

Knowledge Graph-Driven Process-Level Carbon Emission Control for Green Building Construction

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Abstract: Carbon emissions during the building construction phase are characterized by high intensity, temporal concentration, and complex influencing factors. Traditional post-event accounting and static evaluation methods cannot achieve dynamic monitoring or precise control of process-level carbon emissions. To address this issue, this paper proposes and constructs a Green Construction Carbon Emission Knowledge Graph (GCCE-KG). First, a 50-project green construction case library is built. It has a three-dimensional stratification covering building type, climate zone, and optimization standard. A two-stage expert verification process confirms its representativeness. Second, a four-dimensional carbon reduction measure system is developed for the four major high-carbon work packages. The dimensions are material, process, equipment, and management. A precise mapping matrix linking measures, processes, and emission sources is also established. On this basis, a knowledge graph ontology model is designed with the construction process as the core hub. Six core entity types and their semantic relationships are clearly defined. A hybrid strategy combining structured data mapping and deep learning-based extraction from unstructured text is used for knowledge extraction. Furthermore, based on the reasoning capability of the knowledge graph, a full-process intelligent reasoning system is constructed. It covers high-carbon process identification, emission exceedance root cause tracing, similar case matching, and carbon reduction measure recommendation. A three-tier hierarchical early warning and closed-loop control mechanism is also established. A public building renovation project in Beijing was selected as the demonstration scenario. A six-month engineering application validation was conducted during the main structure

construction period. The results show that the average carbon emission intensity of core processes decreased by 24.1%. The average response time to emission exceedance incidents was reduced by 66.7%. The on-site implementation rate of carbon reduction measures reached 100%. The comprehensive evaluation score of green construction improved by 16.6%. This study provides a reusable knowledge base and technical paradigm for refined and intelligent carbon emission control during the building construction phase.

Keywords: Green Construction; Carbon Emission; Knowledge Graph; Process-Level Control; Ontology Model; Intelligent Reasoning

1. Introduction

China has set strategic goals of carbon peaking and carbon neutrality [1]. As a result, green construction and low-carbon buildings have become national imperatives. However, current research and practice show a clear imbalance. Most attention has been given to design, material selection, and operational energy saving. The construction phase, by contrast, remains relatively weak in carbon management.

Construction carbon emissions have distinct characteristics. They are highly intensive, concentrated in time, and driven by complex factors [2,3]. Their magnitude depends closely on process-level technology choices, equipment efficiency, material consumption, and on-site management [4]. Therefore, extending carbon control to the process level is an inevitable step toward precise carbon reduction in building construction.

Research on carbon accounting methods for construction has now become mature. The emission factor method, based on the Standard for Building Carbon Emission Calculation (GB/T 51366-2019), provides a standardized

quantification framework. It covers emission sources such as material production and transportation, machinery use, and temporary facility energy consumption [5]. However, most existing accounting practices still rely on post-event statistics. They use construction drawing budgets or as-built settlement data. This leads to long accounting cycles and coarse data granularity. Such an approach cannot support real-time decisions that respond to dynamic construction processes [6].

Some scholars have explored dynamic carbon calculation using Building Information Modeling (BIM) [7]. Yet, systematic solutions are still missing. Specifically, we lack process-level real-time accounting and effective linkage with on-site control measures.

At the same time, the field of green construction evaluation has produced many research outcomes. Examples include the G1-entropy weight method [8], cloud model-based evaluation [9], hybrid AHP-TOPSIS approaches [10], and fuzzy analytic network process [11]. Most of these studies, however, focus on static overall assessment. They do not turn evaluation results into targeted commands for specific processes.

In the area of carbon emission optimization, multi-objective models have made significant progress. These models address the trade-off between time, cost, and carbon emissions using intelligent algorithms [12]. However, they usually operate at the project planning level [13]. As a result, they cannot respond to real-time emission exceedance risks caused by changing site conditions during construction [14].

In recent years, knowledge graph technology has started to be applied in construction engineering. Its strengths lie in knowledge representation, semantic association, and intelligent reasoning. These strengths offer new ways to address information fragmentation and the difficulty of reusing experience in carbon emission control. Yet, no knowledge graph currently exists that targets process-level carbon management. Existing knowledge graphs mainly focus on safety risks [15] or general building knowledge. A knowledge network designed for green construction carbon emissions has not yet been built. Such a network should use the process as the central hub and connect emission sources, carbon reduction measures, and control rules.

To fill these gaps, this paper proposes the Green Construction Carbon Emission Knowledge

Graph (GCCE-KG). The main contributions are as follows:

We build a 50-project green construction case library with a three-dimensional stratification. The dimensions are building type, climate zone, and optimization standard. A two-stage expert verification process ensures representativeness and scientific validity.

We develop a four-dimensional carbon reduction measure system for the four major high-carbon work packages. The dimensions are material, process, equipment, and management. We also establish a precise mapping matrix linking measures, processes, and emission sources.

We design a knowledge graph ontology model with the construction process as the core hub. The model specifies six core entity types: Case, Process, Emission, EmissionSource, Measure, and Rule. We also define their semantic relationships. A hybrid strategy extracts knowledge from both structured data and unstructured text.

We construct a full-process intelligent reasoning system. It covers high-carbon process identification, root cause tracing of emission exceedances, similar case matching, and recommendation of carbon reduction measures. The system is based on the rule reasoning and case matching capabilities of the knowledge graph. We also build a three-tier hierarchical early warning and closed-loop control mechanism.

We validate the engineering effectiveness of the system. A full-process application was conducted over six months at a public building renovation project in Beijing.

This study provides a reusable knowledge base and technical paradigm. It supports refined and intelligent carbon emission control during the building construction phase.

2. Related Work

2.1 Carbon Emission Accounting and Driving Factors in the Building Sector

The building sector is widely recognized as a major contributor to global carbon emissions. Its carbon footprint spans the entire life cycle. This includes material production, construction, operation, and demolition. The IPCC Sixth Assessment Report stresses the urgent need for deep emission cuts in all sectors, including buildings, to meet the Paris Agreement goals [16]. Within the building life cycle, the

construction phase is relatively short compared to the operation phase. However, it has concentrated and intensive carbon emissions. Chen et al. [17] calculated energy consumption and carbon emissions during the construction stage of large public buildings. They used an improved STIRPAT model to identify key influencing factors. Their results showed that construction carbon emissions are driven by a complex mix of scale, technology, and management factors. Sandanayake et al. [18] compared environmental emissions at the foundation and structure construction stages. They found significant variations in emission intensity across different construction activities. At the macro level, understanding what drives building sector carbon emissions is essential. It helps formulate effective mitigation strategies. Huo et al. [19] used an integrated DEMATEL-ISM model to investigate the driving mechanism for carbon emissions in the building sector. They identified critical factors and their causal relationships. Their findings highlighted that economic scale, building stock growth, and energy intensity are among the most influential drivers. Abulibdeh [20] conducted a geospatial assessment of the carbon footprint of water and electricity consumption in residential buildings. This illustrated the importance of spatially explicit analysis for targeted carbon reduction. Furthermore, the effect of building material choices on carbon emissions has attracted considerable research attention. Zhao et al. [21] compared the carbon emissions of traditional, prefabricated, and green material buildings during the materialization stage. They provided quantitative evidence that material selection greatly influences the overall carbon footprint. Chen et al. [22] reviewed recent developments in converting waste into sustainable construction materials. They presented a promising pathway for reducing embodied carbon through circular economy principles.

2.2 Green Construction Evaluation and Multi-Objective Optimization

Green construction performance evaluation has been a sustained research topic. Various multi-criteria decision-making (MCDM) methods have been used to assess sustainability and greenness. Cheng et al. [23] proposed a green construction evaluation model for prefabricated buildings. It is based on the

G1-entropy-independence weight method. This model effectively combines expert judgment with objective data to produce comprehensive evaluation results. Wenjie et al. [24] developed an evaluation model for novel technologies in green substation construction. They integrated AHP group decision-making with the entropy weight method in a variable-weight framework. Khoshnava et al. [25] used a hybrid MCDM approach to rank green building material criteria. They based their ranking on the three pillars of sustainability. This showed the value of structured decision frameworks in material selection. In a broader context, Qiu and Luo [26] proposed a grey multi-level evaluation method for industrial park ecology. It uses a coefficient of variation-attribute hierarchy model. Although applied at the industrial park level, it shares common methods with green construction evaluation, such as handling indicator hierarchies and weight determination. However, as noted in the Introduction, these studies mainly produce static overall assessments. They have not yet linked evaluation outcomes directly to real-time, process-level control actions on construction sites.

Alongside evaluation research, multi-objective optimization has become a powerful tool. It addresses the trade-offs among time, cost, quality, and environmental goals in construction projects. Eirgash and Toğan [27] proposed a novel oppositional teaching learning strategy. It was based on the golden ratio. This method solved time-cost-environmental impact trade-off problems and showed improved convergence over conventional algorithms. Later, Eirgash and Toğan [28] developed a dual opposition learning-based multi-objective Aquila Optimizer. This handled the more complex trade-off of time, cost, quality, and CO₂ emissions in generalized construction projects. Su et al. [29] investigated construction program optimization for both economic and environmental sustainability. This provided decision support at the project planning level. Zhao et al. [30] focused on low-carbon highway construction scheduling. They proposed an ACEMO-TOPSIS algorithm for multi-objective optimization. Despite these algorithmic advances, existing optimization studies mostly work at the planning or scheduling level. They do not respond to real-time emission exceedance risks that arise from changing site conditions during actual construction.

2.3 Knowledge-Driven Approaches in Construction Engineering

Knowledge-driven approaches, especially knowledge graphs and ontology-based systems, have drawn increasing attention in construction engineering. Knowledge graphs offer unique strengths. They support structured knowledge representation, semantic association, and rule-based reasoning. These capabilities are well suited for managing the complex, interconnected information in construction projects. Tan et al. [31] applied ontology and case-based reasoning to safety risk assessment of deep foundation pit construction. They built a domain-specific knowledge base that could identify safety risk factors through semantic retrieval and rule matching. Their work proved the feasibility and value of knowledge graph techniques in construction risk management. Beyond safety, knowledge graphs have been used for quality inspection knowledge representation and construction method selection. However, existing applications have mainly focused on safety and quality. The environmental dimension, particularly carbon emission management and control, has received limited attention.

In parallel, digital twin technology has emerged as a promising way to bridge the physical construction site with virtual information models. Tao et al. [32] comprehensively analyzed the concept of digital twins. They proposed a five-dimensional model and identified ten major application domains, including construction. Dietz and Pernul [33] discussed how digital twins can empower enterprises toward a system-of-systems approach. Park et al. [34] developed a digital twin-based cyber-physical production system framework. Digital twins provide a conceptual architecture for real-time data integration and simulation. However, they typically lack the structured knowledge representation and semantic reasoning that knowledge graphs naturally possess. This suggests that integrating the two could bring synergistic benefits for intelligent construction management.

In the broader knowledge engineering field, advances in knowledge extraction and representation have made knowledge graph construction easier from heterogeneous data sources. Sequence labeling models like BERT-BiLSTM-CRF have performed well in named entity recognition from domain texts. For

knowledge graph completion, Chao et al. [35] proposed the PairRE model. It uses paired relation vectors for knowledge graph embeddings. This enables effective link prediction to discover implicit relationships among entities. These technical advances provide methodological support for building a domain-specific knowledge graph for construction carbon emission management. However, their systematic integration and application in this vertical domain still need to be explored.

In summary, substantial progress has been made in each relevant area-carbon emission accounting, green construction evaluation, multi-objective optimization, and knowledge-driven approaches. Yet a significant research gap exists where these areas intersect. Currently, there is no knowledge graph that uses the construction process as the core hub. Nor is there one that integrates emission sources, carbon reduction measures, and control rules into a unified, reasoning-capable knowledge network. This study aims to fill that gap. We construct a Green Construction Carbon Emission Knowledge Graph (GCCE-KG). It systematically links these knowledge elements. It also enables intelligent, process-level carbon emission management and control throughout the construction phase.

3. Methodology

3.1 Construction of Knowledge Graph for Carbon Emission Control in Green Construction

3.1.1 Green construction case library construction and standardization

To address the fragmentation issues existing between dynamic monitoring and scheme optimization decision-making for green construction carbon emissions, this paper constructs a Green Construction Carbon Emission Knowledge Graph (GCCE-KG).

The case library, serving as the data foundation for knowledge graph construction, sources its data from green construction demonstration projects and LEED/BREEAM certified projects in a certain province from 2020 to 2025, following the principles of type coverage, data comprehensiveness, and full-cycle monitoring, ultimately incorporating 50 cases. To resolve the issues of singular structure and insufficient representativeness in existing research case

libraries, this study adopts a three-dimensional stratified design comprising building type, climate zone, and optimization standard. The sample size of each subcategory is allocated according to its implementation proportion in

actual green building projects to ensure the statistical representativeness and generalization capability of the case library. The specific stratified structure of the 50 cases is presented in Table 1.

Table 1. Stratified Design of the 50-Project Green Construction Case Library

Hierarchical Dimension	Subcategory	Case Quantity	Data Source & Screening Criteria
Building Type	Public Buildings (Office / Stadium / Municipal)	16	Public buildings awarded the title of China Green & Safe Demonstration Construction Site and with LEED Gold / BREEAM Excellent or above certification; including new-built and reconstructed projects; data integrity $\geq 95\%$.
	Residential Buildings (Prefabricated / Ordinary High-rise / Small High-rise)	18	Green building project database of real estate enterprises; domestic green building certified residential projects; covering refined decoration in South China and simple decoration in North China, with prefabrication rate ranging from 0 to 60%.
	Industrial Buildings (Workshops / Supporting Facilities)	16	Green renovation project database of industrial parks; demonstration green building projects of industrial enterprises; covering light industry and heavy industry, with qualified environmental acceptance and complete energy consumption monitoring data.
Climate Zone	North China Climate Zone(Beijing-Tianjin-Hebei / Shanxi / Inner Mongolia)	19	Covers severe cold and cold regions, meeting green construction requirements for winter construction, wind and sand prevention.
	East China(Shanghai / Jiangsu / Zhejiang / Anhui)	10	Humid regions, complying with green construction requirements under high precipitation and high humidity, as well as water pollution control regulations.
	South China(Guangdong / Guangxi / Hainan)	8	Tropical and subtropical regions, satisfying green construction requirements of high temperature and humidity as well as typhoon resistance, with green vegetation restoration included.
	Northwest China(Shaanxi / Gansu / Ningxia)	13	Arid and semi-arid regions, meeting green building requirements of water conservation, wind and sand prevention, and heating energy saving.
Optimization Standard	Chinese Standard(GB/T50640-2010)	35	All projects are certified as China Green & Safe Demonstration Construction Sites; complete monitoring data of core measures (four savings and one environmental protection) and full green construction optimization reports.
	International Standard(LEED / BREEAM)	15	LEED Gold and above / BREEAM Excellent and above; including Sino-foreign joint venture construction projects; relevant measure data can be mapped and converted according to Chinese standard specifications.

To further validate the scientific validity and representativeness of the case library, this study adopts a two-stage expert verification process. In the first stage, oriented toward the overall architecture of the case library, five industry experts with senior professional titles and over 10 years of experience in green building research were invited to evaluate the structural rationality, dimensional completeness, and subcategory delineation logic of the three-dimensional stratified design framework. The five experts

independently rated using a five-point Likert scale (1 = very unreasonable, 5 = very reasonable), yielding an average score of 4.7, indicating high expert recognition of the stratified framework design. In the second stage, oriented toward the content validity of the case library, the 50 cases were organized into anonymized case characteristic summary cards according to the stratification dimensions. Each expert independently reviewed all summary cards and rated each case's degree of

representativeness for its assigned subcategory (1 = very low representativeness, 5 = very high representativeness). A consistency test was conducted on all ratings from the five experts across the 50 cases, yielding a Fleiss' Kappa coefficient of 0.81, classified as high consistency (*p* < 0.001), indicating statistically significant consensus among experts in their judgments of case representativeness. The combined results of the two-stage verification demonstrate that the stratified framework design of this case library is reasonable and the included cases possess adequate representativeness, effectively meeting

the research requirements for cross-scenario applications.

To ensure the credibility and traceability of case data, all original monitoring data of the cases are stored using blockchain encryption technology. To verify data consistency between collection and transmission, 100 sets of monitoring data were randomly selected and checked against their corresponding manual records. The comparison results show that the overall data consistency reaches 91.0%, with zero tampering records. Detailed data are presented in Table 2.

Table 2. Comparison of Consistency Between Monitoring Data and Manual Data

Data Type	Sample Quantity	Consistent Samples	Consistency Rate	Tampering Attempt Records
Material consumption	30	27	90.00%	0
Machinery shift quantity	30	28	93.30%	0
Transportation mileage	20	19	95.00%	0
Process duration	20	17	85.00%	0
Total	100	91	91.00%	0

3.1.2 Process-level green construction carbon reduction measure system

According to the Standard for Building Carbon Emission Calculation (GB/T 51366-2019) and existing construction carbon emission research, the carbon emission accounting boundary during the building construction phase encompasses building material production and transportation, construction machinery usage, temporary construction facilities, and construction energy consumption, with main structure construction

accounting for over 85% of total construction phase carbon emissions [36]. This paper takes the corresponding unit processes within the four major work packages of main structure construction-concrete works, earthwork works, steel reinforcement works, and formwork works [37,38]-as the minimum units of investigation and control, clarifying the carbon emission sources and composition of each process. The carbon emission sources for each work package are summarized in Table 3.

Table 3. Carbon Emission Sources of Main Structure Construction Processes

Work Package Type	Covered Processes	Main Carbon Emission Sources	Key Influencing Factors
Earthwork Works	Excavation, on-site transfer, off-site transport, backfill and compaction	Fuel consumption of construction machinery such as excavators, compactors, and transport vehicles	Machinery selection, transport route planning, and equipment load rate
Steel Reinforcement Works	On-site processing, welding, binding, and installation	Embodied carbon of steel reinforcement raw materials, electricity consumption of processing and welding equipment, embodied carbon corresponding to steel material loss	-
Formwork Works	Formwork erection, dismantling, on-site transfer, and turnover maintenance	Embodied carbon of formwork base materials, electricity and fuel consumption of erection/dismantling and transfer equipment, carbon emissions corresponding to formwork material loss	Formwork turnover frequency and material selection

Based on the current national green construction evaluation standards and the evaluation indicators of green construction demonstration projects across various provinces and municipalities, combined with the carbon emission characteristics and reduction targets of

the four major high-carbon processes clarified in Section 2.2, this study systematically reviewed and conducted frequency analysis of the carbon reduction measures actually adopted in the 50 industry benchmark project cases to select measures with high carbon reduction

contribution. These were further optimized and confirmed through 85 valid questionnaires (effective response rate of 92.39%) and semi-structured interviews with six senior industry experts, forming a process-oriented green construction carbon reduction measure system. This system organizes each category of

high-carbon works from four dimensions-material optimization, process upgrading, equipment efficiency improvement, and management control-with the mapping relationships between each measure and specific processes and emission sources presented in Table 4.

Table 4. Measure-Process-Emission Source Association Matrix

High-Carbon Works	Measure Dimension	Specific Carbon Reduction Measures	Associated Unit Process	Associated Emission Source	Carbon Reduction Mechanism
Steel Reinforcement Works	Material Optimization	High-strength steel bar replacement	Processing, Binding	Embodied carbon of steel	Reduce steel consumption per unit bearing capacity
	Material Optimization	Local procurement of steel materials	Transportation link	Transportation fuel	Shorten transportation radius
	Material Optimization	BIM optimized blanking	Processing	Embodied carbon from steel waste	Reduce offcut and material loss
	Process Upgrading	Straight thread sleeve mechanical connection	Connection	Equipment electricity consumption	Eliminate welding power consumption and welding material loss
	Process Upgrading	Factory prefabricated reinforcement components	Processing	On-site processing energy consumption	Reduce energy consumption via standardized processing
	Management & Control	Requisition-processing-recovery account ledger	Processing, Binding	Embodied carbon from steel waste	Strictly control material loss rate
	Management & Control	Centralized processing scheduling	Processing	Equipment electricity consumption	Reduce no-load operation
Formwork Works	Material Optimization	Steel/aluminum formwork replacement	Erection	Embodied carbon of formwork base material	Dilute embodied carbon through high turnover frequency
	Material Optimization	Recycled plastic / bamboo plywood	Erection	Embodied carbon of formwork base material	Source substitution with low-carbon base materials
	Process Upgrading	Early stripping formwork system	Erection, Dismantling	Formwork occupation cycle	Reduce one-time material investment
	Process Upgrading	BIM digital formwork matching	Erection	Embodied carbon from formwork waste	Optimize cutting to reduce material loss
	Management & Control	Full-cycle formwork management ledger	Erection, Turnover & Maintenance	Embodied carbon from formwork waste	Standardize operation to reduce abnormal loss
Concrete Works	Material Optimization	Low-cement / recycled aggregate concrete	Pouring	Embodied carbon of cement	Replace clinker with fly ash and other admixtures
	Material Optimization	Local procurement of commercial concrete	Transportation link	Transportation fuel	Shorten transportation distance
	Process Upgrading	Optimize pumping parameters	Pumping	Electric power consumption	Improve pumping efficiency
	Process Upgrading	Film covering / intelligent sprinkler curing	Curing	Energy and water consumption	Achieve energy saving via precise water regulation

	Process Upgrading	Super retarding concrete	Pouring	Embodied carbon from rework	Reduce cold joint defects and construction rework
	Equipment Efficiency Improvement	Variable-frequency pumping & vibrating equipment	Pumping, Vibrating	Electric power consumption	Match load by frequency conversion
	Equipment Efficiency Improvement	Optimize equipment scheduling	Pumping, Vibrating	Invalid energy consumption	Strictly control no-load operating duration
Earthwork Works	Process Upgrading	On-site earthwork balance optimization	Excavation, Backfilling & Compaction	Transportation fuel	Reduce off-site transportation volume
	Process Upgrading	Optimize excavation-backfilling sequence	Excavation, Backfilling & Compaction	Construction machinery fuel	Reduce repeated mechanical operations
	Equipment Efficiency Improvement	New energy construction machinery	Excavation, Transshipment	Construction machinery fuel	Replace fossil fuel at the source
	Equipment Efficiency Improvement	Route optimization and full-load control	Transshipment, Off-site transportation	Transportation fuel	Reduce invalid mileage and no-load travel
	Management & Control	Full-cycle machinery energy consumption ledger	Excavation, Transshipment	Construction machinery fuel	Real-time monitoring of abnormal fuel consumption
	Management & Control	Optimization of transportation time period and route	Off-site transportation	Transportation fuel	Avoid traffic congestion and reduce idling fuel consumption

3.1.3 Knowledge graph ontology model construction

This study constructs a knowledge graph with the construction process as the core hub, oriented toward full-process management and control of green construction carbon emissions. The graph formally defines core entities, attributes, and mutual semantic relationships in a standardized and structured manner, establishing a unified and inferable knowledge network to provide foundational knowledge support for intelligent carbon emission management, control, and decision-making. This section elaborates on the construction method of the knowledge graph through three successively progressive levels: ontology model definition, knowledge extraction and graph construction, and hybrid storage architecture.

(1) Ontology Model Definition

The core entities of the ontology and their attributes are defined as follows. Construction Case (Case) has attributes including Case ID, Project Type, Climate Zone, etc. Construction Process (Process) serves as the knowledge core, with attributes including Process ID, Name, Hierarchy Level, Carbon Emission Threshold per Unit Work Quantity, etc. Process Carbon Emission (Emission) has attributes including Emission ID, Monitoring Period, Emission

Intensity (kgCO₂e/unit work quantity), Data Source, and Confidence Level. It should be noted that the emission value stored in this entity is the carbon emission intensity indicator after normalization by unit work quantity, rather than the absolute total carbon emission of the process; its calculation process is as follows: the system obtains the original total monitoring quantities of process energy and material consumption through sensors and ledger records, calculates the total carbon emission within the monitoring period according to the emission factor method in the Standard for Building Carbon Emission Calculation (GB/T 51366-2019), and then performs normalization calculation in combination with the actual completed work quantity during that period obtained from the Process entity, ultimately yielding carbon emission intensity values that can be horizontally compared across processes, time periods, and projects, serving as the unified benchmark for subsequent threshold determination, emission exceedance early warning, and carbon reduction benefit evaluation. Emission Source (EmissionSource) links to the specific source of carbon emissions, with attributes including Emission Source ID, Category, and Associated Process ID. Optimization Measure (Measure) corresponds to

the 26 core measures, with attributes including Measure ID, Name, Dimension, Standard Value, and Data Type. Early Warning Rule (Rule) stores the business logic of carbon emission management and control, with attributes including Rule ID, Rule Type (threshold determination/trend prediction), Trigger Condition, Applicable Process ID, and Corresponding Early Warning Level.

The semantic relationships between entities are defined using the UML model, with the overall design illustrated in Figure 1. The core relationships include: Case and Process are associated via Has_Process; Process and Emission are associated via Has_Emission; Emission and EmissionSource are associated via

Has_Source, enabling the tracing of emission records to specific sources; Measure and EmissionSource establish targeted association via Targets_Source, clarifying the specific emission source targeted by each measure; Emission and Measure are associated via Reflects_Measure, reflecting the feedback of emission data on measure implementation effectiveness; Rule and Process are associated via Applies_To, binding early warning rules to specific control processes; Case and Measure are associated via Has_Measure; Case is associated to the case library index entity CaseLibraryIndex via BelongsToLibrary, supporting rapid case retrieval.

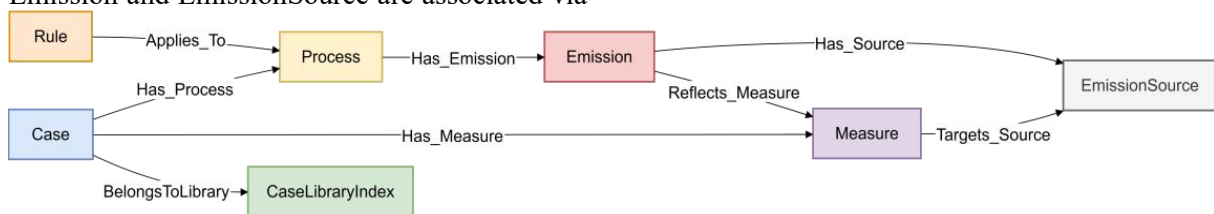


Figure 1. Definition of Semantic Relationships Between Entities

(2) Knowledge Extraction and Graph Construction

Based on the clarified ontology model, entity and relation extraction is carried out from the multi-source data of the 50 cases, adopting a hybrid strategy combining structured data rule mapping and deep learning-based extraction from unstructured text.

For structured data, 80 pre-defined mapping rule templates are used to directly convert fields from construction ledgers, BIM model parameters, and monitoring databases into corresponding entities and attributes. For unstructured text, a BERT-BiLSTM-CRF sequence labeling model is employed for named entity recognition, extracting key entity mentions such as process names, measure names, emission source types, and carbon emission values from documents including construction organization designs, green construction special reports, and emission exceedance disposal records.

In the relation extraction phase, a rule matching method based on dependency parsing patterns is adopted. A total of 150 extraction rules covering relation types such as measure-process association, process-emission source association, and emission-measure association are summarized from annotated corpora, with rule templates jointly defined by dependency arc paths and trigger word conditions. For example, for the extraction of the RelateTo relation, a

typical rule can be described as follows: if a sentence simultaneously contains an identified Measure entity and a Process entity, and the dependency path between them is "nsubj → verb ← dobj", with the verb lemma belonging to a predefined set of association trigger words (e.g., {"applied to", "targeted at", "applicable to", "used for"}), then a Measure→RelateTo→Process triple is automatically generated. For the extraction of the Has_Source relation, matching is performed based on emission source category trigger words (e.g., "electricity consumption", "fuel consumption", "embodied carbon emission") and their dependency combination patterns with process entities. Verified through manual sampling, the relation extraction accuracy of this rule set on the test set reaches XX%, meeting the precision requirements for knowledge graph construction.

Through the above process, a total of 50 Cases, 1,260 Processes, and 1,300 Measure records are instantiated, generating over 8,500 triples. After the initial extraction, the PairRE model [39] is employed for link prediction and completion, adding approximately 15% potential associations to ensure knowledge completeness. The schematic diagram of the main components of the knowledge graph entity creation and ingestion process is illustrated in Figure 2.

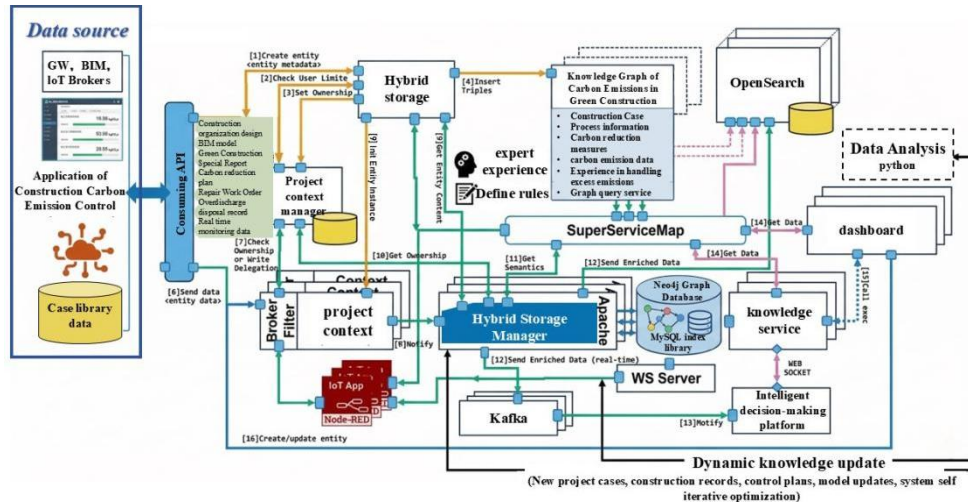


Figure 2. Schematic Diagram of Main Components in the Knowledge Graph Entity Creation and Ingestion Process

The knowledge graph extraction covers multi-source heterogeneous construction data: process hierarchies and logical relationships are extracted from construction organization designs and BIM models; carbon reduction measure information is extracted from green construction special reports and carbon reduction implementation plans; typical disposal cases are extracted from emission exceedance disposal records and control work orders; process carbon emission and operating condition status information is extracted from real-time monitoring data; finally, carbon emission control rules and hierarchical early warning rules are solidified by incorporating industry expert experience. Furthermore, this knowledge graph supports dynamic iterative updating. When new project cases, construction records, control plans, or rule optimizations are introduced, new knowledge can be integrated into the graph through automatic or semi-automatic processes, achieving autonomous iterative optimization of the knowledge system and control capability.

(3) Hybrid Storage Architecture

This study adopts a hybrid storage architecture

combining the Neo4j graph database and MySQL index database for knowledge storage. The extracted entities, attributes, semantic relationships, and inference rules are stored in the Neo4j graph database to support efficient associative query and intelligent reasoning; MySQL is used to construct the green construction case library index table, with its structural design presented in Table 5, for rapid case retrieval, balancing knowledge association depth with query response efficiency. Each construction case corresponds to an independent case entity in the graph, associated through exclusive semantic relationships with its contained process entities, adopted carbon reduction measure entities, and corresponding carbon emission entities, forming a standardized semantic subgraph with the case as the unit; the historical case library index entity only stores the core summary characteristic information of each case, rather than complete entity attributes, thereby ensuring case data independence while enabling rapid case retrieval and similarity matching.

Table 5. Design of Case Library Index Table Structure

Field Name	Field Type	Description	Index Type
Case Id	VARCHAR(50)	Unique identifier of the case	Primary Key Index
Case Library Id	VARCHAR(50)	Attribution identifier of the case library	Normal Index
Project Type	VARCHAR(30)	Type of engineering project	Normal Index
Core Processes	TEXT	List of core construction processes	Full-text Index
Key Indicator	JSON	Compliance status of key measures	None (JSON field)
Create Time	DATETIME	Data storage entry time	Normal Index

3.2 On-Site Monitoring and Control System Based on Knowledge Graph

3.2.1 Overall control system architecture

With the constructed green construction carbon emission knowledge graph as the core, and targeting the pain points of fragmented carbon emission control data, insufficient targeting, and

difficulty in experience reuse at construction sites, this chapter constructs a four-level closed-loop control system comprising the perception layer, knowledge layer, decision layer, and execution layer.

Distinguished from traditional generalized construction site environmental monitoring, this system takes the Process entity of the knowledge graph as the core anchor, constructing a targeted process-level monitoring system that achieves real-time mapping and dynamic updating between monitoring data and graph entities. The monitoring content is organized into four core dimensions:

Perception Layer: the on-site monitoring terminal, achieving real-time collection and standardized transmission of process operating conditions, energy and material consumption, carbon emissions, and measure implementation status, providing dynamic data input for the knowledge graph.

Knowledge Layer: the core layer of the green construction carbon emission knowledge graph, receiving real-time data from the perception layer, completing entity matching, data fusion, and rule validation, providing knowledge reasoning and case support for upper-level decision-making.

Decision Layer: based on the reasoning capability of the knowledge graph, achieving high-carbon process identification, emission exceedance root cause tracing, similar case matching, and intelligent recommendation of carbon reduction measures, synchronously outputting hierarchical early warning information and standardized disposal plans.

Execution Layer: the on-site control implementation end, achieving information visualization, hierarchical early warning push, and closed-loop disposal processes through the project department large screen and management personnel mobile terminals, with execution effects synchronously fed back to the knowledge graph, completing the dynamic iterative optimization of the knowledge system.

3.2.2 Process-level on-site monitoring system based on knowledge graph

Distinguished from traditional generalized construction site environmental monitoring, this system takes the Process entity of the knowledge graph as the core anchor, constructing a targeted process-level monitoring system that achieves real-time mapping and dynamic updating between monitoring data and graph entities. The

monitoring content covers four aspects.

In terms of process condition monitoring, through the construction progress system, BIM model progress synchronization, and on-site video recognition, core information such as process type, start and end time, work face, operating personnel, and process scheme is collected, and real-time matching is performed with the construction process entities in the knowledge graph to lock the control target.

In terms of energy and material consumption monitoring, through smart meters, fuel consumption sensors, weighbridge terminals, and material requisition systems, data on construction equipment electricity/fuel consumption, main material requisition and consumption quantities, and turnover material usage are collected, corresponding to the emission source attributes of the carbon emission entities in the graph, providing basic data for real-time carbon emission accounting.

In terms of real-time carbon emission accounting, based on the Standard for Building Carbon Emission Calculation (GB/T 51366-2019), process-level carbon emission real-time accounting is completed in combination with monitoring data, synchronously updated to the process carbon emission entities in the knowledge graph, achieving real-time association between emission data and process and measure entities.

In terms of measure implementation status monitoring, through on-site inspection ledgers, mobile terminal check-in, and video review, information on the implementation progress, implementation status, and compliance rate of green carbon reduction measures is collected, matched with the carbon reduction measure entities in the graph, providing a basis for measure suitability analysis and carbon reduction benefit evaluation.

3.2.3 Knowledge-driven intelligent carbon emission reasoning

Leveraging the entity associations, rule constraints, and case retrieval capabilities of the knowledge graph, this system achieves intelligent reasoning functions for the full process of construction process carbon emission management and control, covering four core components: high-carbon process identification, emission exceedance root cause tracing, similar case matching, and carbon reduction measure recommendation.

As real-time monitoring data continuously flows

into the knowledge graph, the system first updates the accounted process carbon emission data to the corresponding Emission entity and automatically triggers the early warning rules defined by the Rule entity bound to the Process entity of that process. Through multi-dimensional comparison of the current emission value with the carbon emission intensity threshold preset in the rules, the historical emission level of the process during the same period, and the emission distribution characteristics of similar processes in the same type of case library, the system can automatically determine the carbon emission status of the current process, accurately identifying emission exceedance processes and high-emission hotspot links, thereby locking onto the core targets of on-site carbon management and control. Once a high-carbon process is successfully identified, the system immediately initiates automatic root cause tracing of the emission exceedance. The reasoning process unfolds layer by layer along the pre-constructed semantic association links in the knowledge graph: through the Has_Source relationship from the Emission entity, the specific Emission Source entity is directly located-for example, a particular emission exceedance event is precisely associated with excessive electricity consumption of a certain pumping device or excessive embodied carbon from cementitious materials in a certain batch of concrete. On this basis, the system further utilizes the Targets_Source targeted association pre-established between the Measure entity and the Emission Source entity to reverse-check whether the carbon reduction measures deployed for that emission source have been implemented as planned and whether the implementation status meets the standards, thereby completing end-to-end layer-by-layer decomposition from the emission exceedance phenomenon to the emission source and then to the measure implementation status, fundamentally resolving the prominent pain point in traditional carbon emission control practice where emission exceedance events are easily discoverable but the causes are difficult to locate.

While completing emission source root cause

localization, the system simultaneously initiates intelligent matching of similar cases and precise recommendation of carbon reduction measures. Using the currently identified emission exceedance process type, the localized emission exceedance root cause attributes, and the project's own working condition characteristics such as climate zone and building type as multi-dimensional retrieval labels, the system traverses historical benchmark cases and similar emission exceedance disposal records in the case library index entities of the knowledge graph, filtering out reference cases highly matching the current scenario through semantic similarity algorithms, achieving rapid retrieval and effective reuse of mature engineering experience. Based on the matching results, the system further utilizes the semantic binding relationships between carbon reduction measure entities and processes and emission sources, following multi-level reasoning rules of process suitability, target matching, scenario compatibility, and carbon reduction benefit priority, to filter out feasible carbon reduction schemes applicable to the current emission exceedance scenario from the measure library, and performs comprehensive ranking according to carbon reduction efficiency, implementation cost, and on-site implementation difficulty, ultimately outputting a standardized disposal plan containing specific operational recommendations, providing directly executable decision support for on-site management personnel and fundamentally resolving the problem of disconnection between carbon reduction measure recommendation and on-site control needs under traditional modes.

3.2.4 Hierarchical early warning and closed-loop control process

Integrating construction site management practices and the severity of carbon emission exceedance, and based on the rule layer of the knowledge graph, a three-level hierarchical early warning mechanism is established, clearly defining the trigger conditions, notification recipients, and disposal requirements for each level, as presented in Table 6, to achieve hierarchical control and precise response to emission exceedance risks.

Table 6. Process-Level Carbon Emission Hierarchical Early Warning Standards and Disposal Requirements

Early Warning Level	Warning Status	Trigger Condition	Recipient	Core Disposal Requirements
Blue Warning	Potential	Carbon emission	Construction	Continuously monitor data trends, optimize

(Level I)	Risk	intensity reaches 80%~100% of the threshold	workers, Team leaders	construction parameters, and avoid excessive emission risks in advance.
Orange Warning (Level II)	Slight Exceedance	Carbon emission intensity exceeds the threshold within 10%	Technical person-in-charge, Production manager	Suspend non-critical operations of the working procedure, locate excessive emission causes via knowledge graph, and complete scheme adjustment and implementation within 24 hours.
Red Warning (Level III)	Severe Exceedance	Carbon emission intensity exceeds the threshold by more than 10%	Project manager, Green construction supervisor	Immediately suspend relevant procedure operations, launch special disposal procedures, match the optimal carbon reduction scheme through knowledge graph, and resume construction only after rectification and acceptance are qualified.

4. Case Study and Results

4.1 Application Scenario and Data Collection

This study selected a public building renovation project in Beijing as the demonstration scenario. It was used to test the process-oriented green construction carbon emission knowledge graph control system. The main structure construction phase of this project involved intensive high-carbon processes. It consumed large amounts of energy and building materials. Activities such as steel reinforcement processing, formwork erection and dismantling, concrete pouring, and earthwork operations generated substantial carbon emissions. This made the project a typical concentrated carbon emission scenario during the building construction phase. At the same time, the project had set specific targets. One was to become a Beijing Green Construction Demonstration Project. Another was a mandatory requirement to reduce the carbon emission intensity of core processes in the main structure by more than 20%. These created an urgent demand for refined low-carbon control and green upgrading. To achieve precise carbon emission control throughout the entire construction process and to meet the carbon reduction targets, the project fully deployed the knowledge graph-based green construction carbon emission control platform developed in this study.

The deployed control platform consisted of two parts: on-site hardware terminals and software functional modules. At the hardware terminal level, equipment was arranged according to the project construction layout and process operation areas. A total of 39 data collection terminals, 2 edge computing nodes, and 13 interaction and display terminals were deployed. These formed a complete on-site sensing network for collection, transmission, analysis, and interaction. At the

software functional level, three core modules were built. These were real-time monitoring visualization, early warning and closed-loop control, and knowledge decision-making services. The modules were fully integrated with the green construction carbon emission knowledge graph constructed in this paper. This provided full-process technical support for on-site management and control. The layout of the on-site sensing network is shown in Figure 3.



Figure 3. On-Site Sensing Network Layout

Relying on the platform functions and the knowledge graph ontology architecture, a systematic identification and classification of carbon emission sources was carried out throughout the entire construction process. Four core high-carbon work packages were clearly identified: steel reinforcement works, formwork works, concrete works, and earthwork works. Four core emission categories were also demarcated: building material embodied carbon, construction equipment energy consumption, material transportation emissions, and temporary facility energy consumption. On this basis, a multi-dimensional and full-coverage on-site data collection system was constructed. First, smart meters, fuel consumption sensors, weighbridge identification terminals, and IoT monitoring equipment were deployed on site. These collected dynamic data on construction energy consumption, material consumption, and equipment operation in real time. Second,

standardized ledger verification, on-site inspection records, and green construction special documents were used. These supplemented management data such as manually counted measure implementation and process progress. Third, interfaces were built with the project's BIM model, progress management system, and material management system. These provided online data on engineering structures, process logic, and material requisition. Through these channels, key data were fully obtained. These included process operating condition parameters, energy consumption quantities, building material loss rates, real-time carbon emission accounting values, and carbon reduction measure implementation status.

The entire data collection process followed the principles of authenticity, accuracy, and completeness. All collected data underwent anomaly filtering, standardized verification, and semantic alignment before being stored in a unified manner. This provided high-quality data support for project-level carbon emission knowledge graph construction, carbon emission dynamic analysis, and intelligent reasoning. At the same time, historical carbon emission data from similar benchmark projects and baseline condition data from the project before construction were collected. This laid the foundation for comparative analysis before and after technology application.

Specifically, the "pre-technology application" baseline values used for subsequent effectiveness verification consisted of two parts. The first part was the core process carbon emission intensity baseline. This was derived from the historical carbon emission accounting data of three completed public building renovation projects in the same region, of the same building type, and with the same construction level. The data covered the main structure construction phase. The mean value of their unit work quantity carbon emission intensity across the four core processes was calculated. These processes were concrete works, steel reinforcement works, formwork works, and earthwork works. The resulting value of 28.6 kgCO₂e/m² was used as a comparable reference baseline for measuring the carbon reduction effectiveness of this project. The second part was the control efficiency and measure implementation baseline. This was derived from records during the project's construction

preparation period, which lasted about one month. During this time, the traditional mode of manual inspection, ledger recording, and experience-based task assignment was still in use. Emission exceedance incident response and disposal records were collected. On-site inspection sampling data of green construction measures were also gathered. From these, the average response time, average disposal time, and measure implementation rate were calculated. These served as the self-comparison baseline for measuring the management efficiency improvement before and after the application of this control system. Both parts of the baseline data were collected and verified before platform deployment. This ensured the independence and objectivity of the comparative analysis.

4.2 Project Carbon Emission Control Status Analysis

Based on the collected multi-source construction and carbon emission data, a systematic review and in-depth analysis of the project's carbon emission control status were conducted. The results showed that carbon emissions during the construction phase were primarily contributed by the main structure construction activities. Among them, concrete works and steel reinforcement works accounted for 62% and 21% of carbon emissions, respectively. The embodied carbon of commercial concrete and steel reinforcement raw materials, along with the energy consumption of construction equipment operation, made up the main components. At the same time, several factors had significant influence on process carbon emission intensity and emission patterns. These included the dynamic switching frequency of construction processes, process scheme selection, equipment energy efficiency levels, the rate of carbon reduction measure implementation, and construction load fluctuations.

It should be noted that this carbon emission proportion analysis was based on the total carbon emission of each process within the monitoring period. The purpose was to identify the main contributing processes from a macro perspective. This provided directional guidance for subsequent control resource allocation. The process-level monitoring, early warning, and effectiveness evaluation discussed in this paper all use the carbon emission intensity per unit work quantity as the core control indicator. This

indicator is stored in the Emission entities of the knowledge graph. Both types of data coexist in the knowledge graph and are linked to the same Process entity through the Has_Emission relationship.

Using the multi-source standardized data as the foundation, a project-level green construction carbon emission knowledge graph was constructed. This achieved real-time semantic mapping between the physical construction site and the virtual knowledge network. It faithfully reproduced the spatiotemporal distribution characteristics of carbon emissions across all processes of the project. Through the association analysis and quantitative accounting functions of the knowledge graph, precise carbon emission accounting was completed for 36 subdivided unit processes. This accurately identified the high-emission hotspot processes, core emission exceedance risk targets, and control weaknesses of the project. The project's carbon emission status and control capability were comprehensively evaluated. This evaluation combined the Standard for Building Carbon Emission Calculation, the Standard for Green Construction Evaluation of Building Engineering, the project's low-carbon control targets, and the advanced levels of the industry. It clearly defined the process-level emission reduction priorities, optimization directions, and control pathways. This provided data support and decision-making basis for subsequent targeted carbon reduction strategy formulation and closed-loop control.

4.3 Comprehensive Evaluation of Technical System Application Effectiveness

Throughout the entire main structure

Table 7. Comparison of Core Indicators Before and After Technical System Application

Core Indicator	Before Technical Application (Baseline)	After Technical Application	Improvement Range
Average carbon emission intensity of core processes	28.6 kgCO _{2e} /m ²	21.7 kgCO _{2e} /m ²	-24.1%
Average response time of over-emission incidents	30 min	10 min	-66.7%
Average disposal time of over-emission incidents	4.5 h	3.0 h	-33.3%
On-site implementation rate of carbon reduction measures	72%	100%	+28.0%
Comprehensive evaluation score of green construction	76.5 points	89.2 points	+16.6%

In a typical application scenario, the concrete pouring process on the third floor of the project's main structure triggered an orange emission exceedance warning. The system rapidly completed emission exceedance root cause tracing through the knowledge graph. It

accurately located two core contributing factors. One was the excessive no-load operating duration of the pumping equipment. The other was the high cementitious material dosage in the concrete mix proportion. At the same time, similar benchmark project cases were matched. construction cycle of the project, the knowledge graph-based green construction carbon emission control system and supporting platform were fully deployed and stably operated. Round-the-clock dynamic monitoring, intelligent reasoning, and continuous data tracking of carbon emissions across all project processes were carried out. After six months of stable operational verification during the main structure construction period, the application of the technical system achieved significant carbon reduction and control results. The carbon emissions of core processes were effectively controlled and significantly reduced. The disposal efficiency of emission exceedance risks was substantially improved. The comprehensive green construction control capability and low-carbon construction level were notably enhanced. The project's preset carbon reduction targets and green construction establishment requirements were exceeded.

Using the full-cycle monitoring data of the platform as the core, a before-and-after comparison method was adopted for quantitative evaluation of application effectiveness. Five core indicators were selected: average carbon emission intensity of core processes, average response time to emission exceedance incidents, average disposal time of emission exceedance incidents, on-site implementation rate of carbon reduction measures, and comprehensive evaluation score of green construction. These were used to systematically evaluate the technical efficiency and application effectiveness of the control system. The quantitative comparison results are presented in Table 7.

accurately located two core contributing factors. One was the excessive no-load operating duration of the pumping equipment. The other was the high cementitious material dosage in the concrete mix proportion. At the same time, similar benchmark project cases were matched.

A targeted carbon reduction optimization plan was output. After the measures were implemented, the carbon emission intensity of this process was reduced by 18.6% compared to the pre-rectification level. This achieved rapid closed-loop disposal of the emission exceedance incident.

Meanwhile, questionnaire surveys and on-site interviews were conducted. These investigated the acceptance, satisfaction, and low-carbon construction awareness levels of project management personnel and on-site construction teams. The focus was on the carbon emission control process and intelligent recommendation measures. The survey results showed that over 92% of respondents believed that the control system effectively reduced the work difficulty of low-carbon construction control. They also felt it improved the operability of carbon reduction measures. This verified the practicality, engineering adaptability, and promotability of this technical system from two dimensions: technical application effectiveness and on-site management acceptance.

It should be noted that among the above five core indicators, the improvement range of the average carbon emission intensity of core processes reflects the carbon reduction effectiveness of this project. This is in comparison with the historical carbon emission level baseline of similar completed projects in the same region. The improvement ranges of the remaining four control efficiency indicators reflect the management efficiency improvement after the deployment of this control system. This is in comparison with the traditional management mode used during the project's construction preparation period. This hybrid baseline design balances the external comparability of emission benchmarking with the internal reference of management efficiency evaluation. It makes the comprehensive evaluation conclusions more objective and comprehensive.

5. Discussion

5.1 Technical Advantages and Engineering Application Value

The process-oriented green construction carbon emission knowledge graph control system was applied in a real public building renovation project. The full-cycle operational data and control results reveal several core technical

advantages and engineering application values.

Real-time monitoring and precise source tracing capability. The system can collect, dynamically calculate, and visually display carbon emission data for construction processes around the clock and across the entire workflow. This breaks through the lag limitation of traditional manual statistics and post-event accounting. The system can complete one-click precise positioning of emission exceedance root causes along the semantic links of the knowledge graph. It provides project managers with accurate and real-time control decision-making support. This strongly supports the rapid adjustment and implementation of carbon reduction strategies. In the demonstration project, the average response time to emission exceedance incidents was shortened from 30 minutes to 10 minutes. This fully validates the practical effectiveness of this capability.

Intelligent reasoning and hierarchical early warning capability. Relying on the rule reasoning and case matching functions of the knowledge graph, the system can predict carbon emission trends and abnormal emission exceedance risks in advance. It also issues hierarchical early warnings. This achieves a transformation from traditional passive post-event disposal to active pre-event prediction in carbon emission control. The three-tier early warning mechanism allows different levels of emission exceedance risks to be matched with corresponding disposal levels and response speeds. This effectively avoids carbon emission exceedance risks. It significantly enhances the prevention and control capability for carbon emission risks at construction sites.

Knowledge reuse and closed-loop control capability. The system possesses dynamic knowledge iteration and autonomous optimization capabilities. It can automatically match suitable carbon reduction measures and control plans based on dynamic changes in project construction conditions, process progress, and equipment status. At the same time, new project cases, disposal experiences, and carbon reduction effectiveness data can be continuously integrated into the knowledge graph. This enables efficient reuse of historical engineering experience and continuous iteration of control capabilities. In the demonstration project, the on-site implementation rate of carbon reduction measures increased from 72% to 100%. This fully reflects the promoting effect of

knowledge-driven decision-making on on-site execution.

5.2 Comparison with Existing Approaches

Compared with traditional construction carbon emission control methods, this technical system has achieved breakthroughs in several aspects. First, in terms of control granularity, traditional methods mostly remain at the overall project or unit engineering level. This system extends control down to the process level, achieving more refined emission management. Second, in terms of control timeliness, traditional methods rely on post-event statistics from construction drawing budgets or as-built settlement. This system achieves dynamic accounting and real-time early warning based on real-time monitoring data. The response time has been substantially shortened. Third, in terms of decision support, traditional methods rely on the personal experience of managers for judgment. This system provides managers with data-driven and traceable intelligent decision support through the semantic reasoning and case matching of the knowledge graph.

Compared with recently emerging methods such as BIM-based carbon emission calculation and intelligent algorithm-based multi-objective optimization, this system has distinctive features. BIM methods focus on carbon emission estimation in the design phase and carbon emission accounting during the construction process. Multi-objective optimization methods focus on scheme comparison at the project planning level. This system, by contrast, focuses on dynamic control during the construction execution phase. It fills the gap between optimization schemes and on-site execution. It connects the full-process closed loop of "monitoring-diagnosis-decision-execution-feedback."

5.3 Limitations and Future Work

Although this study has achieved relatively significant results, several limitations still exist and need to be addressed in future research. Regarding the case library, the current library contains 50 projects. Although the three-dimensional stratified design ensures a certain degree of representativeness, the sample size is still limited. This is especially true considering the vast territory, diverse climate types, and rich variety of building types in actual practice. In particular, some climate zone

subcategories have relatively few cases. This may affect case matching accuracy during cross-scenario promotion. Future research should continuously expand the scale of the case library and increase the coverage of more regions and building types.

Regarding knowledge extraction, the current relation extraction relies on a rule matching method based on dependency parsing patterns. Although this method is highly interpretable, its coverage and generalization ability are limited for implicit and complex semantic relations. Future research could explore the introduction of deep learning-based relation extraction models. These could complement the existing rule-based methods and further improve the recall rate and accuracy of knowledge extraction.

Regarding engineering validation, this study conducted a six-month validation on only one public building renovation project. Although positive results were achieved, the scope of validation in a single case limits the generalizability of the conclusions. Future research should carry out multi-project, long-cycle validation on more project types, such as residential buildings and industrial buildings, and over longer time scales. This would further test and improve the generalizability and robustness of the technical system.

In addition, the knowledge iteration of the current system mainly relies on manually triggered or pre-set update processes. Future research could explore automated knowledge update methods based on online learning and active learning mechanisms. This would further enhance the self-evolution capability of the knowledge graph.

6. Conclusion

This paper addresses several pain points in carbon emission control during the building construction phase. These include information fragmentation, insufficient targeting, and difficulty in reusing experience. We proposed and constructed a process-oriented Green Construction Carbon Emission Knowledge Graph (GCCE-KG). Based on this knowledge graph, we established an on-site monitoring and closed-loop control system. This system covers four layers: perception, knowledge, decision, and execution. Through a research path combining theoretical construction and engineering validation, this paper draws the

following main conclusions.

A 50-project green construction case library was constructed. It has a three-dimensional stratification covering building type, climate zone, and optimization standard. The two-stage expert verification results show that the stratified framework score was 4.7 out of 5.0. The Fleiss' Kappa consistency coefficient was 0.81. These results verify the scientific validity and representativeness of the case library design. This case library provides a reliable data foundation for knowledge graph construction. Its three-dimensional stratified design also offers a methodological framework that can be referenced for similar case library construction.

A four-dimensional carbon reduction measure system was formed for the four major high-carbon work packages. The dimensions are material, process, equipment, and management. A precise mapping matrix of "measure-process-emission source" was established. It covers 26 specific measures. This system breaks through the traditional approach of describing measures in parallel by dimension. Instead, it organizes measures with the process as the vertical classification axis. This makes the emission reduction target of each measure clearly traceable. It provides an operational guide for precise on-site policy implementation.

A knowledge graph ontology model was designed with the construction process as the core hub. Six core entity types were clearly defined: Case, Process, Emission, EmissionSource, Measure, and Rule. Their semantic relationships were also specified. A hybrid strategy combining structured data rule mapping and BERT-BiLSTM-CRF-based extraction from unstructured text was adopted. From 50 multi-source heterogeneous cases, over 8,500 triples were extracted and generated. A unified and reasoning-capable carbon emission control knowledge network was constructed.

Based on the rule reasoning and case matching capabilities of the knowledge graph, a full-process intelligent reasoning system was established. It covers high-carbon process identification, emission exceedance root cause tracing, similar case matching, and carbon reduction measure recommendation. A three-tier hierarchical early warning mechanism and a closed-loop control process were also developed. This achieved a transformation of carbon emission control from passive post-event disposal to active pre-event prediction.

A public building renovation project in Beijing was used as the demonstration scenario. An engineering application validation was carried out over a six-month main structure construction period. The results show that the average carbon emission intensity of core processes decreased by 24.1%. The average response time to emission exceedance incidents was shortened by 66.7%. The average disposal time of emission exceedance incidents was shortened by 33.3%. The on-site implementation rate of carbon reduction measures increased from 72% to 100%. The comprehensive evaluation score of green construction improved by 16.6%. These results verify the engineering effectiveness and promotability of the technical system.

This study provides a reusable knowledge base and technical paradigm for refined and intelligent carbon emission control during the building construction phase. Future research will further deepen work in several areas. These include expanding the scale and diversity of the case library, improving the automation level of knowledge extraction, and conducting multi-project, long-cycle validation. These efforts will promote the continuous improvement and widespread implementation of this technical system.

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