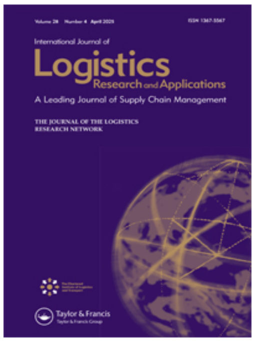

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Integrated green supply chain system development with digital transformation

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ABSTRACT
Green Supply Chain Management (GSCM) integrated with digital transformation (DT) presents a twin transition opportunity for balancing economic growth and environmental sustainability. This study addresses leveraging digital technologies to reduce carbon emissions while enhancing operational efficiency, reflecting the global emphasis on green transformation as seen in UN Climate Change Conferences (COPs) and policies like the EU's Carbon Boundary Adjustment Mechanism (CBAM). Using a combination of science-based system dynamics (SD) modelling approach and case study, we develop a comprehensive green supply chain zero carbon emission management system with DT. The selected case company exemplifies successful integration of green supply chain strategies and DT, demonstrating twin transition strategies that strengthen the synergy between green and digital transformations. Six scenario analyses highlight that adopting green eco-strategies promotes both economic growth and environmental sustainability, offering a win-win solution for global supply chains and providing practical guidance for sustainable business transformation.

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Green supply chain; digital transformation; carbon management; system dynamics; sustainable system development; ESG

1. Introduction

Over the past two decades, the need to protect the environment and conserve resources has grown significantly (Zhu and Sarkis 2004; Villena, Wilhelm, and Xiao 2021), placing green supply chain management (GSCM) at the forefront of corporate sustainability efforts (Linton, Klassen, and Jayaraman 2007; Govindan et al. 2014). The recently concluded COP29 has also demonstrated the growing significance of digitalisation and green transformation on the global agenda. Governments worldwide have crafted policies and regulations that enterprises are expected to adhere to, steering their development towards a sustainable transformation (United Nations 2015). For example, the EU is gradually implementing its Carbon Boundary Adjustment Mechanism (CBAM) starting in 2023, which imposes a carbon tax on specific imported goods, including iron and steel, aluminum products, and cement, to promote global low-carbon production. The World Environment Assembly continues to urge countries to adopt a green and eco-friendly development model to mitigate environmental degradation resulting from economic growth.

As the pace of global digitalisation accelerates, there is a coordinated effort among governments, businesses, and social organisations to investigate innovative approaches to leveraging digital

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technologies for promoting green transformation. This journey necessitates the adoption of digital transformation (DT), encompassing the integration of green energy, advancements in energy storage, and the development of smart grids (Teece 2010). The precision offered by DT enables a meticulous accounting of carbon emissions, facilitating the strategic acquisition or innovation of carbon rights to reach carbon neutrality (Qiao et al. 2023). Should businesses fall short in their efforts to conserve energy and slash carbon emissions, they risk being sidelined by the market, witness a decline in competitive edge, and suffer a loss of customer credibility. The reluctance of new talent to join and the escalation of operational costs could precipitate a protracted downward spiral (Feng, Lai and Zhu 2022). A strategic, systematic approach is essential to pinpoint the carbon peak and subsequently embark on an energy transition that curtails carbon emissions, aiming for carbon neutrality (C3S 2023). As pointed out by Blanco (2021), most of the carbon emissions of enterprises exist in the supply chain link, which means that the green development of the supply chain is crucial for the realisation of the overall carbon emission reduction target of enterprises. Therefore, it is of great relevance to delve into the role of supply chain digitisation in promoting green development. Because supply chains are typical complex systems with important feedbacks among the partners, system dynamics (SD) is well suited for supply modelling and policy design (Sterman 2000).,While DT brings opportunities for sustainability, there is a need for systematic integration between digital technology and the operation of the complex system (Yan, Chien and Yang 2016). The complexity and dynamics of modern supply chain networks require advanced research methodologies to fully understand and implement effective DT strategies. Thus, twin transition strategies that enforce indisputable complementary relationship between green and DT provide a proper angle to foster the supply chain system development.

Despite the increasing importance of DT in business operations, current research on DT of green supply chains is still significantly deficient. Most of the existing research focuses on theoretical model construction or assessment of the impact of transformation on economic performance (Balakrishnan and Ramanathan 2021; Hallikas, Lmmonen, and Brax 2021), and there is a lack of sufficient research support on the practical effects of embedding digital technologies into various aspects of GSCM. This has resulted in a lack of effective theoretical guidance and practical references for companies seeking to achieve GSCM through DT. Moreover, the dynamism of the industrial environment requires companies to have the ability to flexibly adjust their strategies to cope with the ever-changing market conditions and technological advancements (Teece 2010). The resources and capabilities that a company possesses are the foundation of its strategic planning, and effective strategic planning often relies on the unique utilisation of these resources and capabilities (Barney 1991). Therefore, studying how companies demonstrate dynamic strategic capabilities in imperfect environments and under resource constraints has become a focus of attention in academia and industry.

In order to gain insight into the key success factors, major barriers, and potential best practices in green supply chain systems, this study integrates in-depth insights from a successful real-world case study and a systems approach. The objective is to provide a comprehensive theoretical and practical framework for the DT of green supply chain system development. The analysis of exemplary enterprise cases and the development and verification of SD models facilitate the optimal integration of sustainability and DT in green supply chain systems.

2. Related literature

2.1. Green supply chain management

GSCM is defined as integrating environmental thinking into the management of supply chain relationships to obtain value enhancements (Sarkis, Zhu, and Lai 2011; Liew and Cao 2024). GSCM aims to maximise resource utilisation throughout the entire supply chain while minimising its negative impact on the environment (Li, Zhang, and Li 2020). Previous research on GSCM has focused on four main areas: pressure, practice and performance, and the relationship between the three.

GSCM stress, the push for companies to engage in GSCM practices, was an early research topic and is now widely studied, mainly from internal and external perspectives (Li et al., 2020) and stakeholder perspectives (Sarkis, Gonzalez-Torre, and Adenso-Diaz 2010; Kitsis, Thoben, and Zsidisin 2011). The organisation's internal drivers are the focus of pressure to engage in GSCM practices, including organisational support, firm-specific competencies and cross-functional communication, and the necessary human and financial resources (Wu, Ding, and Chen 2012; Wang, Li, and Wang 2018). Institutional theory explores how external pressures can drive companies to implement certain organisational practices (Dacin, Goodstein, and Richard 2002; Sarkis, Zhu, and Lai 2011). Based on this foundation, external pressures can be categorised as regulatory pressures (coercive) (Liang et al. 2007), market pressures (normative) (Zhu and Sarkis 2007; Sarkis, Zhu, and Lai 2011), and competitive pressures (mimetic) (Sarkis, Zhu, and Lai 2011; DiMaggio and Powell 1983; Zhu and Sarkis 2007). Early literature also highlights the importance of imitation in the implementation of GSCM by firms in developed countries such as Canada, France, and Germany (Aerts, Cormier, and Magnan 2006). The above view is consistent with Zheng et al. (2020), who argue that institutional pressure is a significant driver of corporate environmental action.

Since 2010, there has been a growing body of research on GSCM practices and their impact on performance (Tseng et al. 2019a). According to Seman et al. (2019), businesses can use GSCM practices to withstand environmental pressures from regulators and the public. In-house green practices focus on company-wide eco-design of internal processes to improve environmental performance (Wang, Li, and Wang 2018; Stekelorum et al. 2021). The former focuses on reducing waste and improving efficiency within the company, while the latter involves green cooperation with suppliers (Wang, Li, and Wang 2018; Li et al., 2020). Zhu and Sarkis (2004) argue that the rationale for the existence of GSCM practices is to improve environmental performance, and that these relationships are moderated by quality management and lean manufacturing practices. Vachon and Klassen (2008) suggest that upstream practices are more closely linked with process-based performance, while downstream collaboration is associated with product-based performance. Li et al. (2020) revealthe relationship between GSCM pressures, practices, and performance under the moderating effect of Quick Response (QR) techniques. Liew and Cao (2024) hold that higher GSCM quality increases the likelihood that firms will disclose information about their Category 3 carbon emissions and reduces their Category 3 carbon emissions. Wu et al. (2024) propose that institutional investors' ESG activism leads target firms to improve their GSCM performance, where technology integration and technology impact positively moderated the relationship between institutional investors' ESG activism and GSCM performance.

2.2. Digital transformation for green supply chain

DT is a prominent feature of the new era of economic activity. UNIDO (2019) defines digital technologies in the Industry 4.0 era as hardware, software, and connectivity that facilitate the transformation of manufacturing activities and operational integration among supply chain members. Frank, Dalenogare, and Ayala (2019) suggest that these technologies can converge to provide digital solutions that support specific activities in supply chain operations, creating smart supply chains. Vial (2019) defines DT as a process through which an organisation uses digital technologies to respond to changes in the environment and transform its value creation process.

In recent years, the carbon emission reduction effect of DT has attracted increasing attention from scholars. Existing studies focus more on the impact of DT on carbon emissions within their firms. For example, Shang et al. (2023) propose that DT can significantly reduce carbon emission intensity by improving the enterprise's technological innovation capability, internal control capability, and environmental information disclosure capability; Zhou and Liu (2024) regard that DT notably improves ESG performance based on the perspective of environmental regulations.

Li and Zhang (2024) find that DT positively contributes to ESG performance, with absorptive capacity being the channel through which DT affects their ESG performance.

At the supply chain level, a growing debate in academia and practice focuses on how DT can support the implementation of GSCM (Hohn and Durach 2021). Feng et al. (2022) propose that manufacturing enterprises can enhance the efficiency of their GSCM activities by using digital technology applications by a concept of Green supply chain innovation (GSCI). GSCI is defined as an innovative practice by manufacturers that uses emerging digital technologies to integrate environmental issues into supply chain management activities. Belhadi et al. (2024) posit that the integration of data analytics capabilities into a comprehensive business transformation is instrumental in enhancing supply chain carbon transparency, thereby optimising its carbon and economic performance. While some of these technologies may not be as powerful as expected, the widespread adoption of new digital technologies clearly signals the need for firms to undergo DT (Verhoef et al. 2021). Despite the growing literature on DT in operations management and the development of supply chain management (Erboz, Hüseyinoğlu, and Szegedi 2021), there is a serious lack of research on the role of digital technology-related innovations in GSCM, and few systematic studies on the concept and practice of green supply chain digital transformation (GSCDT). In fact, GSCDT is gaining traction in practice, especially with manufacturing companies such as Huawei and BYD. BYD, a new energy vehicle manufacturer in China, and its partners have jointly launched a blockchain-enabled green ecosystem with supply chain partners. The ecosystem provides new value to customers by issuing carbon points to users who have made efforts to reduce their daily carbon emissions (Han et al. 2020). Apple is also trying to green its supply chain by using recycling robots for removable phones.

Therefore, it is of great significance to reinforce the research on GSCDT and thoroughly explore its application and realisation mechanism within organisational contexts. This will enable the development of guidance for enterprises on how to leverage digital technologies to enhance their GSCM capabilities. In this study, based on Sarkis, Zhu, and Lai's (2011) definition of GSCM and Vial's (2019) definition of DT, we define GSCDT as a process centred on environmental protection that promotes supply chain sustainability by deploying information technology, computing power, communication and connectivity technologies in different implementation dimensions of supply chain management to significantly improve operations.

3. Methodology

SD is a powerful method for gaining useful insights into situations of dynamic complexity and policy resistance (Sterman 2000). SD has an analytical capability that can be more science-based to be adopted for visualising the strategic architecture and model building (Yan, Hong and Warren 2022). Many of the tools of SD are designed to help develop useful, reliable and effective models to serve as virtual worlds to aid learning and policy design. The principle for realising GSCDT in this study is the use of causal loop diagram (CLD) analysis and computer model scenario analysis to project into the future. The pragmatism research philosophy emphasises the practical consequences and real-world applications of ideas and theories. It is therefore axiomatic that theoretical studies must be integrated with field work. CLD and stock and flow diagram (SFD) here are the analytical models. How the GSCDT system and strategic architecture facilitate knowledge visualisation and decision-making is well explained and illustrated with the demonstrations of a real-world case company, where we can explore and find evidence from the real world to make the analysis more comprehensive. Thus, the case study approach and system dynamics modelling are complementary. It is not a purely qualitative study, but also relies on empirical data for quantitative exploration, and therefore data availability is one of the core considerations in this study.

This research is designed for both quantitative analysis and a qualitative case study (Figure 1). Firstly, a representative international manufacturing company with global supply chain operations was selected for a case study. The objective is to examine the ways in which the company has

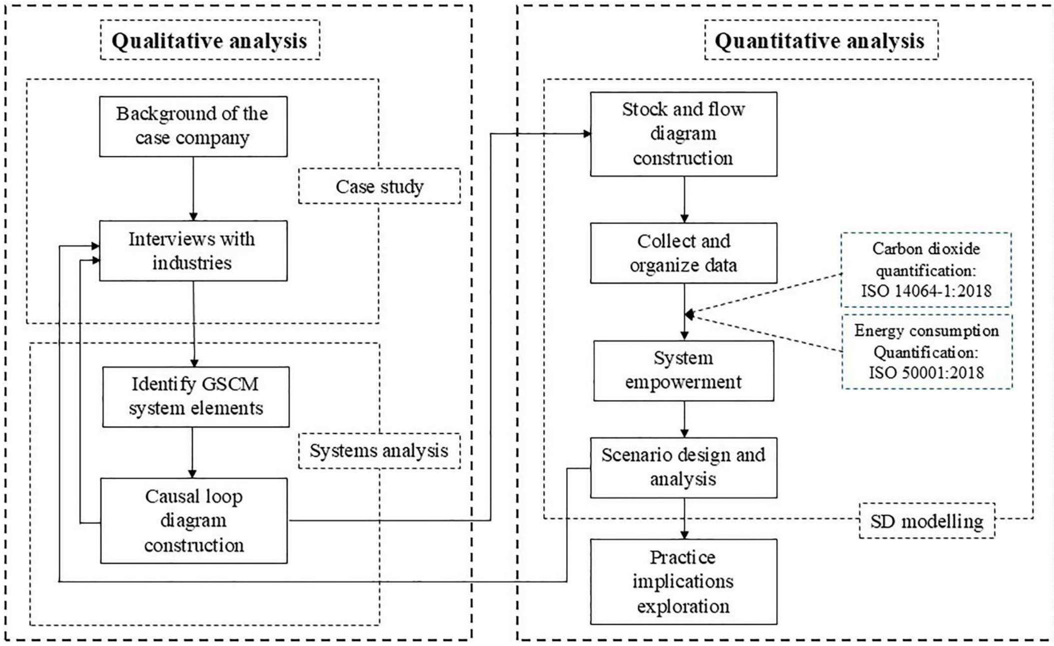

Figure 1. Research design.

enhanced its competitive advantage through the implementation of GSCM and DT strategies, enabling it to more effectively navigate environmental standards in the EU and other global markets. Subsequently, a systems analysis approach was employed to identify the system components of GSCM, and a CLD was constructed to analyse the main feedback loops of the system and their interactions. On the basis of a qualitative analysis, we employ the SD modelling method to construct an SFD and quantify the corresponding carbon emissions and energy consumption in accordance with the standards set forth in ISO 14064-1:2018 and ISO 50001:2018, respectively. We then assign and validate the model to conduct scenario analysis and propose corresponding policy recommendations. The case study is a team work from identifying the model scope to the modelling development of strategic architecture and simulation-based scenario analysis, working closely with the company for empirical research.

3.1. System dynamics

SD is a computer simulation method for studying the dynamic behaviour of complex systems, often referred to as 'strategy labs'. It was first developed by Jay Forrester in the mid-1950s (Forrester 1994). By constructing system models that contain dynamic causal relationships, SD can reveal patterns of system behaviours, demonstrate complex interactions between variables, and simulate system evolution and future trends. At its core, SD uses feedback loops and stocks and flows to model how changes in one part of a system can affect other parts over time. Feedback loops are categorised into reinforcing (positive) loops, which amplify changes, and balancing (negative) loops, which tend to stabilise the system. Stocks represent accumulations of material or information, while flows dictate the rates at which these stocks change. By integrating these elements, SD models can capture the intricate causal relationships within systems, providing a comprehensive view of how various components interact and influence each other (Sterman 2000).

SD modelling has significant advantages in forecasting with high accuracy and transparency (Lyneis 2000). This study highlights the importance of using SD to combine qualitative and quantitative aspects, address complex system dynamics (as noted by Yu et al. 2020), and link observable patterns of system behaviour to microstructures and decision-making processes (as discussed by Hassan and Baek 2010). In essence, the system can capture and analyse the intricate causal relationships within the supply chain, thereby revealing the dynamic evolution and potential impacts of the GSCM process. The process is represented using CLDand SFD. CLDs visually depict the feedback loops and causal relationships between variables, helping to identify key leverage points for intervention. SFDs provide a detailed representation of the system's structure, showing how stocks accumulate and change over time due to inflows and outflows. We construct a personalised SD model to simulate the key elements and processes in a green supply chain. These elements include energy consumption, carbon emissions, green procurement, internal carbon pricing, etc. The processes cover the entire life cycle from raw material procurement to product production, distribution, and final consumption. By simulating the dynamic changes of these elements and processes over time and space, potential bottlenecks and opportunities in GSCDT can be revealed. This provides a scientific basis for enterprises to develop effective green strategies. Additionally, SD facilitates scenario analysis, allowing organisations to explore different policy interventions and their long-term impacts. For instance, what-if scenarios can help assess the effects of varying levels of green procurement or internal carbon pricing on overall sustainability goals (Ford 2010). In brief, by employing dynamic thinking, SD can assist us in making informed decisions and predictions. It offers a thorough and methodical analytical framework for resolving practical issues. As a tool for visualisation, risk prediction, dynamic simulation, and cost saving in test execution, it is undoubtedly a highly beneficial theory and tool for companies or organisations of all sizes (Yan 2022).

3.2. Case study

Case studies are frequently cited in education and other social science research, and a case study is defined as a methodology, methodology, or research design. The purpose of the case study is to explore and describe the context in which understanding is promoted. A case study can be defined as an in-depth study of a person, a group of people, or a unit, and if the researcher only wants to study a single thing or a single group, then a single case study is the best option (Yin, 2013). It allows us to gain a deeper understanding of the topics being explored. Another benefit is that a single case study can richly describe the existence of a phenomenon (Gustafsson 2017). It helps to gain a deeper understanding of a particular company's strategies, practices, and outcomes in the direction of the content being studied, providing more specific and in-depth analysis and insights.

The case study approach enables the observation of specific manifestations and impacts of DT in a real-world context, capturing the nuances and individualised strategies of companies in the transformation process. By deeply analyzing the strategic behaviour of specific companies, researchers can reveal how companies respond to environmental changes through innovation and adaptive adjustments (Yin 2013).

In this study, the selected case study is an exemplary application of the model. The company has used the modelling and management system to predict the feasibility of GSCDT, and has continued to expand the scale of its green supply chain to attract a large number of green consumers, which is a representative example of the development and practice of the model. The case study was carefully selected based on the following key characteristics: (1) it excels in demonstrating the dynamic evolution of the GSCDT process and strategic decision-making in response to business challenges, providing the study with rich and valuable dynamic information and a clear insight into the actual logic of how the field operates; (2) the case company's co-founder and chief executive officer (CEO) has actively collaborated with the researchers. This collaboration played a key role in the empirical investigation and data collection process, not only ensuring the accuracy and timeliness of the data, but also facilitating in-depth investigation, such as helping to open up some data access channels and answering professional questions during the research process; (3) the company used a scientific data-driven model as the planning framework for the GSCDT to accurately assess the real-time data collection work and business challenges, compared to the traditional data-driven model, which is a more accurate assessment than the traditional data-driven model. Compared with traditional models, this science-driven model can integrate resources and optimise decision-making more efficiently, enabling the company to move forward steadily on the road to green supply chain transformation.

4. Causality model

4.1. Introduction of the case company

Founded in 1990, Everbiz Industrial CO., Ltd. has positioned itself as a leader in Taiwan's electronic wire industry. With a global clientele across diverse sectors, Everbiz Industrial distinguishes itself from general wire processing plants through its dedicated R&D department, providing comprehensive wire solutions.

Committed to meeting international green supply chain standards and aligning with the CBAM, Everbiz Industrial integrates environmental protection awareness and persistence into daily operations, and continues to strengthen sustainable environmental protection measures in five aspects: climate change, energy management, water management, waste management and air pollution control, so as to protect the global environment and enhance corporate value. Everbiz Industrial has vigorously promoted the DT for 17 years. The company has set up a smart management department to optimise some processes, such as the application of RPA process optimisation in pre-production operations, reduce costs, improve personnel efficiency and consulting inheritance, and optimise the power grid and process, optimise quality, and use AI AOI, improve quality and efficiency.

Embracing the role of a 'carbon handprint' in the industry, Everbiz Industrial is committed to delivering tangible carbon reduction benefits to its customers while maintaining its core value of digital green energy. The company's dedication to sustainability and digital innovation has earned it prestigious accolades such as the DT Dingge Award in 2021, the National Rock Award, and the Taiwan Sustainable Action Gold Level in 2023.

4.2. GSCM causal loop diagram

The basic elements of a CLD consist of variables, causal chains, and delays. Causal chains have positive and negative polarity and describe the sequence of events that result in a change in the system's state. Delay indicates a significant time delay for the causal chain to function, which creates instability and increases the system's tendency to oscillate (Sterman 2000). A feedback loop is formed when variables return to themselves through the causal chain. The number of causal chains with negative polarity determines whether it is a reinforcing or balancing feedback loop. A feedback loop is a reinforcing loop if it has an even number of causal chains with negative polarity. Conversely, it is a balancing loop if it has an odd number (Wu et al. 2015).

In this study, we identify the key variables and the major causal relationships by referring to previous literature and with further logical refinement and interviews with industries. The CLD of the case company's green supply chain is constructed (Figure 2). The main reinforcing feedback loops R1-R7 are introduced as follows:

R1/R2: supply chain resources(+)→DT(-)→GSC energy consumptionGSC carbon emission(-)→GSC customers(+)→order(+)→operation revenue(+)→GSC customer profits(+)→GSC scale(+)→supply chain resources

R3: supply chain resources(+)→DT(-)→GSC carbon emission(-)→carbon tax(+)→GSC customer profits(+)→GSC scale(+)→supply chain resources

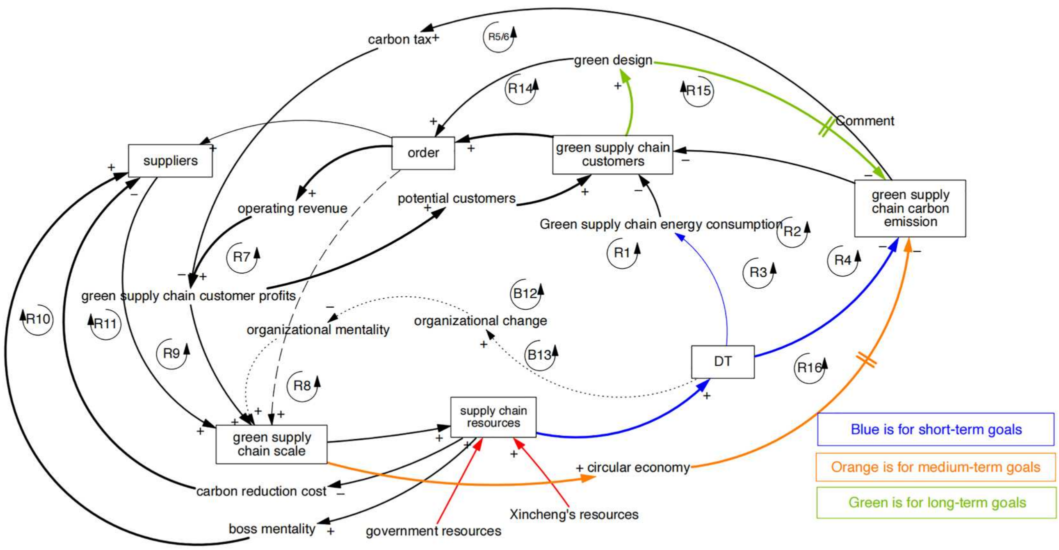

Figure 2. GSCM causal loop diagram.

R4: supply chain resources(-)→carbon reduction cost(-)→suppliers(+)→GSC scale(+)→supply chain resources

R5: supply chain resources(+)→boss mentality(+)→suppliers(+)→GSC scale(+)→supply chain resources

R6: GSC customer profits(+)→potential customers(+)→GSC customers(+)→order(+)→operation revenue(+)→GSC customer profits

R7: GSC customers(+)→green design(-)→GSC carbon emission(-)→GSC customers

The reinforcing feedback loops R1 and R2 in Figure 2 show the effect of reducing energy consumption and carbon emissions on the scale of GSC by adopting DT. Specifically, the inputs of Everbiz Industrial' resources and government resources (e.g. funds, tax incentives, subsidies or technical assistance, etc.) increase the overall supply chain resources, including labour, raw materials and technology. These new resource inputs can improve the accuracy and efficiency of supply chain management in the short term, help reduce GSC energy consumption (R1) and GSC carbon emissions (R2), attract more environmentally conscious customers, and increase order volumes, which in turn increase revenues, customer profits, and supply chain scales.

In particular, the introduction of a carbon tax (R3) shows that reducing carbon emissions not only helps the environment, but also reduces the tax burden, further increasing the profitability of GSC customers and the supply chain scales. In addition, as the number of GSC customers increases, more potential customers are attracted (R6), and supply chain scales are driven by increased orders, which in turn increases supply chain resources. In addition, the growth in orders not only brings more suppliers on board (R9), but also directly contributes to the growth in supply chain scales (R10).

Similarly, the optimisation of supply chain resources reduces the carbon reduction cost (R4), which in turn attracts more suppliers to join, thereby increasing the GSC scale, which in turn further contributes to the enrichment and optimisation of supply chain resources. The increase in supply chain resources also leads to more positive engagement by business owners, and this positive boss mentality (R5) attracts more suppliers to join, driving the expansion of the GSC scale and ultimately enriching supply chain resources.

Over time, the expansion of the GSC scale will have a positive impact on the circular economy, which in turn will help to reduce carbon emissions from the GSC. However, this carbon reduction effect may occur gradually at the end of the product life cycle, i.e. after the product has been discarded, through the implementation of the circular economy, so there will be a time delay in the effectiveness of reducing carbon emissions from the GSC (R11). GSC customers are also beginning to learn how to use green design, which takes into account low energy consumption and low carbon emissions at the product design stage, so there is a delayed effect of GSC carbon emissions (R7), which in turn affects the carbon tax, and finally benefit suppliers and GSC customers in the GSC by increasing the volume of orders (R8).

At the same time, the presence of balancing loops (B1: supply chain resources(+)→DT(+)→organisational change(-)→organisational mentality(+)→GSC scale(+)→supply chain resources) limits excessive system growth and ensures stability. While improving efficiency, DT may cause organisational changes, leading to the emergence of some organisational mindsets that are not adapted to the changes. Such changes may temporarily reduce GSC resources, resulting in a self-regulating mechanism that keeps the system in balance.

5. Stock and flow model

5.1. Main variables and subsystem composition

The SFD provides a comprehensive description of the movement of materials and information within a system by introducing different types of variables, such as level variables, rate variables, auxiliary variables, and constants. Considering the principles of representativeness, accessibility, and simplification, the SFD consists of 41 carefully selected variables that represent the reality of the case company's GSCM.

Level variables, also known as stocks, are variables used to describe the accumulation of certain quantities in the system over time. These variables act as reservoirs that accumulate past events through changes in inflow and outflow quantities, thereby providing the system with a memory function. Stocks can be thought of as accumulations or storages of material, information, or resources within the system. In this paper, the SFD includes eight level variables, which are green potential partners, green supply chain partners, carbon surveys, implementation of energy-saving and emission reduction, supply chain carbon emissions, total reduced carbon emissions, green supply chain customers, and the amount of green supply chain orders. For example, the variable 'green potential partners' represents potential suppliers or partners who adhere to green practices, while 'supply chain carbon emissions' tracks the total emissions generated by the supply chain.

Rate variables, also known as flows, describe the speed at which level variables change over time. Flows are characterised by their immediacy and represent the processes that cause changes in stocks. They depict the rate of inflow or outflow from a stock, illustrating how quickly these accumulations increase or decrease. For instance, flows such as 'joining green potential partners' and 'exiting green potential partners' describe the rate of change in the number of potential green partners. Similarly, the flow 'reducing carbon emissions' indicates the rate at which carbon emissions decrease due to implemented measures.

Auxiliaries are variables used in the model to describe internal relationships within the system, assist in calculating other variables, or simplify complex relationships. These variables help define the logic and rules governing the interactions between stocks and flows. Examples include perpetual innovation demand, which reflects the continuous need for innovation in green practices, and perpetual operation demand, which represents ongoing operational requirements for maintaining green standards.

Constants refer to factors that do not change over time in a given system. These variables provide a stable reference point within the model. For instance, the cost exceeding willingness in the model is a constant, representing a threshold beyond which additional costs are not acceptable.

The purpose of the model is to construct a customised business architecture model for the company, creating a virtual microcosm that simulates issues and trends. This aids in understanding how

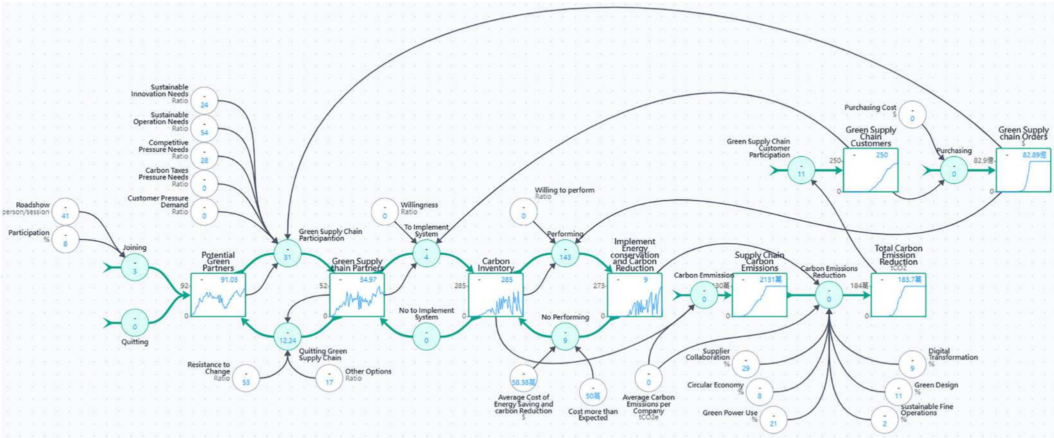

Figure 3. Key stock and flow diagram.

various elements/variables interact over time (Mitropoulos, Adamides, and Mitropoulos 2023). This paper delineates seven key components for the construction of a carbon emission management model, based on Figure 3, which are designed to address various aspects of carbon footprint reduction. These components encompass the greenhouse gas emissions management, carbon reduction solutions, internal carbon pricing and carbon rights, consumption reduction solutions, estimated revenue, profit and carbon emission and buying green power (for further details, refer to Figure 4). They primarily serve the following objectives:

(1) Achieve a 30% reduction in emissions by 2030 by gradually decreasing energy consumption and implementing digital management to establish new standards for green production.
(2) Promote waste reduction in packaging and the use of low-carbon raw materials, build a green supply chain, and reduce the environmental burden.
(3) Optimise plant operations and heavy industry to improve production efficiency, with reducing energy consumption and emissions as the primary means of carbon reduction.
(4) Streamline personnel through smart management, achieve a significant improvement in operational efficiency, and promote sustainable development of the enterprise.

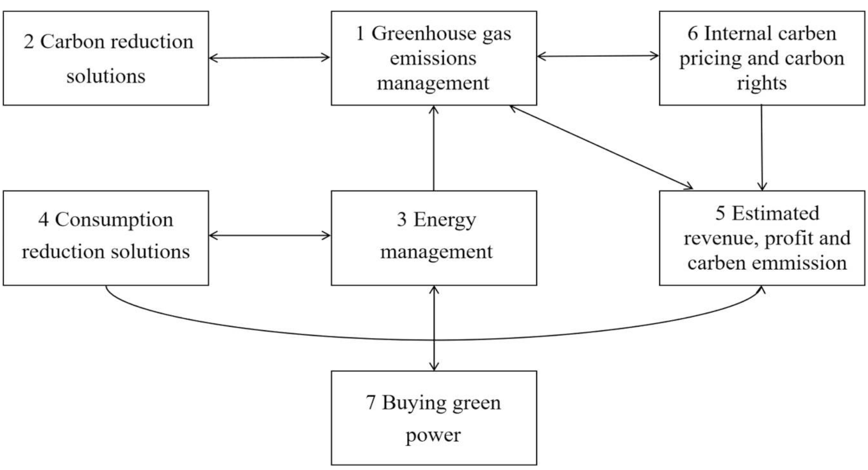

Figure 4. Subsystem composition chart.

The SFD provides a robust framework for modelling the dynamic behaviour of the GSCM process. By incorporating stocks, flows, auxiliaries, and constants, the model captures the intricate causal relationships within the supply chain, revealing the dynamic evolution and potential impacts of the GSCM process. This approach facilitates scenario analysis, allowing organisations to explore different policy interventions and their long-term impacts, ultimately aiding in the development of effective green strategies.

5.2. GSC net-zero carbon emission management model

Based on Figure 4, this paper constructs a net-zero carbon emission management model for the case company's green supply chain, with the ultimate goal of achieving net-zero carbon reduction. Each of the seven components can be further refined and modelled. The model aims to establish an energy management system based on ISO 50001 standards and assist enterprises in understanding their greenhouse gas emissions through the inventory check according to ISO 14064-1:2018. It also helps in forecasting the peak carbon emissions by estimating the expected turnover. The system correlates improvement measures with internal carbon pricing, allowing enterprises to calculate the time and cost that should be invested in profit and carbon reduction through simulation, thereby formulating a carbon-neutral strategy.

The final green supply chain net-zero carbon emission management model constructed in this paper is shown in Figure 5. The model uses different colours and areas to clearly distinguish between the various subsystems. This section will elaborate on the composition and structure of the subsystems that make up this model in five parts, which will serve as the foundational basis for enterprises to conduct GSCM.

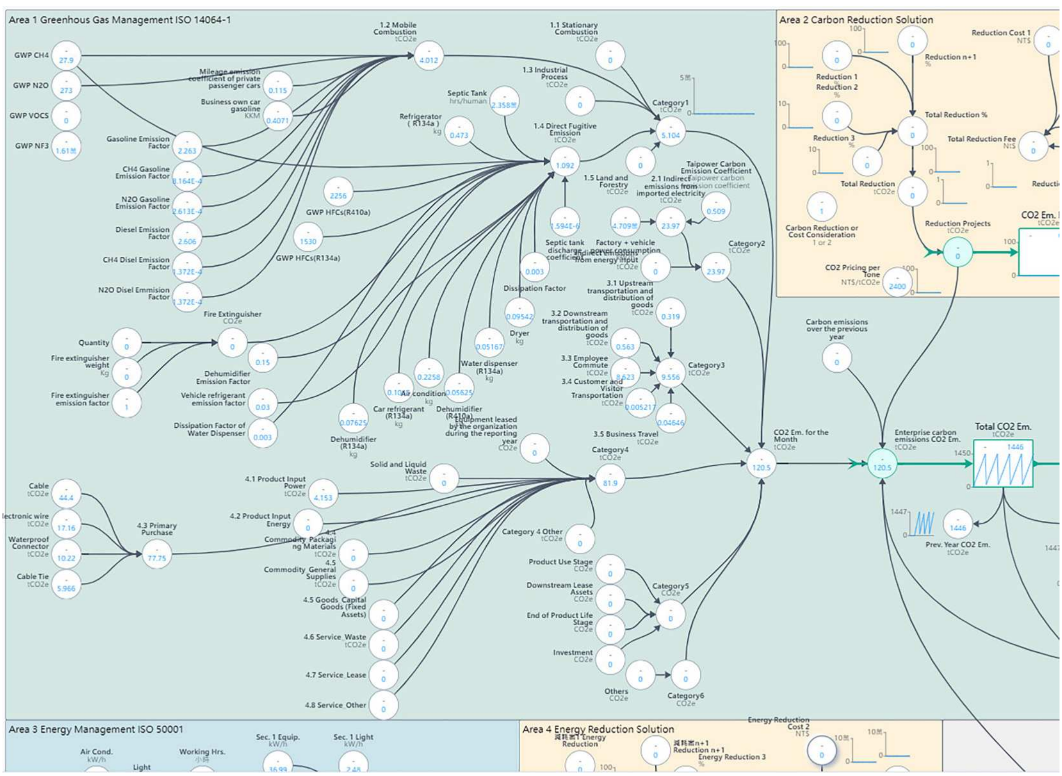

Figure 5. GSC net-zero carbon emission management model.

(1) Subsystems of greenhouse gas emissions management and carbon reduction solutions

The detailed structure of the subsystems of greenhouse gas emissions management and carbon reduction solutions is shown in areas 1 (the light green area) and 2 (the light-yellow area) of Figure 5, respectively.

This paper adopts ISO 14064-1:2018 as the standard to determine the Global Warming Potential (GWP) values for methane (CH4), nitrous oxide (N2O), volatile organic compounds (VOCS), nitrogen trifluoride (NF3), hydrofluorocarbons (HFCs) with R410a, and hydrofluorocarbons (HFCs) with R134a. Greenhouse gases are categorised into six types based on their usage pathways for the purpose of summarisation and representation within the model. Category one pertains to direct emissions, category two to indirect emissions, and categories three to six cover other types. The aggregate monthly carbon emissions from these six categories form the key output variable 'Monthly Carbon Emissions.' Following the identification and classification of greenhouse gas emission sources, data collection and processing are necessary. This process requires not only the selection of appropriate calculation methods and emission factors for the emissions but also ensuring the scientific accuracy and reliability of the data. Thus, this paper conducts a greenhouse gas inventory in accordance with the guidelines for greenhouse gas emissions issued by the environmental protection agency of the country where the case company is based, opting for the emission factor method for calculating emission volumes.

Based on the greenhouse gas inventory outcomes, companies can implement targeted carbon reduction projects to decrease their carbon footprint. As carbon reduction projects vary from year to year, they contribute to a cumulative reduction in carbon emissions. Within the system design, two types of carbon reduction volume indicators are established: one based on the percentage of carbon emissions reduced, and the other, from a cost perspective, based on a predefined investment budget to determine how much carbon can be reduced. Carbon reduction plans are tailored to these different indicators and their results are reflected in the variables 'total carbon reduction percentage' and 'total monthly carbon reduction cost'. Moreover, to quantify the actual reduction effects under the second scheme, the variable 'Price per Ton of Carbon' is introduced, representing the price per ton of carbon dioxide. By dividing the total monthly carbon reduction cost by the price per ton of carbon, the total monthly carbon emission reduction under the second scheme can be calculated.

To address the need for flexible selection of carbon reduction schemes under varying conditions, this paper introduces the variable 'Consideration of Carbon Reduction or Cost.' Through conditional functions, the paper determines which scheme to apply in specific scenarios, with the aggregated results reflected in the 'Total Monthly Carbon Emissions' and quantified annually in 'Total Annual Carbon Reduction.'

Ultimately, by integrating the monthly and cumulative emissions from the previous year, and considering the annual revenue growth rate, an adjusted carbon emission volume is computed. Subtracting the emissions reduced due to carbon reduction improvement projects yields the 'Corporate Carbon Emissions.' The effectiveness of carbon reduction is then visually presented in the 'Total Annual Carbon Emissions' stock through a line chart format.

(2) Subsystem of energy management and consumption reduction solutions

The energy management system is constructed based on the ISO 50001:2018 standard. This paper refines the practices of Everbiz Industrial in the field of energy consumption management into three categories, each corresponding to the management of different types of energy consumption:

Category one focuses on the management of direct emissions, covering aspects that directly generate energy consumption, such as official vehicles.

Category two is aimed at controlling indirect emissions, including electricity usage in workshops for lighting, air conditioning, instrumental equipment, and office computers.

Category three introduces green electricity to offset the current electricity consumption.

The sum of the monthly energy consumption of these three categories is the output result of the variable 'Monthly Energy Consumption,' which serves as the basis for calculating the total energy consumption of the enterprise. Based on this, the enterprise can continuously track the dynamic changes in the energy consumption management model, quickly promote energy-saving projects, and effectively reduce energy consumption.

Since carbon reduction projects may vary each year, the cumulative amount of energy reduction will also differ. Similar to the basic principles of the carbon reduction improvement plan subsystem, this article also establishes two types of energy reduction targets in the process of constructing the energy reduction improvement plan subsystem: one focuses on energy reduction, setting monthly energy reduction percentage targets; the other focuses on cost, with preset investment amounts, to then evaluate the achievable energy reduction effects. The results are presented through the variables 'Total Energy Reduction Percentage' and 'Monthly Total Energy Reduction Cost.' Additionally, the variable 'Consideration of Energy Reduction or Cost' is introduced to toggle between these two approaches. The 'Monthly Total Energy Reduction Cost' is then converted using the 'unit price of electricity,' and the comprehensive energy reduction outcome is displayed through the 'Monthly Total Energy Reduction Quantity'. Ultimately, by combining the monthly energy consumption and that of the previous year, and considering the impact of the annual business turnover growth rate, an adjusted total energy consumption is calculated. Based on this, the energy consumption reduced due to the implementation of energy reduction plans is subtracted to derive the 'Enterprise Energy Consumption Quantity.' The effectiveness of energy reduction is visually presented in the 'Total Annual Energy Consumption' stock through a line chart.

(3) Subsystem of buying green power

The purpose of buying green power is to reduce energy consumption. For every certain amount of buying green power d, there is a corresponding reduction in energy consumption. The proportion of buying green power d is set according to the ISO 50001 target of 10% (RE10). The amount of energy reduction that needs to be purchased is calculated by multiplying the enterprise's total energy consumption with the proportion of buying green power d, and this determines the amount of green power to be acquired.

In addition, users must bear the investment cost when utilising the purchased green power. The investment cost is calculated by multiplying the amount of energy reduction that needs to be purchased by the cost of green power. The cost of green power refers to the price per kilowatt-hour of green power, with an initial value set at 6 yuan per kilowatt-hour. The subsystem for buying green power is detailed in area 7 of Figure 5 (the light blue area).

(4) Subsystem of internal carbon pricing and carbon rights

This subsystem offers an option for internal carbon pricing, enabling enterprises to select the pricing format based on their internal requirements. Internal carbon pricing comes in three forms: shadow pricing, internal carbon fee, and implicit pricing. The implicit price is derived from the historical costs associated with purchasing carbon rights and the market price of carbon. Furthermore, to simplify calculations, a US dollar exchange rate variable has been included. Specifically, the computation of internal carbon pricing relies on the value assigned to the 'ICP Choose' variable. When 'ICP Choose' is set to 1, 2, or 3, the calculation employs either the internal carbon fee, shadow pricing, or implicit pricing, which is then multiplied by the US dollar exchange rate. In all other instances, the internal carbon pricing is designated as zero.

Internal carbon pricing is designated as a fund specifically for the acquisition of carbon rights, and it also dictates the purchase of these credits. When the internal carbon pricing exceeds zero, the quantity of carbon rights is determined by multiplying the company's carbon emissions by the proportion of carbon rights intended for purchase. Once a certain volume of carbon rights is owned or acquired, the enterprise can then proceed to implement actual measures to achieve carbon offsetting, effectively counterbalancing its initial carbon emissions by reducing greenhouse gas emissions in other areas.

In conclusion, the internal carbon pricing and carbon rights subsystem is depicted in area 6 of Figure 5 (the light gray area). Utilising this subsystem, it is possible to assess whether profits are entirely depleted following the implementation of energy conservation, carbon reduction, and the purchase of carbon rights.

(5) Subsystem of estimated revenue, profit and carbon emissions

The subsystem of estimated revenue, profit and carbon emissions is shown in area 3 of Figure 5 (the light purple area).

In the process of building the sub-system, the logic is to set a carbon base year, i.e. to establish a reference point for measuring and evaluating the carbon emissions in a given period of time. In this paper, 2021 is chosen as the carbon base year, and the analysis of the system starts with the setting of the 'base year'. By comparing the data with the base year, the trend in carbon emissions over the years can be clearly demonstrated, and all subsequent projections and calculations are based on the data for that year.

We focus on the results of profit and estimated sales in the system. By combining the monthly estimated sales base, the previous year's monthly sales and the annual sales growth rate, the adjusted estimated sales is calculated, and the sales growth from the innovative second curve is added to this to calculate a more accurate estimated sales. Meanwhile, in order to calculate profit more accurately, this paper further incorporates various cost factors such as marketing expenses. Specifically, by calculating the net profit after deducting various costs from the monthly sales, and further deducting the carbon cost determined by the previous year's carbon emissions, the proportion of purchased carbon rights, the internal carbon price, and the total cost of implementing carbon reduction and consumption reduction, the final profit adjusted for comprehensive costs is obtained.

The annual revenues growth rate is estimated using the ratio of historical revenues to carbon emissions and is set at 20% per year. As revenues increase, so do carbon emissions. To estimate carbon emissions, this is quantified by introducing the variable 'carbon emissions per dollar', which is derived by dividing total carbon emissions in 2021 by sales in the same year. Finally, the 'carbon emitted per dollar' is multiplied by the 'estimated revenue' to arrive at the estimated carbon emissions.

6. Scenario analysis

In the context of contemporary globalisation, the EU and international markets are placing increasing emphasis on green development. This trend is resulting in more stringent requirements being placed on companies. For the case company, this poses a considerable challenge, and its market competitiveness will be seriously undermined if it fails to adapt to the green development trend. The case company has demonstrated commendable market acumen and has proactively implemented strategic adjustments to advance the GSCDT, aiming to meet market demands in an anticipatory manner rather than merely responding to changes. Such forward-looking initiatives have yielded valuable opportunities for the company, enabling it to secure more international orders and gain a favourable position in the global market. The company's strategic planning is aggressive, and it is committed to achieving growth-oriented development. To this end, we have carefully designed six scenarios (Table 1). These scenarios have been formulated through a

Table 1. Scenario design.

Scenarios		Objectives
Scenario I	20% annual turnover growth, no carbon and consumption reduction solutions	Simulating the impact of pursuing revenue growth without taking environmental and cost optimisation measures.
Scenario II	turnover unchanged, carbon reduction only	Simulating the impact of purely environmental or cost-control objective, given constant annual turnover
Scenario III	Turnover unchanged, consumption reduction only	
Scenario IV	20% annual turnover growth, 3% energy savings, 1% carbon reduction, 10% carbon offsets	Simulating the impact of abandoning internal carbon pricing
Scenario V	revenue growth, carbon and consumption reduction and carbon rights change ICP80	Simulating the impact of adjusting internal carbon pricing in the pursuit of revenue growth alongside carbon and consumption reduction.
Scenario VI	revenue growth, carbon and consumption reduction and carbon rights change ICP50	

thorough examination of the company's potential outcomes under various growth trajectories. It is imperative to utilise eight variables: estimated turnover, profit, total carbon emissions, total electricity consumption, carbon neutrality, carbon right purchase, green electricity purchase and internal carbon cost. This will allow for a comprehensive reflection of how the system behaves in different contexts. Of the eight variables, particular attention should be paid to the outputs of three key variables, namely estimated turnover, profit and carbon neutrality. This will allow for an exploration of whether enterprises can realise the dual goals of economic growth and environmental protection under different scenarios.

It is important to acknowledge that these scenarios extend beyond rudimentary alternatives and are founded on divergent objectives and decision-making factors that may arise in genuine business operations. From a pragmatic standpoint, each scenario is characterised by distinct attributes and practical implications. In summary, Scenario I simulates a situation in which firms pursue revenue growth without implementing environmental and cost optimisation measures, which is common in reality, as many firms tend to prioritise economic growth over environmental impacts. Global environmental problems have brought environmental protection into the international spotlight, and the external environment of enterprises has changed profoundly. Public opinion has led to heightened scrutiny of environmental responsibility, with regulators imposing increasingly stringent policies on carbon emissions and other indicators. Market demand has shifted towards green products, and enterprises are under mounting pressure to make critical strategic decisions. In this context, Scenarios II and III focus on carbon and energy reductions, respectively, reflecting a single strategic direction that firms may take in response to environmental pressures.

On the basis of the previous three scenarios, Scenario IV simulates a transitional strategic option at the beginning of the transition, whereby a company aims to attain a specific degree of revenue growth (20% annual turnover growth) while implementing energy saving (3% energy saving) and carbon reduction (1% carbon reduction) measures. However, a comprehensive internal carbon management mechanism has yet to be established, with the pivotal element of internal carbon pricing being neglected. This scenario exemplifies the initial endeavours of an organisation grappling with the dual demands of economic advancement and environmental responsibility, seeking to sustain the impetus of economic growth in a competitive market whilst also attempting to address environmental imperatives. Nonetheless, there has been an absence of comprehensive integration of environmental costs and economic decision-making within the organisation's internal management system.

Scenarios V and VI provide further insights into a company's overall implementation of carbon and energy reduction measures and adjustments to its internal carbon pricing strategy (ICP 80 and ICP 50) as it aggressively pursues revenue growth. By rationalising internal carbon pricing, companies can achieve a more accurate balance of economic costs and environmental benefits, thus enabling them to achieve their strategic goals of sustainable development. The analysis of these scenarios enables companies to develop a more nuanced understanding of the impact of strategic choices on operational performance and sustainability objectives, thereby facilitating more informed decision-making processes.

6.1. Analysis of Scenarios I, II and III

Through in-depth analysis of Scenario I, we can better understand the key role of carbon reduction and consumption reduction solutions in promoting sustainable development and provide a basis for the comparison of subsequent optimisation strategies and other scenario analyses. After running the system in Scenario I, the outputs of the three variables, namely carbon purchase, buying green power and internal carbon cost, are all 0. Specifically, 0 for carbon purchase means that the enterprise does not participate in carbon trading to compensate for its own emissions. A 0 for buying green power indicates that it does not choose to use more environmentally friendly green power, but continues to rely on traditional energy sources with higher carbon emissions, which further increases the environmental burden. The zero internal carbon cost reflects the fact that carbon emissions are not included in the cost accounting system in the financial management of the enterprise, and there is a lack of effective control and management of environmental costs.

In addition, the data shows that the estimated turnover and profit show a trend of steady growth year on year, but the company has not achieved carbon neutrality, and the carbon emissions increase year on year, indicating that the economic benefits have increased, but the environmental burden has also gradually increased. The estimated turnover and profit and the output of carbon neutral operation are shown in Figure 6.

As with the results of Scenario I, the output results of the three variables-carbon rights, buying green power and internal carbon cost – are shown to be 0 after the system runs in Scenarios II and III. In addition, the total electricity consumption of scenarios II and III remains the same, and is not shown in the figure because the turnover remains the same at NT$500 million per year. The output results of profit and carbon neutral operation are shown in Figure 7.

As shown above, where companies only committed to reducing carbon emissions or focused only on reducing energy consumption, none of them achieved carbon neutrality, indicating that

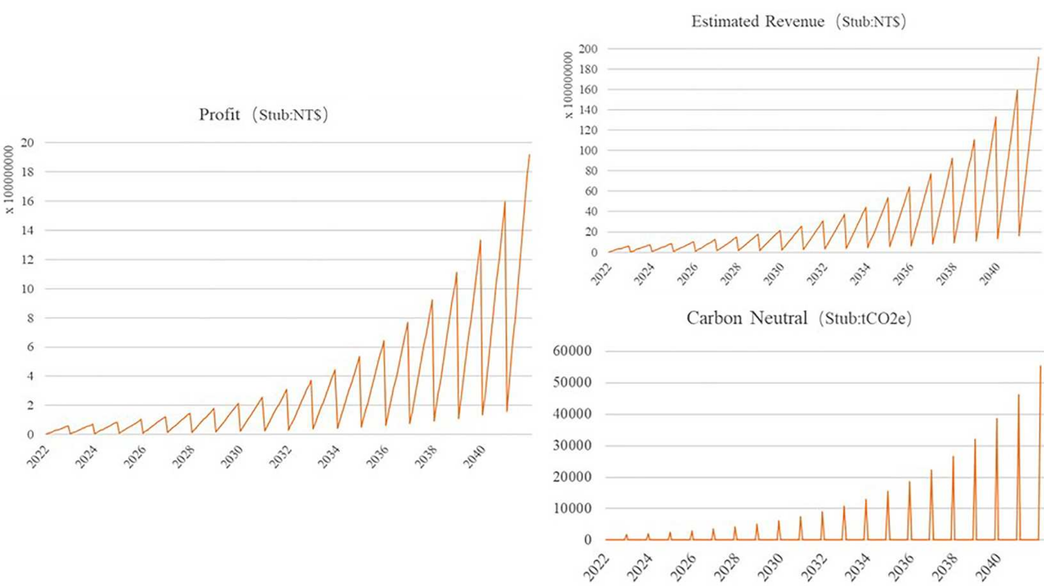

Figure 6. Simulation results of key variables for Scenario I.

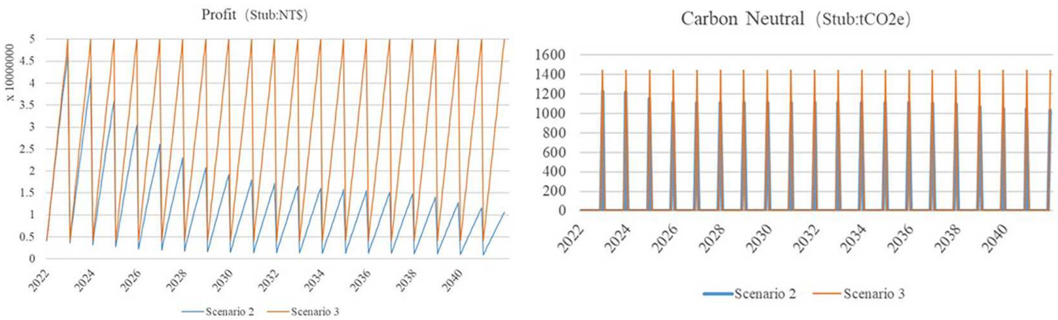

Figure 7. Simulation results of key variables for Scenarios II and III.

a single emission or consumption reduction measure has a limited impact on achieving carbon neutrality in the overall context. Further analysis showed a gradual decline in annual profits in the carbon reduction-only case, suggesting that carbon reduction-only measures gradually erode companies' profitability.

6.2. Analysis of Scenarios IV, V and VI

After running the system, as in the previous three scenarios, the outputs of the three variables of carbon right purchase, buying green power and internal carbon cost in Scenario IV are still zero, while Scenario V shows that none of the eight variables are zero, indicating that all the subsystems are involved. For scenario VI, only the buying green power is shown as 0. The results of the three key scenario variables are shown in Figure 8.

As can be seen in Figure 8, if the company abandons internal carbon pricing, although profits will also increase year on year, the company will ultimately fail to achieve carbon neutrality and its annual carbon emissions will increase, posing a significant threat to the environment. Scenarios V and VI show that adjusting internal carbon pricing can significantly affect the participation of other sub-systems, and the impact on three key variables is very large. Specifically, if the internal

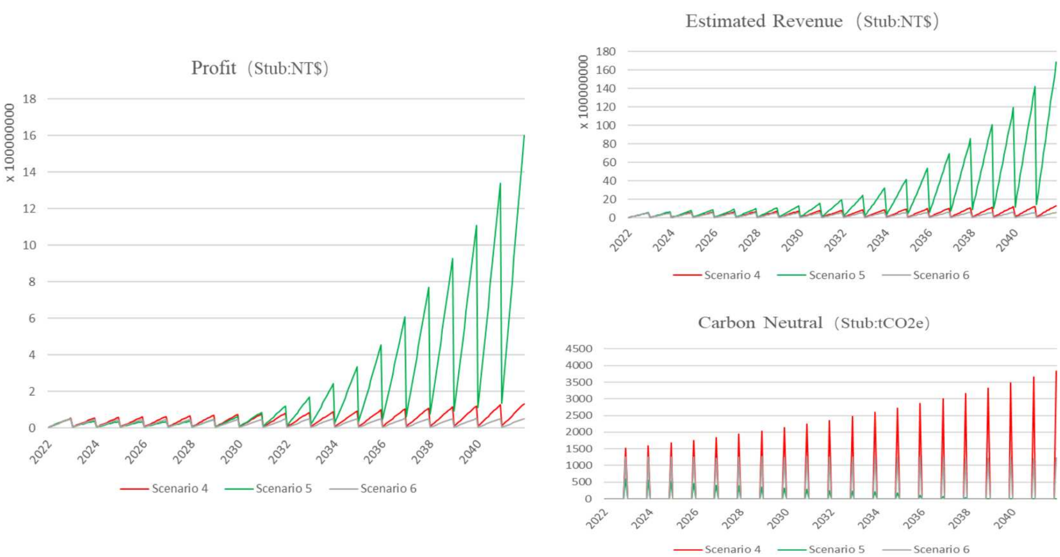

Figure 8. Simulation results of key variables for Scenarios IV, V, and VI.

carbon price (ICP) is set at $50 per ton, profits do not change significantly compared to a strategy that seeks only to grow revenues, but they increase annually and more and more, reaching almost $1.6 billion in 2040, with a profit margin of 9.679%. The company also achieved its carbon neutrality target in 2040. When the ICP was set at $80 per ton, the results were much less effective, with an annual profit of only about $50 million, and ultimately no carbon neutrality was achieved, which not only failed to achieve economic growth, but also harmed the environment.

In summary, with the full activation and synergy of the subsystems of the whole system, by rationally adjusting the internal carbon pricing, not only the turnover and profit show a stable growth trend, but also the company's carbon neutrality target can be achieved. This result shows that a company's adoption of a comprehensive system synergy strategy can have a positive impact on both economic efficiency and environmental sustainability, contributing to the achievement of its sustainable development goals and demonstrating that economic efficiency and environmental responsibility can go hand in hand.

7. Conclusions and future directions

By establishing a comprehensive GSCM zero-carbon emission management model and combining six scenario analyses, this paper delves into the central role and status of corporate green eco-strategies in the pursuit of the dual goals of economic growth and sustainable development. Research results show that neglecting environmental protection and sustainable development in the process of economic growth will lead to a surge in carbon emissions, cause irreversible damage to the ecological environment, jeopardise the social image of enterprises, and threaten their long-term competitiveness and sustainable development capability. Therefore, the green eco-strategy of enterprises is related to economic efficiency, social responsibility and sustainable development. Implementing carbon reduction and energy saving measures can respond to climate change, improve resource efficiency, reduce costs, and enhance the economic efficiency and competitiveness of enterprises. The reasonable setting of internal carbon pricing strategy can incentivize enterprises to increase emission reduction efforts, and achieve win-win situation in terms of economy and environmental protection. This shows the role of corporate green eco-strategies as a bridge between promoting economic growth and environmental protection.

At the same time, it is important to emphasise that due to the variability between different industries and regions, the constructed models will exhibit significant individual characteristics . However, the characteristics do not prevent the models from being generalisable. First, when looking at the CLD and SD model construction process, the CLD construction has gone through several rounds before being determined, so the construction of CLD for stakeholders is transformable and consensus. Therefore, this CLD can be a generic model suitable for other industries as well. In addition, the subsystems constructed by the SD model are also generic and can be transferred to other companies to consolidate CO2 emissions and achieve other carbon management goals. Finally, the selected case is an international manufacturing company with global supply chain operations that mainly does business in the EU, so the case itself is illustrative and can function as a practical reference for other companies operating in international markets.

Furthermore, based on the research findings, this paper provides the following practical insights for enterprises and governments:

(1) Strengthening regulatory frameworks and standards. The study clearly shows that in the absence of strict regulatory oversight, firms are prone to ignoring environmental costs, as shown by the rising carbon emissions in Scenario I when carbon and consumption reduction measures are not implemented. For this reason, governments should develop and enforce strong environmental protection standards and carbon regulations. These standards should be formulated taking into account international best practices and the specific characteristics of the domestic industrial landscape.

(2) Policy support and incentives for synergizing green and DTs. Research shows that while companies may face increased costs in the initial stages of implementing a low-carbon strategy and promoting DT, the long-term benefits of integrating the two are significant in the long run. In order to help companies break through the short-term cost dilemma, and to promote green and DT in tandem, the government should provide a series of multifaceted policy support and effective incentives. In this way, companies will be better able to find their way through the wave of green and DT, achieve sustainable development goals, and improve their overall competitiveness and adaptability in the context of global economic and environmental challenges.
(3) Promote international co-operation in GSCM. The case study illustrates the challenges faced by multinational enterprises in responding to different national policies and standards. To address this issue, international cooperation on GSCM is crucial. International cooperation could include the establishment of a global green supply chain alliance comprising governments, businesses, research institutions and NGOs. This alliance would serve as a platform for sharing best practices, coordinating policies and jointly developing standards. For example, through joint research and consensus-building, a unified set of green supply chain standards could be established, covering areas such as carbon footprint accounting, sustainable procurement and product life cycle assessment. Another avenue for international co-operation could be the implementation of cross-border technology transfer and joint R&D projects.

Although this paper makes a significant contribution to GSCM and has important practical implications for companies, it still has some limitations. Firstly, this study focuses mainly on carbon emissions management and energy and carbon reduction solutions at the company level, rather than on supply chain carbon reduction solutions and cross-industry collaboration. Future research could take a broader perspective and explore a wider range of carbon emission reduction and environmental performance through supply chain management and cross-industry collaboration. Finally, although this study attempted to evaluate the impact of different strategies through multiple scenario analyses, the scenarios considered did not cover all possible conditions of business operations and environmental changes. Future research could design more diverse and specific scenarios to further explore the impact of different environmental factors and management decisions on the carbon neutral process of companies.

Data availability statement

The data that supports the findings of this study are available from the corresponding authors, HY Y and YK Z, upon resonable request.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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