have combined processing and finished product facilities.
6. Finished product is sent to distribution warehouses and customers.

In comparison with industries representing a greater share of global meat consumption such as chicken, pork, and cattle, less information relating the turkey production process and supply chain is publicly available. Much of this information is derived from the author's personal experience working in the industry, from historical data provided by the Company, and from consulting with Company farm managers and production planners, however, additional and confirmatory details may be found in USDA (2013) and Cardona et al. (2018).

As stated above, the MIP model formulated in this paper aims to reduce transportation distance and subsequent GHG emissions from the movement of poults between brooders and finishers (steps two and three). The following points are important in clarifying to the reader the details of this process and in generating assumptions and constraints for the model described in Section 3.3 of this paper.

The Importance of Brooders, Former Utilization of "Brood to Finish" Farms: the brooder to finisher step in the turkey supply chain is one element which distinguishes this commodity from other types of poultry, such as chicken or duck. In comparison to the ∼20-week life cycle and 20 kg harvest weight for turkey at the Company, commercial broiler chicken may take only 7 weeks to grow and weigh a comparative 3 kg at harvest (USDA, 2024a). Thus, manufacturers find it convenient to have chicken spend their entire life cycle in one building. Such a production model was formerly favored in the turkey industry via the use of so-called "brood to finish" farms, however, this model has fallen out of favor, mainly due to the increased biosecurity risk, higher cost, and poor utilization of space associated with "brood to finish" growing schemes.

Farm Capacity: as implied by Figure 1 and explained in Section 3 of this paper, the number of brooder farms is generally significantly less than the number of finisher farms. Brooders and finishers also have varying capacities of flock sizes they accommodate. It remains important to note that the *demand is fixed* at the brooder to finisher level, as contracts with the turkey hatcheries supplying the brooders are negotiated years in advance. Historical data (3 years) and production forecasts (2 years) provided by the Company indicate that demand at the hatchery to brooder level is also consistent, further validating this fixed-demand assumption.

Timing: some elements related to this constraint have been discussed in previous sections. The amount of time required to raise the turkey would depend on the breed, the sex, the feeding schedule, and a variety of other factors. The turkeys utilized by the Company in this problem spent an average of 5 weeks in the brooder prior to transfer to a finisher, where the livestock was grown for a further 15 weeks. This schedule may be extended or condensed to some extent dependent upon the performance of the flock and the processing facility, however, every effort is made to harvest the birds at a weight of 20 kg, which, in the case of the Company, is the design specification of the turkey harvesting equipment at the processing facility; too great of a deviation from this weight results in decreased yield. Due to the concern for biosecurity, there is also a need to sanitize farm equipment and replace litter between each flock. The time allotted for this would depend slightly on the production schedule and flock performance, but, for the Company's farms, this historically took 3–4 weeks for brooder farms and 2–3 weeks for finisher farms. The time to completely turnaround a brooder farm for a new flock shall be taken as *60 days* (35 days growing, 25 days sanitization/preparation) and the time taken to completely turnaround a finisher farm shall be taken as *120 days* (105 days growing, 15 days sanitization/preparation). Thus, the model will formulate an "A/B" system wherein each brooder farm will be assigned to two groups of finisher farms; *this could be contrasted against the Company's current "first available" system in which poults from a brooder are sent to whichever finishers are currently available, without consideration for distance traveled.*

Biosecurity: the importance of this constraint was discussed at length in Section 2.2.2. As it relates to its application in this problem, the primary biosecurity concern taken into account in the model formulation is that *different brooder flocks may not be combined upon transfer to the finisher* (finisher farms are comprised of multiple barn buildings). While it may be efficient from a logistical point of view to allow brooders to "share" finisher assignments, this would result in an unacceptable biosecurity risk. Thus, finishers may be assigned to only one brooder.

Further Remarks on Transportation Between Brooders and Finishers: upon the transfer of birds from brooders to finishers, poults are loaded into trailers at the brooder farm and then unloaded at one of a few finishers. Trailers used for transfer hold up to 3,000 poults. Thus, a brooder with a capacity of 120,000 would require 40 trailer trips to empty to a set of finishers, a finisher with a total capacity of 33,000 would require 11 trips to fill, and so on.

4 Statements related to timing are specific to the data provided by the Company. However, the time required to raise a turkey would generally depend on the sex, the breed, the feed efficiency, and the health of each flock.

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2.4 Previous research in green logistics and application in the present study

Prior to the 1960's, relatively little concern in academic literature was given to the environmental degradation caused by freight transport, and a common assumption was held that the environment's ability to effectively absorb wastes and replace resources was effectively infinite (Murphy et al., 1995). However, as the environmental externalities associated with freight transport continued to mount throughout the latter half of the twentieth century this erroneous assumption was increasingly cast aside, and an increasing number of logistics publications and corporations began to investigate methods of decreasing the negative environmental impacts of their supply chains (Aronsson and Huge-Brodin, 2006; Mckinnon, 2015). In a more recent review by Ma and Kim (2023), the researchers reveal that "green logistics" has become a vibrant area of scholarly inquiry. They demonstrate the rapid growth of the field from only a few 100 publications annually in the mid-2000's to almost 3,500 in 2021, and identify "optimization analysis of low-carbon vehicle routing and time" (the subject of this paper) as one of the most active research topics in the last few years.

Although many definitions of varying scope have been proposed for the term "green logistics," for the purposes of this paper we utilize the definition provided by Blanco and Sheffi (2017): "the systematic measurement, analysis, and ultimately, mitigation of the environmental impact of logistics activities." This might encompass supply chain activities involved in purchasing, warehousing, production, transportation, delivery, or reverse logistics. One might reasonably assume that any type of cost-reduction effort realized by a more "efficient" supply chain could be considered "green," however, this is not the case. As many studies have shown, some supply chain "efficiencies" including centralization of inventory, wider sourcing of materials, and just-in-time inventory systems come with a greater environmental cost (Whitelegg, 1994; Garnett, 2003; Matthews and Henrickson, 2003). Nevertheless, implementing green logistics solutions are *frequently* associated with decreased cost and improved financial performance (Rao and Holt, 2005; Wang and Sarkis, 2013; Ahmad et al., 2022). In PwC/APIC's 2013 survey of 162 supply chain professionals representing large US companies, "cost reduction" was cited as the top benefit derived from sustainable supply chain initiatives (PwC and APIC, 2014).

In this study, we develop a MIP model with the objective of reducing the distance traveled (and, subsequently, GHG emissions) when transporting turkey poults from brooders to finishers. This transportation problem may be classified as a Vehicle Routing Problem (VRP), a class of problems first described in 1959 by Dantzig and Ramser which seeks to determine the least-cost delivery route from a facility to a set of geographically disbursed customers; this class of problem has seen numerous successful applications (Dantzig and Ramser, 1959; Laporte, 2009). The Pollution Routing Problem (PRP), is a variation of VRP in which variables such as speed of travel, terrain, equipment characteristics, load weight, loading time, and congestion are utilized in the construction of the optimal network design (Bektaş and Laporte, 2011). While in this model we do consider equipment characteristics in the overall GHG emissions calculation, factors such as speed of travel, terrain, and congestion are assumed to be negligible due to homogeneity of the vehicles used in transport and the flatness of terrain and lack of congestion in the area surrounding the farms located in this study. As such, the way we formulate this problem more accurately resembles a traditional VRP.

Several authors have applied a variety of mathematical modeling approaches toward improving the efficiency and/or sustainability of chicken processing and distribution operations, although none have ventured to apply similar methods to turkey growing. A significant proportion of these studies apply linear programming approaches to either nutrition delivery (Chagwiza et al., 2016; Alqaisi et al., 2017) or manure management (Ma et al., 2018; Deng et al., 2022). Islam et al. (2016) applied a MIP approach to the poultry industry in Bangladesh, effectively assigning retailers to manufacturers with the objective of maximizing profits to retailers. Boudahri et al. (2011) approached a chicken processing facility and chicken farm citing problem wherein processing facilities were allocated to areas around customer clusters and farms allocated around processing facilities; this was done in such a way to minimize the transportation costs in the network. While both of these studies approach similar problems as those addressed in this study (assignment and transportation cost minimization), neither adequately approximates the circumstances.

Expanding the scope of this literature review beyond just the poultry industry, one may—in some respects—find a greater similarity between the pre-processing animal transport supply chain of cattle and turkey than between chicken and turkey. In the cattle industry, calves are raised with their mothers for ~6 months prior to being weaned (for 2 months on average) and then transported to feedlots; additional transport nodes and logistics stopovers are possible at auction markets, classification centers, or health checkpoints (Miranda-de la Lama et al., 2014; Machado and Michael, 2022). This may be contrasted against the transport nodes found in the pre-processing turkey supply chain (hatcheries, brooders, finishers, and processing facility). In an attempt to optimize this aspect of the cattle supply chain, a variety of authors taken approaches similar to the one we present in this paper. Frisk et al. (2018) deployed a MIP via the RuttOpt route optimization system for the purposes of solving a pick-up and delivery problem with the objectives of minimizing transport time and distance driven. Morel-Journel et al. (2021) effectively assigned weaned calves to sorting centers via an algorithm that could be classified as an MIP with Time Windows (TW) with the objective minimizing transport distance. As a final case example, Gebresenbet et al. (2011) utilized the commercially available Route LogiX software to simulate and arrange transportation assignments between feedlots and an existing and prospective new processing facility. A summary of the objectives, methodology used, and results obtained by some of the foregoing research relevant to our paper is reviewed below in Table 1.

From this review of green logistics and some recent applications, we conclude that (1) implementing supply chain solutions directed at reducing GHG emissions is a topic of increasing importance and interest, (2) amongst a variety of approaches, the use of VRP MIPs for the purposes of

TABLE 1 Summary of related research.

Study	Industry	Objective	Methodology	Results
Boudahri et al. (2011)	Chicken	Minimize total fixed and transportation costs (a function of distance) in the assignment of chicken processing facilities assigned around customer clusters, and subsequently assign farms around identified processing facilities.	Two-phase MIP	Development of a theoretical network of chicken processing facilities/farms that minimizes total costs of the network in the region.
Frisk et al. (2018)	Cattle	Minimize transportation costs (given as a function of driving time and distance) across a cattle production network, feedlot to processing facility.	MIP	14% reduction in transportation time, reduction in number of stops, and 67% reduction in transportation distance.
Morel-Journel et al. (2021)	Cattle	Minimize transportation distance across a cattle production network, weaning to sorting center	MIP-TW	18% reduction in average annualized travel distance compared against historical records.
Gebresenbet et al. (2011)	Cattle	Assign least-distance transportation routes between cattle feedlots and processing facilities	Simulation	Expected 42% reduction in transport distance, 37% reduction in transport time.
Present Study	Turkey	Minimize transportation distance between turkey brooders and finishers in a turkey production network	MIP	Expected 50% reduction in transport distance and 40% reduction in transport-related mortalities.

At this time, there is no other available literature describing a quantitative approach (similar to what has been done for chicken, cattle, and other livestock) toward optimizing transportation in the pre-processing segment of the turkey supply chain. This is one fact underscoring the utility and contribution of this study.

solving assignment problems has been successful in similar industries, and (3) *no similar approach to optimizing the turkey growing supply chain has yet been proposed*. Thus, a significant contribution of this study lies in its novel application of a well-proven and applied method to the turkey industry.

3 Problem formulation

Now that the reader has been provided with a sufficient level of background information necessary to understand the challenges faced by the turkey industry, the energy-intensive nature of transporting poults between brooders and finishers, and the potential for application of green logistics in this process, we propose the following MIP model formulated as a VRP.

3.1 Symbol descriptions

Let i denote the index of brooders and j denote the index of finishers. The capacity of brooder i shall be given as a_i and the capacity for finisher j shall be given as b_j. The number of trailer trips required to fill finisher j would be equal to the capacity of finisher j divided by the number of poults delivered to the finisher by each trailer trip (3,000). Thus, a finisher with a capacity of 33,000 would take 33,000/3,000 = 11 trailer trips to fill. The number of trailer trips times the distance between brooder i and finisher j would equal the total travel distance required to fill finisher j from poults provided by brooder i, a value which shall be described as d_{ij}. The binary decision variable x_{ij} shall be equal to 1 if finisher j is assigned to receive poults from brooder i and 0 otherwise. The notation for this VRP is summarized in Table 2.

TABLE 2 Notation for the brooder-finisher VRP.

	Index and parameters
i	Index for brooders, for all $i = 1, 2, \ldots, n$
j	Index for finishers, for all $j = 1, 2, \ldots, m$
a_i	The capacity of brooder i
b_j	The capacity of finisher j
d_{ij}	The travel distance (km) required to fill finisher j with poults from brooder i
x_{ij}	The decision variable that = 1 if finisher j is assigned brooder i and = 0 otherwise

3.2 Data collection

The dataset used in the application of this model may be found in the Supplementary material. All data related to capacity and distance is based on the operational and geographical data provided by one of the largest turkey manufacturers in the US (referred to as "the Company"). The Company operates 10 brooder farms with a capacity of 110,000 to 187,000 birds/farm and 66 finisher farms with a capacity of 22,000, 33,000, 44,000, or 55,000 birds/farm. The distances between brooder and finisher farms ranges from 1.5 to 135 km. On an annual basis, this collection of farms would be expected to grow ∼9 million turkeys/year.

3.3 Model formulation and solution methodology

The objective function applied to optimize brooder-finisher routing is described in Equation (1):

$$Minimize\ Z = \sum_{i=1}^{n} \sum_{j=1}^{m} d_{ij} x_{ij} \quad (1)$$

The model is subject to the following constraints:

$$\sum_{j=1}^{m} x_{1j} + x_{2j} + x_{3j} + x_{4j} + x_{5j}$$
$$+x_{6j} + x_{7j} + x_{8j} + x_{9j} + x_{10j} = 1 \quad (2)$$
$$\sum_{i=1}^{n} 2a_i \leq \sum_{j=1}^{m} b_j x_{1j} \quad (3)$$
$$x_{ij} \in \{0, 1\} \quad (4)$$

Equation (1) seeks to minimize the total travel distance between brooders and their assigned finishers. The constraints represented by Equations (2) and (4) ensure that each finisher may be assigned to only one brooder while the constraint represented by Equation (3) ensures the collective capacity in those finishers assigned to brooder i is sufficient to accept two flocks of brooder poults. This also ensures that assignments intrinsically allow any output to observe the timing constraints, since the turnaround time for finishers is twice that of brooders. Additionally, as argued in the following section, the use of Equation (3) results in a system organization that better promotes biosecurity than a "first available" production model.

The solution methodology we employ for solving this MIP is exemplified by the combination of root relaxation and the branch-and-bound algorithm. Initially, the root node is determined via root relaxation, wherein the integer constraints are relaxed, allowing the variables to assume continuous values. As the branch-and-bound algorithm progresses, cutting planes are employed to further tighten the bounds and eliminate fractional solutions, thereby enhancing the efficiency of the search process.

4 Results and discussion

The objective function and constraints described in the previous section were built into a program utilizing the Gurobi Optimizer software (output and parameters may be found in the data availability statement). This model was then solved utilizing the capacity and distance data provided by the Company as well as the solution methodology just described.

4.1 Model results

Solving the foregoing model with the given constraints yields the optimal brooder-finisher assignments (Data and code may be found at this repository: https://github.com/bazylhorsey/livestock-logistic-optimizer). This output details the exact assignments of brooders to each finisher given the objective and constraints detailed above. For example, brooder 2 in this case is assigned to send poults to finishers 8, 16, 22, 23, 24, 33, 40, 46, and 64. The capacity of the identified finishers would enable the associated brooder to continuously supply these finishers indefinitely given a constant production demand, a reasonably justifiable assumption given 3 years of historical production records and the 2-year production forecast (see Section 2.3).

With this derived set of brooder-finisher assignments, the expected annual travel distance may easily be calculated and compared against historical records. The value of the solution obtained by the model is 27,856.1 km. Note that this is the travel distance for trailers going *to* the finisher from the assigned brooder *once*. Thus, the expected value of the annual travel distance may be calculated by multiplying the solution value by the number of times per year each finisher could be expected to receive birds $\left(\frac{120\ day\ finisher\ turnaround\ time}{365\frac{days}{year}} = 3.04\frac{deliveries}{year}\right)$, and again by two to account for return trips. Executing this calculation yields the following:

$$27,856.1\frac{km}{delivery} \cdot 3.04\frac{deliveries}{year} \cdot 2 = 169,458\frac{km}{year}$$

Given that the brooder-finisher production supply chain arrangement is shared by most large turkey manufacturers, this model could be readily re-applied by another manufacturer, given considerations to some of the parameters that may not be shared in common between manufacturers (breed, growing time, farm capacity, etc.—further discussed in Section 4.2). Turkey manufacturers implementing the framework provided by this model could expect operational improvements including a reduction in GHG emissions/costs from transportation and improved animal wellbeing and biosecurity, as demonstrated in the two sub-sections below.

4.1.1 Reduction in GHG emissions and transport costs

Based on records provided by the Company, a total of 371,825 and 309,978 km were traveled (delivery and return trips) in their 2020 and 2021 fiscal years, respectively. This could be contrasted against the 169,458 km of expected travel distance determined by the optimal assignment model constructed by the MIP. A performance comparison between the optimal assignment model and previous years is demonstrated in Table 3.

There exist a variety of popular methods for calculating GHG emissions from freight transport. These include fuel-based, distance-based, and weight-distance based methods. Fuel-based approaches require knowledge of total fuel consumption, which is not a metric tracked by the Company, and thus not a viable approach for calculations in this study. Weight-distance methods are generally applied when using shared modes of transportation or when only a minimal amount of information (related to the exact vehicle used and route) is known about a shipment (Blanco and Sheffi, 2017). Thus, the most appropriate calculation for GHG emissions in this study would be the distance-based approach using the appropriate emissions factor (*EF,* as defined by the GHG Protocol) of $1.07\frac{kg\ CO_2-e}{km}$ for diesel-powered articulated heavy goods vehicles (IPCC, 2017). Thus, calculating GHG emissions in this problem is executed as follows:

$$Emissons = EF \cdot \sum \left(distance\ traveled\right) \quad (5)$$

As shown by Table 3, implementation of the brooder-finisher assignments according to the model results would yield an ∼50% reduction in travel distance and GHGs emitted. Other benefits which could be reasonably associated with adoption of the results of this model would include reduction in driver labor costs (fewer drivers required, less time driving), reduction in costs associated with vehicle repair and maintenance, and reduction in the comparatively high administrative production planning overhead affiliated with a "first available" system.

TABLE 3 Distance/GHG emissions performance under optimal assignment model compared to previous years.

Case	Annual distance traveled (km)	Annual GHG emissions (metric tons)	GHG emissions improvement vs. assignment model (metric tons)	% reduction in GHG emissions and travel distance vs. assignment model
2020	371,825	398	−217	−55%
2021	309,978	332	−151	−45%
2020/2021 avg	340,902	365	−184	−50%
Optimal assignment model	169,458	181	–	–

GHG emissions calculated using Equation (5).

4.1.2 Improved wellbeing and biosecurity

As emphasized in Section 2.2.1, transportation of turkey poults from brooders to finishers represents a very stressful event for the livestock. Upon transport, poults are removed from their environmentally-regulated pens by laborers and loaded into trucks. During this process, the poults are subjected to the psychological and physical stresses of being handled by laborers as well as the stresses associated with exposure to the outside environment. As the transportation distance between brooders and finishers increases, the time poults spend exposed to these psychological and climactic conditions increases. Table 4 exhibits this association. As demonstrated by the historical data collected by the Company (columns 2–4 of Table 4), poult mortality rate is heavily associated with transport distance. Columns 5 and 6 of Table 4 demonstrate the expected number of trips taken in each distance category and the subsequent number of moralities due to transport (given similar trip mortality rates as previous years) over 1 year. The estimate of total mortalities after adoption of the brooder-finisher MIP model results indicates that an annual mortality reduction of almost 40% (∼7,000 fewer mortalities per year) could likely be achieved. This reduction in mortalities would indicate an overall improvement in animal wellbeing because the poults would find themselves subjected to the stresses associated with transport for significantly less time.

A significant additional benefit of the "A/B" assignment model formulated by the MIP over the "first available" system currently used at the Company could be attributed to reduced biosecurity risk. Figure 2 shows an modified depiction of the turkey supply chain given adoption of the MIP model assignments. A visual comparison of Figures 1, 2 indicates this potential biosecurity improvement. Under a "first available" system, poults are sent to a finisher which formerly received birds from a different brooder, whereas in the supply chain arrangement organized by the MIP each brooder-finisher group is segregated. Despite sanitization efforts between finisher flocks, variants of the HPAI virus possess a demonstrated ability to persist in a variety of media for over a month (Cardona et al., 2018). Thus, in the event of an infectious disease outbreak, a "first available" system leaves poults from an incoming flock at risk of contracting a disease that may have formerly been confined to only the flocks associated with a different brooder farm. Adoption of segregated brooder-finisher groups generated by the MIP model would thus represent a more effective way of confining disease outbreaks.

4.2 Study limitations

The primary limitations of this study could be categorized into three main groups. Firstly, assumptions related to brooder-finisher turnaround time and a variety of other related factors (bird breed/sex, farm capacity, network design, etc.) are derived from only one turkey manufacturer. The second broad category of limitations could be ascribed to the difficulty of implementation pre-existing turkey manufacturers may face when attempting to transition from a "first available" brooder-finisher turkey growing system to one resembling optimal brooder-finisher assignments formulated by a MIP. Finally, more accurate and comprehensive methods of measuring GHG emissions may yield improved results.

In addressing the first limitation described in the preceding paragraph, a turkey manufacturer must consider the breed and sex of the turkeys which they grow, the feed efficiency which they are able to realize, and the potential flexibility of the sanitization times and processing facility schedule. These factors all contribute to the overall turnaround time of a brooder or finisher, and the performance of this or any similar model would be sensitive to a modification in these parameters. Production delays at the processing facility or an underperforming finisher flock might require a delay in the processing of a given finisher flock or group of finisher flocks, which would in turn delay the arrival of a new finisher flock from the finisher's respective brooder and thus require a more condensed sanitization schedule for both finisher and brooder farms. Despite the near-inevitability of such delays in any manufacturing operation, the Company analyzed in this study demonstrated significant flexibility when faced with such challenges. For example, historical data reveal that the sanitization time for brooders and finishers *could* be condensed to as little as 1 week or extended to as much as 4 or 6 weeks, respectively; this could be contrasted against the greater-than 3-week and 2-week brooder/finisher sanitization time assumptions adopted in the foregoing model. The growing time of poults at a brooder had also historically been extended for up to an additional week. Furthermore, operating the processing facility for an additional shift (a common practice at the Company) would constitute another strategy for addressing a surplus of fully-grown finisher flocks. A stochastic MIP model was considered in an attempt to capture this variability, however, on account of the fixed hatchery→brooder→finisher→processing

TABLE 4 Comparison of historical poult mortality rates during transport and expected mortality rates after adoption of MIP model results.

Trip distance (km)	From actual poult morality data recorded over 2 years (2020 and 2021). Expressed as the *average annual* number of trips taken and mortalities per distance category.			Projected number of trips taken and *expected* mortalities given adoption of MIP model results.	
	Number of trips taken	Mortalities due to transport	Mortality rate per trip	Number of trips taken	Mortalities due to transport
0–10	219	491	2.2	1,118	2,510
11–20	333	957	2.9	762	2,192
21–30	573	1,941	3.4	612	2,074
31–40	545	2,600	4.8	428	2,042
41–50	542	2,353	4.3	83	361
51–60	300	1,503	5.0	0	0
61–70	281	1,679	6.0	232	1,386
71–80	184	1,216	6.6	46	305
81–90	125	607	4.9	0	0
91–100	54	398	7.4	0	0
101–110	39	421	10.8	58	625
111–120	41	647	16.0	0	0
120+	187	3,808	20.4	0	0
Total	3,419	18,616	–	3,339	11,495

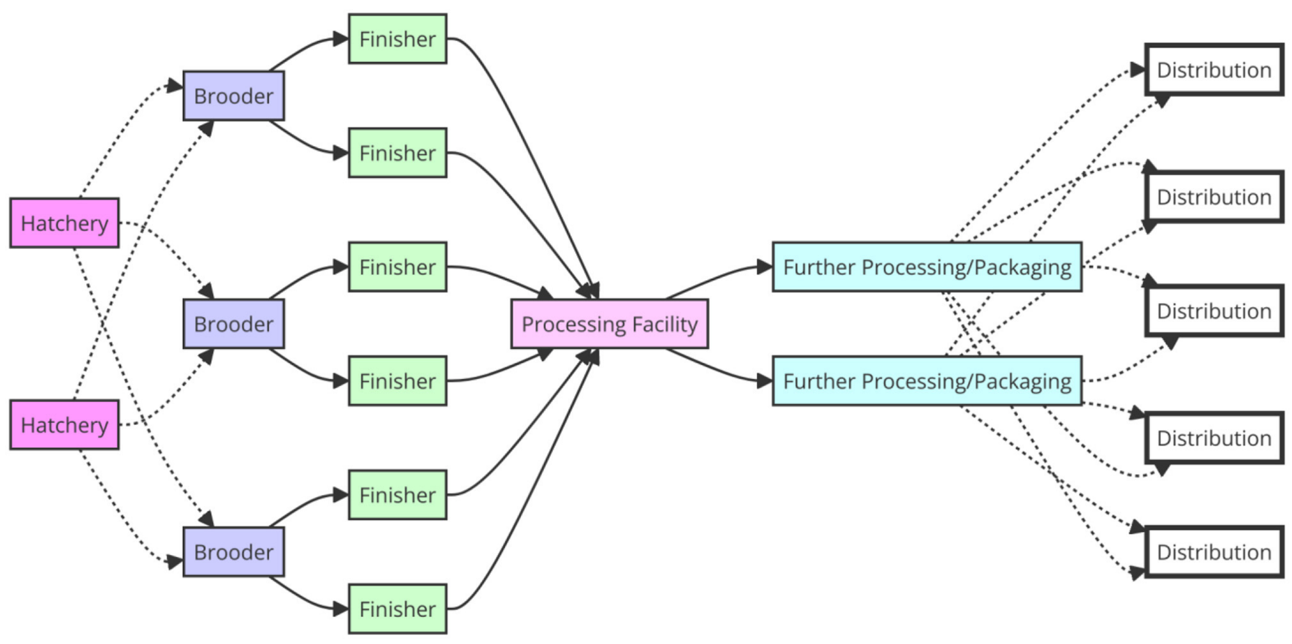

FIGURE 2
Modified depiction of turkey supply chain given adoption of MIP model results.

facility growing/production volume (see Section 2.3) and the operational flexibility just described, a stochastic model was determined to have little additional benefit. Sensitivity analyses examining the effects of turnaround time modification (again, generally a function of a combination of bird breed and sex, feed composition, feed efficiency, husbandry practices, and labor availability) or siting of additional farms may demonstrate improvements in the model, or require modifications to the model constraints and input variables. In summary, any change in the turnaround time or capacity assumptions described in Section 2.3 would necessitate a change in or additions to Equations (2, 3) of the foregoing model. However, the overall framework of the model could nonetheless see adoption by any turkey manufacturer, given that the manufacturer operates under the industry standard practice of having standalone brooder and finisher farms.

The second, and perhaps foremost, limitation could briefly be encapsulated as "difficulty of implementation for existing manufacturers." The model formulated above generates the optimal brooder-finisher assignments, but does not detail how a manufacturer might transition from a "first available" or other system to this more sustainable system. When attempting to implement the results of this more sustainable production and transportation system, and existing manufacturer might: (1) cease growing and production for a period of several months before re-starting under the brooder-finisher assignments resulting from model execution or (2) engage in a carefully-planned slow transition (likely spanning at least 2–3 years) from the manufacturer's current practices to the arrangements identified by the MIP model output. Barring anomalous circumstances, the first option would likely present an untenable solution to most large manufacturers. Thus, in implementing the recommended solution from the model designed in this paper an existing manufacturer would likely need to select the second option, which represents the approach currently being taken by the Company in this study. Further research in this area, describing how a turkey manufacturer might quickly transition from their current state to a more sustainable state, would constitute an auspicious area of inquiry. Ideally, a manufacturer would consider the sustainability of a potential new turkey growing and processing operation prior to construction of the network; the review in Section 2.4 of this paper as well as reviews conducted by other authors indicate that manufacturers are increasingly considering sustainability in their network design (Joshi, 2022). In such a case, the prospective manufacturer would be able to more easily execute and implement a similar MIP model as the one described herein.

In this study, the distance-based method was utilized in calculating GHG emissions. This represents an inferior approach to the fuel-based method (not used due to a lack of data), but a superior approach to the weight-distance based method (in this case). Factors related to congestion and landscape were considered as negligible to the overall GHG emissions. Given the geographical setting of the Company, this was an appropriate assumption, however, this assumption may not be valid in a re-application of this approach. Additionally, factors such as vehicle idling time, vehicle speed, and road characteristics were not considered. Consequently, the GHG emissions reduction calculations presented in this paper likely present an *underestimate* of the *actual* reductions realizable upon implementation. With additional data related to road characteristics, vehicle characteristics, and idling time, the objective function might be reformulated as a PRP (with factors affecting GHG emissions in the objective function) rather than a VRP. PRPs constitute a new and developing area of academic inquiry, and reformulation of the objective function to account for the assortment of variables affecting GHG emissions in freight transport presents a promising direction for future research (Marrekchi et al., 2019).

5 Conclusion

In this paper, we develop a MIP model aimed at reducing the travel distance and subsequent GHG emissions in a network of turkey brooders and finishers. This model is then applied to a network owned by one of the largest turkey manufacturers in the US. Implementation of the ensuing model results could be expected to reduce GHG emissions in the network by ∼50% (a 184 metric ton CO_2-e reduction) while also favorably addressing the other preeminent challenges currently facing the turkey sector (cost of production, biosecurity, and animal wellbeing). The foremost limitation of this model may be identified as the difficulty an existing manufacturer might face when implementing the model results. However, it must be pointed out that trends in the global turkey market indicate the sustained increase in *new* production units in developing countries. As such, this timely publication may enable these new and expanding turkey operations an avenue by which to decrease the environmental impact of their products. This opportunity is underscored by the model's simplicity and subsequent ease of execution when supplied with a new data set. Furthermore, this study provides a broader contribution to the existing literature by describing and analyzing the supply chain of turkey products, a commodity whose *supply chain* had previously only been sparsely described in the popular press and industry manuals.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/supplementary material.

Author contributions

GW: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. BH: Formal analysis, Methodology, Software, Visualization, Writing – review & editing. RS: Resources, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Power plant units for CO_2 neutral energy security in Switzerland

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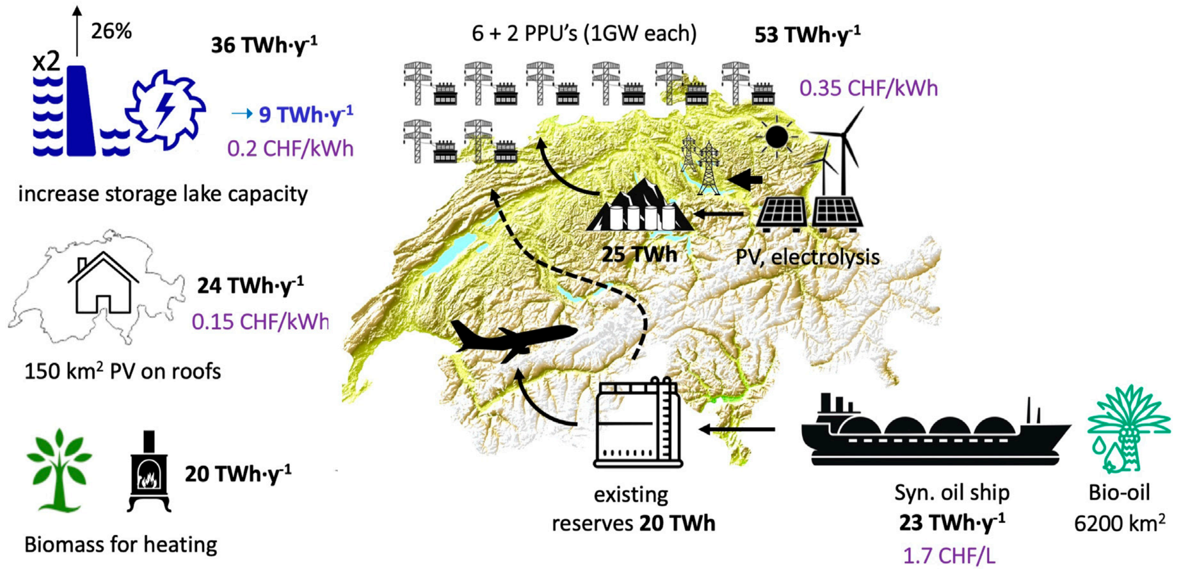
A new concept based on Power Plant Units, able to deliver renewable energy on demand, for the transition from fossil fuels to renewable energy in Switzerland is presented. The technically realized efficiencies showed that complete electrification leads to the most efficient energy system and cheapest electricity. The electricity demand is expected to almost double, and the overall energy cost will increase by 20% compared to 2019. However, the technical challenges of seasonal electricity storage, without any reserves and redundancy, amounts to 20 TWh. Hydropower and PV without storage produce the cheapest electricity. Future nuclear fission technologies, e.g., molten salt Thorium breading reactor - currently still in an experimental stage–might become the most economical and least environmental impact solution for CO_2 neutral continuous electricity production. The opportunities for a massive increase of hydroelectric production are limited, already shifting the use of water (9 TWh) from summer to winter is a great challenge. PV and hydrogen production in Switzerland have the advantage to provide approximately 75% of the electricity without seasonal storage leading to significantly lower electricity cost than from imported hydrogen or synthetic hydrocarbons. The most economical solution for aviation and reserves is imported bio-oil converted to synthetic Kerosene, for which large storages already exist.

KEYWORDS

renewable energy, energy storage, cost of energy, power plant units, CO_2 free, nuclear

Highlights

- Renewable energy on demand is essential for replacing fossil fuels and can be realized by combining intermittent energy supplies like photovoltaic and wind with battery and seasonal storage in a power plant unit.
- Importing renewable energy carriers requires a storage capacity similar to the seasonal storage for domestic production of renewable energy.
- Renewable energy production in Switzerland with seasonal storage and importing renewable energy carriers is a technical and economic challenge, respectively.
- The fuel for aviation and the energy reserves for the power plant units can be realized with synthetic oil produced by hydriding bio-oil, avoiding the need for new large and expensive storage systems and CO_2 capture from the atmosphere.
- Thermal power plants fueled with renewable energy carriers provide equal amounts of electricity and heat. Both forms of energy are of high value in the wintertime.



GRAPHICAL ABSTRACT
Future supply of Switzerland with renewable energy. Assuming the volume of the hydroelectric storage lakes is doubled, the roof area is covered with photovoltaics, and eight power plant units are able to produce 1 GW on demand and are fueled with hydrogen or bio-oil. The reserves are the existing oil tanks, and the bio-oil is also used for aviation. Bio-oil can be produced in abundant places, e.g., Australia or Africa, where palm oil plantations are installed.

1 Introduction: production and storage requirements

1.1 Background

Industrialization has led to a global economic trading system and increased **global** wealth by orders of magnitude. The use of fossil energy to run the engines has two important consequences, i.e., the emission of carbon stored in the earth's crust to the atmosphere as CO_2 (Figure 1) and the consumption of fossil fuel reserves several orders of magnitude faster than their formation, which leads to a depletion of these fuels. Besides the biological origin of the fossil fuels, hydrocarbons can also be formed deep under the surface by other non-plant-based processes (Thomas, 1992). As a consequence, the amount of hydrocarbon reserves may be larger than estimated today. Only around 50% of the emitted CO_2 remains in the atmosphere (Sarmiento and Gruber, 2002). The other 50% is absorbed by natural sinks (Friedlingstein et al., 2022), e.g., the ocean and geological and biological processes (Springer, 1992). The CO_2 absorbing processes depend on the concentration of CO_2 in the atmosphere, and the absorption rate increases with increasing concentration (Canadell et al., 2007). The CO_2 concentration in the atmosphere increases linearly with the cumulated CO_2 emissions. In any case, fossil fuels have to be substituted by renewable energy in a sustainable manner, i.e., by carbon-neutral renewable energy. To provide energy on demand, the main challenges are the production of electricity and heat from renewable energy as well as local and seasonal storage. In addition, non-fossil aviation fuel needs to be produced in future.

After the Fukushima Dai-ichi nuclear-plant disaster caused by the Tsunami due to the earthquake on 11. March 2011, the Swiss Federal Council has decided **not to rely on nuclear power** in the future. The existing nuclear power plants should remain connected to the grid for as long as they are safe. This decision was confirmed by the national parliament on 8. June 2011. On 21. May 2017 the Swiss electorate accepted the revised Federal Energy Act. The aims behind the revision are, according to the Paris climate agreement from 2014, to reduce energy consumption, increase energy efficiency and promote the use of renewable energy. In addition, the revised version prohibits the construction of new nuclear power plants. Switzerland's Long-Term Climate Strategy (Bafu, 2024) includes the reduction of greenhouse gas emissions as far as possible in every sector–whether through a sufficiently high price for emission-intensive technologies, through technical measures or by promoting alternatives. The buildings and transport sectors can cut their fossil emissions to zero by 2050 and energy-related emissions can also be almost completely eliminated in industry too.

1.2 Problem statement

The Swiss railway investigated in 1912 the situation of the railway development based on coal fired steam engines and concluded (Berichthaus, 1912), that the railway will be electrified and the steam locomotives will be replaced by electrical locomotives. Therefore, numerous hydroelectric power plants were built in the following years in order to provide the electricity for the railway and all other applications. The current energy economy based on renewable hydropower and nuclear power for electricity and fossil fuels, is able to deliver power and energy on demand. With the substitution of fossil fuels with renewable energy, i.e., photovoltaics and wind, the energy system becomes more and more production controlled and a significant gap between production and demand is opening. Therefore, renewable energy storage has to be introduced in order to close the gap and provide energy on demand from renewable energy sources.

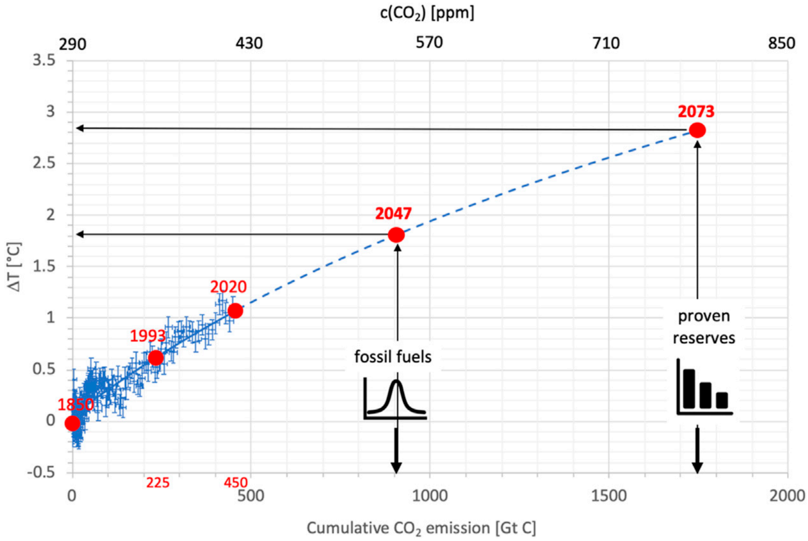


FIGURE 1
Global average temperature as a function of the cumulated CO_2 emissions observed. The fitted curve corresponds to ΔT [°C] = 2.85·ln (c/c_0) with c_0 = 286.6 ppm CO_2 (blue line, extrapolation: blue dotted line) the radiative forcing of the CO_2 (Appendix 4). The years are indicated (red markers. The end of the reserves, according to Campbell (Campbell and Laherrere, 1998) (900 Gt C) and proven reserves (Friedlingstein et al., 2022) (1750 Gt C), are indicated with the year assuming a continuous growth of the usage of fossil fuels and CO_2 emissions of 1.5%/year.

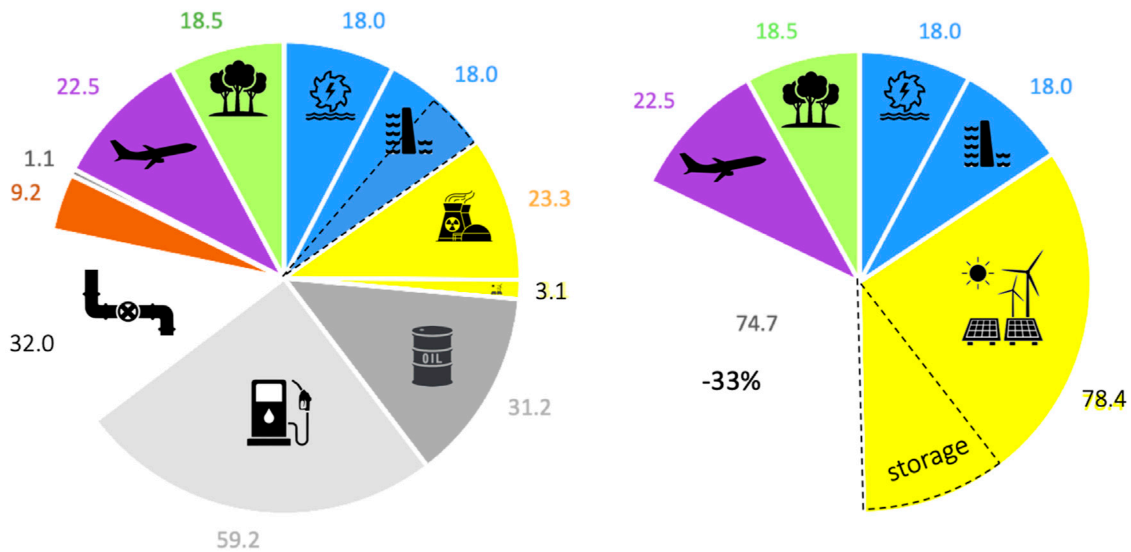


FIGURE 2
Summary of the end energy demand in Switzerland of 232 $TWh \cdot y^{-1}$ (2019, left hand side)) and after electrification 156 $TWh \cdot y^{-1}$ (right hand side) of the applications, e.g., mobility and heating. Imported, exported and lost electricity are not shown in the figure but accounted for in the sum. The sectors (clock wise) are Hydroelectricity (blue), nuclear (orange), PV and wind (yellow), heating oil (dark gray), petrol and diesel (light gray), natural gas (white), distance heating (brown), coal (black), kerosene (violet), Biomass (green). Based on only technical energy conversion efficiency increase, the energy demand of the electrified energy economy decreases approximately 33% (ZÜTTEL et al., 2022)

1.3 Review of solutions

The potentials, costs and environmental assessment of electricity generation technologies was published in 2017 as a report (PSI, 2023). The maximum renewable generation potentials in Switzerland was estimated to be 18 $TWh \cdot y^{-1}$ for roof-top photovoltaics (PV), additional to existing (36 $TWh \cdot y^{-1}$) hydropower 4.5 $TWh \cdot y^{-1}$, geothermal 4.5 $TWh \cdot y^{-1}$, additional biomass and wind 4 $TWh \cdot y^{-1}$, each. These estimates were compared to several other available published data with a close agreement. The PV installations in Switzerland are growing (Swissolar, 2024) and reached 2023 an installed peak power of 1.3 $GW_p \cdot y^{-1}$, with a total PV electricity production of 4.8 $TWh \cdot y^{-1}$. A detailed analysis (Walcha et al., 2020) of the available roof-top area

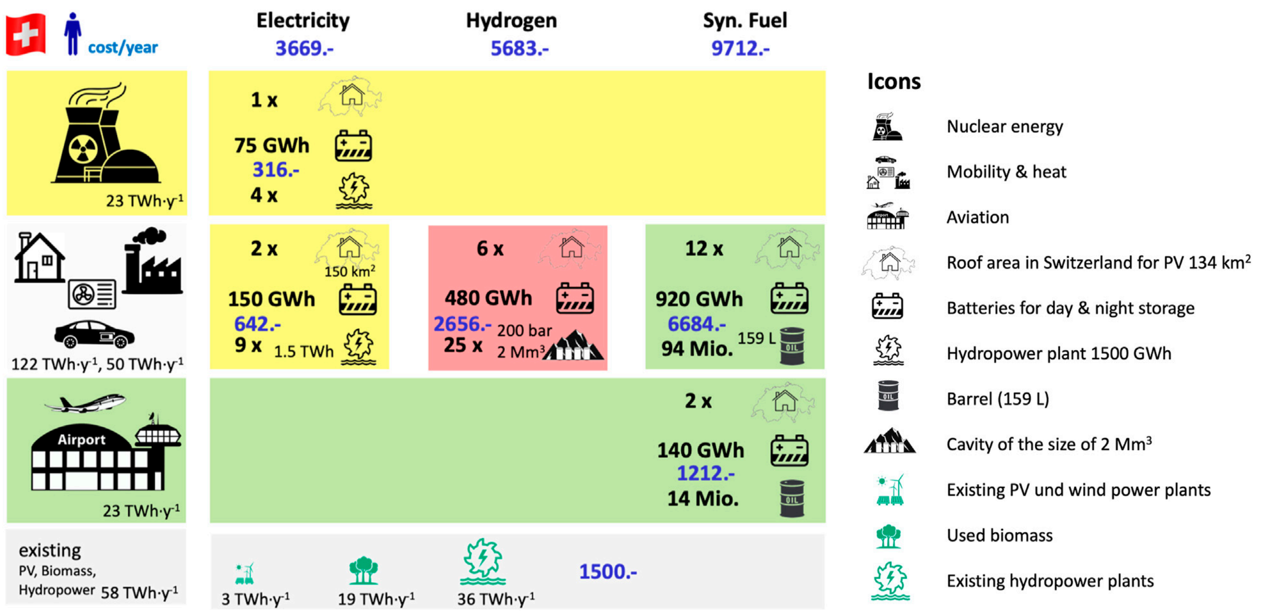


FIGURE 3
The three energy systems presented for the complete substitution of fossil fuels with renewable energy. The PV surface area is shown as the roof area in Switzerland. The battery represents the local day/night storage and the seasonal storage as compared to Grande Dixence storage lake, the volume of the Gotthard base tunnel, and barrels of oil (ZÜTTEL et al., 2022). The total annual cost of energy *per capita* is indicated on top; currently the energy cost *per capita* amounts to 3,000.-/year.

in Switzerland for PV installations (150 km^2) showed a potential PV electricity production of 24 ± 9 TWh·y^{-1}.

Biogenic and nonbiogenic carbon footprints in Switzerland were quantified, and the circular economy associated with a net-zero-emission society was optimized (Xiang et al., 2020). The impacts of an increased substitution of fossil energy carriers with electricity-based technologies in Switzerland was analyzed (Rudisuli et al., 2019). The complete electrification of the mobility and domestic heating with heat pumps leads to an increased electricity demand of 32 TWh·y^{-1} and an additional electricity power demand of 6 GW$_p$ are needed. An annual electricity deficit and surplus of 24.1 TWh·y^{-1} and 7.5 TWh·y^{-1}, respectively, will result. With (perfect) seasonal-storage, surpluses could be eliminated completely, while deficits would remain at 15.9 TWh·y^{-1}, which is the absolute difference of the annual electricity consumption and production.

The seasonal storage requirement in Switzerland is a technical and economic challenge and contributes significantly to the cost of the energy. However, without the storage the energy consumer has to adapt to the renewable energy supply (Desing and Widmer, 2022) like sunflowers do. Adding energy storage significantly reduces the attainable speed of the energy transition due to its high energy costs. Combining supply side measures, such as sector coupling and smart grids, with aligning demand patterns to solar supply can reduce the storage requirement at least for short term storage.

Replacing the fossil fuels with bio oil or with hydrogen upgraded oxygen free bio oil has the potential to realize the energy transition to a CO_2 neutral energy economy on a global level. At present, global forest carbon storage is markedly under the natural potential, with a total deficit of 226 Gt (model range = 151–363 Gt) in areas with low human footprint (Mo et al., 2023). Therefore, all the CO_2 in the atmosphere emitted from fossil fuels could be absorbed by increasing the number of trees. Furthermore, with 142 oil palm trunk (OPT) per ha of plantation land and a replanted area of 100′550 ha in 2017, the estimated dry weight of OPT (74.48 t ha^{-1}) generated amounted to a total of 7.49 Mt (Pulingam et al., 2022). 4.0 t ha^{-1}·y^{-1} palm oil (Sustainablepalmoilchoice, 2024) is produced and the oil palm plants are replanted every 20 years. Therefore, 30 kg oil·y^{-1} per oil palm tree with 524 kg dry biomass. The 226 Gt C realized with oil palm trees produce 13 Gt oil·y^{-1} more than the current world demand of fossil fuels!

Based on the energy demand of 2019, the substitution of fossil fuels in **Switzerland** was analyzed with three energy systems in (Figure 2, Figure 3) view of the energy production and storage requirements (Züttel et al., 2022). The electricity produced by the current nuclear power plants with Uranium fission reactors is replaced with electricity from photovoltaics, the kerosene for aviation is substituted with CO_2-neutral kerosene produced from renewable energy and CO_2 air capture or biomass, and the remaining energy demand is covered either by electricity, hydrogen, or synthetic hydrocarbons.

The main technical challenges in substituting fossil fuels are the production of electricity and seasonal storage to shift 20%–30% of the annual energy production from summer to winter. For comparison, an analysis of the hourly energy demand in Germany over the last 35 years, assuming complete coverage with renewable energy, resulted in a storage requirement of 10% of the annual electricity demand (540 TWh·y^{-1} without substitution of the fossil fuels, 3,000 TWh·y^{-1} with electricity). The scarcity period defining storage requirements extends over as much as 12 weeks (Ruhnau and Qvist, 2022).

While the electric energy chain is the most efficient, storage is technically demanding and expensive at low energy density. The conversion of electricity to an energy carrier is less efficient due to conversion losses but facilitates the storage, increases the energy storage density, and reduces the cost of storage. Finally, the form of energy that offers the necessary energy density at the lowest possible cost is the most favorable for a future energy system and depends significantly on the application.

The energy transition to a fossil-free energy economy requires the generation of end energy (3.2 kW·capita^{-1}) from renewable energy. Currently, 0.86 kW·capita^{-1} is produced from renewable generation including biomass, and the electricity production from nuclear power corresponds to 0.24 kW·capita^{-1}. The nonrenewable end energy is 2.02 kW·capita^{-1}.

Approximately 75% of the energy demand can be covered with renewable electricity at a cost comparable to today's energy cost. The remaining 25%, i.e., the winter months, are technically and economically challenging. Due to the concave shape of the energy demand and the convex shape of the renewable energy production from January to December, the renewable energy has to provide band energy, and the storable forms are used to adapt production to demand.

The PV area for an electricity-based system, including aviation fuels, is around 80 m^2·capita^{-1}. For a hydrogen-based energy system, this area becomes twice as large, and for a synthetic hydrocarbon-based energy system, the PV area again almost doubles. However, building 13 hydroelectric power plants like Grande Dixence or a facility 25 times the Gotthard base tunnel for hydrogen storage are constructions beyond everything Switzerland has realized so far.

Feasible technical solutions based on low-carbon technologies, efficiency, and flexibility were analyzed (Panos et al., 2023). Import independency and net-zero emissions by 2050 require an additional cumulative discounted investment of 300 billion CHF_{2019} in energy efficiency, negative emissions and renewable technologies. The electricity in each net-zero scenario in 2050 is estimated to be between 73 and 102 TWh·y^{-1}, with an electricity storage requirement of only 0.52 TWh and demand-side response. Possible technology paths for Switzerland to respond to the finite availability and to meet international climate goals were assessed (Brethauer and Hans-Peter Studer, 2021), a change to a renewable energy and raw material basis is inevitable. Biomass is the most versatile renewable energy and carbon source, although with a limited availability.

The integration of renewable energies into the electricity sector from social, environmental, and economic view point was reviewed (Osman et al., 2023) with a special focus on hybrid systems. Renewable energy shows a great potential in reducing the overall CO_2 emission, however, the various sources of renewable energy exhibit different effects on the CO_2 emission (Yuan et al., 2022). The potential of the conversion of biomass to bio fuels including life cycle assessment was reviewed (Osman et al., 2021) with the conclusion that comparing thermochemical and biological processes for the same biomass feedstock and geographical and temporal span, thermochemical processes caused less greenhouse gas emissions compared to biological path-ways. The **global** transition from fossil to renewable energy was investigated and it was calculated that the world would need to spend around US$62 trillion to build up the wind, solar, and hydro power generating capacity to fully meet demand and completely replace fossil fuels (Jacobson et al., 2022). However, a rapid transition to green energy sources such as wind and solar power could save anywhere between US$5 to US$15 trillion compared to taking no action in 80% of scenarios modelled and could save even more money if green technology continues to improve (Way et al., 2024).

1.4 The research gap

The hydropower plants with storage lakes are the only technically realized and economically competitive large-scale electricity storages available today. However, hydroelectric power plants are only possible in some designated areas, where mountains offer the altitude difference and valleys the storage room. The research work on the assessment of renewable energy focusses mainly on the energy or electricity production and not on delivering energy on demand, with the consequence that these analyses do not allow to determine the consequences of the substitution of fossil fuels with renewable energy but rather assume the availability of some fossil fueled power plants to fill the energy cap. In this work we present a new approach, where we investigate renewable energy not as a production-controlled energy source but **offering renewable energy on demand**. A sustainable approach is to combine renewable energy conversion with appropriate storage that allows delivery of renewable energy on demand. This includes short term (day/night) storage as well as seasonal storage. In addition, adapting the renewable energy production to the seasonal energy demand pattern and installing storage for imported renewable energy carriers will increase energy security by having redundancy and reserves.

1.5 Organisation of the manuscript

First, we are identifying the increase of electricity demand in the future Swiss energy economy under the assumption that the energy system is going to be electrified. Then a new approach for renewable energy systems is introduced called power plant units (PPUs). The PPU's decouple the energy production and the energy delivery by an energy storage and provide energy on demand. PPU's are able to produce 1 GW electricity on demand at any time of the year. The question on how the energy demand can be covered with renewable energy will be addressed. Furthermore, the PPU's allow to compare renewable energy solutions independent of the local requirements and lead to a general applicable solution. For each possible solution the technical requirements are described and the economic analysis of the energy chain is provided. Therefore, the cost of the renewable energy for each individual solution is estimated in view of capital cost (investment), operational cost and levelized cost of energy.

2 Methodology

Each power plant unit consists of a series of components (C_i) transferring the energy from the source to the grid or to an energy carrier, e.g., synthetic hydrocarbon. The components transfer the energy (W_i) with a specific efficiency (η_i) and may also consume auxiliary electricity (E_i). Therefore, the finally available energy at the end of the conversion chain is

$$W_n = W_1 \cdot \eta_1 \cdot \ldots \cdot \eta_n \quad (1)$$

The sum of the auxiliary electricity (ΣE_i) is added to the last electric component in the conversion chain. The total efficiency is given by

$$\eta_{tot} = W_n / W_1 \quad (2)$$

Based on the power and the time or energy and cycle number the total amount of energy transferred through the components is determined during the entire lifetime of the component. The cost for each individual component, the capital cost (CAPEX) is assumed to be amortized during the whole lifetime (n years) and an interest of Z = 2%/year on the capital. The constant annual payback, P_b, can be calculated from the cost series $0 = (((\mathrm{CAPEX} \cdot (1+Z) - P_b) \cdot (1+Z)) - P_b) \cdot (1+Z)) - P_b \ldots = \mathrm{CAPEX} \cdot (1+Z)^n - P_b (1+Z)^{n-1} - P_b \cdot (1+Z)^{n-2} \ldots$

$$P_b = \mathrm{CAPEX} \cdot Z \cdot (1+Z)^n / [(1+z)^n - 1] \quad (3)$$

and the specific cost contribution per energy unit is

$$C_W = [P_b + \mathrm{OPEX}] / W_y \quad (4)$$

The sum of all cost contributions of the components multiplied with the transferred energy corresponds to the cost of the delivered energy of the conversion chain.

This general model allows to determine the correct size of all the components in the energy conversion chain and leads to the true cost of the finally delivered energy, i.e., the levelized cost of energy (LCOE).

3 Renewable energy on demand from power plant units

3.1 Adapting to future energy demand

The future developments are changing the energy demand, e.g., energy saving measures are expected to reduce the energy demand *per capita*. Also, the efficiency of energy converters is increasing. The efficiency of the PV panels has the potential to increase in the future by up to 50%. The energy demand for mobility can be partially covered by coating the roof area of cars (4–8 m^2) with PV producing the energy to drive 4,000–8,000 km y^{-1}; 50% of the average annual driving distance in Switzerland. The climate change leading to increased temperatures lowers energy demand for heating in winter, while air conditioning becomes necessary when high solar intensity provides PV-electricity in summer.

Population growth and increasing wealth will increase energy demand. The general trend of most countries is a linear relationship between energy demand *per capita* and GDP *per capita* with a slope of 0.6 CHF/kWh (Figure 4), especially in countries with a GDP <25,000 CHF/capita (>75% of the world population (Wir, 2022)). However, a new trend exhibiting increasing GDP/capita while the energy demand/capita is decreasing is observed in many countries and especially in most industrialized countries. This effect is very positive for the future development of the world. However, it is still questionable whether this trend is going to take place in all countries, especially on the continents of Asia and Africa, which will represent more than 70% of the world population and is expected to reach 10 Billion capita in 2050 (Lutz et al., 2001).

The electrification of the applications, i.e., battery electric mobility, heating with heat pumps, air conditioning, information technology, *etc.*, requires stable electricity production on demand. The electricity demand is expected to almost double from the current demand in Switzerland when the electrification is completed in 2050. In order to cover the electricity demand in the electrified energy economy, an additional 53 TWh·y^{-1} are required. For the decided replacement of the nuclear power plants running on Uranium fission, an additional 21 TWh·y^{-1} is required. In total, 74 TWh·y^{-1} more renewable electricity will be requested than is produced today. The electricity demand will increase from 62 TWh·y^{-1} in 2019 to 113 TWh·y^{-1}. As a consequence, in the coming 30 years, an additional +2.4 TWh·y^{-1}, approximately the production of Grande Dixence storage lake or 4 times Grengiols alpine PV-field in its projected size, will have to be installed every year. Estimations assuming additional energy savings beyond the technical efficiency gains lead to an annual electricity demand (VSE/AES, 2024) between 80 and 90 TWh·y^{-1} in 2050. This lower electricity demand in 2050 will be due to the import of electricity (7 TWh), the lack of storage, and the assumption that backup power plants (10 TWh) will cover the need in case the renewable energy production is not sufficient.

3.2 Energy demand covered by power plant units (PPUs)

Renewable energy appears in a variety of qualities. While solar energy (solar thermal, photovoltaics, solar concentrator) and wind are intermittent sources of energy, geothermal power plants deliver heat continuously. The precipitation used by hydroelectric power plants depends on the type of installation and can provide storage in the mountain lakes. Furthermore, biomass is a storable form of renewable energy and even represents a CO_2 neutral carbon source. Tidal power goes through predictable oscillations, but it is only available in certain regions of the earth and not in Switzerland. Finally, geothermal energy provides heat continuously (independent of the season). Its extraction is technically challenging in Switzerland due to the low intensity.

Harvesting renewable energy requires more than just converters to provide electricity. Transport, local and seasonal storage is necessary to turn an intermittent renewable source of energy into band energy to deliver on demand.

A power plant unit (PPU) represents an energy system able to deliver 1 GW of electricity on demand or approx. 8.7 TWh·y^{-1} of electricity per year and with the flexibility to adapt the produced power to meet the electricity demand. In a future energy economy, where most applications are electrified, the grid has to provide

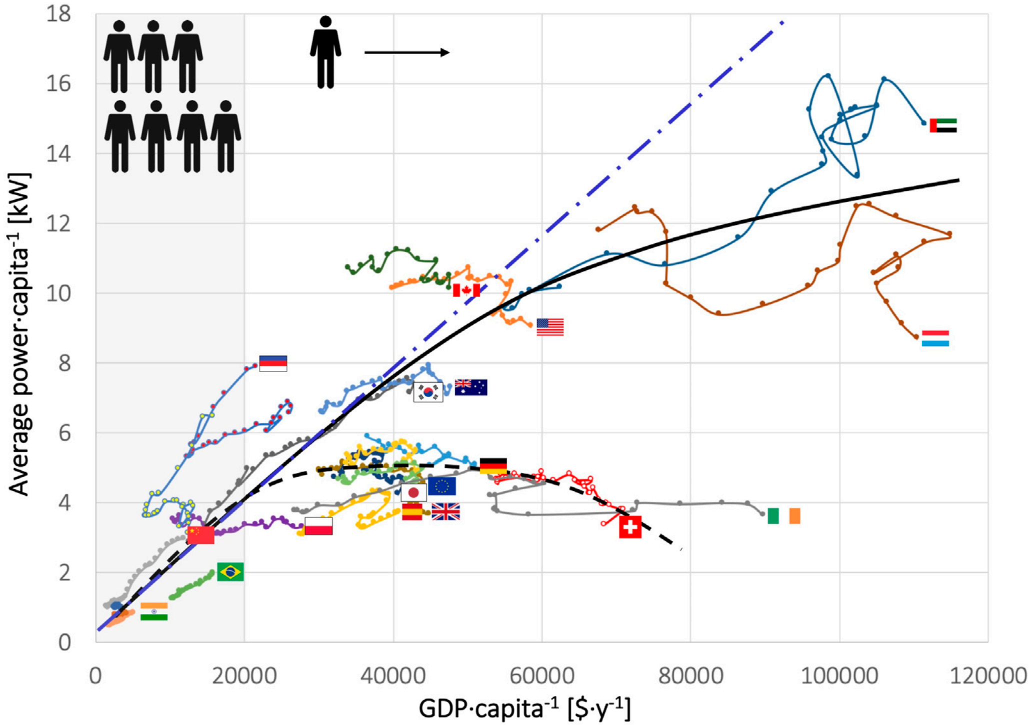


FIGURE 4
Primary energy demand *per capita versus* GDP *per capita* over the last 30 years for selected countries (Ourworldindata, 2024).

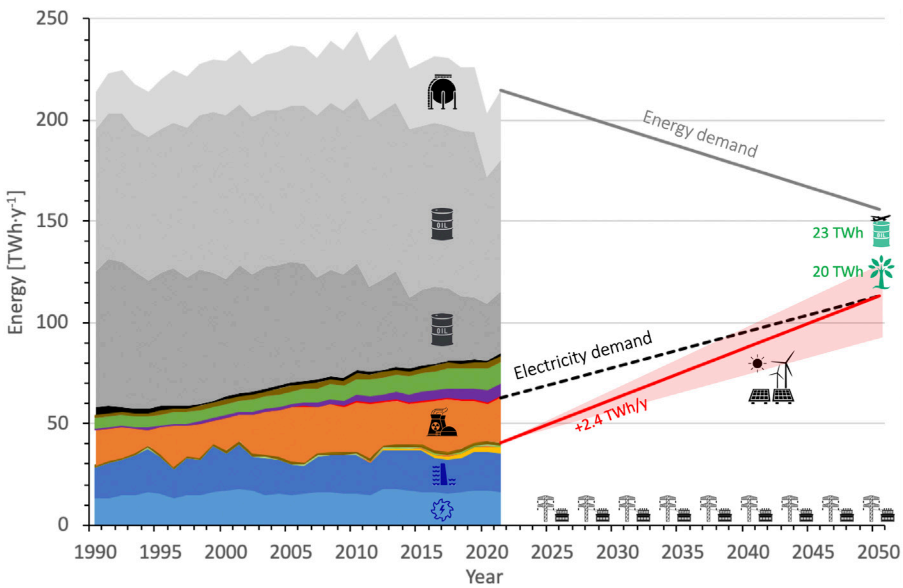


FIGURE 5
Renewable electricity production (BFE, 2024) together with the electricity demand in Switzerland and the expected growth of the electricity demand in future due to the electrification of applications. The difference between renewable production and demand is currently filled with nuclear power in Switzerland and imported electricity (from nuclear, coal, and gas fired power plants). Above the electricity are the fossil fuels, heating oil (dark grey), fuel for mobility (middle grey) and natural gas (light grey).

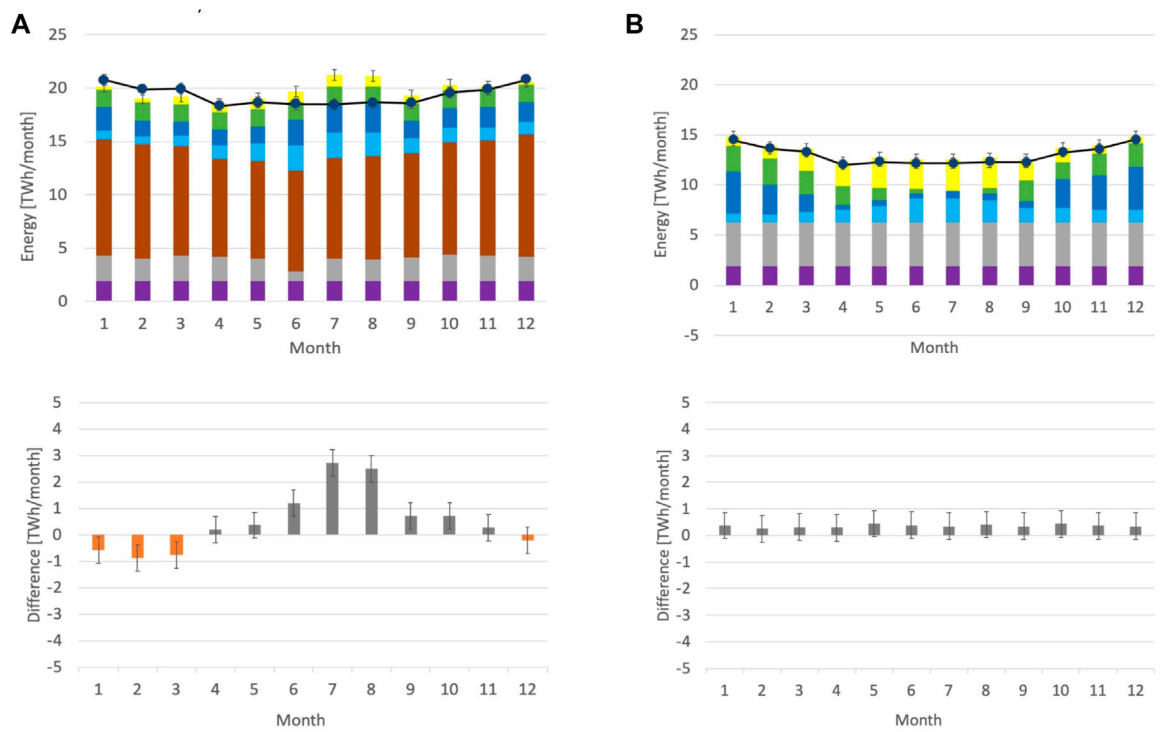


FIGURE 6
(A) Current Swiss energy system (2019) with contributions from the different sources of energy: Photovoltaic, Biomass, Storage hydropower, River hydropower, Fossil fuel, Nuclear power plants, Aviation fuels. The energy demand is shown by the black markers and line, energy demand 232 TWh·y^{-1}. Monthly difference between production and demand. **(B)** Electrified Swiss energy system (based on 2019) with the contributions from the different sources of energy: Photovoltaic, Biomass, Storage hydropower, River hydropower, 6 Power Plants Unit's (PPU's), Aviation fuel (CO_2 neutral). The energy demand is shown by the black markers and line, energy demand 156 TWh·y^{-1}. Monthly difference between production and demand.

reliably electricity on demand (Figure 5). This is only possible if the entire electricity system has the necessary reserves and redundancy. An energy system that works according to the sunshine (Desing and Widmer, 2022) or is dependent on importing electricity (Empa, 2024) is unstable and decreases the productivity of the economy drastically due to the delays and interruptions caused by a lack of power. Only a reliable energy supply allows human beings to develop prosperity.

Considering the monthly energy demand in Switzerland (Figure 6) and the transition of the current energy system to an electrified energy system based on renewable energy, electricity production has to be adapted to the increased demand in winter by the following measures:

1) The height of the dams on the storage lakes is increased by 26% in order to double the storage capacity of the lakes and to shift 9 TWh of electricity produced during the summer to winter.
2) Most of the currently used biomass (15 TWh·y^{-1}) and an additional 5 TWh·y^{-1} of biomass (Burg et al., 2018) is used for heating.
3) All feasible roof areas are covered with photovoltaics producing 24 TWh·y^{-1}, according to Walch et al. (Walcha et al., 2020)
4) The remaining missing band electricity of 53 TWh·y^{-1} is produced by 6 Power Plant Units (PPUs).
5) At least two additional PPUs are built for redundancy and supply security.
6) Aviation fuel is produced either by 3 Power Plant Units (PPUs) or imported bio-oil based synthetic fuel.

These six measures provide renewable electricity on demand and synthetic fuel for the airplanes without the need for direct air capture of CO_2 (Figure 6B). The two backup PPU's represent a redundancy and reserve of 33% or 4 months of the year. The first three measures can also be replaced by PPU's, however, they would then only run part time of the year or at a fraction of the nominal power.

3.3 Power plant units (PPUs)

A PPU is an energy system able to produce energy on demand rather than intermittent energy given by the natural occurrence of energy flow. Hydroelectric power plants with a storage lake are able to store a large amount of energy and deliver electricity on demand. Fossil fuels and nuclear power plants are operated continuously to provide band energy. Only gas-fired combined cycle power plants burning gas with a large gas storage capacity are able to produce electricity on demand. A PPU has to be able to deliver the band electricity and, in the ideal case, it is also able to follow the electricity demand. Based on our previous energy analysis, the day-night storage and the seasonal storage correspond to 0.25% and 25% of the annual electricity demand, respectively. This storage also covers the fluctuations in demand between day and night as well as the increased demand in winter Table 1.

3.4 Description of the power plant units

3.4.1 **HYD-S** (storage lake hydropower plant)

Hydroelectric power plants with a storage lake 500 m above the turbine are able to produce electricity on demand with up to >1 GW of power and an efficiency >80% between the potential energy in the stored water and the electricity delivered. Approximately 1 m^3 of stored water with a height difference of 500 m produces one kWh of electricity. Some of the hydroelectric power plants work between two lakes and are able to pump water up and store electricity. The HYD-S PPU, with a height difference of 500 m, has a lake with a volume of 4,000 Mm^3 (approximately the volume of the lake of Zürich). The area to collect the precipitation amounts to 5,800 km^2.

3.4.2 **HYD-R** (river hydropower plant)

Hydroelectric power plants in rivers exhibit a small height difference and profit from the large flow of water. Serial installations of river hydropower plants are often found where the height difference allows it. A HYD-R PPU consists of at least 22 hydropower plants in a river with a flow of 500 $m^3 s^{-1}$ leading to a power of 45 MW each.

3.4.3 **THERM** (oil- or gas fired power plant)

Modern thermal power plants fueled with oil or gas are combined cycle power plants (CCPP), where the fuel powers a combustion turbine connected to a generator. The exhaust gas is used to produce steam which is then powers a steam turbine connected to another generator. The modern CCPP reaches an efficiency (Kotowicz and Brzęczek, 2018) from 44% to >60% from fuel to electricity and the remaining heat is available for heating. A THERM PPU requires 112 t h^{-1} of natural gas (CH_4) or 146 t h^{-1} of petrol, oil or kerosene and emits 2.7 Mt $CO_2 \cdot y^{-1}$ or 4 Mt $CO_2 \cdot y^{-1}$, respectively.

3.4.4 **NUC** (future nuclear power plant)

The uranium fission reactors have some disadvantages in terms of safety, uranium resources, and the long living isotopes as fission products (nuclear waste). Future nuclear power plants may overcome the disadvantages of the current nuclear reactors. A NUC PPU is a nuclear power plant that delivers a constant power of >1 GW and consumes <30 t y^{-1} of nuclear fuel per year. The conversion from nuclear fuel to electricity exhibits an efficiency of around 25%. Therefore, >3 GW of heat are produced, available for a centralized heating network. The molten salt (MSR) Thorium nuclear breeding reactors (Woodhead Publishing, 2017) are after first tests in the middle of the 20th century in the US again under development and China has commissioned an experimental reactor with a power of 2 $MW_{th.}$ in July 2023 (Sinap, 2023). The advantages of the MSR are the possibility to use the nuclear waste from Uranium fission reactors as a fuel leaving almost only short living isotopes, the general flexibility in nuclear fuel and higher efficiency. The technical and economic estimations are based on the conventional Uranium-fission reactors and may be different for the future Thorium-MSR.

3.4.5 **PV-HYD** (PV with hydroelectric storage plant)

The PV-HYD uses a photovoltaic (PV) field for electricity production. Due to the intermittence of solar energy, a PV installation with an annual average power of 1 GW exhibits a peak power of 8 GW and a daily average power of 3 GW in summer. Therefore, local battery storage for peak saving and day/night storage with a capacity of 0.4% of the annual energy production is required in order to reduce the peak power in the grid and to provide electricity during the night. Furthermore, a hydroelectric storage power plant is used for seasonal storage. The electricity consumed during midday in summer is cheap, while the electricity at midnight in winter becomes most expensive. The PV-HYD PPU consists of a 53 km^2 PV active PV area, which corresponds to >100 km^2 PV field (greater than the area of the lake of Zürich), a battery capacity of 45 GWh, and an additional 25% of HYD-S PPU with pump storage capability.

3.4.6 **PV-H_2** (PV with hydrogen storage and CCPP)

The PV-H_2 is similar to PV-HYD except for the seasonal storage that is realized with underground hydrogen storage and a combined cycle power plant. Due to the conversion efficiency of the CCPP and the hydrogen production by electrolysis, the PV active area is 86 km^2, corresponding to a PV field of >170 km^2 (twice the area of the lake of Zürich). The underground storage of 4.4 TWh hydrogen (112′000 t H_2) under a pressure of 200 bar is around 7 Mm^3, a sphere with a diameter of 240 m. The CCPP with up to 1 GW of electric power delivers electricity and the same amount of energy in form of heat.

3.4.7 **Bio-SF** (biomass to synthetic fuel)

The use of biomass, which consists of CO_2 absorbed from the atmosphere (KEITH, 2009), as carbon and hydrogen sources is much more efficient and less costly than direct air capture (DAC). According to the overall reaction $(CH\text{-}OH)_n + (n+1) H_2 \rightarrow (CH_2)_nH_2 + nH_2O$ the synthetic hydrocarbons can be produced from reacting biomass with hydrogen, and water is formed as a by-product. The technical process works in two steps: the conversion of biomass to syngas and the Fischer-Tropsch synthesis to produce hydrocarbons. The ideal reaction produces 1 kg of synthetic hydrocarbon from 2.1 kg of biomass (wood) and consumes 0.14 kg of hydrogen (5.6 kWh) produced by PV. The upper heating value of biomass (dry wood) (Demirbaş, 1997; Sheng and Azevedo, 2005) is 4.8 $kWh \cdot kg^{-1}$ and that of synthetic hydrocarbons (kerosene) is 12.83 $kWh \cdot kg^{-1}$. Therefore, the energy in biomass and the energy in synthetic hydrocarbons is almost equal in the ideal process. In order to produce 23 TWh of synthetic aviation fuel, the biomass currently used for heating (Bfe, 2024) (16 TWh) plus additional available biomass (Burg et al., 2018) (7 TWh) are needed.

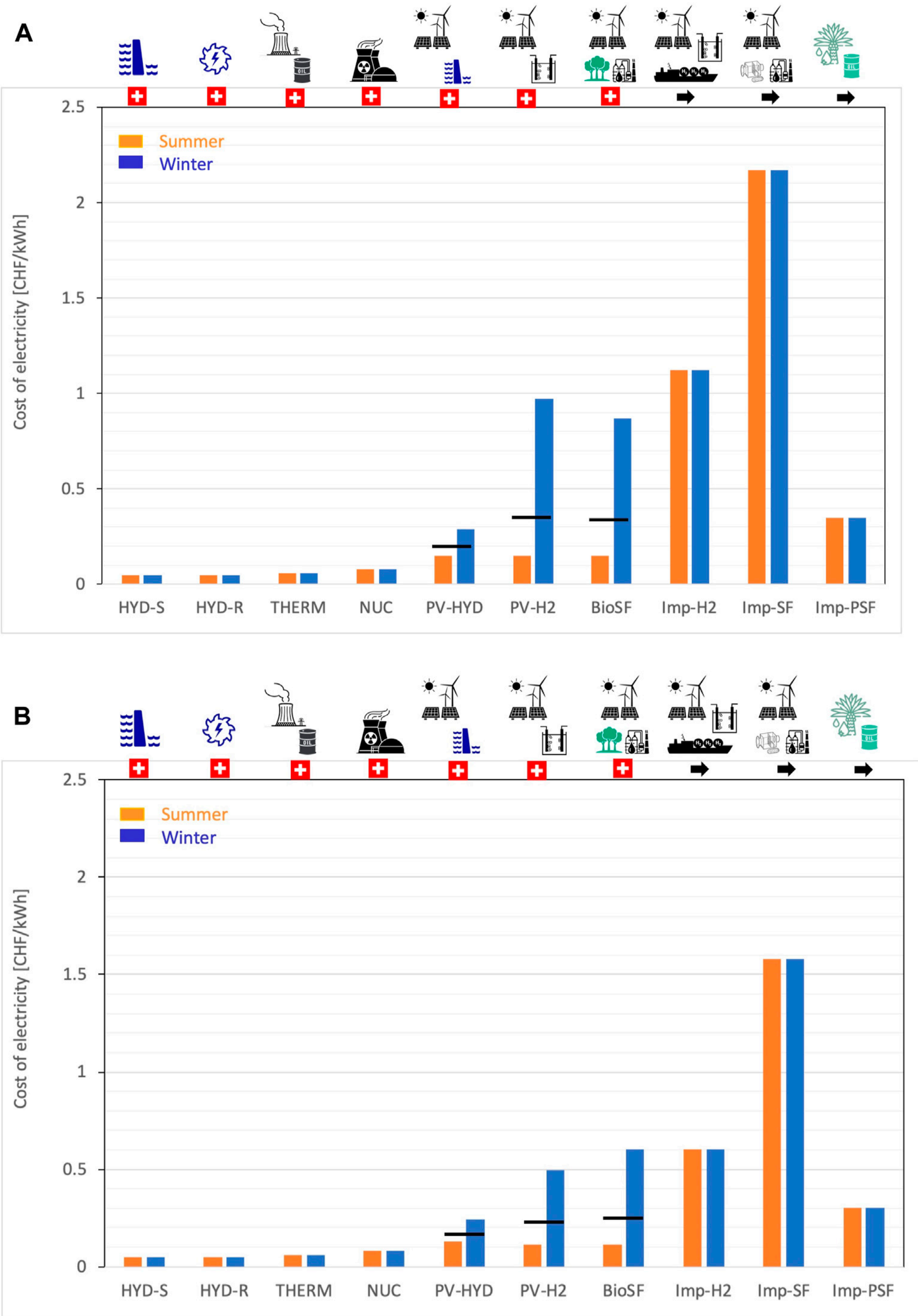


FIGURE 7
(A) Production cost of the electricity (without grid cost per kWh without and with seasonal storage for the 3 winter months. Bars represent the cost today. The average cost (–) is composed of 75% cost without seasonal storage and 25% cost with seasonal storage, solid line for current average cost. **(B)** Production cost of the electricity (without grid cost per kWh without and with seasonal storage for the 3 winter months. Bars in bold color represent the future cost (PV 400 CHF/kW$_p$, Battery 50 CHF/kWh, electrolyzer 500 CHF/kW, efficiency 90%). The average cost is composed of 75% cost without seasonal storage and 25% cost with seasonal storage, solid line for future average cost (–).

3.4.8 **Imp.-H_2** (imported hydrogen and CCPP)

The IMP-H_2 PPU is based on imported hydrogen produced in places with a high solar intensity and available space outside of Switzerland. The H_2-CCPP consumes 448,000 t y^{-1} H_2 in order to continuously deliver 1 GW of electricity and 1 GW of heat. A transport system delivering 1,200 t H_2 per day needs to be built, and for redundancy, a storage of the same size as for PV-H_2 is required, which corresponds to a reserve of about 3 months. The

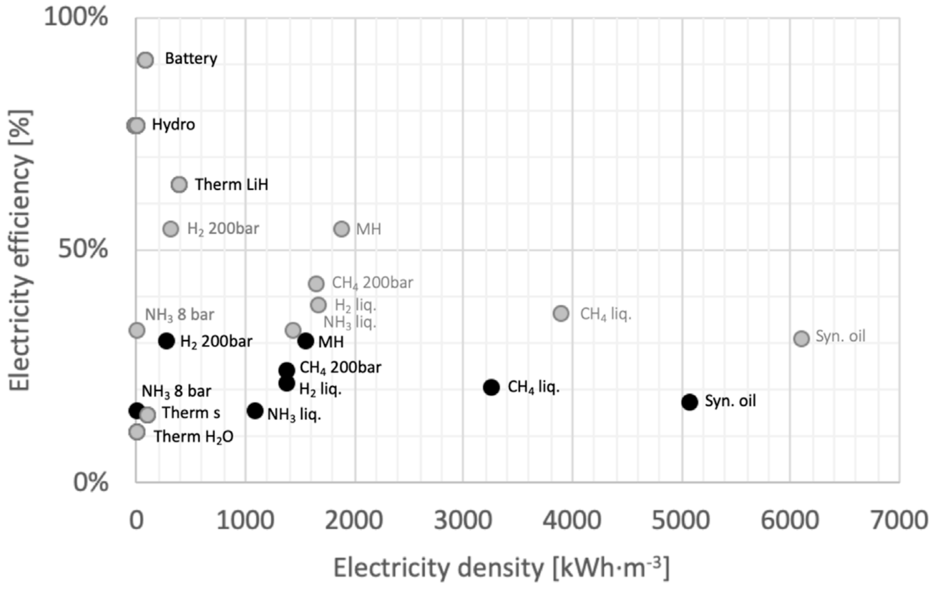


FIGURE 8
Conversion efficiency from electricity to energy carrier, storage, and back to electricity versus the storage density of electricity in kWh·m^{-3} (1 MWh·m^{-3} = 1 TWh/ Mm^{-3}). The efficiencies are based on technical efficiencies(●), which are in some cases far from the thermodynamic limit, and with future increased efficiencies(●)close to the thermodynamic limit.

imported hydrogen is transported on the sea in liquid form. Storage of liquid hydrogen is 4 times more compact than pressurized hydrogen (200 bar). A liquid hydrogen storage unit of 1.6 Mm^3, a sphere with a diameter of 150 m, holds 112,000 t H_2.

3.4.9 **Imp-SF** (imported synthetic oil from PV, direct air capture (DAC) of CO_2 and FT-synthesis)

Hydrogen is produced from PV electricity (s. PV-H_2) and CO_2 is directly captured from air. The CO_2 is reduced to CO with hydrogen and syngas (CO + 2H_2) is converted into synthetic oil by the Fischer-Tropsch synthesis (s. Bio-SF). The heat produced in the exothermal reaction of the FT-synthesis is used for the DAC.

3.4.10 **Imp-PSF** (imported palm oil to synthetic oil)

Palm oil as starting product for synthetic oil has many advantages over stark based biomass, because of the low oxygen content and the large degree of saturation. The oil palm is a very efficient plant and produces 4.5 t/ha of oil with an energy content of 10.8 kWh·kg^{-1}. The palm oil is catalytically hydrided and cracked with hydrogen under pressure. The complete hydriding of palm oil reduces the mass by 15% but conserves the energy in the oil due to the addition of the energy in the hydrogen, resulting in 12.8 kWh/kg.

4 Energy conversion economy

4.1 Cost of the renewable electricity on demand

The cost of the electricity produced by the PPUs is determined by a model energy chain consisting of all components in the energy conversion from the input energy to the electricity output. Each component has a specific efficiency for the energy transferred, and the size is determined by the energy for storage or energy per time (i.e., power) for transformation. In addition, components that require additional energy or electricity for the storage or transformation add this electricity to the electric part of the energy chain.

For each component, the capital cost (CAPEX) including the interest (Z) on the capital cost with a constant annual payback (P_b: Eq. 3) over the lifetime is added to the operational cost (OPEX) leading to an additional energy cost per component (C_c: $C_c = P_b$ + OPEX). Finally, the amount of energy (E_{tot}) transferred during the lifetime (n) of the component is considered, and the specific cost per energy unit (C_E: $C_E = n \cdot C_c / E_{tot}$) is calculated. The specific costs along the energy chain are multiplied with the energy transferred at the component and summed up in order to be divided by the available energy at the output, leading to the specific energy cost of the final energy. The costs of the components are based on current minimum costs, which are expected to decrease in future for most of the components.

Figure 7 shows the cost of the energy (Changeoracle, 2022) (electricity and synthetic fuel) at the production site, i.e., without the grid cost which adds around 0.09 CHF/kWh, for summer and winter, i.e., without and with seasonal storage. The classical renewable energy from hydroelectric power exhibits a constant cost over the year, like the thermal and nuclear power plants. PV together with a hydroelectric storage plant or with hydrogen production and storage lead to an electricity cost increase in summer by a factor of three and in winter by factor of times 6 and 20 higher, respectively, when compared to the electricity cost of the hydroelectric power plant. The cost of electricity from imported hydrogen is independent of the season, it is always 1.02 CHF/kWh. The cost of synthetic fuel produced in

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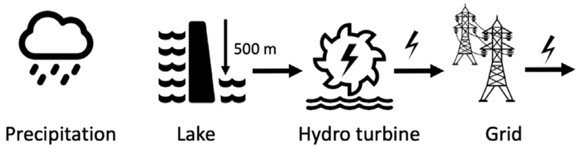
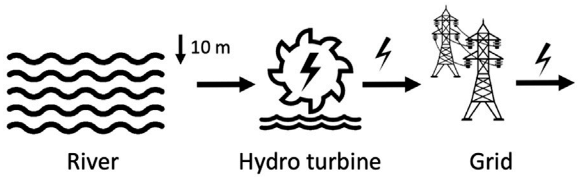
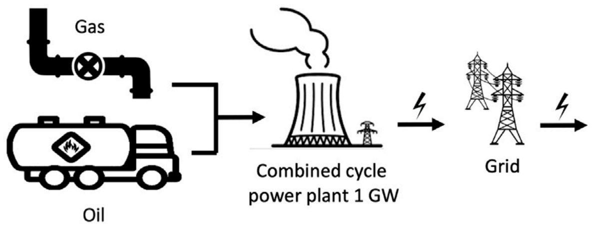
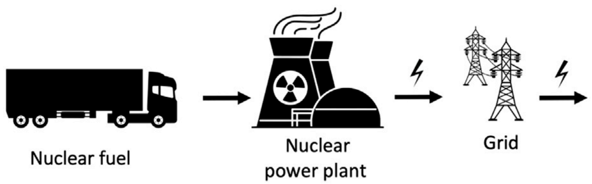
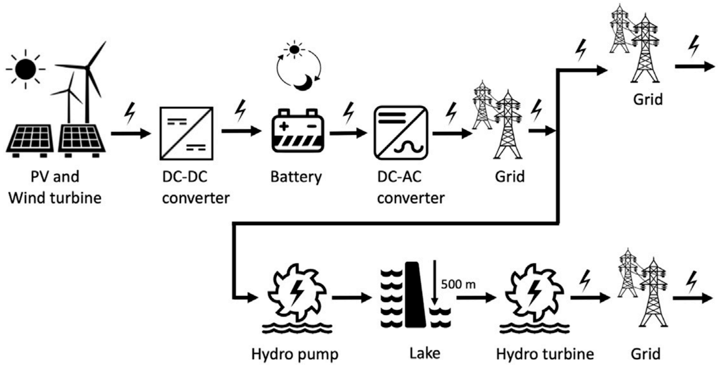
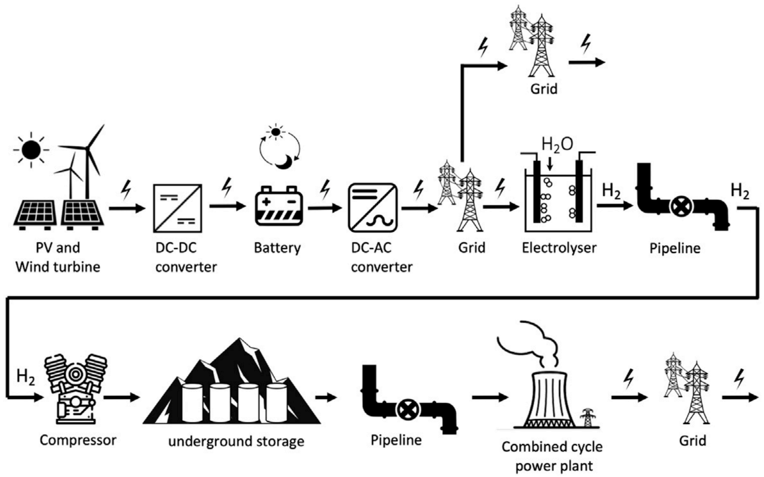
TABLE 1 The 10 different PPUs provide >8 $TWh \cdot y^{-1}$ of electricity all the time and on-demand, except for Bio-SF, Imp.-SF and Imp. PSF these deliver >8 $TWh \cdot y^{-1}$ as synthetic fuel (synthetic hydrocarbons). PV area is active area, the PV field would be approximately 2–2.5 times larger. The levelized cost of energy (electricity) (LCOE) is given in the last column.

Input energy and parameters	Schematics of the power plant units (PPU)	Output energy and storage requirement	LCOE of 1 kWh electricity [CHF] + grid cost
HYD-S 11.1 $TWh \cdot y^{-1}$ Rain 8.1 $km^3\ y^{-1}$ (Δh = 500 m), A = 5,800 km^2	 Hydroelectric power plant with storage lake and water turbine with generator	Electricity: 8.76 $TWh \cdot y^{-1}$ continuously and on demand, storage 4 TWh	0.04 + 0.09
HYD-R 11.1 $TWh \cdot y^{-1}$ River 405 $km^3 \cdot y$-1 (Δh = 10 m) 13,000 $m^3\ s^{-1}$	 Turbine in river with generator	Electricity: 8.76 $TWh \cdot y^{-1}$ continuously according to flow	0.04 + 0.09
THERM 20 $TWh \cdot y^{-1}$ CH_4: 2,700 t d^{-1} Oil: 3,500 t d^{-1}	 Combined cycle power plant using biogas or biological oil	Electricity 8.76 $TWh \cdot y^{-1}$ continuously and on demand	0.06 +0.09
NUC 32 $TWh \cdot y^{-1}$ U^{235}: 27.6 t y^{-1} (data from U-fission)	 Future nuclear power plant (e.g., molten salt Th breeder reactor)	Electricity 8.76 $TWh \cdot y^{-1}$ continuously	0.08 (Bauer et al., 2017) +0.09

(Continued on following page)

TABLE 1 (*Continued*) The 10 different PPUs provide >8 TWh·y[-1] of electricity all the time and on-demand, except for Bio-SF, Imp.-SF and Imp. PSF these deliver >8 TWh·y[-1] as synthetic fuel (synthetic hydrocarbons). PV area is active area, the PV field would be approximately 2–2.5 times larger. The levelized cost of energy (electricity) (LCOE) is given in the last column.

<table>
<tr><th>Input energy and parameters</th><th>Schematics of the power plant units (PPU)</th><th>Output energy and storage requirement</th><th>LCOE of 1 kWh electricity [CHF] + grid cost</th></tr>
<tr><td>PV-HYD
11.2 $TWh \cdot y^{-1}$
51 km^2 PV (I = 1,100 $kWh \cdot m^2 \cdot y^{-1}$) or 1,280 wind turbines x 2 MW (50% P_p)</td><td>

Photovoltaics with a local battery storage and hydro pump at the hydroelectric power plant with storage lake for seasonal storage</td><td>Electricity 8.76 $TWh \cdot y^{-1}$ continuously and on demand, storage 2.5 TWh</td><td>0.20/0.35
+0.09</td></tr>
<tr><td>PV-H_2
18.3 $TWh \cdot y^{-1}$
83 km^2 PV (I = 1,100 $kWh \cdot m^2 \cdot y^{-1}$) or 2′075 × 2 MW (50% P_p)</td><td>

Photovoltaics with a local battery storage providing electricity and an electrolyzer for hydrogen production with underground storage of compressed hydrogen linked to a combined cycle power plant</td><td>Electricity 8.76 $TWh \cdot y^{-1}$ continuously and on demand, storage 4.4 TWh</td><td>0.2/1.18
+0.09</td></tr>
</table>

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TABLE 1 (*Continued*) The 10 different PPUs provide >8 TWh·y^{-1} of electricity all the time and on-demand, except for Bio-SF, Imp.-SF and Imp. PSF these deliver >8 TWh·y^{-1} as synthetic fuel (synthetic hydrocarbons). PV area is active area, the PV field would be approximately 2–2.5 times larger. The levelized cost of energy (electricity) (LCOE) is given in the last column.

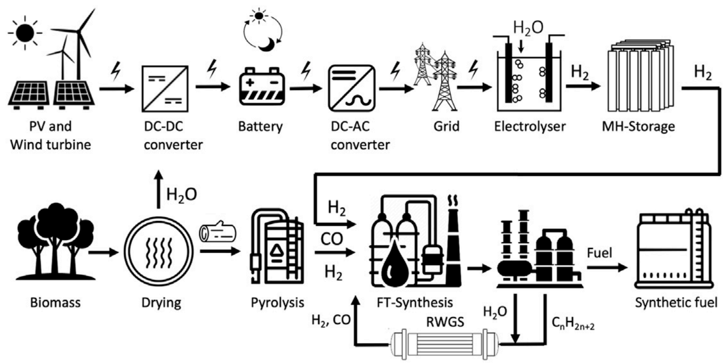
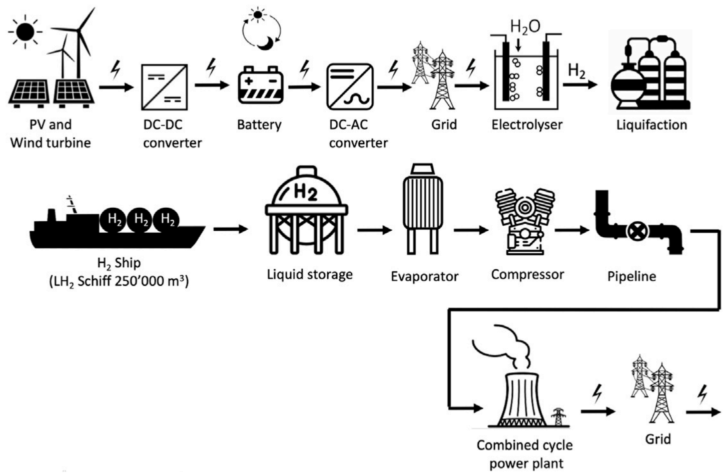
Input energy and parameters	Schematics of the power plant units (PPU)	Output energy and storage requirement	LCOE of 1 kWh electricity [CHF] + grid cost
Bio-SF 20 TWh·y^{-1} PV: 89 km^2 (I = 1,100 kWh·m^2·y^{-1}) or Wind turb.: 2,225 × 2 MW (50% P_p) and Biomass: 1.5 Mt grown on 7′500 km^2	 Photovoltaics with a local battery storage and an electrolyzer for hydrogen production. Biomass as a carbon source for the production of syngas, followed by Fischer-Tropsch synthesis and a refining cycle	Synthetic fuel 8.7 TWh·y^{-1} = 5.5 M barrel·y^{-1}	Fuel: 6.2/L 0.2/1.28 + 0.09
Imp-H_2 50 TWh·y^{-1} or 441 kt H_2·y^{-1} 113 km^2 PV (I = 2,200 kWh·m^2·y^{-1}) or 2′900 × 2 MW (50% P_p)	 Imported hydrogen with underground storage of compressed hydrogen for reserves and redundancy and a combined cycle power plant	Electricity 8.7 TWh·y^{-1} continuously and on demand, storage 4.4 TWh	1.02 + 0.09 H_2: 19.4/kg

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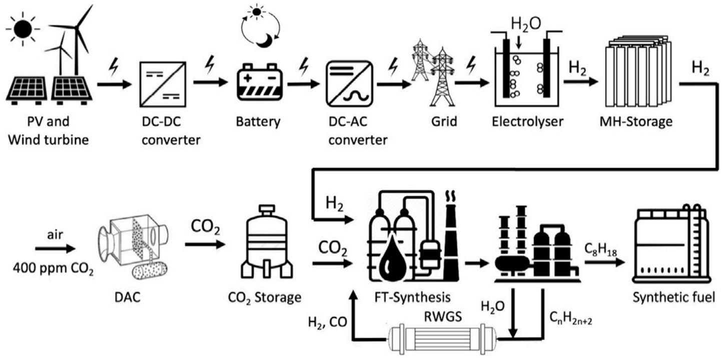
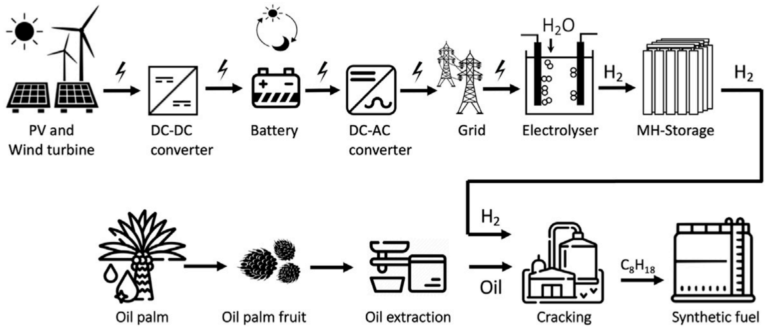
TABLE 1 (*Continued*) The 10 different PPUs provide >8 TWh·y⁻¹ of electricity all the time and on-demand, except for Bio-SF, Imp.-SF and Imp. PSF these deliver >8 TWh·y⁻¹ as synthetic fuel (synthetic hydrocarbons). PV area is active area, the PV field would be approximately 2–2.5 times larger. The levelized cost of energy (electricity) (LCOE) is given in the last column.

Input energy and parameters	Schematics of the power plant units (PPU)	Output energy and storage requirement	LCOE of 1 kWh electricity [CHF] + grid cost
Imp-SF 27 TWh·y^{-1} PV: 62 km^2 (I = 2,200 kWh·m^2·y^{-1}) or Wind turb.: 1,550 × 2 MW (50% P_p) and CO_2: 2.3 Mt y^{-1}	 Photovoltaics with a local battery storage and an electrolyzer for hydrogen production. CO_2 air capture as a carbon source for the production of syngas, followed by Fischer-Tropsch synthesis and a refining cycle	Synthetic fuel 8.7 TWh·y^{-1} = 5.5 M barrel·y^{-1}	Fuel: 10.8/L 2.2 + 0.09
Imp-PSF 12.2 TWh·y^{-1} PV: 5.6 km^2 (I = 2,200 kWh·m^2·y^{-1}) or Wind turb.: 140 × 2 MW (50% P_p) and Biomass: 0.9 Mt grown on 2,350 km^2	 Photovoltaics with a local battery storage and an electrolyzer for hydrogen production. Palm oil as a hydrocarbon source hydrided to oxygen free oil	Synthetic fuel 8.7 TWh·y^{-1} = 5.5 M barrel·y^{-1}	Fuel: 1.7/L 0.35 + 0.09

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Switzerland from wood is 6.2 CHF/L, while the imported synthetic fuel produced from PV with CO_2 from DAC and FT-synthesis costs 10.8 CHF/L. Imported synthetic oil from Palm oil cracked with hydrogen produced by PV costs 1.7 CHF/L.

The future cost is estimated based on the assumption that the CAPEX of components will drop to PV 200 CHF/kW$_p$, Batteries 55 CHF/kWh, electrolyzer 500 CHF/kW$_{el.}$ with an efficiency of 90%, electronics 200 CHF/kW, DAC of CO_2 200 CHF/kg and liquefaction of hydrogen 2000 CHF/kg. Therefore, the cost of hydrogen will decrease to 5 – 7 CHF/kg and synthetic oil will cost 2.3–2.7 CHF/kg. The main challenge for future cost reduction of hydrogen and synthetic fuels, beside the economy of scale, is the increase of the efficiency of electrolyzers. The cost of hydrogen and synthetic fuels is, therefore, expected to decrease to 50%–25% of the cost today.

4.2 The power challenges

The electricity demand of 60 TWh·y^{-1} in Switzerland (Swissgrid, 2024) corresponds in the annual average to a power of 6.8 GW, with a low of 6.5 ± 2 GW in summer and a high of 8.7 ± 1.5 GW in winter. If the additional electricity demand of 50 TWh·y^{-1} will be mainly produced by photovoltaics (>400 km^2) a peak power of 90 GW is expected, leading to a day/night average power of 34 GW in summer, which is still much larger than the expected electricity demand of 12 GW. Therefore, the local battery storage is inevitable to bring the max. power down from 90 GW to 32 GW and cover the electricity demand during the night. In addition, the seasonal storage needs to absorb >20 GW during the summer months in order to store 20 TWh electricity for the winter.

4.3 Seasonal storage and transport options

The high efficiency of an electrified energy distribution is compromised by the requirement to produce at every moment exactly the electricity that is demanded. The resilience of an electric grid is very small compared to fuel-based distributed energy systems. Furthermore, the transport of electricity around the world is not an option for technical and geographical reasons unless a superconducting cable around the world will be realized one day. Local short-term storage in batteries is an option if the battery is cycled frequently, but very expensive for seasonal storage.

The conversion of electricity to hydrogen and further to ammonia or synthetic hydrocarbons (CH_4 or oil), i.e., transforming electricity into a chemical energy carrier, opens other options for storage as compressed gas, cryogenic liquid, or liquid at ambient conditions. The conversion of the electricity into an energy carrier and back to electricity is limited by the technically realized efficiencies. The amount of energy carrier produced is determined by the production efficiency and the amount of energy recovered in the conversion back to electricity.

Hydroelectric plants with a storage lake exhibit a low electricity storage density of 1–4 kWh/m^3 for 500 m and 1800 m of height difference and a roundtrip efficiency >70%. Furthermore, the size of the dam only depends on the hydrostatic pressure and not in the amount of water behind the dam. The volume of the stored water is determined by the shape of the valley. Removing soil and rocks from the valley to increase the volume is only possible for the construction of the dam due to the high energy demand (Bieniawski, 2024) of excavation of around 30 kWh/m^3. In storage lakes with a large height difference of 1800 m the energy for excavation corresponds to less than 10 years for seasonal storage.

Alternatively, large underground caverns for pressurized gas or for liquified gas use the surrounding rock to hold the pressure (Wang et al., 2019) (max. 180 bar) or as a thermal insulator (thermal conductivity approximately 1–7 W m^{-1}·K^{-1}).

Figure 8 shows the conversion efficiency from electricity to energy carrier, storage, and back to electricity *versus* the storage density of electricity. Hydroelectric storage and batteries reach a roundtrip efficiency of more than 70%. However, the storage density is 10^{-3} TWh/Mm^3 and <0.5 TWh/Mm^3, respectively. The efficiency of heat storage depends on the temperature of the heat extracted from the storage and can reach 50% for the latent heat of the phase change of LiH at 700 °C and up to 30% for the sensible heat in sand at 600 °C. The efficiency of the chemical energy carriers (hydrogen (H_2), ammonia (NH_3), and synthetic hydrocarbons (CH_4)) are at or below 20%. The electricity density of the chemical energy carriers shows three groups. The first one is located below the electricity density of 200 MWh·m-3 consisting of hydroelectricity, batteries and thermal storages as well as ammonia below 8 bar and hydrogen at 200 bar. Compressed hydrogen at 200 bar (H_2 density 15 kg/m^3 at 25°C) with 294 kWh/m^3 less than the theoretical energy density of 400 kWh/m^3 of Li-ion batteries but 3 times more than the realized energy density of 95 kWh/m^3 in the Tesla Megapack2 (Wikipedia, 2023). The second group consists of liquid hydrogen (H_2 density 70.8 kg/m^3 at −252.87 °C and 1.013 bar), compressed methane at 200 bar (CH_4 density 180 kg/m^3 at 25 °C), liquid ammonia (NH_3 density 682 kg/m^3 at −33°C and 1.013 bar) and is 1.2–1.5 TWh/Mm^3 and metal hydrides with 1 mass% of hydrogen and 67 kg H_2·m^{-3} and 1.6 MWh·m^{-3}. The third group represents the maximum storage density and consists of liquid methane (CH_4 density 422.8 kg/m^3 at −161.5°C and 1.013 bar) and liquid hydrocarbons (oil density 850 kg/m^3 at 25 °C and 1.013 bar) and is around >3 TWh/Mm^3.

4.4 Import and storage of liquid hydrogen and synthetic oil

The production of hydrogen from renewable energy in regions with high solar intensity and available land area, e.g., Australia has several advantages: (1) The solar intensity is twice as high as in Switzerland, consequently size of the photovoltaic field is only half of what it would be in Switzerland. (2) Space for the PV fields is available and not difficult to reach. (3) The seasons in Australia (southern hemisphere) are opposite those in Europe. Consequently, the production and demand patterns match each other much better. (4) Global transport in liquid form by ship with propulsion of the ship with the boil-off is efficient and CO_2 neutral. (5) Global trading of renewable energy carriers produces economic growth and benefits in regions where no economy currently exists. If Switzerland imports most of the renewable energy to produce 53 TWh of electricity in 6 - 8 thermal power plants with central district heating, 2.7 Mt y^{-1} (7,400 t d^{-1}) of hydrogen has to be imported. In 2022, Switzerland imported 8.85 Mt y^{-1} of crude oil and oil products, and the mandatory reserves of oil and products are equivalent to 4.5 months, therefore, around 3 Mt.

TABLE 2 Comparison of the parameters of the different PPUs, i.e., estimated resulting electricity cost per kWh, initial capital investment (CAPEX) for the PPU, the PV area, and the plantation area. The areas and CAPEX outside of Switzerland are indicated in parenthesis. Future developments of the renewable energy components may reduce the CAPEX more than 50%.

	NUC	PV-HYD	PV-H_2	BioSF	Imp.-H_2	Imp_SF	Imp. PSF
Electricity cost [CHF·kWh^{-1}] at PPU	0.08	0.24	0.44	0.47	1.02	2.20	0.35
Init. CAPEX [BCHF]	8–12	32	84	60	7 (106)	5 (57)	4 (10)
PV area [km^2]	0	51	83	89	(113)	(124)	(12)
Plantation area [km^2]	(6′200)	(6′200)	(6′200)	7′448 + (6′200)	(6′200)	(CO_2: 4.6 Mt y^{-1}) + (6′200)	(4′688) + (6′200)
Product	8.7 TWh·y^{-1}	8.7 TWh·y^{-1}	8.7 TWh·y^{-1}	5.5 MBarrel	8.7 TWh·y^{-1}	5.5 MBarrel	5.5 MBarrel
Challenge	law against nuc. PP	PV area, storage lakes	PV area, H_2 storage volume	available biomass in CH	cost of imp. H_2 and H_2 storage volume	cost of syn. fuel	area of plantation

Importing liquid hydrogen or liquid synthetic fuel (hydrocarbons) allows to produce electricity in combined cycle thermal power plants which consume a small space as compared to local PV fields. However, with the currently available technology and the cost of the components this approach leads to very high costs of the electricity produced from hydrogen and from synthetic fuel of >1 CHF/kWh and >2 CHF/kWh, respectively. In order to be competitive with the local PPU's the liquid hydrogen and the synthetic fuel cost has to be <7 CHF·kg^{-1}H_2 and <1.75 CHF·L synfuel, respectively, and the electricity produced costs around 0.35 CHF·kWh^{-1}.

Importing renewable liquid energy carriers and building the necessary storage for redundancy and reserves is mainly an economic challenge for Switzerland and requires that enough producers of renewable fuels worldwide will be available.

4.5 Synthetic fuels from bio oil

The production of synthetic hydrocarbons from renewable energy via PV is expensive because of the components: Electrolysis, CO_2 capture and the Fischer-Tropsch synthesis. These three components determine 90% of the cost of the synthetic fuel. Today, the energy cost (PV electricity) contributes only <5% to the final cost of the synfuel. Bio mass with the general chemical composition of HCOH already contains the carbon as well as the hydrogen for a synthetic hydrocarbon. An additional hydrogen molecule is needed to reduce the oxygen in the compound. In case of palm oil, the energy in the palm oil is conserved in the hydriding process by adding 11wt% of hydrogen to remove the oxygen and to saturate the unsaturated carbon, leading to a mass loss of 15wt% and an increase of the energy content from 10.8 kWh·kg^{-1} to 12.8 kWh·kg^{-1}. The synthetic fuel is similar to diesel or kerosene and can be stored in the already existing fuel storage tanks. Palm oil plantations are very efficient in harvesting solar energy and producing bio-oil. For 1 t y^{-1} of bio-oil an area of only 2,600 m^2 is needed, close to the equator, approximately 5 times less area than for rapeseed oil (Rahman et al., 2024). In Switzerland, the reserves for redundancy of the power plant units and the fuel for aviation can be covered by imported bio-oil produced on approximately 7,000 km^2 close to the equator and shipped to Switzerland with a rate of 2.4 Mt y^{-1}.

5 Discussion

5.1 Technical requirement and cost of the substitution of fossil fuels with renewable energy

The substitution of fossil fuels with renewable energy in Switzerland is possible if sufficient renewable energy is produced (+72 TWh·y^{-1}) or renewable energy carriers are imported, and sufficient storage capacity (+20 TWh) is built up to provide electricity on demand. Six power plant units cover a large amount of the electricity demand, in addition to double the volume of the storage lakes of the hydroelectric power plants (+9 TWh·y^{-1}), covering all feasible roof areas with photovoltaics (+21 TWh·y^{-1}), and using a large fraction (20 TWh·y^{-1}) of the available biomass for heating.

The most economic PPUs (Table 2) are the hydroelectric power plants (storage HYD-S and river HYD-R), the thermal power plants (THERM) using biogas, and the nuclear power plants (NUC). The construction of an additional hydroelectric power plant of the size of a PPU (HYD-S), i.e., 50% of all hydroelectric power plants with a storage lake existing in Switzerland, is very difficult to realize. Already, doubling the volumes of existing storage lakes is technically possible by increasing the height of the dam by 26% or by excavation of the lake, but this is a huge technical challenge. Adding a hydroelectric river plant PPU (HYD-R), i.e., 50% of all hydroelectric river plants existing in Switzerland, is technically impossible.

Construction of 6 + 2 thermal power plants or nuclear power plants is feasible. However, the new nuclear powerplants with a higher flexibility in the fuel supply and that are able to breed fuel are still in an early stage of development. China's Ministry of Ecology and Environment has approved the commissioning of an experimental molten salt thorium nuclear reactor in Wuwei City, Gansu Province, China (Interestingengineering, 2024). The technology has the potential to contribute significantly to energy security in the future with a minimum of negative impacts on the environment. Furthermore, the breeding technology is able to reuse

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TABLE 3 Comparison of the parameters of the different PPUs, i.e., estimated resulting annual energy cost *per capita*, initial capital investment (CAPEX) for 6 PPU's, the PV area, and the plantation area. The areas and CAPEX outside of Switzerland are indicated in parenthesis. The cost of doubling of the hydroelectric storage lake volume is not considered. Future developments of the renewable energy components may reduce the CAPEX more than 50%.

	2019	NUC	PV-HYD	PV-H_2	BioSF	Imp.-H_2	Imp.-SF	Imp. PSF
Energy cost [CHF·y⁻¹·capita⁻¹]	3′000	2′764	4′397	6′118	6′347	11′148	21′385	5′306
Init. CAPEX [BCHF]	20	48	189	563	362	42 (638)	24 (345)	24 (59)
PV area in CH [km^2]	10	150	454	650	418	150 (681)	150 (746)	150 (68)
Plantation area [km^2]		0	0	0	22′343	0	(CO_2: 28 Mt y^{-1})	(28′134)
Plantation area [km^2] Aviation		(6′200)	(6′200)	(6′200)	(6′200)	(6′200)	(6′200)	(6′200)

current nuclear waste and convert it to short-living isotopes and solve the problem of finding deep long-term storage cavities for nuclear waste.

Production of renewable electricity by photovoltaics is a feasible option for the future. The PV-field area, which is roughly twice the active PV-area, for one PPU corresponds approximately to the surface area of the lake of Zürich (100 km^2). The advantage of the local production of renewable electricity is the high efficiency and low cost of the directly used electricity. The technical challenge is the seasonal storage of 25% of the produced electricity by a hydroelectric storage power plant.

Alternatively, hydrogen can be produced from PV electricity and stored. Due to the energy losses in conversion, the PV area needs to be large as for the hydroelectric storage, and the cost of electricity produced from hydrogen after storage increases significantly. Building large hydrogen storage units in Switzerland is feasible and necessary, also if the hydrogen would be produced outside of the country and imported. The necessary reserves are of a similar size as the seasonal storage, in the order of 20 TWh. The storage has to be built no matter where the hydrogen is produced. In addition, for redundancy and energy security, at least two more power plant units would have to be installed. Producing electricity from hydrogen in a combined cycle power plant (THERM) would deliver an equal amount of heat and electricity, the heat can be used for district heating in winter, cover most of the heating demand of Switzerland, and reduce the demand of local biomass for heating. The biomass is then available for synthetic fuels, i.e., biomass is pyrolyzed to syngas with hydrogen and converted to synthetic fuel and thus prevent capturing CO_2 from a point source or even directly from air. The synthetic fuel is stored in the already installed oil storage tanks (mandatory reserves of 4.5 months). Furthermore, the synthetic fuel can be used for aviation as well as backup fuel for the thermal power plants. The cost of the synthetic fuel is estimated 4 CHF/L and, therefore, the electricity produced 1 CHF/kWh. This rather high cost is mitigated by the heat produced at the same time and by the mixture with lower cost electricity directly from PV and from the hydroelectric power plants resulting in an average cost of <0.33 CHF/kWh of energy.

As an alternative to the production of synthetic oil from biomass (wood) in Switzerland, bio-oil could be imported. The bio-oil has a high energy density (10.8 kWh/kg) and a synthetic oil similar to kerosene can be produced by a heterogeneously catalyzed hydriding reaction. The main advantage of bio-oil, especially palm oil, is its much lower cost compared to synthetic oil produced in Switzerland. Furthermore, the palm oil plant is efficient and requires 5 times less surface area compared to other bio-oils, e.g., oil from rapeseed. Switzerland could import up to 23 TWh·y^{-1} of bio-oil for aviation and hold a reserve of 20 TWh of bio-oil for the THERM PPUs, which are fueled either with hydrogen or bio-oil. Currently the synthetic bio-oil is estimated to cost around 1.7 CHF/L and, therefore, the electricity would cost around 0.35 CHF/kWh. The plantation area for Palm oil is about 5 times larger as compared to the field area of PV for the same amount of synthetic oil from hydrogen and CO_2.

Table 3 shows an overview of the expected annual energy cost, the capital investment, the PV-area in Switzerland, and the area of the oil palm plantation outside of Switzerland for the different PPUs, as compared to the current (2019) energy economy. In any case, the energy reserves and the aviation fuel are assumed to come from imported bio-oil or bio-oil-based synthetic kerosene. The 6 PPUs would deliver 54 TWh·y^{-1} of electricity per year. This, combined with the 24 TWh·y^{-1} produced by photovoltaics on the roofs would provide 72 TWh·y^{-1} of renewable energy. However, a smart combination of PPUs, e.g., nuclear and combined cycle thermal plants including two thermal plants as reserves, allow to optimize the cost for energy. The use of the combined cycle thermal power plants as well as the nuclear power plants for central heating, further reduces the energy demand in winter below the demand estimated in this work (s. Figure 6B).

If we do not consider importing hydrogen or importing synthetic fuel until the cost decreases by a factor of 3 and 4, respectively, the annual cost for energy increases by a maximum of 54% to 42 BCHF. In 2022, Switzerland spent 12.4 BCHF for fossil energy carriers (Bazg, 2023) and approximately 27 BCHF in total for energy.

5.2 Energy security of supply

Energy security requires the availability of energy on demand at all times and in addition, reserves of at least 25% of the annual energy demand (>3 months). The future electricity demand in 2050 in Switzerland will increase to 80–130 TWh, depending on the development of the population and the future reduction of energy demand *per capita* due to improved efficiency and change of behavior. The analysis in the current work is based on an estimated electricity demand of 113 TWh in 2050. The replacement of nuclear power with renewable energy requires 3 PPUs. Depending on the development, 3 – 8 PPUs would cover the increase in electricity demand, and at least 2 PPUs are needed for reserve and energy security. District heating will make an important contribution to the increased energy demand in winter but is a challenge for redundancy since the heat also has to be produced on demand in a secure manner.

Trading of electricity across the border in Europe may still be economically interesting in the future, but this will not replace the reserves nor support energy security since all countries have the same seasons. Every country will have to build up their reserves. Storing energy in the form of synthetic oil is by far the easiest and most economical solution.

Expanding or reinforcing the grid does not replace storage. The local battery storage increases the cost of electricity production but reduces the maximum power. The peak power of PV in Switzerland is equal to close to 8 times the average power. Therefore, the local battery storage allows increasing the local consumption (night) without using the grid and reduces the maximum grid power by almost an order of magnitude (Cárdenas et al., 2021).

5.3 Production of renewable energy

The annual solar irradiation determines the size of the photovoltaic field as well as the ratio of peak power to average power and, therefore, the size of the local battery storage and the power in the grid. Australia has twice the solar irradiation of Switzerland, plenty of abundant land area, and the seasons are shifted by half a year. A PV field of approximately 1′600 km^2 (40 km × 40 km) in Australia is sufficient to deliver the energy for Switzerland. A PV field of 1.5 Mkm^2 in Australia can replace all fossil fuels for the world with renewable energy. This is only about 20% of the land area of Australia or just slightly more than the Gobi Desert. More regions, e.g., in the Sahara or in North and South America, are available. In addition, a large wind power installation in Patagonia or tidal power in the Bristol channel (United Kingdom), yellow sea (Korea), and Penzias Bay (Russia) can contribute to the renewable energy production. Today, Africa produces 4 Mt y^{-1} of palm oil (Weforum, 2022), approximately twice as much as the Swiss aviation would consume. The global palm oil production has to increase significantly to make a very important contribution to the transformation from fossil to renewable energy. The price for palm oil on the world market is 720 CHF/t, that corresponds to 130 CHF per barrel (August 2023), and it has doubled in the last 20 years (Tradingeconomics, 2024). Palm oil plantations are biologically sustainable because they do not drain essential elements from the soil, are not toxic and highly efficient (385 t of palm oil per year on 1 km^2) (WUR, 2024). It is a unique opportunity for the world's development, because there are many regions that are abundant today and could be transformed in oil palm plantations creating an income for the local population and providing work and wealth especially in the less wealthy societies. Furthermore, the combination of the palm plantation with the upgrading of the palm oil with hydrogen will create a developing economy for the future. The price for the upgraded oil may be as high as 2.5 CHF/L and provide more benefit to the producer while it is still a factor of four cheaper than synthetic oil produced via Fischer-Tropsch synthesis from CO_2 air capture and hydrogen from PV.

Finally, the oil plant plantations increase the amount of biomass on earth and bind a significant amount of CO_2. If the current oil production of $90 \cdot 10^6$ barrels per day (4.4 Gt y^{-1}) would be replaced with oil from the palm oil a plantation area of $12 \cdot 10^9$ km^2 has to be created additionally to the current agricultural land of $44 \cdot 10^9$ km^2. This is theoretically possible especially if some of the deserts are converted into palm oil plantations equipped with a solar sea water desalination.

5.4 The investment challenges

The transition of Switzerland from fossil fuels to renewable energy involves an investment of approximately the energy cost of the coming 30 years. If we assume the energy cost of today (3′000 CHF·y^{-1} *per capita*), the investments are on the order of 50% of the annual GDP. In order to complete the transition in 27 years, Switzerland would have to invest 1.5% of the GDP every year. Such large investments over a period of 27 years are risky and difficult to realize. Currently, the costs for photovoltaic installations are covered by private persons and by industry, besides the subsidies of the government. As soon as the energy market is successfully transformed to renewable energy and stable, the free market will be able to take control. However, redundancy and stability are not provided by the free market because of the lack of benefits. The cost of nuclear power plants increased significantly in the last 20 years and is estimated today to range from 6 to 9 BCHF for a 1.1 GW plant (Schlissel and Biewald, 2008). With the technical improvement and the scale effects some of the components for the renewable energy conversion will decrease in cost which will lower the CAPEX as well as the cost of renewable electricity in future by approximately 50% as compared to today.

6 Conclusion

This paper addresses the question how renewable energy can substitute fossil energy and deliver energy on demand rather than on production on the example of Switzerland. A new concept of power plant units (PPUs) based on photovoltaic or wind is introduced. A PPU consists of the energy conversion and storage units and delivers a constant power of 1 GW, similar to a nuclear power plant. This makes a direct comparison of a renewable energy supply with a fossil energy supply possible. The capital cost (investment) and the levelized cost of energy are determined for the various PPUs. Furthermore, the amount of renewable energy is estimated and the substitution pathway is shown in order for Switzerland to become CO_2 neutral in 2050.

The hydroelectric power plants with a storage lake, the river hydroelectric power plants, thermal combined cycle power plants (CCPP) and nuclear power plants are compared with photovoltaics (PV) and wind turbines (WT) with a local battery storage and either hydroelectric, hydrogen or synthetic hydrocarbon seasonal storage. Furthermore, import of hydrogen, synthetic hydrocarbon and bio oil for electricity production in CCPP were analyzed.

Beside the hydroelectric power plants and the nuclear power plants, the most economic and efficient PPU is based on PV or WT with a local battery storage capacity corresponding to >0.5% of the annual energy production in order to balance short term fluctuations in production and reduce the maximum power in the grid. The most efficient seasonal storage is pumped hydroelectricity, but the number of feasible hydroelectric power plants is limited. The local production of renewable electricity provides 75% of the electricity for a lower cost, only 25% are more expensive due to the seasonal storage. Importing energy carriers produced far away do not offer this opportunity and the electricity is always more expensive compared to local production.

The large potential for bio-oil production worldwide allows to substitute fossil oil with a CO_2 neutral bio oil and to use the already existing transport, distribution and storage infrastructure. Furthermore, producing bio oil in regions, where currently no plants are growing, opens up new economic opportunities for less developed areas.

About 25% of the electricity on demand, mainly during winter time, is produced by CCPP providing also heat for district heating and hot water supply, which further reduces the electricity demand and energy cost.

The future ideal renewable energy economy is a compromise between the possible local production and storage and the more expensive import of CO_2 neutral energy carriers, i.e., hydrogen or synthetic oil. Furthermore, the local production of renewable energy requires investments in building up the PV fields or WT and the short term and seasonal storage, while importing energy carriers only requires to build the CCPP. However, also imported energy carriers need to be stored just like the current mandatory storage for fossil oil, which corresponds to approximately 25% of the annual demand.

The energy cost *per capita*, which is currently around CHF 3000 per year remains almost the same if the electricity would be produced by nuclear power plants followed by PV in combination with hydroelectric seasonal storage increases the energy cost *per capita* by almost 50%. PV with seasonal storage with hydrogen, PV using the biomass for seasonal storage and importing Palm oil approximately double the energy cost *per capita*. Finally importing hydrogen or importing synthetic fuel increases the energy cost by more than a factor of 3.

The most economic energy system for Switzerland is installing PV and WT to cover 75% of the electricity demand in future and combine it with 6 + 2 CCPPs fueled with hydrogen or palm oil during the winter time and when reserves and redundancy is needed, corresponding to 25% of the electricity demand. This also provides a maximum flexibility and independency and allows to produce the required power at any time of the year. The aviation uses imported palm oil or with hydrogen upgraded palm oil to synthetic kerosene that can be produced today for less than 2 CHF/L.

Switzerland is in a favorable situation, because of the CO_2 free electricity production. However, electrifying the energy economy and producing all the electricity from renewable energy is a technical and economic challenge, but feasible. On a global level, bio oil has the potential to enable the energy transition to a CO_2 neutral and sustainable energy economy, allowing the seasonal (reserves) storage for a low cost and developing currently not used land areas.

The power plant units allow to compare renewable energy plants providing energy on demand rather than supply controlled. This approach can be applied to other countries or even on a global level in order to determine the technological challenges, the capital cost and the levelized cost of energy.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

AZ: Conceptualization, Formal Analysis, Investigation, Methodology, Writing–original draft. CN: Investigation, Validation, Visualization, Writing–review and editing. LS: Resources, Validation, Visualization, Writing–review and editing. PG: Formal Analysis, Resources, Validation, Visualization, Writing–review and editing.

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Conflict of interest

Author CN was employed by Christoph Nutzenadel AG.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2024.1336016/full#supplementary-material

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Nomenclature

HYD-S	Hydroelectric power plant with storage lake
HYD-R	Hydroelectric power plant on river
THERM	Combined cycle thermal power plant
NUC	Nuclear power plant of future generation (e.g. molten salt Th breeder reactor)
PV-HYD	Photovoltaics and hydroelectric power plant with pumped storage lake
PV-H2	Photovoltaics with hydrogen production and storage and THERM
BioSF	Biomass conversion to synthetic fuel with PV and H2
Imp.-H_2	Imported hydrogen
Imp.-SF	Imported synthetic fuel from PV, H_2 and DAC
Imp.-PSF	Imported synthetic oil from hydrogen cracked Palm oil
DAC	Direct air capture
PV	Photovoltaics
CO_2	carbon dioxide
kWh/year	kilowatt hours per year = terawatts·10^{-9}kW/TW·365days/year·24h/day
GW_p	Gigawatt peak
TW_p	Terawatt peak
C	capital cost (CAPEX)
Z	interest
P_b	annual payback
n	number of years
C_E	cost of the energy per energy unit
E_y	annual energy received from the energy system
OPEX	operational cost
LCOE	The levelized cost of energy
C_c	cost of the energy

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Closed-loop supply chain decision making and coordination considering channel power structure and information symmetry

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China is currently undergoing a phase of high-quality development, with increasing emphasis on the circular economy, energy conservation, and environmental protection by both the government and enterprises. This paper examines a secondary supply chain comprising manufacturers and retailers, focusing on three supply chain decision-making models: one where the manufacturer is the channel leader, one where the retailer is the channel leader, and one where both parties have equal power. The study investigates the impact of manufacturers misrepresenting their Corporate Social Responsibility (CSR) information and the challenges associated with recycling efforts on the optimal performance of the supply chain. The findings reveal that when manufacturers lead the supply chain, they do not misrepresent their private information. However, when retailers dominate, manufacturers tend to underreport their CSR levels and the difficulty of recycling efforts. In scenarios where manufacturers and retailers have equal power, manufacturers do not misreport the difficulty of recycling but do underreport their CSR levels. This misreporting benefits the manufacturers at the expense of retailers and overall supply chain profitability, while also discouraging the recycling of used products. Across all three power structures, the study shows that retailers' marketing efforts decrease as the misrepresentation of recycling difficulty increases, and increase as the misrepresentation of CSR levels increases. To mitigate the effects of manufacturers' misreporting under information asymmetry, the paper proposes revenue-sharing contracts and two-part pricing contracts to coordinate the closed-loop supply chain under different power structures. Both contracts are shown to achieve Pareto improvements within the supply chain. This research provides valuable insights for enterprises operating within closed-loop supply chains, highlighting the importance of enhancing communication and cooperation to bridge information gaps and ensuring the coordina.

KEYWORDS

corporate social responsibility, channel power structures, misreporting behaviour, information asymmetry, revenue-sharing contract, two-part pricing contract

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1 Introduction

Under the background of rapid development of social economy and technology, closed-loop supply chain management has gradually become the focus of attention of enterprises. Under the leadership of China's "dual-carbon" strategic goal, how to better practice the environmental and social responsibility of closed-loop supply chain member enterprises, promote the recycling - remanufacturing - sales process of recycled products, and then realize the green and low-carbon transformation has become one of the hot issues nowadays (Xia and Niu, 2021). Recycling strategies for used and end-of-life products, as well as marketing services, have attracted widespread attention from all sectors of society as key elements driving the sustainability of closed-loop supply chains (Du et al., 2019). China's National Development and Reform Commission (NDRC) and other departments have jointly issued relevant guidelines, clearly proposing that by 2025, about 60 large and medium-sized cities should take the lead in building a basically perfect recycling system for waste materials, vigorously developing the recycling economy and remanufacturing of waste products, and actively promoting the mechanism of recycling waste products. In this situation, focusing on the impact of marketing efforts of remanufactured products on the optimization of closed-loop supply chain operation and the environment from the perspective of CSR has significant practical guidance value for promoting the development of low-carbon industry and accelerating the construction of a recyclable and low-carbon consumption system.

On the one hand, with the aggravation of resource depletion and environmental degradation, the continuous upgrading of consumer demand, the environmental pollution caused by improper waste disposal and the increasing number of used products have brought great challenges to the development of circular economy in the country (Murthy and Ramakrishna, 2022). Promoted by the national extended producer responsibility system and other policies, many enterprises have realized the reduction and remanufacturing of waste products through the closed-loop supply chain, and have actively undertaken the ecological responsibility in corporate social responsibility (Cheng et al., 2023). Undertaking corporate social responsibility (CSR) refers to the fact that in the process of production and operation, enterprises should not only consider their own interests, but also integrate their contributions to the environment, consumers and society into their daily business activities. In the 1980s, CSR behaviors began to emerge in developed countries in Europe and the United States, and spread rapidly to other countries in the world with the expansion of multinational corporations' capital. According to the data released by CSR China (www.csr.China.net), the number of enterprises disclosing social responsibility information in China has increased from 739 in 2009 to 2,115 in 2023. By the end of April year 2024, more than 2,000 listed companies disclosed their 2023 sustainability reports or social responsibility reports, and about 3,000 companies disclosed measures taken to reduce carbon emissions and their effects, indicating that CSR has received unprecedented attention in China in recent years.

On the other hand, information asymmetry is prevalent in closed-loop supply chains. Information asymmetry refers to the fact that when firms have an information advantage, they may use the strategy of false information to gain more profits. Therefore, the information asymmetry problem brings a series of new problems to the closed-loop supply chain that are different from those of the traditional supply chain: the information asymmetry greatly hampers the coordination of the closed-loop supply chain and the optimization of remanufacturing decisions (Jian et al., 2021). The problem of information asymmetry arises mainly due to the lack of information exchange and market economic activities between different members of the closed-loop supply chain, especially when one party holds private information that is not held by other members of the closed-loop supply chain, the impact of information asymmetry on the decision-making of remanufacturing in the closed-loop supply chain is more obvious. The increasing trend of economic globalization has led to intensified market competition, which makes members of closed-loop supply chains pay more attention to cooperation and coordination among supply chains.

In summary, the study of the two factors of CSR and information asymmetry in the closed-loop supply chain has important theoretical and practical significance. It not only helps enterprises to optimize decision-making and improve supply chain efficiency, but also provides reference for the government to formulate relevant policies and promotes the sustainable development of the whole society and economy.

Based on this, this paper investigates the problem of manufacturers' misrepresentation of CSR information and recycling effort information in the supply chain, explores manufacturers' misrepresentation strategies under different channel power structures, and introduces two coordination mechanisms to coordinate the supply chain, which is of great theoretical significance and practical value to promote the sustainable development of closed-loop supply chains.

The next part of this paper is organised as follows. In the second part, the related literature is reviewed. In the third part, we introduce the problem and hypotheses. Then, in Part IV, we establish the basic model. In Part V, we propose two coordination strategies. In Part VI, we analyse the given theorems numerically accordingly. Finally, we present the conclusions of this paper in Section 7.

2 Literature review

In this section, we review studies that are highly relevant to the work of this paper. These studies include, among others, recent research trends in closed-loop supply chains, studies related to corporate social responsibility, studies related to information asymmetry in supply chains, studies related to channel power structures in supply chains, and studies related to marketing efforts in supply chains.

2.1 Research on closed loop supply chain

At present, scholars' research on the operation of closed-loop supply chains mainly focuses on issues such as recycling channel selection, pricing decisions, government rewards and punishments, and coordination mechanisms, etc.

In fact, scholars have explored a lot about product recycling and remanufacturing under closed-loop supply chains (Van Engeland et al., 2020; MahmoumGonbadi et al., 2021; Yang et al., 2020). Under the trend of transformation of traditional economy to the development mode of circular economy, product recycling and remanufacturing is an inevitable choice for enterprises (Ming-ge et al., 2021). In the product recycling process, the recycler usually bears heavy recycling costs and obtains low profits. However, research has shown that through recycling cooperation and sharing, the overall efficiency of the closed-loop supply chain is improved, and the profits of each member of the supply chain are also increased (Hosseini-Motlagh et al., 2020). Wang et al. (2019a) and He et al. (2019) constructed a two-level supply chain recycling decision-making model consisting of manufacturers and retailers to analyse, and found that cooperative mechanisms are the main way to improve recycling efficiency. In the current product recovery and remanufacturing environment, it is more common for producers to recycle through third parties. Xiao-gang et al. (2024) examined closed-loop supply chain decision-making under different recycling channels, considering mixed recycling channels of manufacturers, retailers, and third-party recyclers, as well as the fair concern behavior of retailers *versus* third-party recyclers. Four mixed recycling channel models are compared and it is found that recycling competition reduces the total amount of used products recycled and that the optimal recycling model changes when the level of fairness concerns of retailers and third-party recyclers changes. Qiankai et al. (2024) investigated the impact of e-commerce platforms opening second-hand markets on closed-loop dual-channel supply chain decisions. The study found that whether or not an e-commerce platform opens a second-hand market does not affect a company's product pricing decisions, but increases the recycling price of a manufacturer's used products.

Pricing decisions in closed-loop supply chains have also been thoroughly explored by scholars. Fengmin et al. (2021) studied and analysed the impact of CSR behaviours on sales behaviours and pricing strategies in closed-loop supply chains. Subsequently, Fengmin et al. (2022) investigated the impact of socially responsible behaviours of different member firms on the pricing decisions of closed-loop supply chains under different channel power structures. Shan and Dongyan (2021), Shan and Dong (2022) incorporated CSR behaviours into closed-loop supply chain pricing decisions and found that moderate competition among recyclers reduces product prices and increases scrap recycling rates.

In terms of government incentives and penalties, government subsidies to guide the closed-loop supply chain in waste recycling and remanufacturing play an important role in the establishment and effective operation of the closed-loop supply chain (Guo et al., 2019). Some scholars have studied the combination of subsidy policy and other policies, such as (Min and Zhen, 2019) derived the product recovery price and retail price under the four conditions of government non-intervention, government adopting reward and punishment mechanism, subsidy mechanism, and dual mechanism of reward and punishment and subsidy. In addition, the Government has taken measures to subsidise third-party recyclers to ensure that a certain amount of waste is recycled. Zheng et al. (2021) considered the impact of dynamic government penalty and subsidy strategies on the recycling of used and end-of-life products and finds that the government can increase the probability of firms choosing recycling strategies by increasing fines or decreasing subsidies, thereby reducing environmental pollution. Dao-ping et al. (2022) considered the dynamic stochastic situation of WEEE recycling rate and found that the implementation of reward and punishment mechanisms by the government can increase the recycling rate but is not conducive to mitigating the double marginal effect.

For the coordination problem in closed-loop supply chains, most of the studies have improved on individual contracts or multiple individual contracts, such as designing benefit-cost sharing contracts (Fang et al., 2020), price contracts (Fei and Maozeng, 2019), profit compensation mechanisms (Chuan and Yu-xiao, 2021), quantity discounts CSR cost sharing contracts (Xinran and Gang, 2020), etc. To achieve supply chain coordination.

2.2 Research on corporate social responsibility

In recent years, more and more enterprises are actively undertaking corporate social responsibility while pursuing economic benefits. Enterprises that actively undertake social responsibility are more likely to win the favour of consumers and shape a better brand image. Nearly 70 per cent of consumers indicate that they are willing to pay for the products and services of companies with a reputation for social responsibility (Minli et al., 2023).

In the supply chain level social responsibility literature, relevant studies can be divided into two categories: one category of literature, when examining CSR behavior, considers CSR behavior as an endogenous variable in the study of corporate decision-making behavior. Modak et al. (2019) explored the impact of CSR investments on closed-loop supply chain recycling decisions and coordination through social giving. Yan et al. (2019) examined CSR incentives under different channel power structures and showed that suppliers fulfil their social responsibilities at a higher level when retailers act as channel leaders. Liu et al. (2019) investigated the impact of government subsidies on retailer-led socially responsible supply chains, noting that a certain range of government subsidies can stimulate the overall effectiveness of the supply chain. Wang et al. (2019b) found that increasing CSR investment co-operation can effectively improve the level of retailers' CSR investment, increase market share and gain more supply chain profits.

Another category of literature treats CSR as an exogenous variable and considers the impact of CSR as consumer surplus, which is directly added to the firm's profit function. Yu-hui et al. (2024) constructed a green supply chain model to explore the incentive effects of different coordination contracts on product greenness and the impact of CSR preferences. The study finds that an increase in CSR preferences can help improve product greenness, etc., that two-part pricing contracts can harmonize the supply chain, and that CSR preferences can widen the range of their transfer payments. Feng-min et al. (2022) analyzed the operation and coordination of a closed-loop supply chain for third-party recycling in the context of manufacturers' awareness of CSR behaviours and retailers' CSR investments. Jian-yi Qi-chao (2022), in their study of fresh produce supply chains, found that

CSR behaviors have a positive impact on the supply chain, and that the effect of stimulating demand when supply chain members share CSR is better than the effect of suppliers undertaking CSR alone.

In supply chain research that considers social responsibility, most studies assume that market demand is related to price or the extent to which firms fulfil their social responsibility, while fewer studies have explored the joint impact of social responsibility and marketing efforts. In addition, there is little existing research on misrepresentation of the level of corporate social responsibility.

2.3 Research on information asymmetry in supply chains

Information asymmetry is a common phenomenon in supply chains, and when a firm has an information advantage, it may seek to make more profits by concealing key information or even misrepresenting it. Existing related studies can be broadly categorized into three areas: (1) misrepresentation of product quality information; (2) misrepresentation of cost information; (3) misrepresentation of demand information.

In terms of misrepresentation of product quality information, being in a market with product differentiation makes it easy for there to be asymmetry of product quality information between firms and consumers. Consumers often judge product quality based on price, which provides an opportunity for companies to exploit false quality information. Based on vertical product differentiation, Xiong-wei et al. (2020) investigated whether monopoly firms have incentives to adopt false quality strategies in the presence of asymmetric information about product quality, and the results of the study showed that firms have incentives to adopt false quality strategies for high-quality and low-quality products, respectively. Gang and Xiao-yi (2024) have examined the impact of suppliers' CSR disclosure on customer stability using a sample of listed companies' data from 2011–2019. The results show that disclosure quality is positively related to customer stability, more pronounced in voluntary disclosure and private firms, and that stability is enhanced by increasing information transparency and improving corporate governance.

In terms of misrepresentation of cost information, the cost information of supply chain node firms is private, and it is difficult to achieve complete sharing of cost information due to the drive of firms' self-interest and the independence of their decision-making. Minxing et al. (2024) have explored policy inefficiencies in emission reduction policies due to information asymmetry between governments and enterprises. Studies have shown that: when information is not updatable, hybrid policies are superior to quantity and price policies, with bilateral price-constrained hybrid policies being the best; and when information is updatable, the three are equivalent in terms of efficiency. Fang et al. (2019) investigated the impact of recycling operating cost information asymmetry on differential pricing in a closed-loop supply chain. The results of the study show that retailers report higher information on recycling operating costs to gain more profit. Qin and Shao (2019) and Fang et al. (2019) considered only unilateral cost information asymmetry. Xinhui et al. (2021) explored the impact of true sharing and false reporting of supply chain information on efficiency under bilateral information asymmetry and find that both supply and sales parties tend to exaggerate their private information.

For many manufacturers, continually improving the quality of their products is the key to competitiveness in the marketplace, and obtaining accurate information about market demand is critical in this process. In practice, retailers are closer to market demand than manufacturers and thus have access to private information about market demand, which can have a significant impact on both the pricing decisions of manufacturers and the inventory strategy decisions of retailers. Liang-liang and Pan (2022) used refined Bayesian theory and the Stackelberg game model to investigate the retailer's demand information sharing strategy and the manufacturer's optimal innovation model for process and product innovation in the supply chain when demand forecasting information is asymmetric. You-guo et al. (2022) investigated a two-stage dynamic game problem between a manufacturer and a retailer considering that market demand information is private to the retailer. By comparing and analyzing the game equilibrium decisions of different pricing contracts and the profits of supply chain parties under two scenarios of information disclosure and non-disclosure, it is found that the retailer discloses the demand information when the actual market size is smaller than its mean, whereas the retailer does not disclose the demand information when the actual market size is larger than its mean.

In closed-loop and reverse supply chains, information asymmetry between members is also common due to factors such as industry monopoly, trade barriers or conflicts of interest. For example, the information asymmetry problem of recycling costs is particularly prominent in Midea and Haier, which are engaged in recycling manufacturing business. Pan and Zhong-kai (2019) studied closed-loop supply chain decision making with asymmetric cost recovery information among manufacturers and showed that retailers can use two-part pricing contracts to enable manufacturers to share true cost information.

There are many studies on supply chain members' false reporting behaviours and supply chain coordination strategies under information asymmetry, but little literature has considered optimal decision making and channel selection in closed-loop supply chains under different channel power structures. Due to the complexity of closed-loop supply chains, manufacturers' CSR levels are often private information that is difficult for retailers to accurately observe (Zhibing, 2022). Based on this, this paper investigates the impact of channel information asymmetry on the performance of closed-loop supply chains under different power structures in the context of manufacturers' misrepresentation of the difficulty of recycling and the level of corporate social responsibility (CSR) to provide a theoretical basis for the decision-making of firms in closed-loop supply chains.

2.4 Research on channel power structures in supply chains

Research on channel power structure is crucial to this paper. Wenwei et al. (2024) have explored the effects of manufacturer overconfidence and power structure differences on supply chain decisions and profits. The study shows that the total supply chain profit is highest when both parties have equal power; the impact of manufacturer overconfidence on its own and supply chain profit is related to the power level. Feng et al. (2021) focused on the impact of expected regret (AR) on closed-loop supply chain decisions. They investigated how expected regret affects original equipment manufacturers' (OEMs') remanufacturing strategies and pricing decisions in OEMs' competition with third-party remanufacturers (TPRs) under different power structures. Fuan et al. (2024) have explored the impact of trading models and channel power structures on the pricing decisions of electronic closed-loop supply chains under carbon trading mechanisms. It is found that the optimal pricing and service decisions of electronic closed-loop supply chains vary according to the trading model and channel power structure; the choice of supply chain dominant player and trading model affects revenue and carbon emissions from both economic and environmental perspectives. Fengmin et al. (2022) investigated the impact of CSR behaviors of different member firms on pricing decisions of closed-loop supply chains under three different channel power structures. They found that when a channel leader exists in a closed-loop supply chain, channel followers' assumption of CSR is more favorable to the overall development of the closed-loop supply chain than that of the leader. Xing-hua et al. (2023) found that channel power structure not only affects the product durability and selling effort decisions of a durable goods supply chain, but also relates to the optimal profits of member firms by constructing a decision-making model for a durable goods supply chain under different channel power structures. It can be seen that there is a lot of research in the existing literature on supply chains under channel power structure, but the research on channel power structure and information asymmetry is not yet in-depth.

2.5 Research on marketing efforts in supply chains

With the development of economy and science and technology, the life cycle of products is gradually shortening and market competition is becoming increasingly fierce. In order to successfully sell their products, increase market demand and expand their market share, enterprises must achieve their goals through advertising, discount promotions, product exhibitions, training of sales staff and other sales tactics. Currently, a large number of scholars have conducted relevant research on marketing effort, mainly focusing on the supply chain coordination problem under marketing effort and the relationship between marketing effort and firm performance. Zhang et al. (2023) investigated selling effort in a low-carbon supply chain and found that selling effort improves the efficiency of the supply chain and that the level of selling effort is positively related to supply chain profit. Jie and Yu (2023) considered the sales effort behaviour of retailers and constructed a supply chain decision model based on the WCVaR method, discussing the optimal decision of retailers' order quantity and sales effort level. It was found that as the retailer's risk tolerance increases, its order quantity and profit increases. Tong et al. (2021a) considered the assumption of CSR by different members and analyzed the impact of retailers' selling effort behaviour and social responsibility awareness on the decision-making and profitability of member firms of a closed-loop supply chain. They found that retailers' selling effort not only reduces the wholesale price of products, but also increases product demand. Ren and Luo (2024) studied the decision-making and coordination of product quality and marketing efforts in e-commerce supply chains under different power structures. Comparing the profit relationships of different decision-making models, the sensitivity coefficients of profit and product quality and marketing effort are positively correlated. Fu-hai et al. (2024) explored the effects of the shop-in-shop model on the optimal production decisions, sales effort levels and expected profits of supply chain member firms. They found that the shop-in-shop model can effectively incentivise producers to increase production and sales effort when the sales revenue commission ratio and bank loan interest rate satisfy certain conditions, thus increasing the expected profits of producers and the supply chain system. In short, retailers' marketing behavior and sales efforts are key to gaining market share. In fact, advertising and marketing can help supply chain members streamline the sales process and capture the consumer market. Pongen et al. (2024) mentioned the role of the level of marketing effort on product collection and recycling rates, arguing that the collection and marketing efforts of different channel members affect the collection and recycling rates of discarded products, and that firms can increase consumer awareness of recycling participation through incentive programs. In addition, through proper advertising in the recycling and remanufacturing market, consumers will become more aware of the benefits of recycling and remanufacturing. Currently, there is limited literature considering retailer marketing efforts in closed-loop supply chains, which warrants research.

To summarize, previous studies on closed-loop supply chains have mainly focused on the selection of recycling channels and the influence of the power structure of supply chain channels. By summarizing previous studies, we find that few scholars have considered the problem of closed-loop supply chain information decision-making based on CSR. Therefore, based on summarizing previous studies, this paper explores the impact of information symmetry and channel power structure on closed-loop supply chains. By studying the impacts of channel power structure and manufacturers' misrepresentation behavior on closed-loop supply chains and proposing corresponding coordination strategies, this paper provides corresponding theoretical support for communication and cooperation among enterprises in closed-loop supply chains, eliminating the information gap, and enhancing information disclosure.

3 Problem description and assumptions

This paper takes a closed-loop supply chain consisting of a single manufacturer and a single retailer as the object of study. In the forward supply chain, the manufacturer is responsible for producing new products and wholesaling them to the downstream retailer, who sells the products to the end of the market; in the reverse supply chain, it is assumed that the manufacturer is responsible for the recycling and remanufacturing of used products, and that the remanufactured products are identical to the new products in terms of function and quality, and that the two products enter the consumer market in the same way, with the same market acceptance and sales price (Savaskan et al., 2004b).

TABLE 1 Variables and descriptions.

Variables	Descriptions	Variables	Descriptions
D	Total market demand	w	Wholesale price
a	Potential market size	c_1	Production cost of new products
p	Retail price	Δ	Cost savings from remanufacturing
λ	Marketing effort elasticity coefficient	k	Scale of recycling of used products
g	Level of marketing effort	ϕ	Level of CSR
CS	Consumer surplus	b	Transfer price of waste products
τ	Recycling rate of used products	π_m	Manufacturer's real profit function
π_r	Retailer's profit function	Φ_m	Manufacturer's public profit function

TABLE 2 Optimal solution and profitability of the supply chain before and after co-ordination.

Situations		p	τ	Π	Π_m	$\Delta\Pi_m$	Π_r	$\Delta\Pi_r$
Manufacturer-led	pre-coordination	106.7	22.1%	1,055	663.7	—	391.6	—
	revenue sharing $\varphi = 0.71$	65.8	61.4%	1843.4	789.2	125.5	1,045.1	653.5
	two-part pricing $F = 4701$	65.8	61.4%	1843.4	1,057.4	393.7	786.0	394.4
Power equalization	pre-coordination	101.3	31.3%	1,332.0	550.8	—	781.3	—
	revenue sharing $\varphi = 0.71$	65.8	61.4%	1843.4	789.2	238.4	1,045.1	263.8
	Two-part pricing $F = 4450$	65.8	61.4%	1843.4	806.4	255.6	1,037.0	255.7
Retailer-led	pre-coordination	92.2	30.2%	1,366.9	459.6	—	907.3	—
	revenue sharing $\varphi = 0.71$	65.8	61.4%	1843.4	789.2	329.6	1,045.1	137.8
	Two-part pricing $F = 4341$	65.8	61.4%	1843.4	697.4	237.8	1,146.0	238.7

Without loss of generality, the unit production cost of a remanufactured product is lower than the production cost of a new product. Let the unit cost of the new product be c_1 the unit cost of the remanufactured product be c_2, then $\Delta = c_1 - c_2$ represents the unit cost savings of the remanufactured product. The parameter $\tau\,(0 \le \tau \le 1)$ denotes the recycling rate of used products, without considering the variable cost of recycling used products, assuming that the recycling cost is a quadratic function about τ, $C(\tau) = k\tau^2$, where k denotes the difficulty of recycling efforts for used products.

Analysed from a macro perspective, the recycling and remanufacturing of products in closed-loop supply chains can be viewed as an act of socially responsible corporate investment. However, when analysed from the point of view of business operation strategy, the decision to recycle waste products and the decision to invest in corporate social responsibility are independent of each other. Apple has implemented the "trade-in" strategy to recycle products, save costs and improve the efficiency of resource utilisation, while at the same time implementing a number of large-scale social welfare activities and actively donating to the community in order to fulfil its corporate social responsibility. In terms of the nature of the two, the implementation of remanufacturing of used products by enterprises is aimed at saving production costs, with the goal of improving economic efficiency; whereas the CSR input of enterprises is aimed at fulfilling their corporate social responsibility, and ultimately realising the improvement of social efficiency. In order to portray the CSR input behaviour of the manufacturer, the CSR behaviour was expressed in the form of consumer surplus with reference to Panda's study (Panda et al., 2017): $= \int_{p_{min}}^{p_{max}} D dp$, When the degree of corporate social responsibility of the decision-making subject is ϕ $(0 \le \phi \le 1)$, the additional utility brought by corporate social responsibility behavior is $\frac{\phi D^2}{2}$.

Under information asymmetry, the difficulty of recycling efforts and the level of corporate social responsibility are private information of the manufacturer, driven by corporate self-interest, the manufacturer may benefit from its own information advantage and misrepresent its private information to the retailer, which makes the retailer deviate from the optimal decision-making in the process of the game, so as to make more profits for itself. The decision variables for manufacturers are the recovery effort difficulty misrepresentation coefficient η, the CSR level misrepresentation coefficient μ, the wholesale price w, and the product recovery rate τ. The decision variables for retailer decisions are the retail price p, and the marketing effort level g. The relevant parameters and meanings of the model are shown in Table 1 below:

Assumption 1. All information in the supply chain is symmetric except for information on the difficulty of the manufacturer's recycling effort and the level of CSR.

Assumption 2. The total amount of new and remanufactured goods produced by manufacturers is equal to the market demand, i.e., the market can be cleared completely.

Assumption 3. The fact that the coefficient of difficulty of the recovery effort, k, is sufficiently large, together with the fact that the cost is a quadratically convex function of the recovery rate, suggests that it is uneconomical behaviour to over-ambition for a high recovery rate (Savaskan et al., 2004a).

Assumption 4. The difficulty of a manufacturer's recycling effort to a retailer's announcement is ηk and the level of CSR is $\mu\phi$. when $\eta, \mu < 1$ indicates that the manufacturer underreported its private information; $\eta, \mu > 1$ indicates that the manufacturer overreported its private information; and $\eta, \mu = 1$ indicates that the manufacturer does not misrepresent its private information (Lingrong et al., 2023).

Assumption 5. Market demand is linearly related to the retail price of the product by setting $q = a - p + \lambda g$.

4 Modelling and solving models

In order to explore manufacturers' misreporting behaviour under different rights structures, three scenarios will be modelled and analysed separately. Equation 1 represents the market demand for the product:

$$q = a - p + \lambda g \tag{1}$$

Equations 2–4 represents the manufacturer's actual profit, manufacturer's disclosed profit and retailer's profit function:

$$\Pi_m = (w - c_1)q + (\Delta - \mathrm{b})\tau q + \frac{\phi q^2}{2} - k\tau^2 \tag{2}$$

$$\Phi_m = (w - c_1)q + (\Delta - \mathrm{b})\tau q + \frac{\mu\phi q^2}{2} - \eta k\tau^2 \tag{3}$$

$$\Pi_r = (p - w)q - \frac{\beta g^2}{2} \tag{4}$$

4.1 Manufacturer-led supply chain

The manufacturer-led Stackelberg game supply chain structure represents a supply chain consisting of a few large manufacturers and many relatively small retailers, e.g., firms such as Huawei and Apple with their core retailers. In this case, the manufacturer first determines the misrepresentation coefficients μ and η, discloses the difficulty of recycling effort and the level of CSR. The manufacturer, as the leader of the supply chain, first determines the wholesale price w and the recycling rate τ of used products based on the known information. The retailer, as the follower, then determines the retail price p of the product and the level of marketing effort g.

The game sequence of a manufacturer-dominated two-stage closed-loop supply chain is solved using a backward recursive approach. It is easy to see that the retailer's profit function is strictly concave with respect to p and g, according to the first-order condition $\frac{\partial \Pi_r}{\partial p} = 0, \frac{\partial \Pi_r}{\partial g} = 0$. The optimal feedback function for the retailer is: $p = w + \frac{(w-a)\beta}{\lambda^2 - 2\beta}, g = \frac{(w-a)\lambda}{\lambda^2-2\beta}$, bringing in Φ_m to find the optimal wholesale price w and the recycling rate of used products τ.

$$w_1 = \frac{\beta\left(a\beta(b-\Delta)^2 - 4(a+c_1)k\beta\eta + 2(a+c_1)k\eta\lambda^2\right) + 2ak\eta\left(\beta-\lambda^2\right)^2\mu\phi}{\beta\left(\beta\left((b-\Delta)^2 - 8k\eta\right) + 4k\eta\lambda^2\right) + 2k\eta\left(\beta-\lambda^2\right)^2\mu\phi} \tag{5}$$

$$\tau_1 = \frac{(a-c_1)\beta^2(b-\Delta)}{\beta\left(\beta\left((b-\Delta)^2 - 8k\eta\right) + 4k\eta\lambda^2\right) + 2k\eta\left(\beta-\lambda^2\right)^2\mu\phi} \tag{6}$$

According to Equations 5, 6:

$$p_1 = \frac{\beta\left(a\beta(b-\Delta)^2 - 2(3a+c_1)k\beta\eta + 2(a+c_1)k\eta\lambda^2\right) + 2ak\eta\left(\beta-\lambda^2\right)^2\mu\phi}{\beta\left(\beta\left((b-\Delta)^2 - 8k\eta\right) + 4k\eta\lambda^2\right) + 2k\eta\left(\beta-\lambda^2\right)^2\mu\phi} \tag{7}$$

$$g_1 = \frac{2(-a+c_1)k\beta\eta\lambda}{\beta\left(\beta\left((b-\Delta)^2 - 8k\eta\right) + 4k\eta\lambda^2\right) + 2k\eta\left(\beta-\lambda^2\right)^2\mu\phi} \tag{8}$$

$$\Pi_{m1} = \frac{(a-c_1)^2k\beta^2\left(\beta\left(-\beta(b-\Delta)^2 + 8k\beta\eta^2 - 4k\eta^2\lambda^2\right) - 2k\eta^2\left(\beta-\lambda^2\right)^2(-1+2\mu)\phi\right)}{\left(\beta\left(\beta\left((b-\Delta)^2 - 8k\eta\right) + 4k\eta\lambda^2\right) + 2k\eta\left(\beta-\lambda^2\right)^2\mu\phi\right)^2} \tag{9}$$

$$\Pi_{r1} = \frac{2\beta^3\left(ak\eta - c_1k\eta\right)^2\left(2\beta-\lambda^2\right)}{\left(\beta\left(\beta\left((b-\Delta)^2 - 8k\eta\right) + 4k\eta\lambda^2\right) + 2k\eta\left(\beta-\lambda^2\right)^2\mu\phi\right)^2} \tag{10}$$

$$\Pi_1 = \frac{(a-c_1)^2k\beta^2\left(\beta\left(-\beta(b-\Delta)^2 + 12k\beta\eta^2 - 6k\eta^2\lambda^2\right) - 2k\eta^2\left(\beta-\lambda^2\right)^2(-1+2\mu)\phi\right)}{\left(\beta\left(\beta\left((b-\Delta)^2 - 8k\eta\right) + 4k\eta\lambda^2\right) + 2k\eta\left(\beta-\lambda^2\right)^2\mu\phi\right)^2} \tag{11}$$

Since the recycling rate of used products satisfies $0 \le \tau_1 \le 1$, then the manufacturer's misrepresentation factor needs to satisfy $\mu \ge \frac{\beta(\beta(b-\Delta)(a-b-c1+\Delta)+8k\beta\eta-4k\eta\lambda^2)}{2k\eta(\beta-\lambda^2)^2\phi}$, $0 < \eta \le \frac{\beta(b-\Delta)(-a+b+c1-\Delta)}{8k\beta-4k\lambda^2}$.

Theorem 1. When the manufacturer does not misrepresent private information, the optimal decisions of the manufacturer and the retailer are $w_1^*, g_1^*, p_1^*, \tau_1^*$. The profits of the manufacturer, the retailer, and the supply chain as a whole are $\Pi_{m1}^*, \Pi_{r1}^*, \Pi_1^*$.

Proof: Bringing $\mu = \eta = 1$ into Equations 5–11, we can find $w_1^*, g_1^*, p_1^*, \tau_1^*, \Pi_{m1}^*, \Pi_{r1}^*, \Pi_1^*$.

Theorem 2. When a manufacturer dominates the supply chain, the manufacturer does not misrepresent its private information.

Proof: Let $\frac{\partial \Pi_{m1}}{\partial \mu} = 0, \frac{\partial \Pi_{m1}}{\partial \eta} = 0$ the joint equation is: $\mu_1^* = 1, \eta_1^* = 1$. From Theorem 2, in a manufacturer-dominated supply chain, the manufacturer already has a large enough right to ensure that its own interests are maximised, and therefore does not need to adopt additional misrepresentation strategies.

4.2 Retailers -led supply chain

The retailer-dominated Stackelberg gaming supply chain structure represents a supply chain consisting of a number of large retailers (e.g., mega-retail giants such as Metro, Walmart, Carrefour, etc.) and manufacturers that have greater market influence compared to manufacturers. In this case, the manufacturer first determines the misrepresentation coefficients μ and η, discloses the difficulty of recycling effort and the level of CSR. The retailer, based on the known information, first determines the wholesale price of the product p and the level of marketing effort g. The manufacturer, as a follower, subsequently determines the wholesale price of the product w and the recycling rate of the used product τ.

Similarly, in order to make the decision information consistent with the misreported information, the manufacturer should set the optimal wholesale price w and the recycling rate of used products τ to maximise its open profit. According to the inverse solution method, let $\frac{\partial \Phi_m}{\partial w} = 0, \frac{\partial \Phi_m}{\partial \tau} = 0$, the joint equation to find w_2 and τ_2, and then bring it into Π_r, let $\frac{\partial \Pi_r}{\partial p} = 0, \frac{\partial \Pi_r}{\partial g} = 0$ to find the optimal retail price and the level of marketing effort of the retailer. Combining the above equations yields: $\chi = b^2\beta - 2b\beta\Delta, A = (\Delta^2(1+2\eta) - 2k\eta^2(6+\phi+4\mu\phi))$

Equations 12–15 represent the wholesale price, the recycling rate of used products, the level of marketing effort and the retail price of the product:

$$w_2 = \frac{\begin{array}{c} c_1(\chi + 2k\eta\lambda^2(1-\mu\phi) + \beta(\Delta^2 - 2k\eta(3-\mu\phi))) \\ +a(\chi - 2k\eta\lambda^2\mu\phi(1-\mu\phi) + \beta(\Delta^2 - 2k\eta(1-\mu\phi))) \end{array}}{2\left(\chi + k\eta\lambda^2(1-\mu\phi)^2 + \beta(\Delta^2 - 2k\eta(2-\mu\phi))\right)} \quad (12)$$

$$\tau_2 = \frac{(a-c_1)\beta(b-\Delta)}{2\left(\chi + k\eta\lambda^2(1-\mu\phi)^2 + \beta(\Delta^2 - 2k\eta(2-\mu\phi))\right)} \quad (13)$$

$$g_2 = \frac{(a-c_1)k\eta\lambda(\mu\phi - 1)}{\left(\chi + k\eta\lambda^2(1-\mu\phi)^2 + \beta(\Delta^2 - 2k\eta(2-\mu\phi))\right)} \quad (14)$$

$$p_2 = \frac{\begin{array}{c} -c1k\eta(\beta + \lambda^2(-1+\mu\phi)) \\ +a(\chi - k\eta\lambda^2\mu\phi(1-\mu\phi) + \beta(\Delta^2 - k\eta(3-2\mu\phi))) \end{array}}{2\left(\chi + k\eta\lambda^2(1-\mu\phi)^2 + \beta(\Delta^2 - 2k\eta(2-\mu\phi))\right)} \quad (15)$$

Equations 16–18 can be derived from Equations 12–15

$$\Pi_{m2} = \frac{-(a-c_1)^2 k\left(\begin{array}{c} \chi + 4k\beta\eta^2\lambda^2(1-\mu)\phi(1-\mu\phi) \\ -2k\eta^2\lambda^4\phi(1-\mu\phi)^2 + \beta^2(\Delta^2 - 2k\eta^2(2+\phi-2\mu\phi)) \end{array}\right)}{4\left(\chi + k\eta\lambda^2(1-\mu\phi)^2 + \beta(\Delta^2 - 2k\eta(2-\mu\phi))\right)} \quad (16)$$

$$\Pi_{r2} = \frac{-(a-c_1)^2 k\beta\eta}{2\left(\chi + k\eta\lambda^2(1-\mu\phi)^2 + \beta(\Delta^2 - 2k\eta(2-\mu\phi))\right)} \quad (17)$$

$$\Pi_2 = \frac{(a-c_1)^2 k\left(\left(\begin{array}{c} 2k\eta^2\lambda^4\phi(1-\mu\phi)^2 \\ -2k\beta\eta^2\lambda^2(1-\mu\phi)(1-(2-3\mu)\phi - \chi(1+2\eta) \end{array}\right) - \beta^2 A\right)}{4\left(\chi + k\eta\lambda^2(1-\mu\phi)^2 + \beta(\Delta^2 - 2k\eta(2-\mu\phi))\right)} \quad (18)$$

Since the recycling rate of used products satisfies $0 \le \tau_2 \le 1$, then the manufacturer's misrepresentation factor needs to satisfy $\mu \ge 2k\eta(-\beta + \lambda^2)\phi + \sqrt{2}\sqrt{k\beta\eta((b-\Delta)}$ $\frac{(a-2b-c1+2\Delta)\lambda^2 + 2k\eta(\beta+2\lambda^2))\phi^2}{2k\eta\lambda^2\phi^2},$ $0 \le \eta \le \frac{\beta(a-2b-c1+2\Delta)(\Delta-b)}{8k\beta - 2k\lambda^2}$.

Theorem 3. When the manufacturer does not misrepresent private information, the optimal decisions of the manufacturer and the retailer are $w_2^*, g_2^*, p_2^*, \tau_2^*$. The profits of the manufacturer, the retailer, and the supply chain as a whole are $\Pi_{m2}^*, \Pi_{r2}^*, \Pi_2^*$.

Proof: by bringing $\mu = \eta = 1$ into the expression of optimal decision we can find $w_2^*, g_2^*, p_2^*, \tau_2^*, \Pi_{m2}^*, \Pi_{r2}^*, \Pi_2^*$.

Theorem 4. When retailers dominate the supply chain, manufacturers understate the level of CSR and the difficulty of recycling efforts.

Proof: Let $\frac{\partial \Pi_{m2}}{\partial \mu} = 0, \frac{\partial \Pi_{m2}}{\partial \eta} = 0$ The joint equation obtains μ_2^*, η_2^*. From Theorem 3, in the retailer-dominated supply chain, the manufacturer is in a disadvantageous position, driven by its own interests, manufacturers will adopt a two-factor misrepresentation strategy to enhance their interests.

Corollary 1 When retailers dominate the supply chain, manufacturers' misreporting behaviour increases wholesale prices, retail prices, marketing effort levels and their own profits, while at the same time decreasing the recycling rate of used products, retailers' profits and the total profits of the supply chain.

From Corollary 1, it can be seen that when manufacturers report a low level of recycling of used products, this will lead to lower demand in the secondary market, which will lead to a lower rate of recycling of used products; at the same time, meanwhile manufacturers underreport levels of corporate social responsibility, it is actually a case of the manufacturer shifting the focus of its production to the market for new products, which will increase the demand for the market for the new products out of thin air, thus intentionally increasing the wholesale price of the product, and the retailer will then increase the retail price of the product and the level of marketing effort to sell it to the consumer. The retailer then increases the retail price and marketing effort of the product and sells it to the consumer. Ultimately, the manufacturer's profits increase, the retailer and the supply chain as a whole suffer, and the consumer is required to pay a higher price for the new product, which is also detrimental to the consumer's interests and not conducive to building the product's brand image in the long term.

4.3 Power equalization supply chain

Manufacturers and retailers Nash equilibrium game supply chain structure represents a class of manufacturers and retailers of comparable strength to form the supply chain structure, for example, Haier, Lenovo, Huawei and other manufacturers of electrical appliances and retailers such as Suning, Gome, etc. In the market mutual checks and balances evenly matched, which are not able to become a leader in the supply chain. In this case, the manufacturer first determines the manufacturer first determines the misrepresentation coefficients μ and η, discloses the difficulty of recycling effort and the level of CSR. Since there is no dominant player in the supply chain, it is up to the manufacturer and the retailer to simultaneously determine the wholesale price of the product w the retail price of the recycling rate of the used product p and the level of selling effort g.

Let $\frac{\partial \Phi_m}{\partial w} = 0, \frac{\partial \Phi_m}{\partial \tau} = 0, \frac{\partial \Pi_r}{\partial p} = 0, \frac{\partial \Pi_r}{\partial g} = 0$, connecting the above system of equations, you can find the expression of the optimal decision (Equations 19–22):

$$w_3 = a + \frac{2(a - c_1)k\eta(2\beta - \lambda^2)}{b^2\beta - 2b\beta\Delta - 2k\eta\lambda^2(-1 + \mu\phi) + \beta(\Delta^2 + 2k\eta(-3 + \mu\phi))} \tag{19}$$

$$\tau_3 = \frac{(a - c_1)\beta(b - \Delta)}{b^2\beta - 2b\beta\Delta - 2k\eta\lambda^2(-1 + \mu\phi) + \beta(\Delta^2 + 2k\eta(-3 + \mu\phi))} \tag{20}$$

$$g_3 = \frac{2(a - c_1)k\eta\lambda}{b^2\beta - 2b\beta\Delta - 2k\eta\lambda^2(-1 + \mu\phi) + \beta(\Delta^2 + 2k\eta(-3 + \mu\phi))} \tag{21}$$

$$p_3 = a + \frac{2(a - c_1)k\eta(\beta - \lambda^2)}{b^2\beta - 2b\beta\Delta - 2k\eta\lambda^2(-1 + \mu\phi) + \beta(\Delta^2 + 2k\eta(-3 + \mu\phi))} \tag{22}$$

Expressions (Equations 23–25) can be found by bringing Equations 19–22 into Equations 2–4.

$$\Pi_{m3} = \frac{(a - c_1)^2k(\beta^2(-(b - \Delta)^2 + 4k\eta^2) - 2k\eta^2(\beta - \lambda^2)(\lambda^2 + \beta(-1 + 2\mu))\phi)}{(b^2\beta - 2b\beta\Delta - 2k\eta\lambda^2(-1 + \mu\phi) + \beta(\Delta^2 + 2k\eta(-3 + \mu\phi)))^2} \tag{23}$$

$$\Pi_{r3} = \frac{2(a - c_1)^2k^2\beta\eta^2(2\beta - \lambda^2)}{(b^2\beta - 2b\beta\Delta - 2k\eta\lambda^2(-1 + \mu\phi) + \beta(\Delta^2 + 2k\eta(-3 + \mu\phi)))^2} \tag{24}$$

$$\Pi_3 = \frac{(a - c_1)^2k\begin{pmatrix}\beta(-\beta(b - \Delta)^2 + 8k\beta\eta^2 - 2k\eta^2\lambda^2) \\ -2k\eta^2(\beta - \lambda^2)(\lambda^2 + \beta(-1 + 2\mu))\phi\end{pmatrix}}{(b^2\beta - 2b\beta\Delta - 2k\eta\lambda^2(-1 + \mu\phi) + \beta(\Delta^2 + 2k\eta(-3 + \mu\phi)))^2} \tag{25}$$

Since the recycling rate of used products satisfies $0 \le \tau_3 \le 1$, then the manufacturer's misrepresentation factor needs to satisfy $\mu \ge \frac{\beta(b-\Delta)(a-b-c1+\Delta)+6k\beta\eta-2k\eta\lambda^2}{2k\eta(\beta-\lambda^2)\phi}, 0 < \eta \le \frac{\beta(b-\Delta)(-a+b+c1-\Delta)}{6k\beta-2k\lambda^2}$.

Theorem 5. When the manufacturer does not misrepresent private information, the optimal decision of the manufacturer and the retailer is $w_3^*, g_3^*, p_3^*, \tau_3^*$, The profits of the manufacturer, the retailer, and the supply chain as a whole are $\Pi_{m3}^*, \Pi_{r3}^*, \Pi_3^*$.

Proof: Bringing $\mu = \eta = 1$ into the expression of optimal decision makes $w_3^*, g_3^*, p_3^*, \tau_3^*, \Pi_{m3}^*, \Pi_{r3}^*, \Pi_3^*$.

Theorem 6. When manufacturers and retailers have equal power, manufacturers do not misreport the difficulty of recycling efforts but underreport the level of CSR.

Proof: Let $\frac{\partial \Pi_{m3}}{\partial \mu} = 0, \frac{\partial \Pi_{m3}}{\partial \eta} = 0$ The joint equation obtains μ_3^*, η_3^*. The joint equation gives: $\mu_3^* = 1 - \frac{\lambda^2}{\beta} - \frac{1}{\phi}, \eta_3^* = 1$.

From Theorem 6, it can be seen that in the power-equal supply chain, the manufacturer does not obtain absolute leadership, and driven by its own interests, the manufacturer still adopts the strategy of misrepresentation in order to obtain profits.

Corollary 2 When manufacturers and retailers have equal power, manufacturers' misrepresentation leads to higher wholesale and retail prices of products, lower recycling rates and marketing levels of used products, as well as higher profits for manufacturers as a result of their own misrepresentation and lower profits for retailers and the supply chain in general.

Proof: Bringing μ_3^*, η_3^* into $w_3, p_3, \tau_3, g_3, \Pi_{m3}, \Pi_{r3}, \Pi_3$ yields the optimal decision of the supply chain members when the manufacturer has misrepresentation behaviour $w_3^{**}, g_3^{**}, p_3^{**}, \tau_3^{**}$ and profitability $\Pi_{m3}^{**}, \Pi_{r3}^{**}, \Pi_3^{**}$. Easy to prove: $w_3^{**} > w_3^*, p_3^{**} > p_3^*, g_3^{**} < g_3^*, \tau_3^{**} < \tau_3^*; \Pi_{m3}^{**} > \Pi_{m3}^*, \Pi_{r3}^{**} < \Pi_{r3}^*, \Pi_3^{**} < \Pi_3^*$.

From Corollary 2, a manufacturer's misrepresentation of CSR information affects consumer purchasing power, i.e., market demand, and lower market demand leads to higher wholesale and retail prices, lower consumer and recycling markets, and lower recycling and marketing of used and end-of-life products. Manufacturers' misrepresentation only benefits themselves and directly harms retailers, the supply chain and consumers as a whole.

Corollary 3 When the manufacturer and retailer have equal power, the manufacturer's misreporting behaviour makes the supply chain optimal decision the same as when the manufacturer dominates, and the manufacturer, the retailer and the supply chain as a whole are equally profitable.

Proof: It is easy to prove that $w_3^{**} = w_1^*$, $p_3^{**} = p_1^*, g_3^{**} = g_1^*, \tau_3^{**} = \tau_1^*; \Pi_{m3}^{**} = \Pi_{m1}^*, \Pi_{r3}^{**} = \Pi_{r1}^*, \Pi_3^{**} = \Pi_1^*$.

From Corollary 3, it can be seen that in a supply chain with equal power, the manufacturer can bring itself back to a dominant position by misrepresenting its behaviour, and in the context of information asymmetry, the power of each member of the supply chain is no longer equal.

5 Closed-loop supply chain coordination

5.1 Centralised decision-making

When information in the supply chain is perfectly symmetric, the overall profit function of the supply chain under centralised decision making is:

$$\Pi = (p - c_1)q + (\Delta - b)\tau q + \frac{\phi q^2}{2} - k\tau^2 - \frac{\beta g^2}{2} \tag{26}$$

Let $\frac{\partial \Pi}{\partial p} = 0, \frac{\partial \Pi}{\partial g} = 0, \frac{\partial \Pi}{\partial \tau} = 0$, the joint equation can be used to find the optimal decision:

$$\tau_4^* = \frac{(a - c_1)(b - \Delta)(\beta - \lambda^2\phi)}{b^2\beta - 4k\beta - 2b\beta\Delta + \beta\Delta^2 + 2k\lambda^2 + (2k\beta - (b - \Delta)^2\lambda^2)\phi} \tag{27}$$

$$p_4^* = a + \frac{2(a - c_1)k(\beta - \lambda^2)}{b^2\beta - 4k\beta - 2b\beta\Delta + \beta\Delta^2 + 2k\lambda^2 + (2k\beta - (b - \Delta)^2\lambda^2)\phi} \tag{28}$$

$$g_4^* = \frac{2(a - c_1)k\lambda(\phi - 1)}{b^2\beta - 4k\beta - 2b\beta\Delta + \beta\Delta^2 + 2k\lambda^2 + (2k\beta - (b - \Delta)^2\lambda^2)\phi} \tag{29}$$

Bringing Equations 27–29 into Equation 26

$$\Pi_4^* = \frac{(a - c_1)^2k(\lambda^2\phi - \beta)}{b^2\beta - 4k\beta - 2b\beta\Delta + \beta\Delta^2 + 2k\lambda^2 + (2k\beta - (b - \Delta)^2\lambda^2)\phi} \tag{30}$$

5.2 Revenue-sharing contract

If the upstream and downstream parties of the supply chain reach a co-operation, they follow the relevant agreement, i.e., at the beginning of the sales period, the manufacturer provides the retailer with a relatively low wholesale price w. At the end of the sales period, the upstream and downstream parties of the supply chain distribute the overall revenue of the supply chain in accordance with a certain proportion, the manufacturer receives the revenue proportion of φ, the retailer receives the revenue proportion of $1-\varphi$, and the revenues of the members of the channel are as follows:

Combining the above description and bringing it to Equations 2–4 leads to Equations 31–33:

$$\Pi_m^R = (\varphi p + w - c_1)q + (\Delta - b)\tau q + \frac{\phi q^2}{2} - k\tau^2 \tag{31}$$

$$\Phi_m^R = (w - c_1)q + (\Delta - b)\tau q + \frac{\mu\phi q^2}{2} - \eta k\tau^2 \tag{32}$$

$$\Pi_r^R = ((1-\varphi)p - w)q - \frac{\beta g^2}{2} \tag{33}$$

Joint first-order condition $\frac{\partial \Pi_r^R}{\partial p} = 0, \frac{\partial \Pi_r^R}{\partial g} = 0$, Solving yields an expression for p, g with respect to w. Bringing in Φ_m^R and establishing the first-order condition $\frac{\partial \Phi_m^R}{\partial \tau} = 0$, solving yields an expression for τ with respect to w. The p, g, τ expressions are as follows in Equations 34–36:

$$p' = \frac{-w(\beta + \lambda^2(-1+\varphi)) + a\beta(-1+\varphi)}{(2\beta + \lambda^2(-1+\varphi))(-1+\varphi)} \tag{34}$$

$$g' = -\frac{\lambda(w + a(-1+\varphi))}{2\beta + \lambda^2(-1+\varphi)} \tag{35}$$

$$\tau' = -\frac{\beta(b-\Delta)(w + a(-1+\varphi))}{2k\eta(2\beta + \lambda^2(-1+\varphi))(-1+\varphi)} \tag{36}$$

In order for the supply chain under the coordination of the revenue sharing contract to achieve the same effect of centralised decision making, for this purpose it is necessary to satisfy $p' = p_4^*, g' = g_4^*, \tau' = \tau_4^*$, on the basis of which expressions (Equations 37–39) are obtained:

$$w = \frac{\beta(-1+\phi)\begin{pmatrix} 4c_1k\beta - a\beta(b-\Delta)^2 - 2ak\beta\phi \\ +a(2k + (b-\Delta)^2)\lambda^2\phi - 2c_1k\lambda^2(1+\phi) \end{pmatrix}}{(\beta - \lambda^2\phi)(b^2\beta - 4k\beta - 2b\beta\Delta + \beta\Delta^2 + 2k\lambda^2 + (2k\beta - (b-\Delta)^2\lambda^2)\phi)} \tag{37}$$

$$\eta = 1 \tag{38}$$

$$\varphi = \frac{(\beta - \lambda^2)\phi}{\beta - \lambda^2\phi} \tag{39}$$

Introducing Π_m^R, Π_r^R into the optimal decision under the revenue-sharing contract leads to Equations 40, 41:

$$\Pi_m^R = \frac{(a-c_1)^2k\left(-\beta^2(b-\Delta)^2 + 2\left(\beta(b-\Delta)^2\lambda^2 + k(\beta-\lambda^2)^2\right)\phi - (b-\Delta)^2\lambda^4\phi^2\right)}{(b^2\beta - 4k\beta - 2b\beta\Delta + \beta\Delta^2 + 2k\lambda^2 + (2k\beta - (b-\Delta)^2\lambda^2)\phi)^2} \tag{40}$$

$$\Pi_r^R = \frac{2(a-c_1)^2k^2\beta(-1+\phi)(-2\beta + \lambda^2(1+\phi))}{(b^2\beta - 4k\beta - 2b\beta\Delta + \beta\Delta^2 + 2k\lambda^2 + (2k\beta - (b-\Delta)^2\lambda^2)\phi)^2} \tag{41}$$

After coordination using the revenue sharing contract, manufacturers do not misrepresent the difficulty of recycling efforts, while both manufacturers' and retailers' profit expressions are independent of the CSR misrepresentation coefficients, i.e., manufacturers do not engage in misrepresentation behaviour after coordination using the revenue sharing contract. The validation leads to $\Pi_m^R + \Pi_r^R = \Pi_4^*$. That is, the supply chain system is better coordinated and the total profit of the supply chain reaches the level of centralised decision making; Further in order to ensure that both upstream and downstream parties in the supply chain can accept the revenue sharing contract, the constraints must also be satisfied $\Pi_m^R \geq \Pi_{m1}^*, \Pi_r^R \geq \Pi_{r1}^*$. As a result, the profits of both upstream and downstream members of the channel, coordinated by the revenue sharing contract, reach the effect of supply and achieve Pareto improvement.

5.3 Two-part pricing contract

From the analysis in Section 4, it can be seen that when there is information asymmetry in the supply chain, the manufacturer's misrepresentation can harm the overall profitability of the supply chain. Due to the existence of double marginal effects in the closed-loop supply chain under decentralised decision making, the decisions of the supply chain are not optimal. Therefore, this section adopts a two-part pricing contract to coordinate the closed-loop supply chain under information asymmetry.

Under a two-part pricing contract, the manufacturer sets a waste product recycling rate τ_4^* to recycle waste products and offers the retailer an appropriate wholesale price w. The retailer takes a price p_4^* and a level of marketing effort g_4^*, both of which work together to maximise supply chain profits. At the same time, the retailer compensates the manufacturer by paying a fixed transfer fee F which is set by negotiation between the two parties and is designed to ensure that both firms earn more than they would have done under decentralised decision making, achieving a Pareto improvement. The advantage of the two-part pricing contract is that it can maximise the total profit of the supply chain and at the same time redistribute the profit to achieve a win-win effect. The two-part pricing contract is widely used in actual business management, for example, when joining retail chains such as KFC and Haidilao, a certain amount of franchise fee will be collected in advance, and then the corresponding ingredients will be purchased at wholesale prices.

Therefore, the manufacturer's actual profit, open profit and retailer's profit functions when the supply chain uses a two-part pricing contract are:

$$\Pi_m^F = (w - c_1)q + (\Delta - b)\tau q + \frac{\phi q^2}{2} - k\tau^2 + F$$

$$\Phi_m^F = (w - c_1)q + (\Delta - b)\tau q + \frac{\mu\phi q^2}{2} - \eta k\tau^2 + F$$

$$\Pi_r^F = (p - w)q - \frac{\beta g^2}{2} - F$$

Theorem 7. When the parameters in the two-part pricing contract satisfy $w = a + \frac{2(a-c_1)k(2\beta-\lambda^2)}{b^2\beta - 4k\beta - 2b\beta\Delta + \beta\Delta^2 + 2k\lambda^2 + (2k\beta - (b-\Delta)^2\lambda^2)\phi}$, there always exists a $(\bar{F}, \underline{F})$ that is able to coordinate closed-loop supply chains under three different power structures.

Proof: Taking the supply chain when the manufacturer is dominant as an example, the expression for the retailer's optimal retail price and level of marketing effort with respect to the wholesale price w can be derived by using the backward induction method:

TABLE 3 Sensitivity analysis of two-factor misreporting when manufacturers dominate supply chain.

	$\mu = 0.5$		$\mu^* = 1$		$\mu = 1.5$	
$\eta = 0.5$	$\Pi_{m1} = 736.4$	$\Pi_{r1} = 491.0$	$\Pi_{m1} = 708.3$	$\Pi_{r1} = 689.3$	$\Pi_{m1} = 575.9$	$\Pi_{r1} = 1037.6$
	$\Pi_1 = 1227.4$	$\tau_1 = 49.5\%$ $g_1 = 16.5$	$\Pi_1 = 1397.6$	$\tau_1 = 58.7\%$ $g_1 = 19.6$	$\Pi_1 = 1613.5$	$\tau_1 = 72.0\%$ $g_1 = 24.0$
$\eta^* = 1$	$\Pi_{m1} = 785.5$	$\Pi_{r1} = 418.9$	$\Pi_{m1} = 802.1$	$\Pi_{r1} = 571.9$	$\Pi_{m1} = 769.2$	$\Pi_{r1} = 827.1$
	$\Pi_1 = 1204.4$	$\tau_1 = 22.9\%$ $g_1 = 15.3$	$\Pi_1 = 1374.0$	$\tau_1 = 26.7\%$ $g_1 = 17.8$	$\Pi_1 = 1596.3$	$\tau_1 = 32.1\%$ $g_1 = 21.4$
$\eta = 1.5$	$\Pi_{m1} = 774.7$	$\Pi_{r1} = 398.4$	$\Pi_{m1} = 794.0$	$\Pi_{r1} = 539.4$	$\Pi_{m1} = 770.6$	$\Pi_{r1} = 771.0$
	$\Pi_1 = 1173.1$	$\tau_1 = 14.9\%$ $g_1 = 14.9$	$\Pi_1 = 1333.4$	$\tau_1 = 17.3\%$ $g_1 = 17.3$	$\Pi_1 = 1541.6$	$\tau_1 = 20.7\%$ $g_1 = 20.7$

TABLE 4 Sensitivity analysis of two-factor misreporting in power equalization supply chain.

	$\mu = 0.05$		$\mu^* = 0.12$		$\mu = 1$	
$\eta = 0.5$	$\Pi_{m2} = 721.3$	$\Pi_{r2} = 630.6$	$\Pi_{m2} = 709.1$	$\Pi_{r2} = 686.1$	—	—
	$\Pi_2 = 1351.9$	$\tau_2 = 56.1\%$ $g_2 = 18.7$	$\Pi_2 = 1395.2$	$\tau_2 = 58.6\%$ $g_2 = 19.5$	—	—
$\eta^* = 1$	$\Pi_{m2} = 800.8$	$\Pi_{r2} = 527.3$	$\Pi_{m2} = 802.1$	$\Pi_{r2} = 569.5$	$\Pi_{m2} = 49.9$	$\Pi_{r2} = 2216.1$
	$\Pi_2 = 1328.2$	$\tau_2 = 25.7\%$ $g_2 = 17.1$	$\Pi_2 = 1371.6$	$\tau_2 = 26.7\%$ $g_2 = 17.8$	$\Pi_2 = 2256.9$	$\tau_2 = 52.6\%$ $g_2 = 35.1$
$\eta = 1.5$	$\Pi_{m2} = 791.7$	$\Pi_{r2} = 498.5$	$\Pi_{m2} = 793.9$	$\Pi_{r2} = 537.2$	$\Pi_{m2} = 181.9$	$\Pi_{r2} = 1977.9$
	$\Pi_2 = 1290.2$	$\tau_2 = 16.6\%$ $g_2 = 16.6$	$\Pi_2 = 1331.1$	$\tau_2 = 17.3\%$ $g_2 = 17.3$	$\Pi_2 = 2159.8$	$\tau_2 = 33.1\%$ $g_2 = 33.1$

$p'' = w + \frac{(-a+w)\beta}{-2\beta+\lambda^2}, g'' = -\frac{(-a+w)\lambda}{2\beta-\lambda^2}$ taken into the equation Φ_m^F, the manufacturer's optimal recovery rate $\tau'' = -\frac{(b-\Delta)(a-p+g\lambda)}{2k\eta}$ can be obtained. Since the coordinated retail price and the recycling rate of used products will be at the level under centralised decision-making, $p'' = p_4^*, \tau'' = \tau_4^*$, this can be obtained:

$$w + \frac{(-a+w)\beta}{-2\beta+\lambda^2} = a + \frac{2(a-c_1)k(\beta-\lambda^2)}{b^2\beta - 4k\beta - 2b\beta\Delta + \beta\Delta^2 + 2k\lambda^2 + (2k\beta - (b-\Delta)^2\lambda^2)\phi}$$

$$-\frac{(b-\Delta)(a-p+g\lambda)}{2k\eta} = \frac{(a-c_1)(b-\Delta)(\beta-\lambda^2\phi)}{b^2\beta - 4k\beta - 2b\beta\Delta + \beta\Delta^2 + 2k\lambda^2 + (2k\beta - (b-\Delta)^2\lambda^2)\phi}$$

The above equation can be obtained by conjunction: $w' = a + \frac{2(a-c_1)k(2\beta-\lambda^2)}{b^2\beta-4k\beta-2b\beta\Delta+\beta\Delta^2+2k\lambda^2+(2k\beta-(b-\Delta)^2\lambda^2)\phi}, \eta = 1$. That is, the manufacturer will not misrepresent the difficulty of recovery effort after coordination using the two-part pricing contract. From the above equation, we can obtain the manufacturer's true profit function, the retailer's profit function and the overall profit function of the supply chain after coordination, and find that the manufacturer's true profit function is independent of μ, i.e., the manufacturer will not misrepresent the level of CSR. In order to realise the free distribution of supply chain profits between manufacturers and retailers, $\Pi_m^F \geq \Pi_{m1}^*, \Pi_r^F \geq \Pi_{r1}^*$, from which it can be obtained that there exists a closed-loop supply chain $(\bar{F}, \underline{F})$ capable of co-ordinating the manufacturer-led supply chain (Due to the complexity of the analytical formula for the fixed cost F, it is not shown here, but is specified in the next section through the analysis of examples.)

From Theorem 7, the retail price of the product, the recycling rate of the used product, and the level of marketing effort under the two-part pricing contract are the same as the optimal decision under centralised decision making, while the manufacturer and the retailer agree on the wholesale price of the product so that the parameters of the open decision making of both the manufacturer and the retailer are determined. Even if the manufacturer has information about the person, it cannot change its decision through misrepresentation, so a two-part pricing contract can achieve profit coordination among closed-loop supply chain members under information asymmetry while avoiding misrepresentation by the manufacturer. In a two-part pricing contract, retailers can obtain a higher profit share by increasing their negotiation skills or by obtaining patents and exclusivity to obtain lower transfer fees.

6 Numerical analysis

In order to verify the reasonableness of the conclusions and dig deeper into the management insights behind the model, numerical simulation experiments are conducted in this section. At the heart of this paper is the study of the impact that manufacturer misrepresentation brings to the closed-loop supply chain, considering three different decision models with different channel power structures. The arithmetic analysis consists of two parts: on the one hand, it is to analyse the coordination performance of the supply chain and verify the coordination effect of the revenue sharing contract and the two-part pricing contract on the closed-loop supply chain; on the other hand, it is to analyse the impact of the sensitivity of the manufacturer's misrepresentation strategy on the equilibrium of the supply chain and the optimal profit under different channel power structures. Considering the practical significance of the model and combining the relevant

TABLE 5 Sensitivity analysis of two-factor misreporting when retailers dominate the supply chain.

	$\mu = 0.6$		$\mu^* = 0.98$		$\mu = 1$	
$\eta = 0.6$	$\Pi_{m3} = 372.3$	$\Pi_{r3} = 734.8$	$\Pi_{m3} = 363.1$	$\Pi_{r3} = 861.5$	$\Pi_{m3} = 361.4$	$\Pi_{r3} = 869.8$
	$\Pi_3 = 1107.1$	$\tau_3 = 40.8\%$ $g_3 = 10.5$	$\Pi_3 = 1224.6$	$\tau_3 = 47.8\%$ $g_3 = 7.9$	$\Pi_3 = 1231.3$	$\tau_3 = 48.3\%$ $g_3 = 7.7$
$\eta^* = 0.96$	$\Pi_{m3} = 390.1$	$\Pi_{r3} = 666.8$	$\Pi_{m3} = 401.0$	$\Pi_{r3} = 769.4$	$\Pi_{m3} = 400.9$	$\Pi_{r3} = 776.1$
	$\Pi_3 = 1056.9$	$\tau_3 = 23.2\%$ $g_3 = 9.5$	$\Pi_2 = 1170.4$	$\tau_3 = 26.7\%$ $g_3 = 7.0$	$\Pi_3 = 1177.0$	$\tau_3 = 26.9\%$ $g_3 = 6.9$
$\eta = 1$	$\Pi_{m3} = 389.5$	$\Pi_{r3} = 662.7$	$\Pi_{m3} = 400.9$	$\Pi_{r3} = 764.0$	$\Pi_{m3} = 400.8$	$\Pi_{r3} = 700.5$
	$\Pi_3 = 1052.2$	$\tau_3 = 22.1\%$ $g_3 = 9.4$	$\Pi_3 = 1164.9$	$\tau_3 = 25.5\%$ $g_3 = 6.9$	$\Pi_3 = 1171.3$	$\tau_3 = 25.7\%$ $g_3 = 6.8$

literature (Tong et al., 2021b; Juan et al., 2023), the experimental data were standardized and selected as follows: $a = 120, c_1 = 60, \lambda = 0.6, \phi = 0.8, \beta = 0.9, k = 1000, \Delta = 30, b = 10$.

6.1 Analysis of contractual coordination mechanisms

In order to verify the effectiveness of the coordination mechanism, before and after the coordination of the closed-loop supply chain, the optimal decision-making and profit-related situation of each member are compared, as shown in Table 3. As shown in Table 2, no matter which channel power structure is adopted, the optimal retail price of products in the closed-loop supply chain after co-ordination is significantly reduced, and the recycling rate of used products as well as the profits of each member of the supply chain are significantly increased, realising the Pareto improvement of the supply chain, which indicates that the revenue sharing contract and the two-part pricing contract can achieve better supply chain co-ordination and make it reach the level of centralised decision-making, and this also further argues the conclusion of this paper.

6.2 Sensitivity analysis of two-factor misreporting coefficients

As can be seen from Tables 3–5, the manufacturer's profit shows a trend of increasing and then decreasing with the increasing misrepresentation factor η, indicating that with the continuous change of misrepresentation factor η the manufacturer can always find the optimal misrepresentation factor η^* to make its own profit maximisation. When the misrepresentation factor η is smaller than the optimal misrepresentation factor η^*, the manufacturer's profit decreases as the misrepresentation factor µ continues to increase; When the misrepresentation factor η is greater than the optimal misrepresentation factor η^*, as the misrepresentation factor μ increases the manufacturer's profit increases and then decreases, indicating that as the misrepresentation factor η and μ change, the manufacturer can always find the optimal misrepresentation factor η^* and μ^* to make its own profit maximisation. Retailer profits and used product recycling rates decrease with increasing η and decrease with decreasing μ, suggesting that manufacturers' overreporting of the difficulty of recycling efforts leads to decreasing retailer and total supply chain profits and decreases used product recycling rates, while manufacturers' underreporting of CSR levels leads to decreasing retailer profits and total supply chain profits and is detrimental to used product recycling. As the misrepresentation factor η keeps increasing, the total supply chain profit keeps decreasing; As the misrepresentation factor μ decreases, the total supply chain profit decreases. The manufacturer's two-factor misreporting strategy is only good for the manufacturer's own profit, but not for the retailer's profit, the total profit of the supply chain, or the recycling rate of used products. As can be seen from Table 4, the manufacturer's two-factor misrepresentation strategy converges the manufacturer's profit to the level when the manufacturer is dominant under an equal-power supply chain, i.e., the manufacturer's adoption of a two-factor misrepresentation strategy enables the manufacturer to regain its market position when the manufacturer and the retailer are equal in power.

As can be seen in Tables 3–5, retailers' marketing effort decreases as the misrepresentation coefficient of recall difficulty increases, while it increases as the CSR misrepresentation coefficient increases. It means that when the coefficient of misrepresentation of recycling difficulty increases, the recycling market is not prosperous, and retailers are not willing to invest more advertising and marketing in the promotion of used products; when the coefficient of misrepresentation of CSR increases, the remanufacturers show a higher level of social responsibility in the quality of products, environmental protection, brand image, etc., and therefore, retailers are willing to provide a higher level of advertising and marketing to promote the remanufactured products.

7 Conclusion and policy implications

7.1 Conclusion

This paper investigates the closed-loop supply chain coordination problem considering CSR and information asymmetry, and analyses manufacturers' misreporting strategies and their impacts on the supply chain in three scenarios: manufacturer-dominated supply chains, retailer-dominated supply chains, and power-parity supply chains under the asymmetry of information on the difficulty of manufacturers' recycling efforts and the level of CSR. The paper draws the following conclusions.

(1) Manufacturers do not misrepresent their private information when the manufacturer dominates the supply chain; When retailers dominate the supply chain, manufacturers underreport the level of CSR and the difficulty of recycling efforts; and when there is equal power between the manufacturer and the retailer, the manufacturer does not misrepresent the difficulty of the recycling effort, but understates the level of CSR.
(2) Manufacturers' misreporting behaviors only benefit themselves, always harming retailer and total supply chain profits, and also discouraging the recycling of used products. When the manufacturer adopts a two-factor misreporting strategy, it keeps retailer profits, total supply chain profits, and used product recycling lower than they would be without the manufacturer's misreporting strategy.
(3) The manufacturer's two-factor misrepresentation strategy converges the manufacturer's profit to the level when the manufacturer is dominant under an equal-power supply chain, i.e., the manufacturer's adoption of a two-factor misrepresentation strategy enables the manufacturer to regain its market position when the manufacturer and the retailer have equal power.
(4) Under all three supply chain models with different channel power structures, retailers' marketing effort decreases with the increase in the recall difficulty misrepresentation coefficient and increases with the increase in the CSR misrepresentation coefficient.

To address manufacturers' misreporting behavior under information asymmetry, this paper designs a revenue-sharing contract and a two-part pricing contract to coordinate a closed-loop supply chain under different power structures, and finds that both contracts can achieve Pareto improvement in the supply chain.

7.2 Policy implcations

The relevant management implications of this paper are as follows.

(1) The security and stability of the supply chain is the basis for building a Dual circulation. Large manufacturers should continue to improve their sustainable development management capabilities, meet the management needs of customers for sustainable development, build a sustainable development system of the supply chain, and organize material suppliers to exchange information to ensure the transparency of channel information in the supply chain.
(2) Enterprises in the supply chain should implement the concept of sustainable development management, effectively fulfill social responsibility in the supply chain management process, and transmit social responsibility information to upstream partners and core suppliers to ensure the effective implementation of social responsibility requirements in supply chain management, strengthen cooperation to alleviate supply chain risks, and promote sustainable development of the supply chain.
(3) When manufacturers have information advantages, retailers should actively communicate and cooperate with manufacturers to eliminate the information gap; When formulating coordination contracts, retailers can enhance their bargaining power by obtaining patents and exclusive rights, in order to obtain more share of profit distribution.
(4) The government should improve the information disclosure mechanism, strengthen information disclosure, create a fair, just, and open market environment, and ensure the healthy development of the market.

Overall, there are still some shortcomings in this article. This article only focuses on the social responsibility behavior of manufacturers. In fact, with the development and growth of the retail industry, the social responsibility behavior of retail enterprises should also be considered. The model in this article is based on the assumption of demand determination, and future research will be conducted under uncertain demand.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Towards the design of a smart warehouse management system for spare parts management in the oil and gas sector

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Introduction: The oil and gas production industry requires rapid changing. As oil and gas companies around the world are called upon to decarbonize, several sectors within the industry are attempting to find new ways of working to achieve decarbonization. One of those sectors is spare parts warehousing. During the past decades of oil and gas production, spare parts warehousing has not been prioritized in optimization measures. Warehouses have been filled with material, all activities have been performed manually, and financial expenditure has been high. Now, a large oil and gas production company in Norway is looking to optimize its spare parts warehousing to streamline its logistics activities and increase sustainability.

Method: This study addresses the optimization ambitions of the company and proposes key design elements of a smart warehouse management system using Industry 4.0 technology implementation. The study is conducted by performing a review of relevant literature and company ambitions, before embarking on a qualitative design measure to contribute to the company's innovative success.

Results: The study proposes optimization of the warehouse activities goods receipt, issuing of stocked goods, and inventory count. Additionally, the digital supply chain of tomorrow and the technical architecture of a track and trace system in the warehouse is suggested.

Discussion: The study's results can be used in practical implications and provide a foundation for future research. Future research is suggested to include extensive visual simulations, practical implementation studies, and studies on long-term effects of implementation.

KEYWORDS

smart warehouse management, industry 4.0, spare parts, oil and gas, logistics

1 Introduction

Offshore energy production companies place importance on the safety, productivity, and efficiency of their operations. These objectives are achieved through meticulous maintenance of machinery and equipment at their installations, ensuring timely and effective replacement of parts as needed. Consequently, these companies are mandated to implement robust spare parts management systems in strict adherence to operational and safety policies.

In offshore energy production industry, warehousing spare parts is a complex endeavor due to the diverse nature of machinery and equipment used in production. These assets vary in function, size, life cycle, material composition, maintenance requirements, and criticality to production. As a result, spare parts inventory management becomes multifaceted. Some material is supplied directly from vendors to offshore installations upon demand, some is stored at onshore bases or offshore installations, and some items necessitate storage at both locations. The challenges stemming from such diverse supply methods and demand patterns include warehouse overcrowding, excessive expenditure, expiration of stored spare parts, and difficulty in maintaining accurate inventory records. The primary objective of the warehouse is to ensure timely and accurate supply of the required spare parts to offshore installations, and the given challenges increase the likelihood of supply failure during critical demand periods.

Unlike several other industries, technological advancements in logistics activities within the oil and gas sector have not been prominent (Lu et al., 2019). Historically, the industry's profitability has meant that the costs associated with spare parts management were bearable. Therefore, a just-in-case principle to ensure operational safety has been adopted and kept over the years. This approach has facilitated immediate replacements of parts, thereby sustaining high levels of production over time.

In recent years, there has been a growing focus on enhancing the intelligence of warehouse operations across various industries to reduce costs and optimize processes. The concept of smart warehouses, characterized by automated, unmanned, and paperless operations (Liu et al., 2018), has garnered significant attention (Seyedan et al., 2023) describe modern inventory control as companies meeting customer demand while maintaining low costs. Pratap et al. (2024) suggest that all supply chain activities could benefit from increased smartness to combat issues like inaccurate forecasting, delays, and waste. While examples of smart inventory practices can be found in industries like food, e-commerce, and retail (Sgarbossa et al., 2022; Zhang et al., 2021; Mahroof, 2019), the unique functional requirements of the oil and gas sector necessitate tailored approaches to adopting modern supply chain principles for sustainability and profitability (Czachorowski et al., 2023).

The oil and gas industry's slow adoption of smart warehousing practices, due to a lack of tailored approaches, presents a research gap. Thus, there is little to no academic ground for successful implementation of smart warehousing to be rooted in. However, there are indications that Industry 4.0 implementation can enhance spare parts management practices in the oil and gas industry (Khan et al., 2024). This study aims to bridge this gap by proposing foundational elements of a smart warehouse management system specific to the industry's needs.

Guided by this objective, the study draws upon data and insights gathered from a Norwegian oil and gas production company to initiate a transformation from traditional spare parts warehousing to a more intelligent and efficient model. The methodology encompasses a thorough literature review, data analysis, and model development, with the goal of offering practical implications and recommendations for future endeavors.

2 Background

The oil and gas industry's spare parts warehousing is a small part of a complex supply chain that comprises several activities, including transportation, contract management, and warehousing. There are several factors that contribute to the oil and gas supply chain being somewhat more complex than those of several other industries (Jacoby, 2012). These activities are further divided into subtopics and activities, as shown in Figure 1. The complexity of the oil and gas industry's supply chain is not immediately apparent in simplified overviews such as Figure 1. The several factors contributing to the complexity include the uniqueness of the activities performed, special materials required, transportation to and from remote locations, collaboration with numerous stakeholders and suppliers, governmental regulations, high levels of competition, safety regulations, and changing weather conditions (Czachorowski et al., 2023).

2.1 Case selection and validation

The case focuses on a leading company in the oil and gas industry known for its complex logistics and inventory management needs. In early 2024, a mapping of supply chain activities – with a specific emphasis on warehousing – of an oil and gas company was conducted to identify areas of improvement. This is visualized in Figure 2. The mapping is done using action research. Action research is a qualitative research method that integrates theory and practice to solve problems in operational settings (Baskerville and Wood-Harper, 2016). There are various versions of action research relative to different fields. In this study, the four-stage approach consisting of assessment, planning, implementing, and evaluating is used (Kemmis et al., 2014). The assessment stage in this study required data gathering from the company's supply chain department. Five main improvement findings were identified and are presented in Table 1. The mapping particularly emphasized the limitations related to visibility and traceability across the supply chain, which are presented in Table 2. The supply chain and spare parts management challenges are costly for the company, and there is a strong desire to cut costs to redirect funds to emissions reduction and technological innovation.

The company's supply chain initiative for the 2020s, established by the company prior to this study, aims to reduce costs by approximately one billion NOK (approximately 92 million USD by August 2024) across several supply chain activities, as illustrated in Figure 3. Spare parts warehousing mainly falls under the second column titled material management. With appropriate optimization of warehouse practices costs can be reduced.

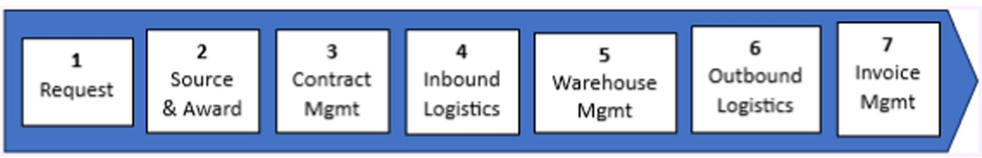

FIGURE 1
The seven supply chain management activities in the oil and gas industry.

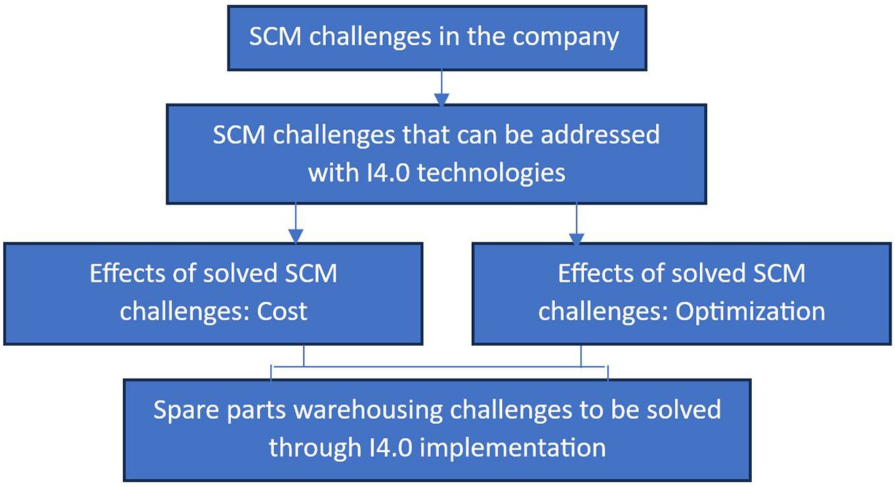

FIGURE 2
The order and content of mapping of challenges in SCM and warehousing as conducted in this study.

TABLE 1 Key findings of challenges in SCM mapping in the oil and gas company in the study.

Key findings—challenges in SCM
Limited visibility and traceability across the supply chain(s)
Supply chain(s) have limited integration and collaboration: fragmentation
Disconnected planning, execution, and prioritization
Communication and information technology sharing across the supply chain network can improve
Limited capacity to handle demand during peak hours

TABLE 2 Challenges with visibility and traceability in the supply chain related to spare parts management.

Challenges with visibility	Challenges with traceability
Limited possibility to plan vessel loading efficiently due to short-term (>2 h) visibility to incoming deliveries to warehouse at base	Limited visibility on materials to be shipped from suppliers to supply bases makes it challenging to plan correct capacity and efficiency on truck loadings
Use of materials in stock is cumbersome if it has already been allocated to another license	Vendors have low visibility on where their materials are located when they are shipped from the supplier base
Late container registration on shipment	Vendors have poor traceability on items transported back from offshore installations
	Limited capability to track status of materials complicates shipment planning and leads to manual follow-up

To achieve these cost reductions, the lack of visibility and traceability outlined in Table 2 can be solved through means of technology, as has been pointed out in research from various industries (Rasool et al., 2021; Nantee and Sureeyatanapas, 2021; Saraceni et al., 2017; Hamdy et al., 2022). The planning and effort spent on optimizing material management and warehousing processes will be directly linked to the outcome, with yields such as cost and waste reductions and sustainable activity, as shown in Figure 4.

However, the path to technological optimization is challenging, and the company identifies numerous challenges and potential complications in achieving operational excellence in the supply chain, listed in Table 3. Warehousing and other supply chain activities have become complicated due to the high demand for their products, many suppliers, stakeholders, departments, workers, and unpredictable factors at play.

Despite these challenges, academic research and industrial initiatives emphasize the benefits of technological optimization, giving large-scale production companies in oil and gas and manufacturing reason to investigate optimization initiatives.

3 Literature study

One of the most, if not the very most, important components that would allow for digital supply chain to be realized in warehousing is Industry 4.0 technologies (Culot et al., 2020). Since their emergence, they have been researched extensively, both conceptually and practically. Suggestions have been made in literature for their implementation in various industrial supply chains, as well as in other processes in the value chain. Industry 4.0 technologies are largely

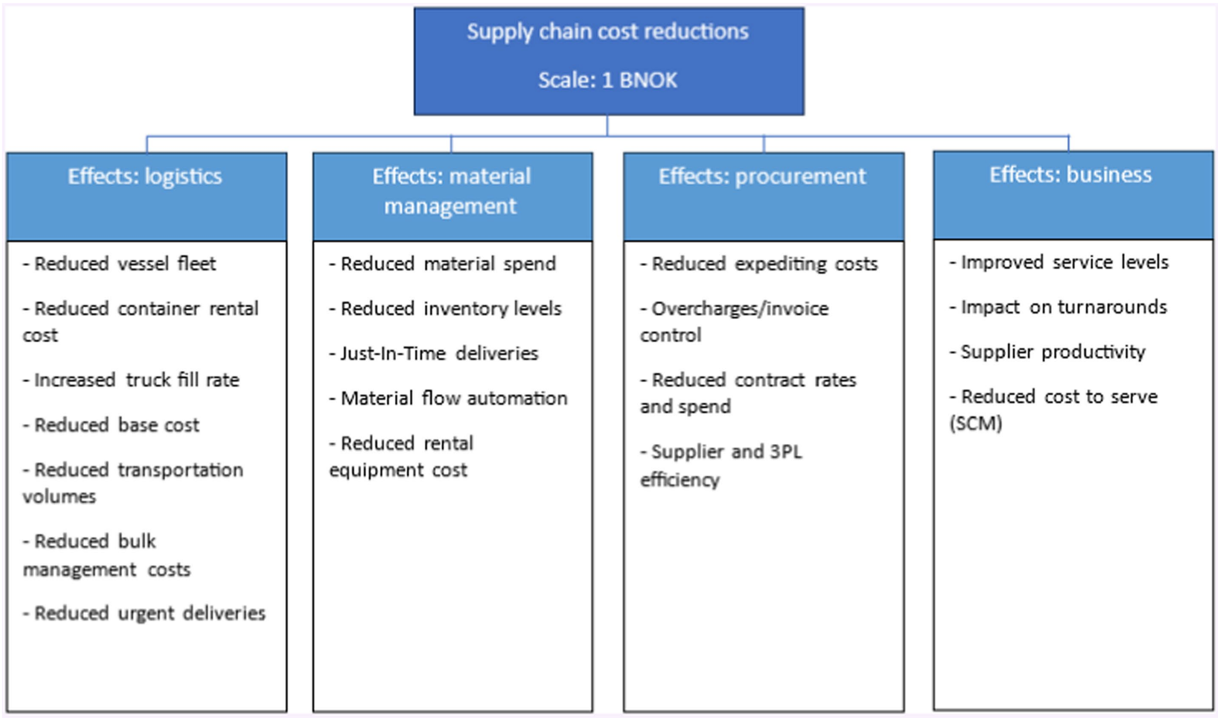

FIGURE 3
Envisioned effects of successful cost reductions in the supply chain.

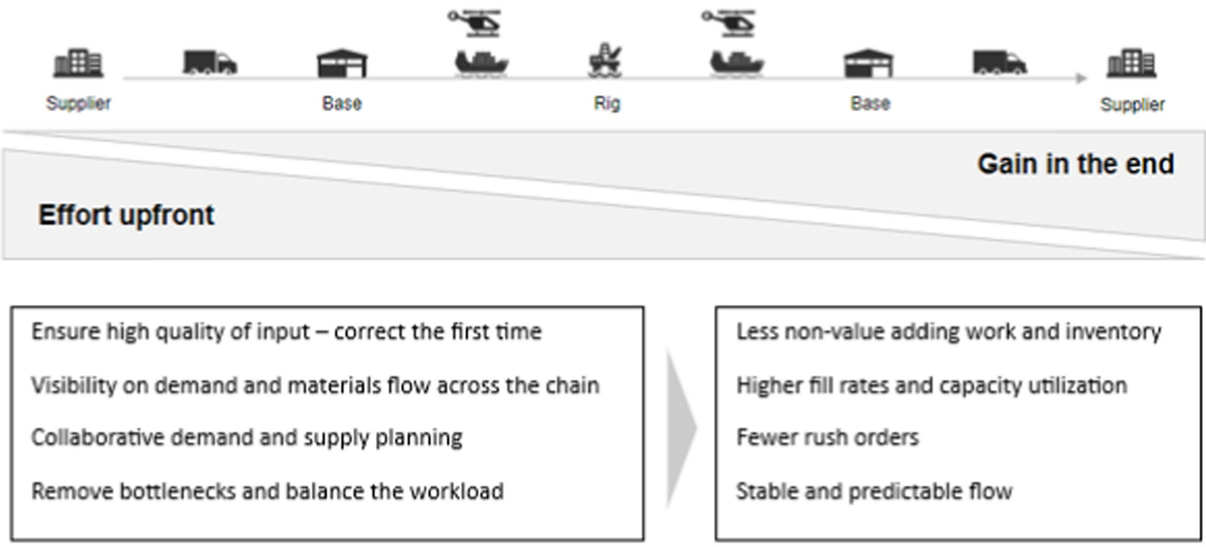

FIGURE 4
Correlation between spare parts warehousing optimization efforts and long-term gain.

considered to be an essential part of the future, especially in industrial practice (Ventura et al., 2023). Therefore, the literature study will be centered on Industry 4.0 technologies to assess their potential for spare parts warehousing.

Literature identifies several technologies that can be identified as Industry 4.0 technologies. All relevant technologies are investigated. This is best done by dividing them into sub-groups of related technologies. Three such sub-groups are established:

1. Digital platforms
2. Analytics
3. Emerging technologies

TABLE 3 Challenges in achieving operational excellence in material and supply chain management.

Challenges in excellence of material management in the supply chain
Many invoices of small amounts
Deliveries to remote areas with poor infrastructure
Many suppliers of small/medium size who prioritize customers that pay on time
Manual-driven processes, with much paper work
Taxation rules can be challenging to understand
Demand, availability, and requirements change often, making planning difficult
Balancing high flexibility and efficiency with control and quality
Compliance with reporting requirements and demands of involved parties
Much time spent on administrative tasks for engineers/materials support personnel
Need for rapid decision making onsite (offshore) with limited access to real-time warehouse data
High volume of payment recipients to maintain in vendor master

3.1 Digital platforms

When referring to digital platforms, there are several examples. The common denominator for many modern digital platforms is Cloud computing (Zhang and Ravishankar, 2019). To achieve optimal understanding of digital platforms in the era of Industry 4.0, Cloud computing must therefore be included.

According to Zhang and Ravishankar (2019), Cloud computing implies computing services being derived through the Internet. Prior to Industry 4.0, it was common for data, systems, and platforms to be stored locally on drives and physical computers. With digital modernization, the ideal for industry has become to adhere to Cloud computing for their digital services.

Remote access, easy configuration and scaling, and tailoring to meet specific business needs are listed as some benefits of Cloud computing (Attaran and Woods, 2018). The flexibility implied in these benefits make Cloud computing attractive in a modern era. According to Nambisan (2017), Cloud computing fosters digital innovation and experimentation, which ultimately helps businesses create new business models. It is argued that this is one of the key elements in entrepreneurship, which is as relevant to established companies as it is to new ones.

Cloud computing holds the potential of affecting a company in several ways. New data structures and new data storage systems would lead to new ways of organizing and managing files, which affects workers and operators unanimously across business areas in a company (Weerasiri et al., 2017).

However, transitioning a company's key systems to Cloud entails several obstacles. Chang (Chang, 2020) recognizes how long-term cost reduction is one of businesses' main motivators of Cloud implementation, yet costs related to the implementation itself can be significant enough to prevent proper implementation initiatives. In other words, dedication throughout the process, from implementation decision through complete implementation, is key.

Cloud computing's presence in warehousing could require entirely new warehouse setups, as its impact could be highly disruptive. Bokrantz et al. (2020) note that monitoring of equipment and goods across the supply chain becomes possible, even easy, with Cloud computing. The ability for human operators in the warehouse to observe, analyze, and monitor goods and products from supplier throughout its cycle in the supply chain to end customer is valuable. With Cloud, this process could be conducted remotely, by all stakeholders involved, requiring only Internet connection and a configured digital device. Dange et al. (2019) identify Cloud implementation as a core requirement for digital transformational success.

Cloud computing constitutes the core of modern digital platforms. In a supply chain context, such platforms connect suppliers and customers with each other through an interactive, remote-based infrastructure (Cennamo and Santaló, 2015). New software and platforms that are created specifically for activities such as purchasing and service provision are rooted in Cloud computing, which is also useful in the context of the increasingly common practice of remote work (Kohn et al., 2023).

3.2 Analytics

The information and data that exists within businesses' information systems after years of operation can easily be envisioned to be extensive. The concept of big data analysis implies corporations actively using this information to observe, analyze, and use trends and information that exists in the data. According to Côrte-Real et al. (2017), big data analysis offers great value to businesses in helping them achieve higher degrees of competitiveness and performance. The importance of data exploitation was identified prior to the characterization of Industry 4.0 and came about after some businesses and researchers pinpointed the availability of extensive data (Kohavi et al., 2022).

There are several concepts present in literature regarding big data analysis, but under different names. Some argue that the concepts are different from each other as well, but similarities exist regardless (Power et al., 2018). Analytics, big data analysis, and data science all describe similar traits of dedicated software and digital architecture: an ability to "interrogate" data to fetch patterns, insights, and value for use in decision-making (Provost and Fawcett, 2013).

Software and information systems of a certain caliber are required to process and analyze large amounts of data. Big data analytics works when there are robust digital systems in place, capable of alleviating human workers of most of the analysis tasks. If the analysis was manual, it would not be possible to identify it as big data analysis and an Industry 4.0 technology. Big data analysis, in its well-functioning form, includes comprehension of problem context with the data, identification of the data sets that are relevant, extraction of knowledge from the data, and consolidation of the knowledge to assist decision-making (Martinez-Plumed et al., 2021).

Software and information systems with the capacity to conduct such operations without human assistance can be related to artificial intelligence (AI) (Shang and You, 2019). Shang and You (2019) describe that AI and machine learning interfaces must be trained to identify the "correct" data and find the data sets that might have been overlooked by untrained AI. Examples of trained AI systems can be found many places in our daily technological use: e-mail spam filters, recommendation engines on the Internet, and customer analytics (Shang and You, 2019).

In digital supply chain context, successful implementation of analytics and AI could prove invaluable (Iansiti and Lakhani, 2020). Among the capabilities they could offer is accurate demand forecasting (Gilliland and Tashman, 2021). Businesses that have managed to implement functioning analytics and AI practices base surprising amounts of decisions on the analysis of such systems – with great success (Iansiti and Lakhani, 2020). However, as with all Industry 4.0 technologies and other disruptive innovations, successful implementation is demanding (Burström et al., 2021). Specific application methods, ethical considerations, and political implications are some areas in which businesses should establish strategies to succeed with analytics (Burström et al., 2021).

3.3 Emerging technologies

Along with software—digital platforms and analytics systems—hardware in the form of technological tools is required to fullfil the digital supply chain (MacCarthy and Ivanov, 2022). Along with the conceptualization of Industry 4.0, new technology has emerged that enable the core concepts of Industry 4.0: interconnectivity, efficiency, and flexibility (Chaplin et al., 2020). A closer look is taken at literature that refers to emerging Industry 4.0 technologies, specifically. Three such technologies are identified: industrial internet of things (IIoT), digital twin, and additive manufacturing (AM).

Industrial internet of things (IIoT) and internet of things (IoT) largely refer to the same concept: a networked connection of smart objects (Birkel and Hartmann, 2019). The difference lies in the name: IIoT is used for industrial purposes, while IoT is normally used by single-point consumers. For this research, IIoT is of relevance. Connected devices on IIoT networks can be used in industrial processes such as manufacturing and supply chain management, to transfer data without human interaction. The key in terms of hardware and Industry 4.0 technology is compatible devices. They must be connected over the Internet and communicate effortlessly.

IIoT especially opens for one component of digital supply chain that is considered key to its success, which is visibility (Tran-Dang et al., 2020). The devices that are connected over a network are either smart objects, or objects with smart sensors attached. These sensors allow for digital systems to collect data on where and how the objects are, enabling visibility and monitoring (Tran-Dang et al., 2020). In industrial supply chains, IIoT can be defined as a network of physical objects that have an ability to sense and interact not only within a company, but among the entire supply chain, to ensure planning, coordination, and control of all supply chain activities (Ben-Daya et al., 2017). Examples of such supply chain activities include warehousing, predictive maintenance, and sustainability improvement (Compare et al., 2020).

In warehousing, IIoT's role would largely be to ensure a complete overview of all products or items present in the warehouse, at all times. When all items are connected over the Internet, all relevant workers—both in-house and others—can access the data. Trends of storage items can be identified and orders of new warehouse items can be made according to the accurate data available consistently.

Industrial success in implementing IIoT is not given. The challenges typically associated with its implementation are costs, security, coordination of an increased level of smart objects or sensors, lack of technical standards, and lack of sufficient competence among human workers and operators [II]. These challenges can be mitigated through competence requirements, strategic decision-making, and frameworks for implementation and usage.

Digital twin relates to IIoT usage because the technology that enables it may be IIoT-based. Digital twin is a digital model of a physical object, process, or system. Its purpose is to simulate the behavior of the object, process, or system, to explore possibilities that lie in changing it (Liu et al., 2021). The digital twin is meant to have strong mutual coupling with the physical model and represent it in real time (Liu et al., 2021). The enabling technologies allowing for digital twin to exist are characterized by their ability to connect over the Internet and transfer information. Such technologies include sensors and other wireless technologies, as in IIoT. Supporting technologies that allow for modelling, visualization, and optimization can be used to optimize digital twin technology (Liu et al., 2021).

According to Liu et al. (2021), the major benefit of digital twin technology is that it enables experimentation and visualization in a safe environment. Instead of conducting optimization measures in a physical environment with high technological and safety risks, a digital model allows for risk-free experimentation. It is also useful for training purposes for new employees and workers, allowing them to learn remotely.

In terms of warehousing, digital twins can prove revolutionary (Kuhl et al., 2022). Their ability to provide accurate digital models of items, equipment, processes, and information involved in warehouse activities could change daily work processes for human operators and relevant workers. According to Kuhl et al. (2022), this complete digital overview of warehousing can help decision-makers in maximizing productivity, safety, and efficiency. This is an ideal situation for businesses operating with large and complex warehouses, many of whom today experience an absence of interconnectivity between digital space and physical space (Feng et al., 2022).

Adding to the interconnectivity between the digital and physical spheres is additive manufacturing (AM). According to Charles et al. (2023), AM is one of the main driving technologies of Industry 4.0. Patalas-Maliszewska and Topczak (2021) describe AM as the consolidation of a combination of materials with the aim of obtaining a real object using 3D CAD data. Such materials can be metals, ceramics, plastics, and metal alloys. Prashar et al. (2022) describe waste minimization, possibilities for changes in design, just-in-time access to parts or products, and cost decreases in just-in-case storages as benefits of AM.

Warehousing could be affected massively by the presence of AM. Sirichakwal and Conner (2016) describe AM as a disruptive innovation that is vital in reducing spare parts inventory costs, which have increased in the past decades. Many businesses have opted to maintain just-in-case storages, to reduce lead time of spare parts and items in case of production failures or emergencies. While the idea behind is understandable—ensuring safety in production through consistent availability of items and parts—the costs relating to warehousing, logistics, and supply chain management increase significantly with these types of policies. The aim would be to achieve production safety and minimized storage of spare parts and other necessary equipment at the warehouse, simultaneously. Sirichakwal and Conner (2016) and MacCarthy and Ivanov (2022) note the numerous challenges in achieving these types of goals, while also stressing that it is possible, with correct competence, strategy, and foundation.

3.4 Smart warehousing enabled by industry 4.0 technologies

Industry 4.0 technologies are the enablers of automation in industrial processes (Ali et al., 2024). However, the technologies' ability to successfully optimize industrial activities is dependent on their level of interconnectivity—the integration of technology is based on their characteristics and compatibility with the warehousing system used (Ali and Kaur, 2022). In warehousing, IoT and CPS (cyber physical system) constitute the breakthrough technologies that in some industries have succeeded in converting manual operations to automated ones (Ali and Kaur, 2022). The use of such technologies lead to warehousing that utilizes fewer resources and improves economic performance, thereby enhancing warehouse operations' sustainability (Ali et al., 2023). According to Simic et al. (2023), Industry 4.0 technologies is the key enabler of the automation of material handling in warehouses. In addition to compatibility of technologies, readiness analyses are wise to conduct before full-scale implementation of smart warehousing (Ali et al., 2024).

4 Data and design

This study focuses on spare parts warehousing systems for oil production installations operated by a Norwegian energy production company. The company operates multiple oil and gas fields, as well as renewable energy projects in wind and solar power. The company's vast oil production portfolio benefits from the experiences gained from several installations over the past 50 years, providing valuable perspectives for shaping the future spare parts warehousing systems.

When a new project commences, such as a new production installation or wind turbine farm, the company determines the digitalization levels in spare parts warehousing through strategy creation and idea workshops to establish the project's direction and philosophy at an early stage. This study considers the company's stated goals and the literature study when creating an optimal design.

The potential operating model for future installations aims to maintain a high degree of automation, digitization, and data-driven decision support, with remote assistance and minimized administration. The operations group working onshore will perform dynamic planning, job preparations, and administration, while the staff offshore will focus on optimizing daily activities. The company and external personnel will run campaigns where maintenance and modifications are carried out. No singular modification jobs without a plan will take place, exempting emergency situations.

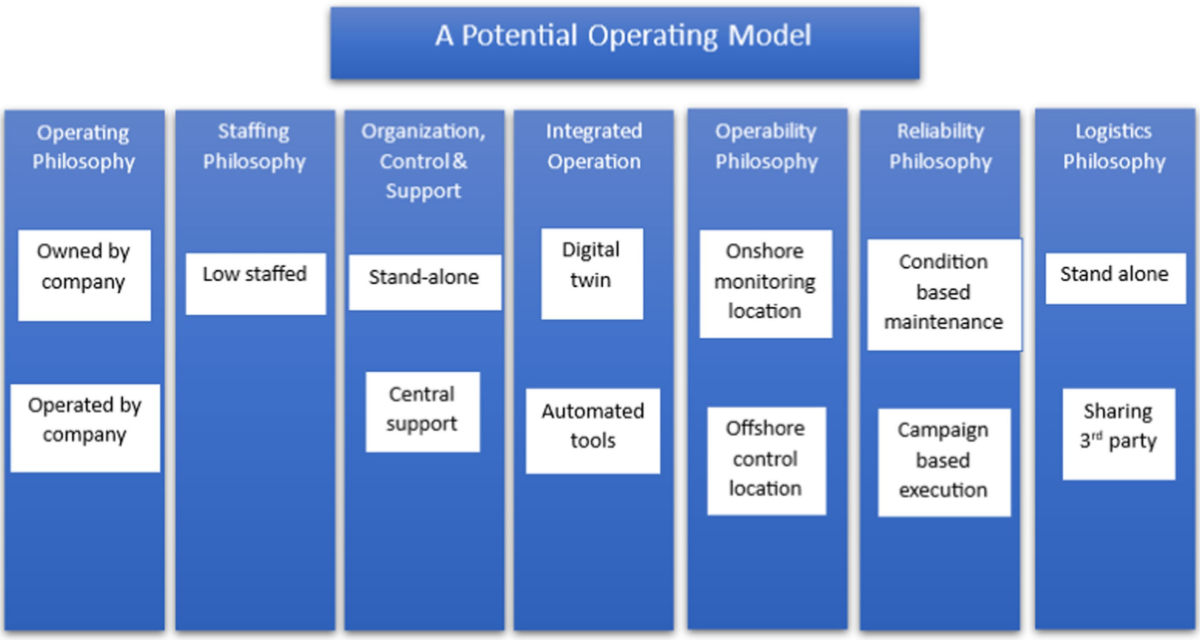

FIGURE 5
The main concepts of a proposed potential operating model. Retrieved from the company.

TABLE 4 The concepts from the operating model consolidated for the logistics activities at installations.

Challenges in transportation	Goals	Requirements
Extended lead time cross-country: 5 days	No shutdowns offshore	Predictability and visibility across the logistics chain
Long sailing time from onshore base to offshore installation	Offshore personnel should have all work on tablets/phones	Correct the first time
	Everything should be automated/scanned	Manual labor must be minimized
		Eliminate the probability of wrong deliveries to offshore installation
		Everything digitally available on tablets for personnel

Figure 5 illustrates the main concepts of the potential operating model, which aims to influence the operation of installations in all areas, including subsea, drilling, integration, logistics, maintenance, and administration. The desired influence of the operating model varies for each area of operation. This potential operating model is supplied by the company and based on their desired direction. For logistics and spare parts warehousing, Table 4 presents the desired influence.

Many of the concepts in Table 4 align with the findings presented in Tables 1–3. The operating model emphasizes visibility, communication, and the reduction of manual work and paperwork as key factors in logistics and supply chain excellence. The operating model proposes a strong focus on technological and automated solutions, which are considered necessary to achieve the set goals within logistics improvement.

The current state of spare parts warehousing and material management for installations operated by the company is considered time-consuming and complex. There is little systems alignment, and much time is spent uploading files and manually inserting data from invoices and emails. There is also little overview of items, as they are not tracked with the help of IIoT along the stages of receipt, storage, and order picking. Thus, there is a need for change if the requirements connected to visibility and manual work are to be achieved.

Prior to gathering and analyzing data, criteria for smart warehouse management design are determined. The criteria are the company's readiness to adopt new technologies, the complexity of its supply chain, and its willingness to participate in the study. Validation methods involve triangulating data from multiple sources, including the mapping (data gathered from the company's supply chain department), document analysis, and direct observation. Key goals such as control and visibility levels in activities and waste reduction are considered to ensure optimal design results.

4.1 Research framework

To propose key elements of a smart warehouse management for spare parts warehousing in the oil and gas industry, an action research approach based on qualitative data is employed. The integration process involves a systematic literature review, case study analysis, and finally the development of key elements of a smart warehouse management framework. This approach ensures robust findings, enhancing the study's validity and reliability.

A structured approach is ensured by using an appropriate research framework. The research framework is rooted in action research's four-step approach. The framework is rooted in gaining an overview of current practices and challenges first, before using that insight to suggest measures for optimization through Industry 4.0 technologies. The following research framework is used:

- Assessment Phase:
  - o Evaluate the current state of warehouse operations.
- Planning Phase:
  - o Develop a plan for implementing Industry 4.0 technologies.
  - o Set objectives and performance metrics.
- Implementation Phase:
  - o Integrate digital platforms, analytics, and emerging technologies.
- Monitoring and Evaluation Phase:
  - o Continuously monitor performance against set objectives.
  - o Adjust strategies based on real-time data and feedback.

4.1.1 Assessment

To gain an understanding of the material management process at warehouses, the current process is evaluated. This is shown in Figures 6, 7.

Traditionally, the process illustrated in Figure 6 has been the norm for spare parts warehousing. As oil and gas production has increased steadily to meet high energy demands for a rapidly developing global society (Norwegian Petroleum, 2024), spare parts warehouses have grown to meet the requirements of increased offshore production. The increased financial expenditure associated with increased warehouses has not been an issue, as the income from high production levels has covered all expenses while still maintaining high profits for the company. However, the focus on smartness in warehousing has now increased (van Geest et al., 2021).

An integral part of the material management process depicted in Figure 6 is the warehouse receipt activity. Today, it is processed and registered on a computer manually. Mapping of the current warehouse receipt process shows that it is an extensive and time-consuming 9-step process. Once again, a high level of manual labor can be observed, which contributes to superfluous time consumption.

With the general identified challenges described in Section 2 as basis, three main culprits that hinder the spare parts warehousing process are identified:

1 The lack of traceability results in a lack of visibility, which makes it more challenging to predict demand, events, and outcomes.
2 The process is manual.
3 There is a lack of interoperability, with no common communication channel between the supplier, warehouse, and offshore operative.

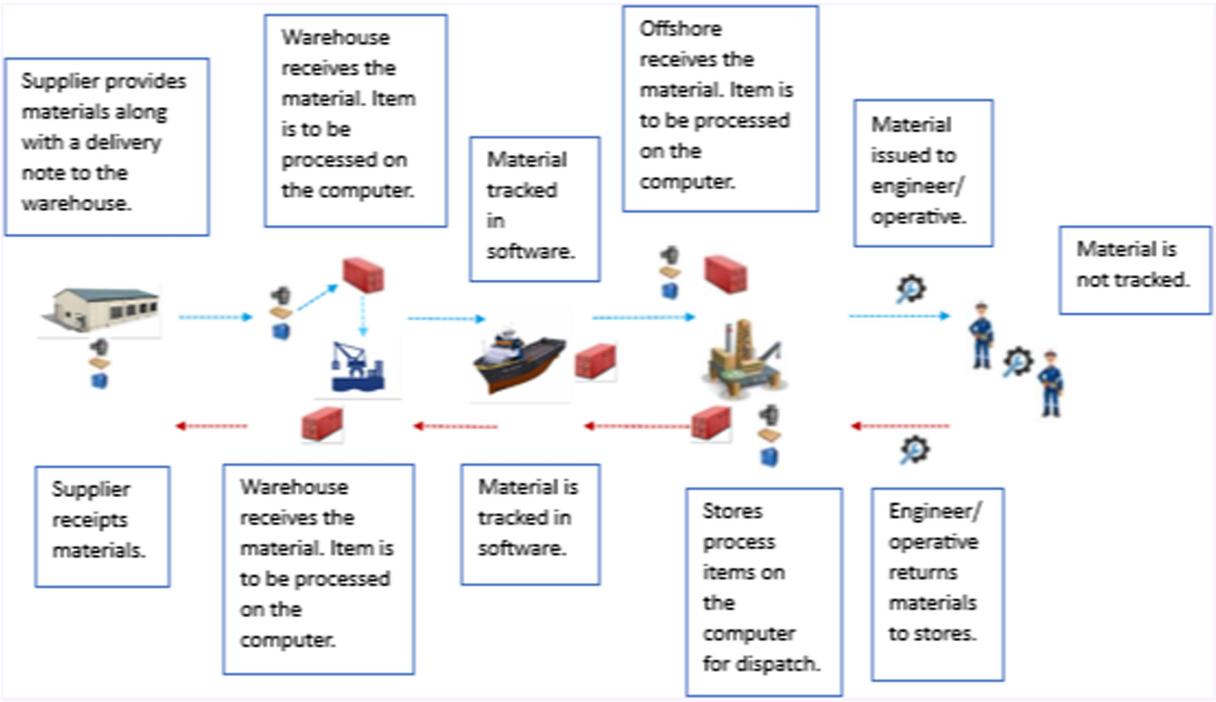

FIGURE 6
The as-is process for material management at current installations.

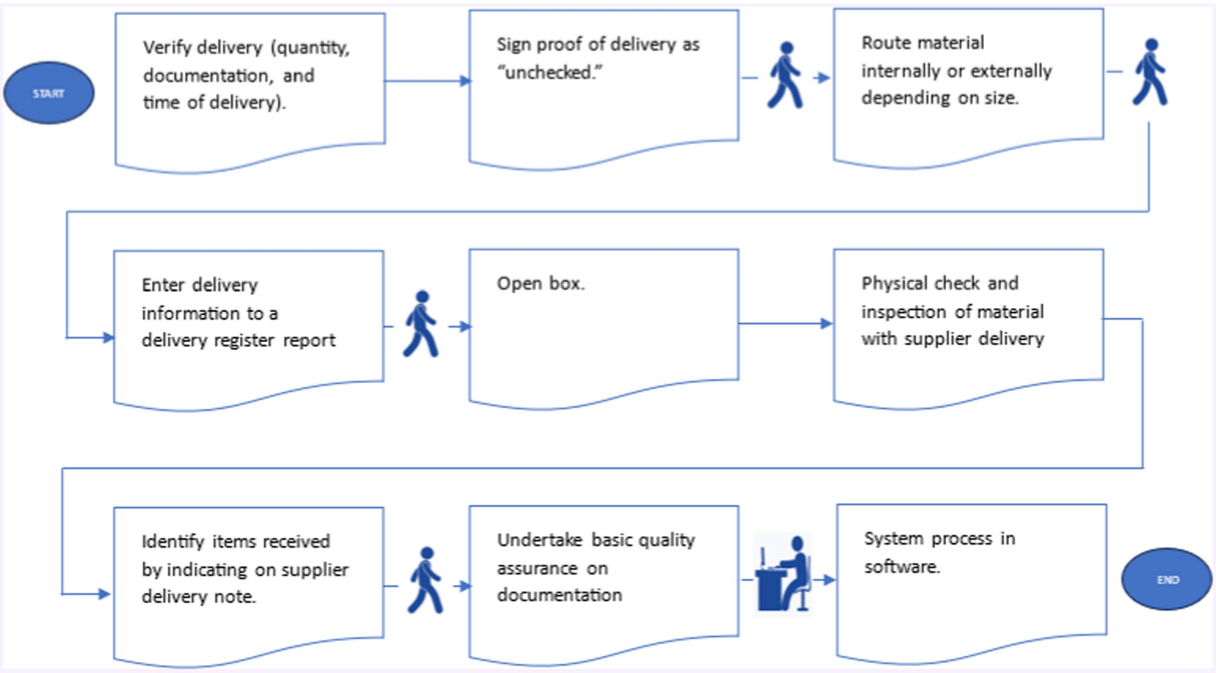

FIGURE 7
The as-is process for warehouse receipt, an integral part of the company's material management.

The current state of spare parts warehousing does not align with the company's goals and requirements for optimized operation. The challenges in the supply chain explained in Tables 1–3 are exemplified in Figures 6, 7, demonstrating the work that awaits the company before achieving its ambitions.

As emphasized in the literature study, the three core concepts that are ideal for making the smart warehouse function ideally are a digital platform, analytical functions (embedded in the software or otherwise) and tracking technologies. However, there is little evidence of current usage of such solutions, and the challenges related to concepts like visibility across the logistics chain can be connected to the lack of optimal solution usage.

Some aspects of the activities in Figures 6, 7 would be very challenging to eliminate. Performing physical checks of received goods at the warehouse before storage or offshore shipment is a must, as the potential consequences of approving damaged goods are costly and time-consuming. Thus, all aspects cannot be changed without compromising safe operations.

Section 3.3 highlights IoT and IIoT, which enable the transfer of data without human interaction and provide visibility, which the company in this study needs to achieve. Similarly, digital twin, based on the same technology, can show improvement possibilities through real-time representation.

There is a lack of interconnectivity in today's material management processes. The supplier delivers information on the material on paper along with the material itself. The receipt of material to the warehouse is registered in the warehouse software manually. When the material is sent offshore for use, engineers or operatives will register the receipt of the material manually in the software. If material is returned, the same manual operation is carried out.

4.1.2 Goods receipt

The current goods receipt process is presented in Figure 8. This process is simple and includes discrepancy handling, system registration, inspection, and storage. However, it does not accommodate technological components like IIoT (sensor or tag attachment to material), registration of goods receipt in new software, or transportation of material within the warehouse with the use of robotics.

Table 2 identified lack of traceability and visibility as the key challenges for spare parts warehousing in the company. For the future, the process depicted in Figure 9 is proposed. A generic requirement has been proposed for the warehouse worker to register discrepancies during the goods receipt process, regardless of where in the process the discrepancy is discovered. The worker who detects any minor discrepancy shall initially try to solve this through contacting the relevant stakeholder directly. If the attempt is unsuccessful, the procurement responsible shall be contacted. The logging of goods at

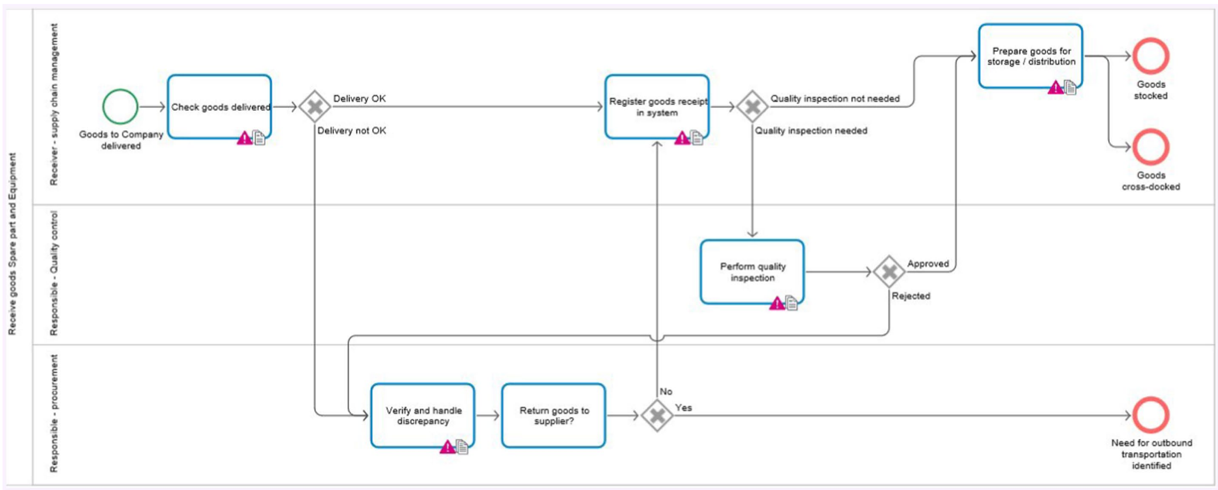

FIGURE 8
The as-is process for goods receipt in spare parts warehousing in the company.

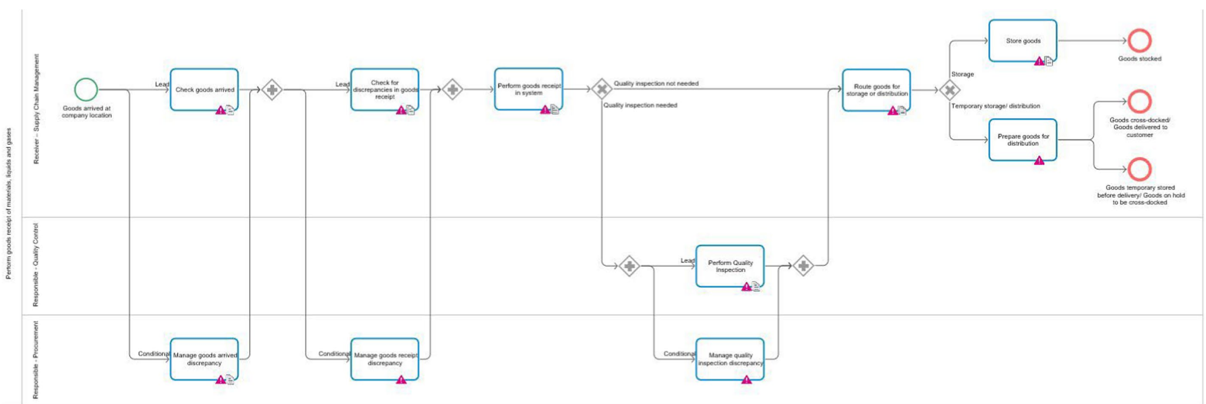

FIGURE 9
The revised process for goods receipt in spare parts warehousing in the company.

arrival is removed from the existing requirement for the checklist upon arrival, as this is not relevant for all business areas. The logging of goods at arrival is now presented as a separate requirement, which can be set by business areas identifying this as a value-adding activity.

The check of goods at arrival is now aligned with the actual performance of the task, which involves an initial check upon arrival of goods and a more comprehensive check when the goods are entered into the system. In connection with goods receipt for material purchase orders, it is now emphasized that the receiver shall ensure that the received material is according to the order through a visual inspection. Information regarding cross-docking is now more visible as it is no longer part of a requirement for a different topic.

The requirement 'Perform goods receipt of IT materials' concerns the receipt of IT equipment with a serialization profile. There is now a simplified requirement on receipt of repaired materials. If the material shall be scrapped upon arrival, the local rules for scrapping shall be adhered to, and correct customs status must be ensured.

It is possible to perform goods receipt for materials the warehouse worker has not personally confirmed in a visual manner, providing the recipient in the warehouse receives a written confirmation that the material has been received and inspected. All relevant documentation shall be part of the written confirmation.

4.1.3 Issuing of stocked goods

The previous issuing of stocked goods process is presented in Figure 10. For the future, the process depicted in Figure 11 is proposed. A second role band, requisitioner, has been introduced to include issues from stock which are manually requested. The requisitioner role is typically twofold: one is the engineer requesting the material and the other is the performing requisitioner, who handles the request in the initial stages. In large-scale production companies, the performing requisitioner is familiar with the spare parts and their suppliers. In the proposed process, a new start point now includes sourcing to other licenses. Withdrawals from stock shall be based on the principle to rotate the inventory when applicable: what comes in first is the first to go out, and the first to expire is the first to go out.

The process begins when there is a need for goods to be issued from the stock. In accordance with the activities in the company today, the proposed process includes three ways in which the need can arise from: reservations and requisitions from stock, sourcing across licenses, or manually requested stock. If the need for goods issue is manually requested, the requisitioner communicates the requisition to the warehouse team. A picklist is gathered – this is a document that details the items and quantities needed from the inventory. Using the picklist, the required materials or goods are picked from the stock. This step involves physically collecting the items from their storage locations. The issuance of goods is recorded in the system. This step ensures that the inventory records are updated to reflect the items that have been taken out of stock. After the goods issue is recorded, the items are prepared for outbound transportation. This step involves organizing the logistics for moving the goods from the warehouse to their next destination. Finally, the goods are delivered to the requisitioner (engineer) who requested them. This completes the process of issuing the stocked goods.

The key to the proposed process is that it is largely automated. The only manual handling that occurs is when stock is manually requested, whereby a requisitioner follows up the request as per company guidelines.

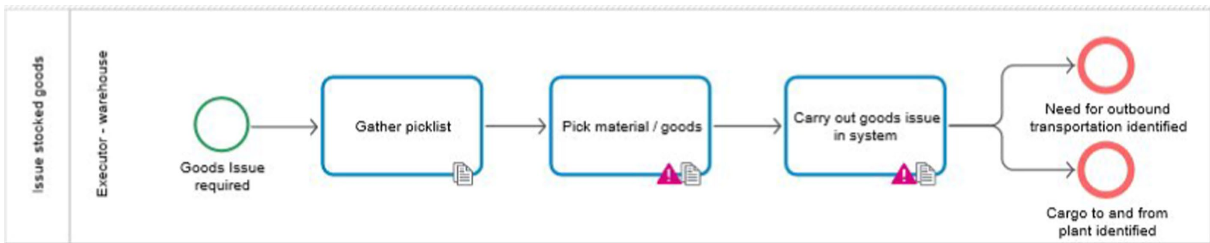

FIGURE 10
The as-is process for issuing stocked goods in the company.

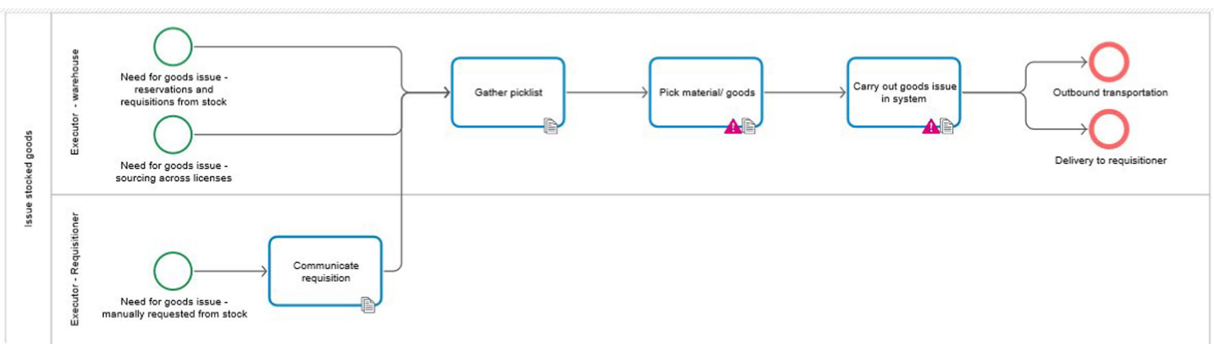

FIGURE 11
The revised process for issuing of stocked goods in spare parts warehousing in the company.

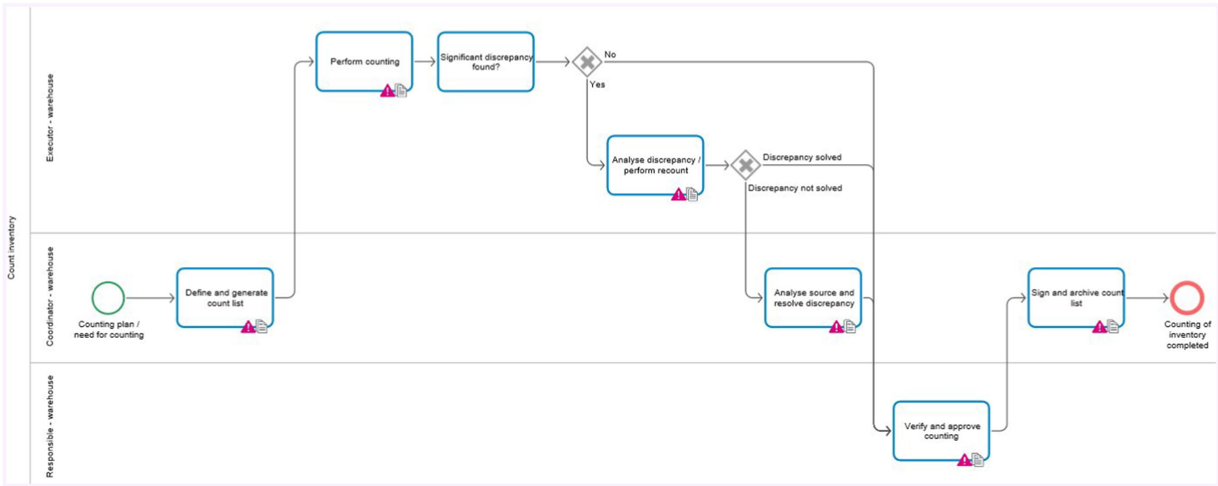

FIGURE 12
The as-is process for inventory counting in spare parts warehousing in the company.

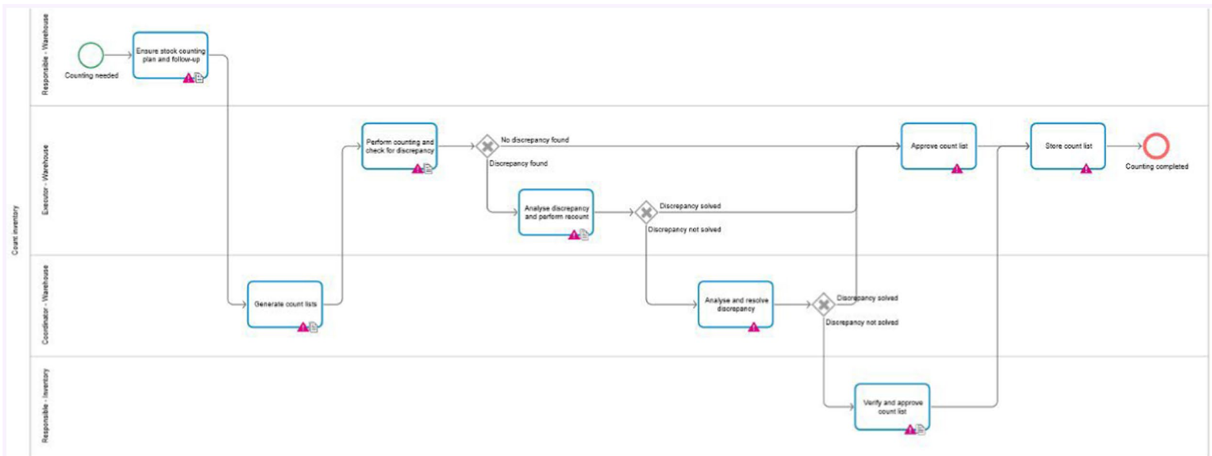

FIGURE 13
The revised process for inventory count in spare parts warehousing in the company.

4.1.3.1 Inventory count

The previous inventory counting process is presented in Figure 12. For the future, the process depicted in Figure 13 is proposed.

A fourth role band named responsible inventory is introduced to secure the segregation of duty. The responsible inventory is an employee and the formal owner of the inventory. The Executor warehouse or Coordinator warehouse can approve the count list if there are no discrepancies. The counting of material from floor to sheet is now included, and the requirement for "blind counting" is removed. Count lists shall be electronically available. All competence requirements that were not in accordance with strategies have been withdrawn.

This process starts when a need for counting of inventory is identified. This need can be recognized either by warehouse software or manually by a warehouse coordinator. A plan for stock counting is put in place to ensure a smooth counting process. This plan can be generated by software, which has access to previous warehouse counting data that can be used as a basis for the planning. A list of items to be counted is then generated, either by the software or manually by the warehouse coordinator. The counting is then performed manually by warehouse staff. Once the counting process is completed, potential discrepancies are handled manually by staff. The handling is done by checking records, transactions, or performing recounts. Then, counting is approved and archived digitally for record-keeping.

4.1.4 Planning

When analyzing the five ambitions of the company three points are made, considering the process updates from Section 4.1.1:

1 The current software used for material management must either be replaced or updated to support interconnectivity. This requires warehouse items to have a tracker, such as a sensor or barcode, that can be tracked in the software without manual insertion of the item's status. The software must also have cloud support to be accessed from anywhere.

2 All workers who handle material, both in the warehouse and offshore, must have access to smart devices such as tablets and computers. Even if the registration of material is done automatically, the devices give workers immediate access to relevant information and reduce time spent on material management by bringing the work to the workers rather than workers having to search for information manually.
3 All maintenance tasks must be planned for predictability to be possible. The exception is maintenance in case of unforeseen events offshore. If too many unforeseen requests are made for material, optimal warehousing processes would be disrupted.

The required interconnectivity involves a large number of personnel. If warehousing and material management workers are to plan warehousing according to maintenance planning and execution, consistent communication with maintenance engineers is necessary. Similarly, consistent communication must be maintained with suppliers, transportation personnel, and installation workers.

The probability of securing the use of only one software for all involved personnel is currently low. The main reason for this is the many different suppliers supplying material, using different software and systems. The company in this study has no mandate to regulate software usage of suppliers. Thus, the best possibility of improving spare parts warehousing is to update the company's own software and accept some level of manual work in adding information and data from suppliers on an item's tag.

The pool of data available in spare parts warehousing is currently large but not fully optimized. Currently, previous orders can be repeated using auto-fill-in, which saves time. However, if there are slight changes to an order, a new order must be created instead of bringing forth a previous order and making slight changes.

In the age of Industry 4.0, companies' awareness of big data analytical software has increased. As detailed in the literature study, utilizing software that can use all collocated data for analysis purposes is valuable. Data can be used to observe trends according to seasons, maintenance campaigns, and material type. In spare parts warehousing, big data analysis has the potential to perform practically all warehouse planning. However, proficiency in big data analytics software among warehouse and supply chain personnel would be necessary for full utilization.

When contemplating the specific installation and usage of big data analytics in spare parts warehousing, the following elements must be included in the planning:

1 Training of personnel is necessary for proficiency in advanced computer and data handling. Although warehouse workers themselves may not be the main users of big data analytics software, a certain level of proficiency is required to understand, interpret, and contribute to the work involved with big data analytics. This could take time, as several of the warehouse workers for the installations do not have extensive experience with advanced computer and data handling.
2 Extensions of current software are preferable for usage. If the supplier of the software currently in use or the one chosen for future use offers big data analytics as an extension package to the warehousing software, this would reduce the risks of non-interconnectivity, which can lead to unnecessary time consumption and extension of simple warehouse and supply chain activities.
3 Necessity must be determined before potential purchase and implementation. If the warehouse software offers possibilities for minor big data opportunities, such as auto fill-ins and access to previous orders for specific maintenance jobs or material, this may be sufficient. Data from installations may be used to predict demand, but these will never be fully accurate. Big data analytics software can be rather costly, and the necessity must be determined before potential purchase and implementation.

Data from several installations are readily available for the company to use in the future. Without software to perform the analysis, the work would have to be performed manually. It is suggested that the warehousing team observe the previous data available. If appropriate planning for material has been conducted in relation to maintenance campaigns, and the risk of missteps is low, investing in big data analytics software could be unnecessary.

Based on the literature study and the insight gathered from the company on current warehouse activities and future ambitions, key parameters upon which smart warehousing's success can be determined is visibility level and waste reduction. The literature study is clear on emerging technologies' key role in the success of smart warehousing – achieving smartness without is impossible. A resulting component of successful digitalization is waste reduction. When manual and paper-based processes are eliminated, physical waste in the form of paper, cardboard, and office equipment is reduced. Additionally, manual labor in the warehouse can also be significantly reduced.

4.1.5 Implementation

4.1.5.1 System design

The study presents an optimal digital supply chain for the company's future, considering the as-is processes for spare parts warehousing and the company's supply chain, as depicted in Figure 14. Each component in the digital supply chain of tomorrow is detailed in Table 5.

The digital supply chain emphasizes the necessity of interconnectivity, enabled by track and trace technology, IIoT sensors or tags, software systems, and data utilization. The exchange of information, logging of data, interpretation of data, tracking of material, optimization of every stage of the chain, and visibility of the process for every involved party are complex processes to implement. However, they could tie activities together and remove challenges connected to visibility and predictability.

While visibility appears to be an easy concept to achieve when presented in the digital supply chain design in Figure 14, the digital necessities behind the realization of full visibility are many. In many cases, oil and gas production companies may have older digital systems in use that are not compatible with sensors and tags, and therefore cannot use track and trace services. To address this challenge, a design for a logical track and trace architecture is presented in Figure 15, created for implementation by installations to enable track and trace technology.

The presented track and trace architecture is aligned with the ambitions of the company, as it enables the monitoring of material

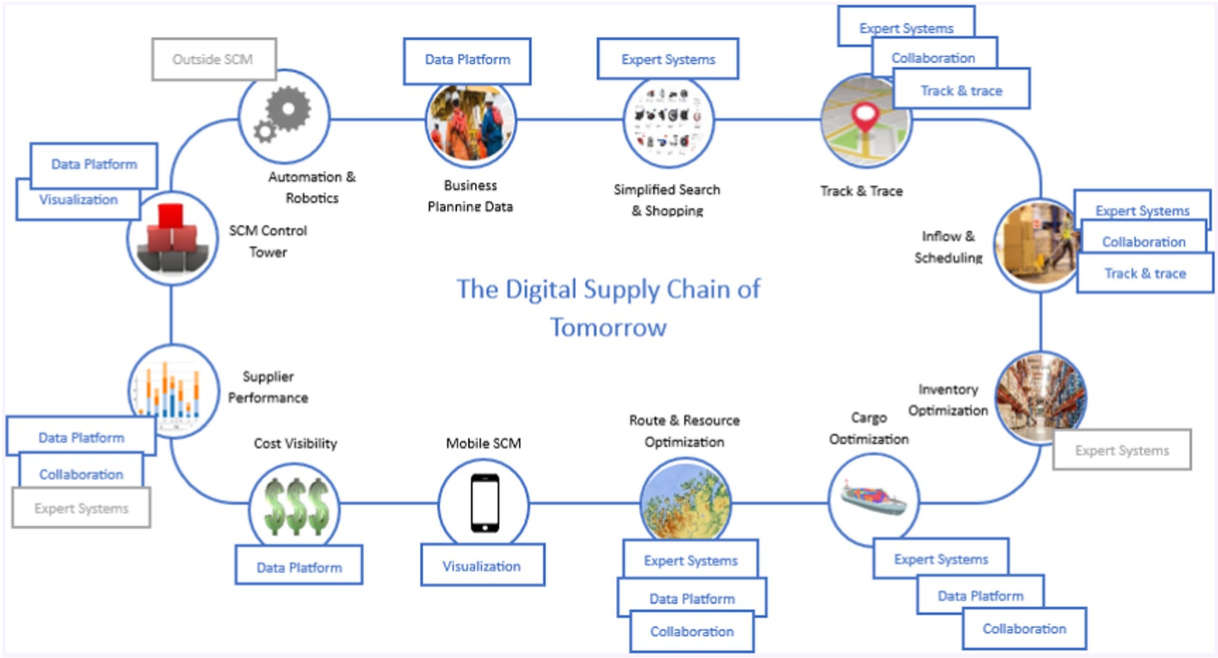

FIGURE 14
Design of the digital supply chain of tomorrow to benefit production installations.

across the supply chain, the exact measurement of performance, and the minimization of deviations. Electronic data interchange (EDI) in an extensible markup language (XML) format is suggested, which is a common practice for computers to encode documents. In the company's case, this will allow for access to relevant data on portable devices such as phones and tablets.

At the center of the process is IIoT technology, enabled by sensors or tags, whose information is processed by a local gateway and sent to the central hub. At the position of integration, all information is integrated and further processed before being used for visualization. Additionally, the processed data is used for analysis, whether through artificial intelligence or other means, and logged in a transactional system, which is the software the company uses for warehousing purposes.

If new systems, technologies, and processes are implemented, the structure of warehouse activities may have to change to accommodate the new additions. The concept of optimization is centered around increased visibility, streamlined activities, efficiency, and effortless communication between involved parties. The changes these optimization measures cause to warehouse activities are interesting, as they do not necessarily decrease the number of steps. Technological implementations may contribute to increasing the number of steps. However, the total time spent should ideally be the same as before or less. While the main priority is visibility, which technology can accommodate, efficiency is also a desired goal.

4.1.5.2 Visual representation of the modern spare parts warehouse

Specifically in spare parts warehousing, there are processes conducted that must be in tune with the digital supply chain design and the track and trace architecture. These were presented in Figures 6, 7. Most of those activities will likely remain, as steps like quality control and packing of shipping-ready materials must be conducted regardless of digitalization levels. However, the visual presentation of the warehouse will be different with the technology implementation. Figure 16 shows a visual representation of one of the onshore warehouses used by the company in this study.

The visualization is built using the software Visual Components, a simulation software that allows for creation and simulation of various warehouse and factory designs. The company in this study uses several onshore warehouses in Norway—for this visualization, one of those warehouses is chosen for illustration purposes. The visualization is an exact copy of the warehouse – the shelf type and dimensions, the available space, the office location, and the consolidation area location are reproduced as accurately as the software allows.

The new input into the visualization is Industry 4.0 technologies. In accordance with the digital supply chain framework illustrated in Figure 14, which includes inventory optimization and inflow and scheduling, unmanned robotics are implemented to conduct the processes described in Figures 9–13. Additionally, IIoT technology is implemented to secure supply chain visibility. This is, however, not visible in the visualization, as it will be small sensors or tags attached to spare parts placed in boxes on the shelves. Modern mobile robots and automated guided vehicles (AGV) hold the possibility of achieving interconnectivity with IIoT technology. This means that when a spare part is digitally cleared for offshore shipment, this information is registered by the AGV which travels to the correct shelf to pick up the item. The key to the function of the optimized warehouse is the IIoT technology and not the robotics, as it is the key enabler of visibility and thereby predictability.

4.1.6 Evaluation

The successful implementation of smart warehouse management in oil and gas material management is extraordinarily

TABLE 5 Explanation of the components of the newly suggested digital supply chain.

Component of the DSC	Operator	Explanation from the context of warehousing
Automation and robotics	Tech. unit in the company, but outside logistics/SCM	Repetitive tasks like item placement and order picking can be automated through robot usage to save time and man hours. Since robots are highly technical tools, their "home department" should not be warehousing or logistics, but rather the robotics/automation department in the company.
Business planning data	SCM in the company	All data on warehousing – orders and spare parts inventory during the year – must be at the hands of SCM personnel to use in future business planning. Trends are observed, and the future of the business is planned accordingly.
Simplified search and shopping	SCM in the company	Orders of spare parts should be simple. One system with access and/or links to all relevant spare parts is ideal.
Track and trace	SCM in the company	The key to traceability in spare parts warehousing is the ability to track parts throughout the supply chain. If the item is to be tracked from supplier to offshore installation, three things are required: close collaboration with the supplier, traceability components, and traceability software.
Inflow and scheduling	SCM in the company	Along with maintenance campaigns offshore for parts replacement, the warehouse must also maintain schedules that align with the receipt and shipments of orders. The scheduling is enabled by software, collaboration with suppliers and offshore personnel, and tracking technology.
Inventory optimization	External	Inventory optimization is enabled by software, which the company always purchases externally rather than develop.
Cargo optimization	SCM in the company	Cargo optimization is conducted according to offshore maintenance campaigns, receipt of material from suppliers, and availability of transportation modes. Software, data availability, and collaboration with all parties are required.
Route and resource optimization	SCM in the company	Conducted in collaboration with offshore personnel, and partly with relevant governing bodies. Appropriate optimization has the potential of decreasing time expenditure. Must be done using relevant software and data.
Mobile SCM	SCM in the company	A stated goal of the company is to move "all" work to mobile workstations, i.e., tablets and smart phones. This enables visualization and is enabled by appropriate data systems.
Cost visibility	SCM in the company	An improved overview of cost is desired by the company. Increased visibility of cost for several parties (maintenance personnel, warehouse personnel, central SCM personnel) raises awareness of expenditure and can be used to limit superfluous expenditure. An appropriate data platform will enable this possibility.
Supplier performance	SCM in the company + external	The performance of suppliers measured against goals and targets set by the company can be measured. This data can then be used for continuous improvement in collaboration with suppliers. Requires a data platform that logs data related to performance.
SCM control tower	SCM in the company	The SCM "control tower" is the central SCM organization in the company. All relevant data is to be logged by SCM centrally for observation, improvement, and analysis purposes.

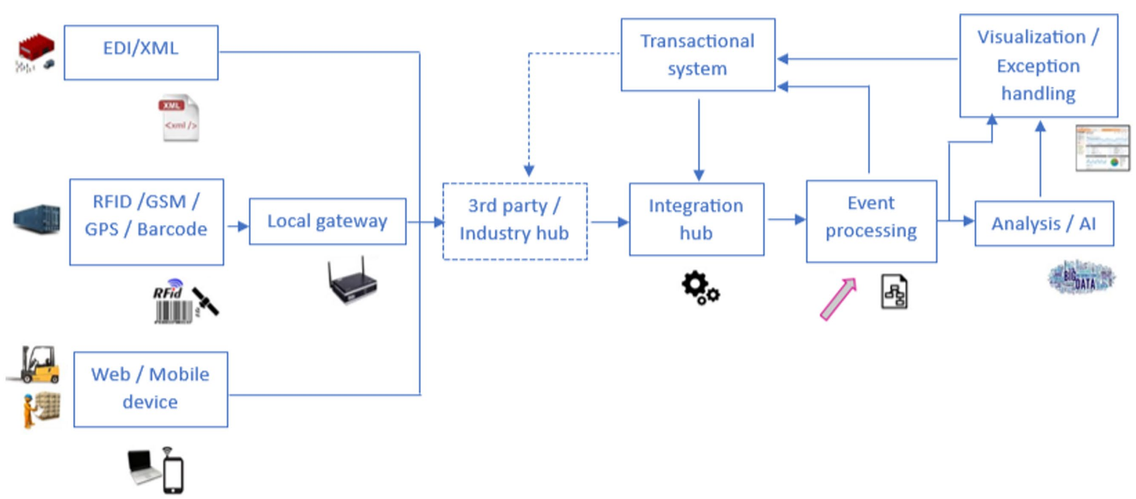

FIGURE 15
Track and trace architecture for enabling visibility and predictability.

challenging. The current processes are a result of decades of work, material, personnel, and suppliers that have been piled up without much optimization work along the way. The result is several software in need of upgrade, excess material stored in warehouses, and lack of traceability of spare parts. It will initially be challenging to "clean up" databases while running operations and implementing

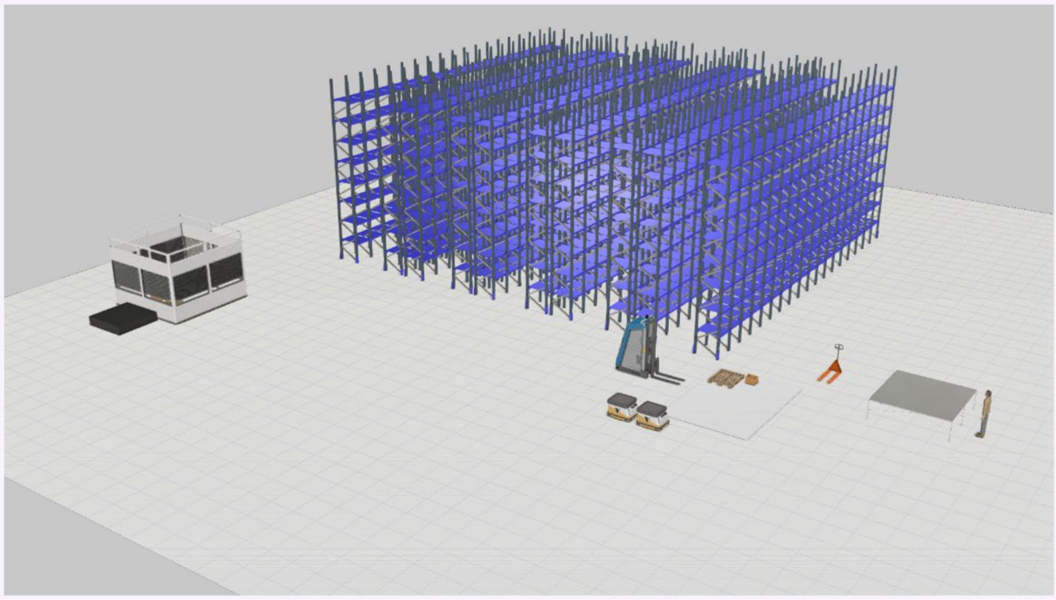

FIGURE 16
A visual representation of the onshore warehouse to be used for one oil production installation at the company in this study. A combination of technological tools such as robotics and IIoT and human warehouse operators is envisioned. There is much shelf space allocated – additionally, there is a control room for human warehouse operators to the left and a consolidation area to the right. The technological tools, such as automated guided vehicles (AGV) and mobile robots, are situated by the consolidation area when not in use.

new digital solutions simultaneously. The initial investments and manpower required to perform such a level of multitasking will be high, and thus the expenditure would increase for a short period of time before starting to decrease. Results will not be observed immediately.

The training and re-training of relevant personnel will be necessary. This will likely be a large effort. As many of the warehouse workers who will be employed have largely performed many tasks manually previously, the learning curves of some personnel will be steep. Additionally, the new software and upgrades will require SCM personnel centrally in the company as well as some supplier personnel to participate in training measures. This will be time consuming and costly.

As software is upgraded gradually in efforts across departments in oil and gas companies, the possibilities of optimization start to improve. For the company in this study this is the exact case. Software upgrades are determined implemented in the company, and future installations get the opportunity to start without many of the issues faced by other installations at their respective times of initiation. Thus, optimization efforts are likely to be successful with optimal planning.

However, this study illustrates that the ambitions of the company are rather high compared to the company's position today. The future digital supply chain and track and trace architecture presented in Figures 14, 15 are achievable, but small steps must be taken for several years before they are fully implemented. Starting with the software upgrade, the next viable implementation step is IIoT technology implementation. As software upgrades allow for tracking of material, sensors or tags should be implemented quickly to enable desired visibility across the value chain. Thereafter, mobile robot solutions such as the ones illustrated in Figure 16 can be implemented gradually to complete the desired level of smartness in the warehouse.

For success to be achieved in smart warehousing in the oil and gas industry, continuous monitoring of optimization efforts must be conducted. The term "emerging technologies" will likely be a continuously evolving term, with new technologies added regularly as technological advancements are made. Objectives such as digitalization levels, waste reduction, and efficiency of activities should be used to measure performance against, ensuring continuous development and progress. As monitoring is done and changes determined, strategies and goals should also change.

5 Conclusion

This research contributes new knowledge by addressing the specific ambitions of an oil and gas company in adopting smart warehousing practices. The framework used offers a strategic approach to implementing these technologies, providing actionable recommendations for industry stakeholders. Updated warehouse activities and IIoT function in the warehouse are presented. A complete depiction of an upgraded digital supply chain is also presented. The findings demonstrate the transformative potential of Industry 4.0 technologies in the oil and gas sector. By integrating digital platforms, analytics, and emerging technologies, companies can achieve improvements in efficiency, cost reduction, and sustainability. These results are supported by earlier studies (Seyedan et al., 2023; Pratap et al., 2024), underscoring the practical implications of smart warehousing.

5.1 Future work

This study presents designs for the future of spare parts warehousing for an oil and gas production company in Norway. Considering the company's ambitions to achieve visibility and predictability of material across the supply chain, it is believed that appropriate technology implementation presented in this study can enable smart warehousing. Other factors such as company readiness must also be considered before full-scale implementation. The work will likely take many years to conclude, as the process is complex. However, the recommendation is to start implementation measures soon to ensure timely progress.

Significant improvement of spare parts warehousing is possible for the industry. Future research is suggested to build upon current knowledge and results. Examples of potential future research include action research where current oil and gas employees are polled for opinions on optimization measures, further visual simulation of technology implementation to observe results of optimization measures, and observational studies of practical implementation in small or large scales in warehouses. Future research should also explore the long-term impacts of these implementations and further refine the proposed framework.

There is a likelihood of increased smart warehousing in the oil and gas industry in the future. Studies such as this demonstrate that inspiration and lessons can be drawn from other industries like e-commerce and retail. Technologies are present in the market, and guiding principles for smart warehouse implementation for the oil and gas industry are increasing in published research. Future research opportunities into smart warehousing in large scale oil and gas or manufacturing companies are increasing as there is more work to base research on.

This study may be used to provide direction for practical studies, either in simulations or in reality. Managers may adopt the new warehouse processes and use the new digital supply chain overview to update practices along the supply chain. Policymakers may use this study's insights to develop regulations and standards that promote the adoption of advanced technologies in the industry. This can help ensure the sector remains competitive and sustainable.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

NK: Conceptualization, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. WS: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. HY: Conceptualization, Supervision, Writing – review & editing. BR: Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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