Low-Carbon Healthcare Industry Interconnection: Carbon-Flow Identification and Scenario Simulation

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Abstract: Against the combined background of global climate governance and the digital transformation of healthcare, low-carbon development in the healthcare industry chain has shifted from energy-saving measures within individual medical institutions to coordinated governance across multiple industrial sectors. This study defines a patient-centered boundary for healthcare industry interconnection. On the basis of direct carbon accounting and input-output embodied carbon-flow analysis, it develops a hierarchical collaborative optimization model that integrates critical-path emissions, terminal-sector-induced emissions, and system-stability constraints. Target cascading is adopted to decompose and coordinate the resulting multi-objective optimization problem. Using publicly available sectoral carbon-emission and input-output data from CEADs, macroeconomic data from the National Bureau of Statistics of China, and total health-expenditure data from national and WHO sources, we calibrate the healthcare industry chain for 2018-2022 and conduct scenario simulations. The results show that the critical-path optimization mechanism reduces calibrated carbon emissions by approximately 18.7% relative to the baseline while maintaining an economic output growth rate of about 4.2%. The coordinated critical-path and terminal-sector mechanism performs better in both emission-reduction performance and system stability. These findings indicate that low-carbon transformation in healthcare should not be limited to terminal energy conservation in hospitals; instead, it should identify and compress high-intensity embodied carbon-flow paths transmitted through upstream manufacturing, logistics and warehousing, chemical inputs, and energy supply.

Keywords: Low-Carbon Healthcare; Industry Interconnection; Embodied Carbon Flow; Target Cascading; Scenario Simulation; Supply-Chain Stability

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1 Introduction

The rapid development of artificial intelligence, big data, cloud computing, and the Internet of Things has blurred traditional industrial boundaries and accelerated cross-sectoral integration. Digital technologies not only reshape production organization within industries, but also promote information sharing, resource coordination, and value co-creation across industries. Industrial interconnection has therefore become an important direction in the evolution of industrial systems in the digital economy [1, 2].

In the healthcare field, the relationships among

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healthcare services, pharmaceutical manufacturing, medical device production, consumable supply, logistics and warehousing, and information technology have become increasingly close. A single-sector perspective is no longer sufficient to explain resource-allocation efficiency, risk transmission, or environmental impacts in the operation of the healthcare industry chain. At the same time, climate-change mitigation and dual-carbon targets impose new constraints on healthcare industry-chain governance. Healthcare systems provide essential public-health services, but they also generate complex carbon footprints through energy use, pharmaceuticals and device production, cold-chain logistics, and medical-waste treatment [3].

Existing low-carbon healthcare studies have mainly focused on energy use and operational emission reduction at the medical-institution level, while insufficient attention has been paid to embodied carbon emissions transmitted from upstream sectors of the healthcare industry chain. It is therefore theoretically and practically important to identify critical carbon-flow paths in a healthcare industry interconnection system and to design mechanisms that balance emission-reduction efficiency with system resilience while maintaining healthcare-service supply.

The remainder of this paper is organized as follows. Section 2 reviews studies on healthcare supply chains, industrial interconnection, and low-carbon governance, and then identifies the research gap and contributions. Section 3 defines a patient-centered healthcare industry interconnection boundary and characterizes direct and embodied carbon-flow relationships. Section 4 develops a low-carbon-driven interconnection mechanism model and designs a hierarchical collaborative optimization process based on target cascading. Section 5 uses public-data-calibrated scenario simulations to examine emission-reduction effects, economic-output effects, and robustness under alternative interconnection mechanisms. Section 6 discusses policy implications, and Section 7 concludes the paper.

2 Literature Review

2.1 Healthcare Industry Chain and Supply Chain

Public-health emergencies have exposed vulnerabilities in healthcare supply chains in terms of demand shocks, inventory coordination, and cross-sectoral response. Shortages of critical medical materials, such as masks and ventilators, have made healthcare supply-chain optimization an important research topic [4]. Existing studies have mainly examined pharmaceutical supply-chain network design, medical-device supply-chain resilience, hospital resource allocation, and emergency-service optimization. For example, Goodarzian et al. [5] developed a multi-objective pharmaceutical supply-chain network model with sustainability considerations, Goodarzian et al. [6] incorporated uncertainty and algorithm comparison into pharmaceutical supply-chain optimization, and Nayeri et al. [7] discussed global response in medical-device supply chains from the perspectives of sustainability and resilience. Overall, this literature provides an important foundation for healthcare industry-chain optimization, but it focuses mainly on individual links or product-specific networks, with insufficient attention to cross-sectoral interconnection and its environmental effects.

Low-carbon transformation studies further show that healthcare systems have become an important source of carbon emissions [8]. The carbon footprint of healthcare is not limited to energy consumption during hospital operation; it also includes embodied emissions induced by upstream pharmaceuticals, devices, consumables, logistics distribution, and waste treatment [9]. Low-carbon healthcare should therefore not be understood merely as energy saving within medical institutions, but as a system-level governance issue covering both upstream and downstream parts of the healthcare industry chain.

2.2 Industrial Interconnection

Industrial interconnection is also referred to in related studies as industrial convergence or the blurring of industrial boundaries [10, 11]. As technology life cycles shorten and market demand becomes more complex, firms increasingly rely on cross-industry resource integration, technological coordination, and service convergence to create new forms of value [12]. Sick et al. [13] proposed an analytical framework for assessing industrial convergence in high-technology environments, while Kwon et al. [14] and Karvonen and Kassi [15] used patent data and technological linkages to identify industrial convergence trends. In the healthcare industry, digital technologies, logistics systems, and green governance jointly promote deep connections among healthcare services, manufacturing, and information-technology sectors. However, existing research has not sufficiently examined how this interconnection structure affects carbon-emission flows and the selection of low-carbon mechanisms.

2.3 Research Gaps and Contributions

In summary, existing studies have produced extensive discussions on healthcare supply-chain optimization, industrial convergence, and low-carbon transformation, but three gaps remain. First, healthcare industry-chain studies usually focus on a single link or actor and pay insufficient attention to interconnections among multiple industrial sectors driven by patient demand. Second, low-carbon healthcare studies often emphasize energy saving in terminal medical institutions, while upstream manufacturing, logistics and warehousing, energy supply, and information-technology sectors are seldom integrated into a unified carbon-flow framework. Third, existing multi-objective optimization studies tend to emphasize emission-reduction efficiency, but the stability constraints of the industry chain and their coordination with low-carbon objectives remain underexplored.

Accordingly, this study makes three marginal contributions. First, starting from the chain relationship of "patient demand-terminal healthcare services-upstream support industries", it constructs a healthcare industry interconnection boundary that incorporates pharmaceuticals, medical devices, consumables, healthcare services, logistics and warehousing, energy supply, and information technology into a unified analytical framework. Second, it combines direct carbon-emission accounting with input-output embodied carbon-flow analysis to identify high-intensity carbon-flow paths in the healthcare industry chain, and compares critical-path optimization, terminal-emission optimization, and stability-constrained coordination scenarios. Third, it introduces target cascading to coordinate low-carbon objectives and industry-chain stability objectives, decomposes system-level targets into computable sub-targets, and uses public-data-calibrated scenario simulations to provide an analytical path that is both theoretically interpretable and empirically reproducible.

3 System Boundary and Carbon-Flow Footprint

3.1 Patient-Centered Interconnection Boundary

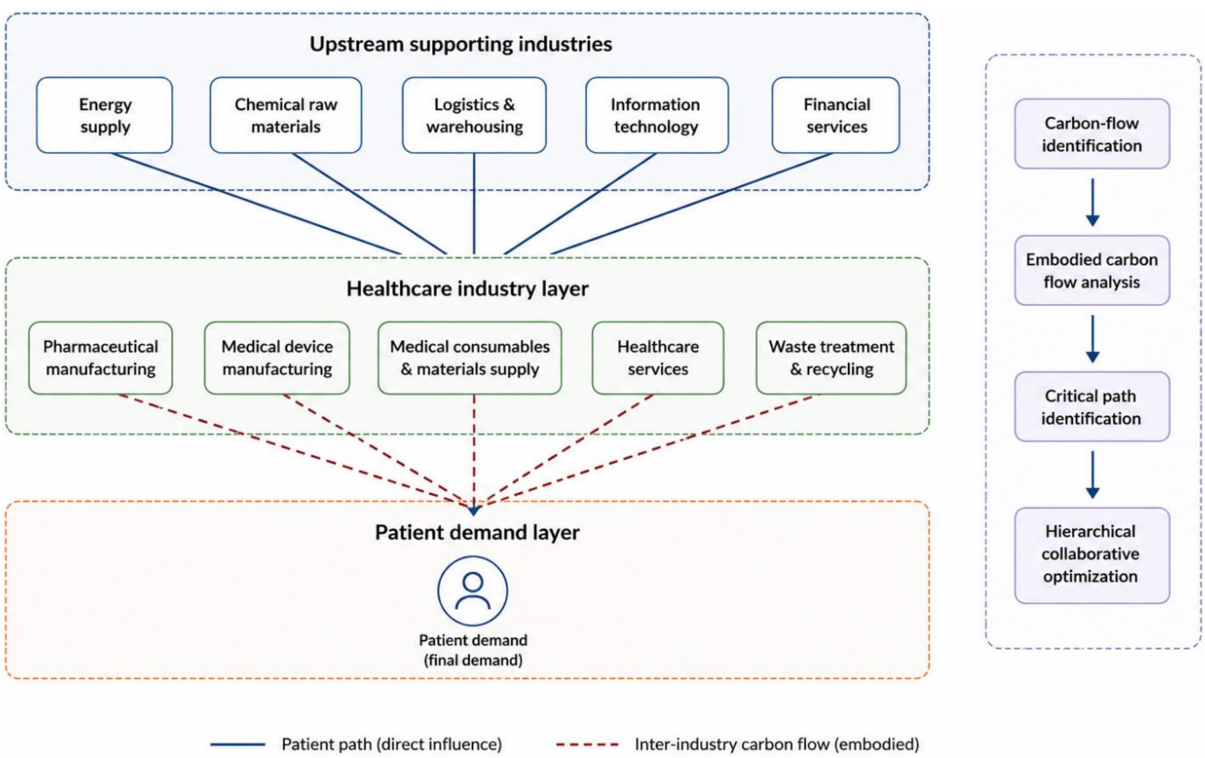


Figure 1 Patient-centered healthcare industry interconnection boundary

This study uses patient demand as the driving point for defining the healthcare industry interconnection boundary.

Terminal sectors that directly provide services or products to patients include pharmaceuticals, medical consumables, medical devices, and healthcare services. Upstream support sectors include energy supply, chemical inputs, equipment manufacturing, transport and storage, and digital support. Compared with a general manufacturing supply chain, healthcare industry interconnection is reflected not only in product and service input relationships, but also in diagnostic demand, inventory information, quality tracing, green procurement, and carbon-emission constraints. The system is therefore a multilayer network centered on patient demand, supported by terminal healthcare sectors and upstream support industries. It is both a healthcare resource allocation network and a carrier through which embodied carbon emissions are transmitted and accumulated across sectors.

3.2 Direct Emissions and Embodied Carbon Flows

Direct sectoral emissions are mainly generated by fossil-energy consumption. Following the apparent-consumption method in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, direct emissions are calculated as follows:

$$\mathrm{CE}_i = \sum_{k=1}^{K} E_{ik} \cdot \mathrm{NCV}_k \cdot \mathrm{EF}_k \cdot O_k \tag{1}$$

where CE_i is the direct carbon emission of sector i; k denotes fossil-energy type; E_{ik} is the consumption of energy k by sector i; NCV_k is the net calorific value; EF_k is the emission factor; and O_k is the carbon oxidation rate.

To capture inter-sectoral carbon transfers, input-output analysis is introduced [16]. The embodied carbon balance, input-output representation, emission-intensity matrix, and inter-sectoral embodied carbon-flow matrix are defined as follows:

$$C_j = e_j y_j + \sum_{i=1}^{n} e_i x_{ij} \tag{2}$$

$$X = AX + Y, A = (a_{ij}), a_{ij} = \frac{x_{ij}}{X_j} \tag{3}$$

$$e = c^T (I - A)^{-1} \tag{4}$$

$$F = (a_{ij}), F_{ij} = e_i x_{ij} \tag{5}$$

where n is the number of sectors; e_i is the embodied emission intensity of sector i; x_{ij} is the intermediate input purchased by sector j from sector i; y_j is final demand; X_j is total output; A is the direct input-coefficient matrix; c is the direct emission coefficient vector; and F_{ij} denotes the embodied carbon flow from sector i to sector j.

4 Model Construction

Under the coexistence of low-carbon constraints and growing healthcare demand, the core issue of the healthcare industry interconnection mechanism is not simply to reduce inputs in a single sector. Rather, it is to reduce the carbon intensity of the whole system and of critical links while maintaining basic healthcare-service supply and stable operation of the industry chain. Based on the carbon-flow analysis in Section 3, this study sets three optimization objectives: minimizing critical-path carbon emissions, minimizing terminal-sector induced emissions, and constraining system stability during low-carbon adjustment.

$$\min Z_1 = C_{\text{path}}(x) = \sum_{(i,j)\in P} F_{ij} z_{ij} \tag{6}$$

$$0 \le x_{ij} \le \overline{x_{ij}}(1 + \delta_{ij}), x_{ij} \ge 0 \tag{7}$$

$$\sum_{j=1}^{n} F_{ij} \le Q_i, i = 1,2,\dots,n \tag{8}$$

$$z_{ij} \in \{0,1\}, (i,j) \in P \tag{9}$$

$$\min Z_2 = C_{\text{terminal}}(y) = \sum_{j\in T} \left[e_j y_j + \sum_{i=1}^{n} F_{ij} \right] \tag{10}$$

$$y_j^{\min} \le y_j \le y_j^{\max}, j \in T \tag{11}$$

$$\sum_{i=1}^{n} x_{ij} \ge D_j^{\min}, j \in T \tag{12}$$

$$\sum_{i=1}^{n} F_{ij} \le Q_j, j \in T \tag{13}$$

Here P denotes the set of critical carbon-flow paths and T denotes the set of terminal healthcare sectors. z_{ij} is a binary variable indicating whether the link from sector i to sector j is active; Q_i and Q_j are sectoral carbon quotas; $D_j^{\min}$ is the minimum terminal demand requirement; $\bar{x}_{ij}$ is the benchmark input level; and δ_{ij} is the allowable adjustment range.

The system-level objective is decomposed through target cascading [17]. At the upper level, the model specifies overall emission-reduction and stability targets. At the lower level, sectoral and path-level subproblems adjust inputs, technology parameters, and carbon-flow intensities.

Consistency constraints ensure that lower-level adjustments remain compatible with system-level targets. The iterative process terminates when the change in the objective value falls below 10-4 or when the maximum number of 500 iterations is reached.

System stability is represented by a composite index that reflects output growth, path concentration, and constraint violations. This design prevents the model from achieving emission reduction by excessively suppressing healthcare demand or by disrupting essential upstream inputs.

$$Y = \sum_{i=1}^{n} v_i\,(x_i), v_i(x_i) = \frac{a_i}{1+\exp[-b_i(x_i-c_i)]} \tag{14}$$

$$S = \omega_1 \frac{Y}{Y_0} - \omega_2 \mathrm{Var}(\Delta x) - \omega_3 V, S \geq S_{\min} \tag{15}$$

where Y is system output, Y_0 is the benchmark output, V is the constraint-violation penalty, and S_{min} is the minimum acceptable stability threshold.

5 Empirical Calibration and Scenario Simulation

5.1 Data Sources and Sector Mapping

To enhance the traceability and reproducibility of the simulation analysis, this study adopts a public-data-calibrated scenario-simulation approach. Carbon-emission totals and sectoral emission definitions are mainly based on CEADs, which provides China's carbon-emission inventories by 47 socioeconomic sectors and 17 fossil-energy types for 1997-2022, together with input-output data access. Macroeconomic scale is represented by annual GDP from the National Bureau of Statistics of China, while healthcare demand is represented by total health expenditure from national health-statistics bulletins and the WHO Global Health Expenditure Database.

Because publicly available statistics cannot directly observe all enterprise-level transactions within the healthcare industry chain, this study follows a "total calibration-sector mapping-scenario simulation" pathway. First, the ratio of total health expenditure to GDP is used to characterize the scale of healthcare demand and calibrate the carbon-emission total of the healthcare industry chain. Second, CEADs input-output sectors are mapped into eight nodes: energy supply, chemical inputs, pharmaceutical manufacturing, medical devices, medical consumables, transport and storage, information technology, and healthcare services. Finally, the embodied carbon-flow matrix is used to identify critical paths and compare emission-reduction performance, economic output, and system stability under alternative low-carbon interconnection mechanisms. The simulation results reveal relative mechanism effects and directions; they do not replace enterprise- or hospital-level micro carbon accounting.

Table 1 Data sources, variable definitions and processing methods

Variable	Symbol	Definition	Source	Processing
Total carbon emissions	CE	National and sectoral carbon-emission inventories	CEADs	Calibrated by healthcare demand scale
Total health expenditure	HE	Scale of healthcare demand	National Health Commission/WHO	Divided by GDP to obtain healthcare-demand weight
Intermediate input	X_{ij}	Product and service flows between sectors	CEADs input-output tables	Merged into eight industry nodes
Embodied carbon flow	F_{ij}	Embodied emissions from sector i to sector j	Calculated in this study	Input structure multiplied by emission-intensity matrix
System stability	S	Coordination of output and input fluctuations	Calculated in this study	Composite of output growth, path concentration and constraint violation

Table 2 Calibration data for 2018-2022

Year	GDP (100 million CNY)	Total health expenditure (100 million CNY)	HE/GDP (%)	Calibrated emissions (Mt)
2018	919281.1	59121.9	6.43	466.76
2019	986515.2	65841.4	6.67	493.51
2020	1013567.0	72175.0	7.12	555.4
2021	1149237.0	76844.99	6.69	549.14
2022	1210207.2	85327.5	7.05	586.24

5.2 Scenario Design and Parameter Settings

Four scenarios are designed. S0 is the baseline scenario without an interconnection mechanism and represents traditional independent optimization. S1 is the critical-path optimization scenario, which prioritizes the compression of high-intensity embodied carbon-flow links. S2 is the terminal-emission optimization scenario, which reduces upstream carbon inputs induced by terminal sectors such as pharmaceutical manufacturing, medical devices, and healthcare services. S3 is the critical-path and terminal-sector coordination scenario, which jointly optimizes critical paths and terminal input structures under system-stability constraints.

The main target-cascading parameters are set as follows: the maximum number of iterations is 500, and the convergence tolerance for the objective function is set to 1×10^{-4}. This means that the iterative procedure is regarded as converged when the absolute change in the objective value between two consecutive iterations is less than 0.0001. In the robustness test, carbon quotas, energy consumption, emission factors, and input-output elasticity are allowed to fluctuate within +/-20%. To further examine the influence of multi-parameter uncertainty on model outputs, 1,000 Monte Carlo simulations are conducted under the critical-path optimization scenario, and the distributions of emission reduction and economic output growth are reported.

5.3 Baseline Results

Table 3 Carbon emissions, economic output and system stability under alternative mechanisms

Scenario	Mechanism	Emissions (Mt)	Reduction vs. baseline (%)	Output growth (%)	Stability index
S0	Baseline: no interconnection mechanism	586.24	0.0	1.8	0.742
S1	Critical-path optimization	476.71	18.68	4.2	0.817
S2	Terminal-emission optimization	513.55	12.4	3.1	0.786
S3	Critical path-terminal coordination	460.46	21.46	4.5	0.834

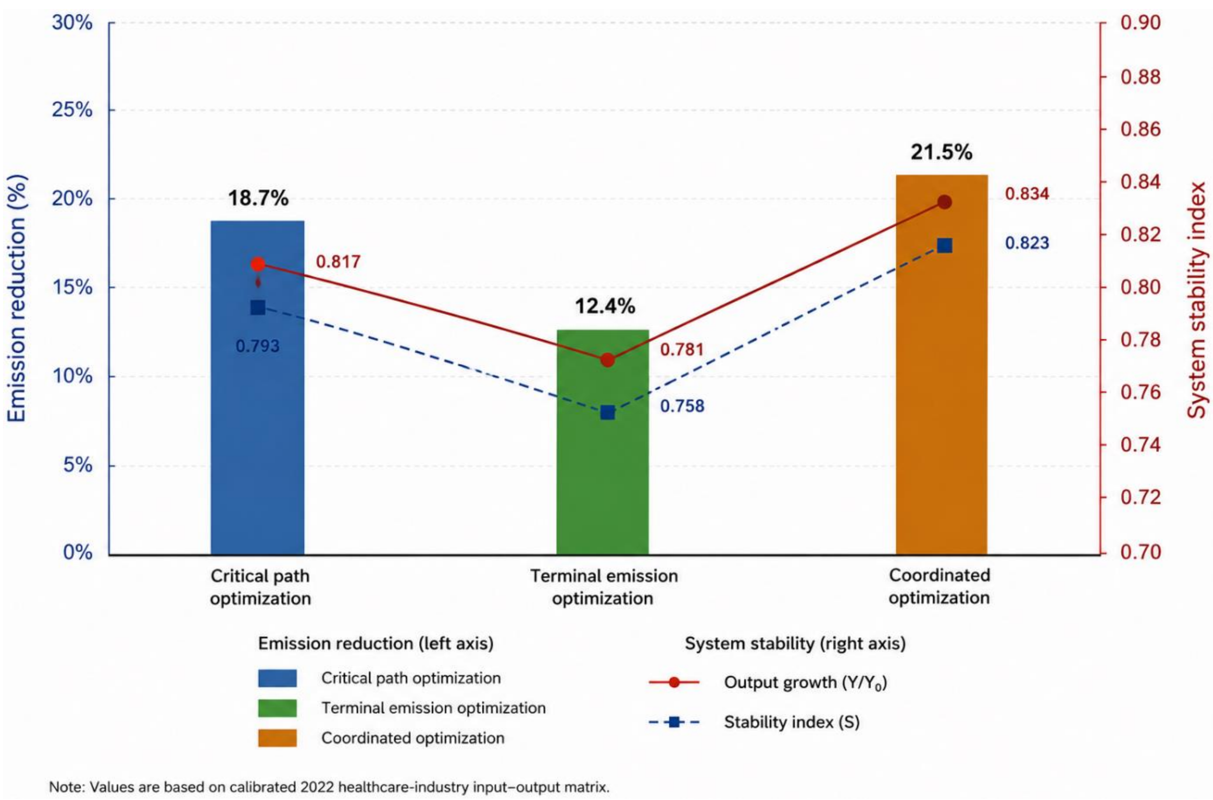


Figure 2 Emission-reduction performance, economic output and system stability under alternative interconnection mechanisms

Table 3 and Figure 2 show that, compared with the baseline scenario, the critical-path optimization mechanism reduces calibrated healthcare industry-chain emissions by approximately 18.7% and achieves an economic output growth rate of 4.2%. The terminal-emission optimization mechanism achieves a reduction of 12.4%, which is lower than that of critical-path optimization. This result indicates that healthcare industry-chain decarbonization does not simply depend on reducing terminal demand; rather, it depends on whether high-intensity embodied carbon flows transmitted from upstream energy, chemical inputs, and transport-storage sectors to terminal healthcare sectors can be identified and governed.

Further comparison shows that the coordinated critical-path and terminal-sector mechanism increases the emission-reduction rate to about 21.5% and achieves the highest system-stability index. This suggests that hierarchical collaborative optimization under stability constraints can better balance low-carbon objectives and industry-chain resilience.

5.4 Embodied Carbon-Flow Paths

Figures 3 and 4 further reveal the structural characteristics of embodied carbon emissions within the healthcare industry chain. The embodied carbon-flow matrix (Figure 3) demonstrates that carbon emissions are highly concentrated rather than evenly distributed across inter-sectoral transactions. The largest embodied carbon flows occur along the pathways from chemical inputs to pharmaceutical manufacturing (33.6 Mt CO_2), pharmaceutical manufacturing to healthcare services (26.4 Mt CO_2), energy supply to chemical inputs (26.4 Mt CO_2), medical-device manufacturing to healthcare services (26.4 Mt CO_2), and chemical inputs to medical consumables (25.2 Mt CO_2). The critical-path network (Figure 4) further illustrates that pharmaceutical manufacturing functions as the key bridge connecting upstream production with downstream healthcare services, while healthcare services represent the primary convergence point of embodied carbon flows. Meanwhile, energy supply and chemical inputs constitute the dominant upstream sources of carbon-emission transmission. These findings suggest that low-carbon healthcare strategies should extend beyond energy-saving measures in hospitals to include upstream interventions in chemical production, pharmaceutical manufacturing, medical-device production, and medical-consumables supply.

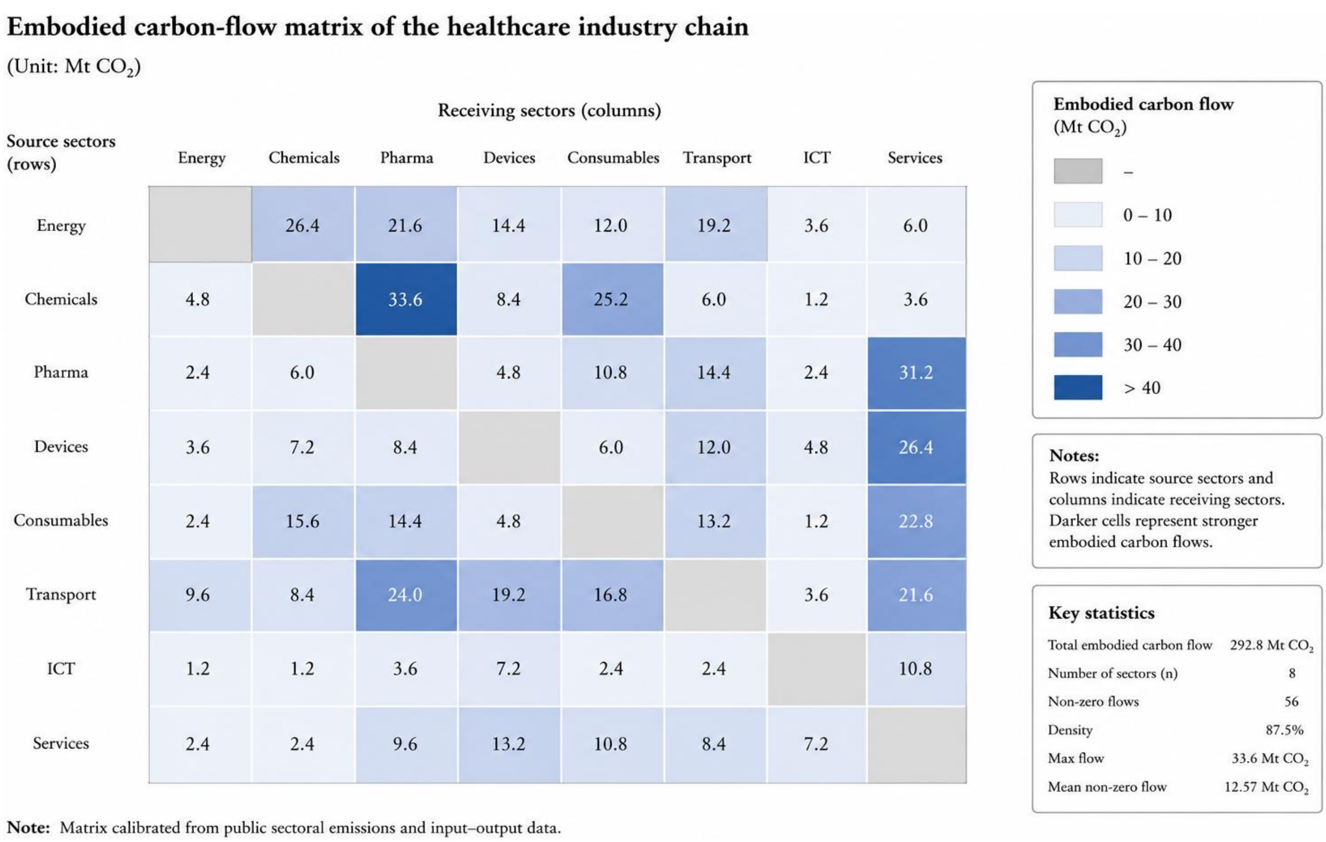
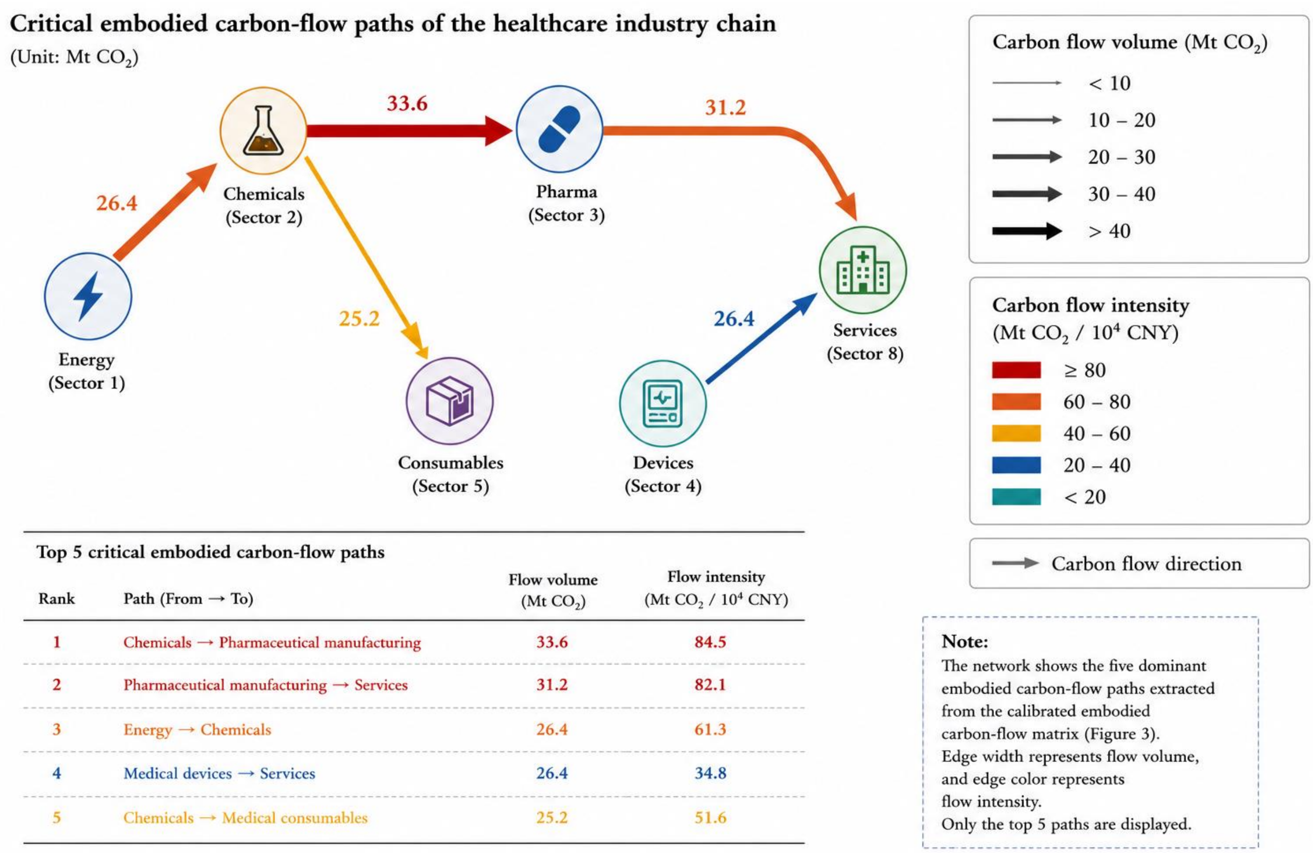


Figure 3 Embodied carbon-flow matrix of the healthcare industry chain



Rank	Path (From → To)	Flow volume (Mt CO_2)	Flow intensity (Mt CO_2 / 10^4 CNY)
1	Chemicals → Pharmaceutical manufacturing	33.6	84.5
2	Pharmaceutical manufacturing → Services	31.2	82.1
3	Energy → Chemicals	26.4	61.3
4	Medical devices → Services	26.4	34.8
5	Chemicals → Medical consumables	25.2	51.6

Figure 4 Critical embodied carbon-flow path network

5.5 Robustness and Sensitivity Tests

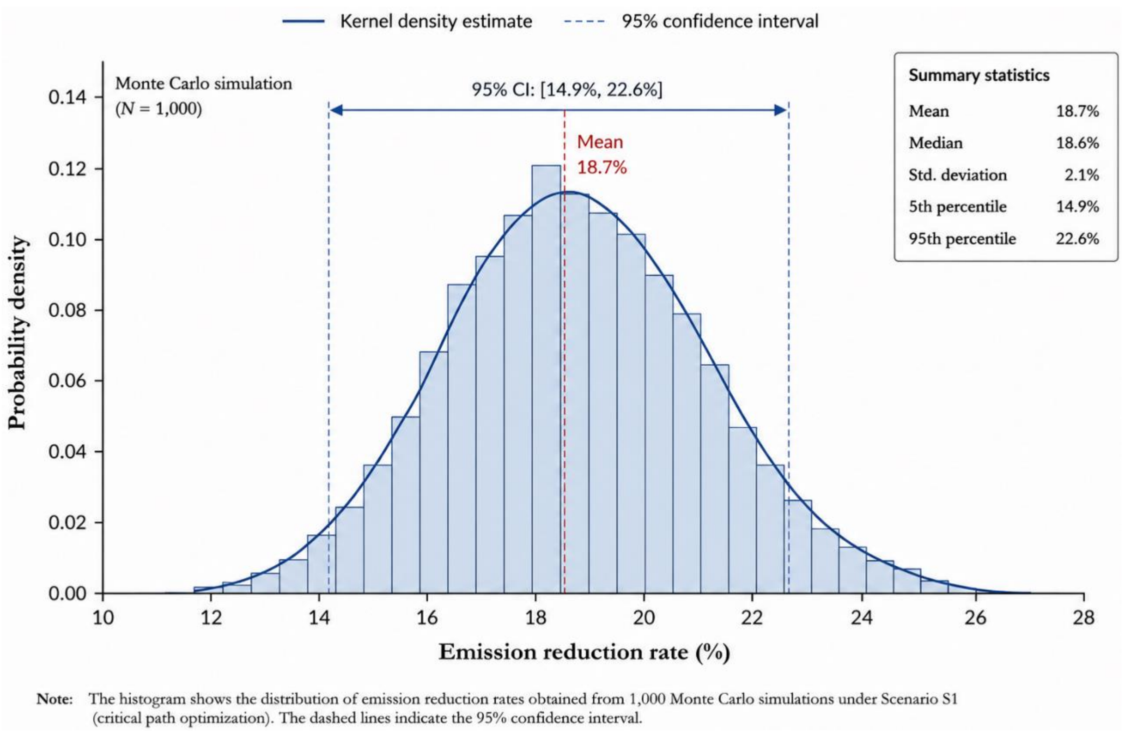


Figure 5 Monte Carlo robustness test: distribution of emission-reduction effects

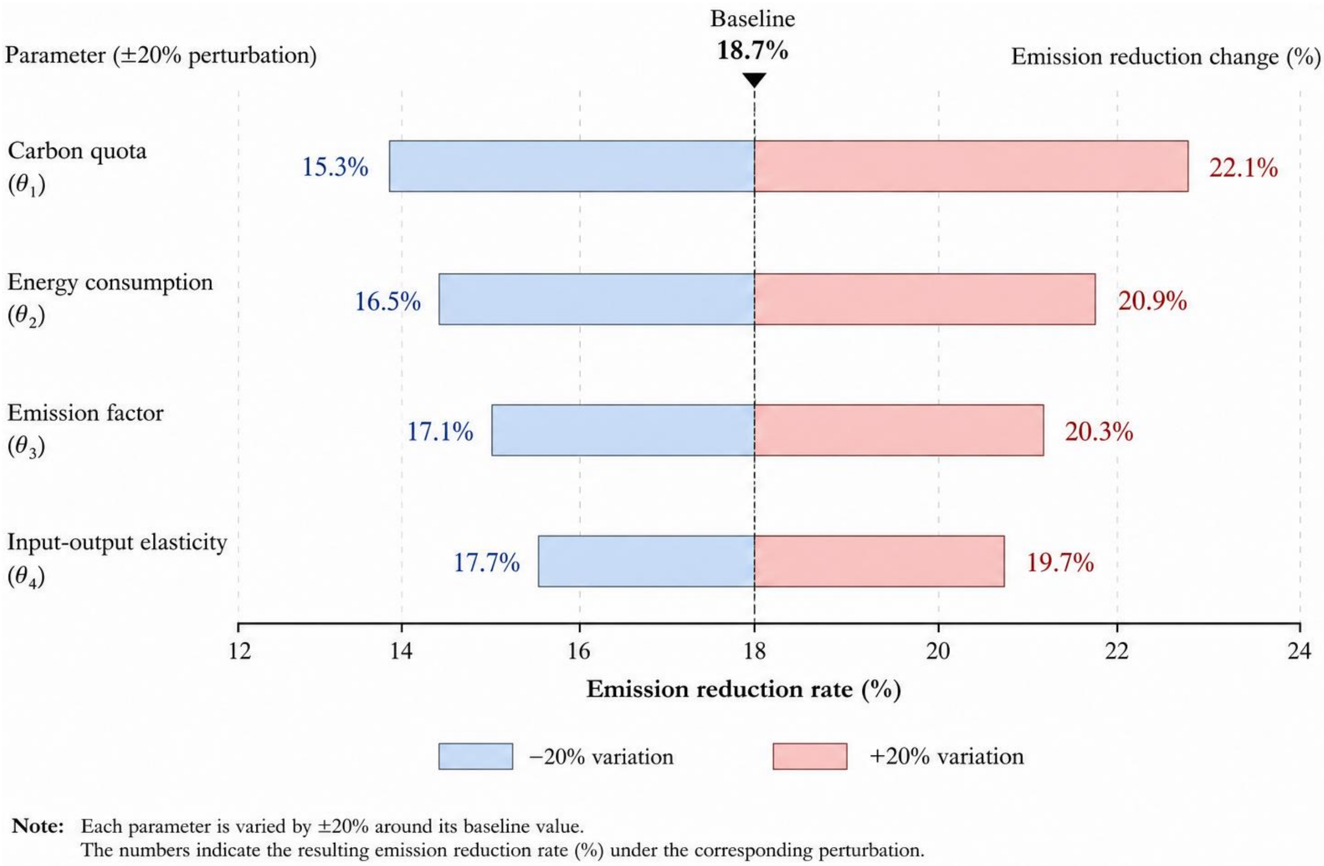


Figure 6 Sensitivity analysis: effects of parameter perturbation on emission reduction

The Monte Carlo simulation shows that, under 1,000 random perturbations, the mean emission-reduction rate of the critical-path optimization mechanism is 18.7%, and 90% of samples fall within the range of 15.0%-22.4%. The mean economic output growth rate is 4.2%, and 90% of samples fall within the range of 3.1%-5.4%. These results indicate that the critical-path optimization mechanism maintains a stable emission-reduction advantage under simultaneous perturbations in carbon quotas, energy consumption, emission factors, and input-output elasticity, and that the model output is not directionally biased by a single parameter setting.

The sensitivity analysis indicates that carbon quotas and energy consumption have the most significant effects on emission reduction and are the main sources of uncertainty in the model outputs. Emission factors have a moderate effect, while input-output elasticity has a more pronounced effect on economic output growth. This suggests that policy stringency and energy-structure adjustment are key external conditions affecting healthcare industry-chain decarbonization, while digital interconnection, supply-chain coordination, and low-carbon technology diffusion can improve input-output efficiency and buffer the potential growth pressure caused by emission-reduction constraints.

6 Discussion and Policy Implications

The results have three implications for low-carbon healthcare governance. First, carbon reduction in the healthcare industry chain has clear network externalities: energy-saving retrofits within individual hospitals cannot fully address embodied emissions generated in upstream manufacturing and logistics. Second, critical-path optimization targets links that account for a disproportionate share of embodied carbon flows, making it more efficient than uniform reductions across all sectors. Third, although the information-technology sector has relatively low direct emissions, it enables data sharing, demand forecasting, inventory coordination, green procurement, and carbon tracing, and thus functions as an important coordination node for low-carbon interconnection.

These findings also clarify the policy boundary of healthcare decarbonization. Green procurement by medical institutions, low-carbon production of pharmaceuticals and consumables, optimization of medical logistics, and construction of industry-chain data platforms should be treated as mutually reinforcing measures rather than as separate policy instruments. For high-intensity embodied carbon-flow paths, sector-specific carbon accounting, dynamic carbon-quota allocation, and cross-sector information-sharing mechanisms are especially important.

7 Conclusions

This study develops a hierarchical optimization model for a low-carbon-driven healthcare industry interconnection mechanism and evaluates it through publicly calibrated scenario simulations. The results show that carbon emissions in the healthcare industry chain are highly path-concentrated, with high-intensity embodied carbon flows mainly occurring in links that connect energy supply, chemical inputs, and transport-storage sectors with pharmaceutical manufacturing and healthcare services.

Critical-path optimization reduces calibrated emissions by approximately 18.7% relative to the baseline while maintaining an economic output growth rate of about 4.2%. The coordinated critical-path and terminal-sector mechanism performs better in terms of both emission reduction and system stability. These findings indicate that low-carbon healthcare governance should extend from terminal energy-saving measures to full-chain collaborative optimization.

Several limitations remain. Because public data do not directly cover enterprise-level transactions or hospital-level carbon-accounting details, the empirical analysis relies on sectoral calibration and scenario simulation. Future research should integrate hospital procurement records, enterprise carbon disclosures, and more disaggregated input-output tables to improve micro-level identification and policy-simulation accuracy.

Data Availability Statement

The data used in this study are derived from publicly available sources: the CEADs China Emission Accounts and Datasets (https://www.ceads.net/data/), annual statistics from the National Bureau of Statistics of China (https://data.stats.gov.cn/), and the WHO Global Health Expenditure Database (https://apps.who.int/nha/database/).

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