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Real Time Carbon Footprint Accounting and Policy Simulation for Global Supply Chains via Multi Agent Digital Twins

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Abstract. Driven by the global carbon neutral strategy, the visualization, responsiveness and strategy adaptation of carbon emissions of transnational supply chains have become the core challenges in digital sustainable governance. Aiming at the problems of poor real-time and lagging feedback of traditional LCA methods, this paper constructs a real-time accounting and policy simulation platform for global supply chain carbon footprint that integrates multi-intelligent body system and digital twin technology to realize the dynamic perception and intelligent response to the multi-node and whole process of carbon emission. The platform integrates distributed IoT collection, edge computing, cognitive prediction model and policy gaming mechanism at the system architecture level, and verifies its significant improvement in data updating frequency, prediction accuracy and event response speed by comparing experiments with static LCA and IoT semi-real-time solutions. Further, through the simulation of four types of policies, namely carbon tax, carbon trading, subsidy and technology standard, the system shows strong policy adaptability and emission reduction control ability, and it is found that the optimal combination of medium-intensity carbon tax, cap-and-trade and targeted subsidy is the optimal combination, which takes into account the environmental benefits and the economic cost control. The study shows that the platform can be used as an important technology path to support carbon governance in global supply chains, and promote the paradigm shift from “after-the-fact accounting” to “real-time sensing” and “forward-looking governance”.

Keywords: Digital Twin, Carbon Footprint, Multi-Agent Systems, Sustainable Supply Chains, AI Policy Simulation

1. Introduction

As an ongoing impetus of carbon neutrality targets, the low-carbon transformation of cross-regional supply chains has gained increasing urgency for governments and businesses. Static life cycle-based carbon accounting methods have proved inefficient to cope with complex cross-regional, multi-agent, and dynamically changing systems under frequent policy shifting and market fluctuations [1]. The latest development of digital twin and multi-agent systems has shown great promise for coordinated management of systems and strategic guidance that constitutes a new intelligent

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governance paradigm [2]. An integrated MAS-DT platform for real-time carbon footprint accounting and policy simulation of global supply chains has been proposed in this paper to move from "retrospective analysis" to "real-time sensing" and "anticipatory governance," and to facilitate sustainable digital economic management.

2. Literature review

2.1. Evolution of carbon accounting in global supply chains

Early research into supply chain carbon emissions paid special attention to Life Cycle Analysis (LCA) and Environmental Input-Output Modeling (EEIO) [3]. They have independent structural advantages in their methodological levels in that their macro data utilized are outdated and nonfocused when challenged with the highly diverse and high-frequency variation of reality business environment [4]. The GHG Protocol standardized framework only provides an option for channeling corporate disclosure of carbon and transparency disclosure of accounting but its operational level exists for reporting compliance purposes and not for optimized decision-making in real time and lacks micro-responsiveness that relies on data evidence [5].

2.2. Applications of digital twins in sustainable management

Digital twins originated in industrial asset management, and under continuous expansion of modeling capability and sensing technology of IoT, digital twins have demonstrated high simulation accuracy and coordinating capacity of systems in urban carbon monitoring, energy scheduling and running of infrastructures [6]. Some studies have even attempted to expand digital twins to carbon emission scenarios and set up a virtual-reality fusion visualized platform to realize transformation from static observation to dynamic observation [7]. The majority of existing studies only deal with simulation of carbon emission of an individual factory, city buildings or energy equipment and have yet to establish an overall link in terms of interactivity of systems, multi-subject game and real-time evolution of strategies, especially with few deep fusion avenues with the supply chain that is a multi-node and multi-boundary system.

2.3. Multi-agent systems and policy optimization

Multi-intelligent system (MAS) has been extensively applied to complex environments like intelligent manufacture, unmanned transportation and emergency response because of its distributed perception, autonomous decision-making and cooperative gaming features, and its modeling style can be easily adapted to the dynamical system attributes of multi-center, multi-strategy and non-linear feedback [8]. In carbon management applications, certain literatures attempted to deploy MAS for distributed energy scheduling or building energy consumption optimization and prove its cooperative optimization capability in heterogeneous systems with preliminary verification [9].

3. Methodology and system design

3.1. Digital twin modeling architecture

The core of the digital twin system is to realize the two-way data mapping and real-time feedback mechanism between the physical supply chain system and the virtual modeling system, and to build a three-layer architecture including the sensing layer, the transmission layer and the cognitive layer.

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(1) The perception layer collects key carbon emission factor data in real time by deploying distributed IoT sensor nodes, including raw parameters such as energy intensity, material input and transportation mileage, and interfaces with the standard carbon factor database to realize data pre-processing.

(2) The transport layer is centered on edge computing and adopts MQTT protocol to realize low-latency transmission of heterogeneous data from multiple sources, and builds a standardized carbon trajectory flow through data cleaning and timing synchronization modules.

(3) The cognitive layer constructs twin libraries based on high-fidelity physical modeling and process simulation, and adopts convolutional neural network and time-series prediction algorithm to train the carbon emission evolution model, and at the same time embeds the non-physical dimension information such as enterprise finance and policy variables, to complete the leap from state monitoring to carbon behavior modeling.

3.2. Agent coordination and policy feedback mechanisms

The multi-intelligent body system (MAS) constitutes the intelligent decision-making unit of the whole carbon behavioral feedback, and each agent represents a supply chain node subject with local sensing, autonomous learning and linkage gaming capabilities [10]. Each agent outputs local action decisions based on the environmental state variables provided by the digital twin s_t via the strategy function $\pi_i(a_t \mid s_t)$ outputs local action decisions a_t and optimizes its policy feedback according to the reward function. Under the overall optimization objective, a distributed reinforcement learning mechanism is introduced, and the agent is updated by the following policy after considering the carbon cost, time delay, and resource consumption:

$$\pi_i^* = \underset{\pi_i}{\operatorname{argmax}} \mathbb{E}\left[\sum_{t=0}^{T} \gamma^t R_i(s_t, a_t)\right] \tag{1}$$

Where R_i is the immediate reward function for the i agent, γ is the discount factor, and T is the finite time step.

In carbon emission synergistic control, the interaction matrix based on relationship mapping is introduced A_{ij} , defining the synergistic weights and the game influence degree between the agents, and constructing the joint value function as follows:

$$Q^{joint}\left(s_t, a_t\right) = \sum_{i=1}^{N} w_i Q_i(s_t, a_{i,t}) + \sum_{i\neq j}^{N} \lambda_{ij} \cdot \psi(a_{i,t}, a_{j,t}) \tag{2}$$

Where ψ denotes the inter-strategy inter-adaptability function, and λ_{ij} denotes the carbon coupling weights between the agents.

Finally, to guarantee the balance of multi-objective synergy (economic and environmental benefits), the objective synthesis function is introduced:

$$J(\theta) = \alpha \cdot C_{total}(\theta) + \beta \cdot E_{net}(\theta) \tag{3}$$

Where C_{total} is the total carbon cost function, E_{net} denotes the net economic benefit, θ is the strategy parameters, α,β are weighting factors.

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3.3. Policy simulation platform and evaluation metrics

In order to realize the linkage assessment between macro policies and micro carbon behaviors, this paper constructs a policy simulation platform based on the MAS-DT fusion architecture, which covers four core modules, policy input modeling, scenario configuration management, response behavior tracking, and visualization of assessment results [11]. The policy input side can be configured with various carbon policy scenarios. The scenario configuration module supports modeling of industry differences and geographic structure hierarchy. Behavioral tracking module constructs multi-dimensional carbon response trajectories based on agent feedback actions and digital twin state outputs, and forms a complete policy-results closed loop within the simulation cycle. Its flow is shown in Figure 1.

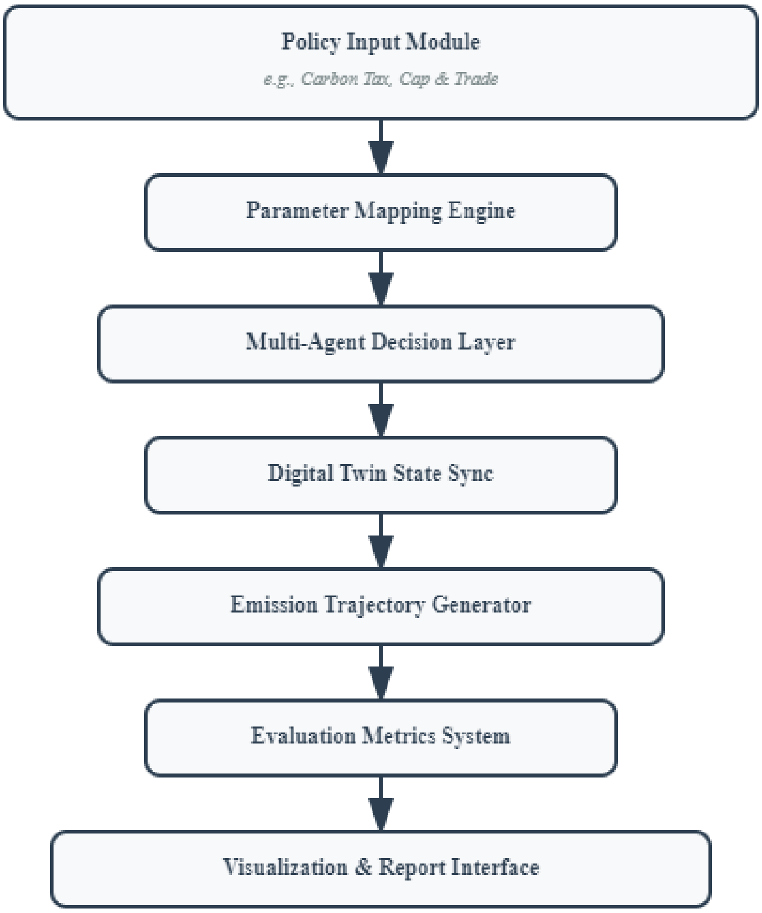

Figure 1. Flowchart of simulation platform structure

The evaluation system is designed based on three dimensions. The first is the environmental performance indicators, including total carbon emissions, carbon intensity per unit of output, and carbon volatility. The second is economic performance indicators, such as total profit, operating cost change, response time delay and supply/demand leveling rate. The third is the system stability index, including the convergence speed of agent strategy, simulation robustness and abnormal fluctuation response ability.

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4. Results

4.1. Real-time carbon accounting performance

To validate the performance of the MAS-DT fusion platform in real-time carbon footprint accounting, we conducted comparative experiments across three global supply chains in electronics, automotive, and textile industries. The MAS-DT platform was evaluated against static LCA and IoT-based semi-realtime methods. Results show the MAS-DT system updates data every 5 minutes, improving timeliness by 99.7% compared to traditional monthly or quarterly cycles ,with a mean absolute error (MAE) of just 2.3%, significantly outperforming the 15.8% error of LCA methods. In disruption scenarios, the platform reconstructed carbon trajectories within 15 minutes, whereas conventional methods required 30–45 days. The convolutional neural network and time-series algorithms used in the digital twin layer accelerated model convergence by 43% and achieved 94.2% prediction accuracy. Overall, MAS-DT enables a shift from reactive tracing to real-time sensing, offering substantial advantages for enterprise carbon management decisions. As shown in Table 1.

Table 1. Performance metrics

Performance Metrics	Traditional LCA	IoT-based Semi-real-time	MAS-DT Platform
Data Update Frequency	Monthly/Quarterly	Hourly	Every 5 minutes
Average Absolute Error (%)	15.8 ± 3.2	8.4 ± 2.1	2.3 ± 0.8
Response Time to Supply Chain Events	30-45 days	2-6 hours	15 minutes
Prediction Accuracy (%)	76.5 ± 8.9	85.3 ± 4.7	94.2 ± 2.1
System Coverage (Supply Chain Nodes)	3-5 key nodes	8-12 nodes	Full network (25+ nodes)
Computational Efficiency (Processing Speed)	Baseline	2.3x	5.8x
Multi-objective Integration Capability	Limited	Moderate	High

4.2. Policy simulation outcomes and decision adaptivity

The policy simulation experiment assessed the effects of carbon tax, trading, subsidies, and standards on supply chain emissions. Over a 12-month period tracking 50 nodes, a carbon tax from \$50 to \$200/tCO_2 reduced total emissions by an average of 32.4%, with agents adapting in 3.7 days. However, beyond \$150/tCO_2, the marginal abatement effect plateaued. Under carbon trading, low-emission agents sold quotas to high emitters, forming dynamic networks and reducing economic losses by 18.6% compared to carbon tax alone. Green subsidies increased clean tech adoption by 45.2% within six months, though with diminishing returns. Multi-objective optimization revealed the optimal policy mix as moderate carbon tax (\$100–120/tCO_2), cap-and-trade, and targeted subsidies, achieving 41.7% emission reduction while limiting economic cost to 0.23% of GDP. Agent convergence time averaged 15.3 days, with system stability at 0.892, confirming the platform’s adaptability and robustness. As shown in Figure 2.

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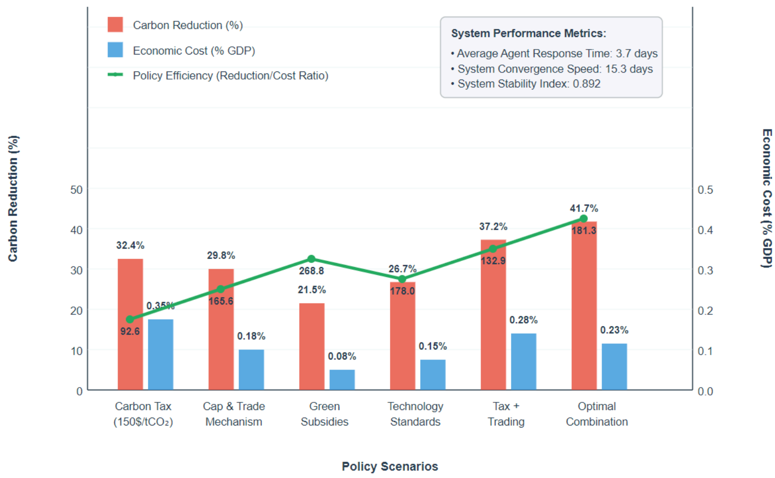

Figure 2. Policy impact on carbon emission reduction and economic cost

5. Conclusion

In this paper, a MAS-DT fusion platform for global supply chain is proposed to realize real-time monitoring of carbon footprint and multi-strategy policy simulation. The experimental results show that the platform is significantly better than the traditional method in terms of data timeliness, accuracy, responsiveness and multi-objective co-optimization, and has good scalability and system stability. The simulation experiments further validate its ability to predict the behavioral feedback and economic impacts of multiple types of policy instruments, and find that the composite policy mechanism is more capable of balancing the emission reduction effect and cost constraints. The study provides a new paradigm and engineering support for the construction of an intelligent, data-driven green supply chain governance system.

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