

BIM-Based Integrated Management System for Intelligent Timber Structure Construction Factories: Production Optimization and Carbon Emission Monitoring

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Abstract

Driven by the carbon peaking and carbon neutrality goals, the construction industry is facing an increasingly urgent demand for low-carbon transformation. As a major form of green building, timber structures require improved digital collaboration in production and more refined carbon emission management. To address this issue, this study proposes a novel integrated management system for the intelligent management of smart timber construction factories. The system develops a BIM-driven production and fabrication mode, constructs an integrated management architecture combining refined production management and carbon emission monitoring, and establishes a corresponding management platform. The platform enables full-process digital closed-loop management from raw material procurement to finished-product shipment, as well as full-chain carbon emission quantification. A practical application in a prefabrication factory demonstrates the feasibility, effectiveness, and engineering applicability of the proposed method and system.

Keywords

Intelligent Timber Construction; Building Information Modeling; Carbon Footprint Tracking; Factory Management System.

1. Introduction

Under the goals of carbon peaking and carbon neutrality, together with the ongoing green transformation of the construction industry, reducing carbon emissions throughout the building life cycle^[1] and advancing the industrialization and digitalization of construction have become important pathways toward high-quality industry development. As a renewable natural material, timber offers several advantages, including carbon sequestration and storage, low environmental impact, and favorable mechanical performance, which make it a promising option for green construction^[2-5]. In recent years, with the development of engineered wood products, prefabricated construction technologies, and mid- and high-rise timber structural systems, the application scope of timber buildings has continued to expand, and industrialized timber construction has attracted increasing attention from both academia and industry^[6-9].

Despite the low-carbon and high-efficiency advantages of timber construction, traditional production management approaches can no longer satisfy the requirements of whole-process coordination and efficient organization in timber factories due to component complexity and order customization. With the development of construction robotics, automated processing equipment, and prefabrication production lines, timber production has gradually achieved mechanization and automation in component fabrication, material handling and assembly, and factory-based manufacturing [10–13]. However, existing studies have mainly focused on the upgrading of production equipment and the optimization of construction techniques, while insufficient attention has been paid to the integrated organization of design information, production information, and construction information during off-site manufacturing, as well as to multi-stage collaborative management mechanisms.

Existing studies have shown that BIM has strong potential for information integration across the design, manufacturing, and construction stages. Babič et al. [14] were among the first to propose the use of BIM to connect resource production with the construction process. Abanda et al. [15] and Yin et al. [16], from the perspectives of off-site manufacturing applications and review studies, respectively, pointed out the significant advantages of BIM in factory production, information exchange, and collaborative management. Li et al. [17] further proposed a conceptual framework for integrating BIM with prefabricated housing production. Villanueva et al. [18] and Jang et al. [19] verified the application value of BIM in factory-based construction from the perspectives of robotic process planning and workflow optimization, respectively. Overall, research on production information integration for factory-based construction has gradually evolved from conceptual exploration to process optimization and system implementation.

Meanwhile, the development of factory management systems and digital twin technology has provided new methodological pathways for the intelligent management of construction factories. Relatively systematic studies have been carried out on multi-agent collaboration, MES development, digital twin shop-floor modeling, dynamic scheduling, and intelligent manufacturing system construction [20–26]. These studies indicate that management mechanisms centered on real-time data, process synchronization, and execution control are becoming an important foundation for the refined management of complex manufacturing processes. In terms of low-carbon management, the integration of BIM, IoT, and carbon accounting has also promoted the transformation of carbon emission management from static accounting to dynamic monitoring, visualization, and process control [27–31]. Nevertheless, existing studies have mainly focused on general prefabricated buildings and precast component scenarios.

In summary, existing studies have made substantial progress in timber structure design, fabrication, and digital collaboration. However, current BIM-based research has not yet been effectively integrated with order-driven production management processes, while carbon emission monitoring is often implemented as an independent module and has not been fully incorporated into the operational logic of order-driven manufacturing.

To address these limitations, this study proposes a BIM-based, order-driven integrated management framework for intelligent timber construction factories. The framework uses the BIM model as the core platform for information integration and collaborative management, drives component production according to order requirements, and incorporates carbon emission monitoring. Through the coordinated integration of design information, order data, production processes, and carbon emission data, the proposed framework supports the digital, refined, and low-carbon management of timber construction factories.

2. Proposed System Framework

The overall system framework is illustrated in Fig. 1. The system is built upon three types of inputs: BIM model data, business data, and carbon-related data, and is organized around three main functional lines: BIM-driven production management, integrated management, and carbon emission monitoring and allocation.

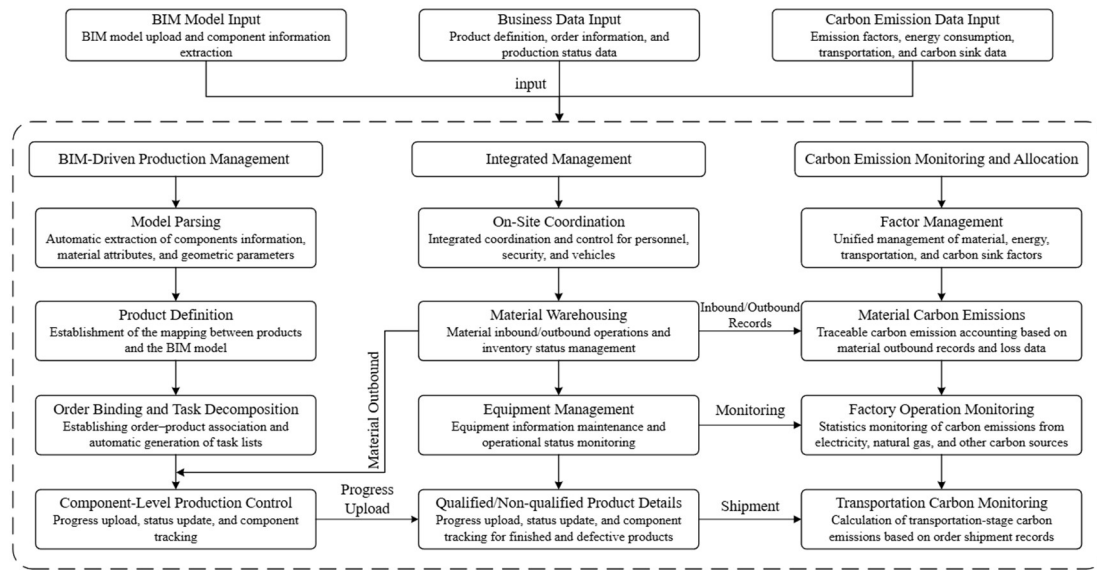


Fig. 1 BIM-Based Integrated Management Framework

In BIM-driven production management, the system parses the uploaded BIM models to extract information such as component names, material properties, and geometric parameters. On this basis, one-to-one relationships between BIM models and products, one-to-many relationships between BIM models and components, and one-to-many relationships between orders and products are established, thereby forming a hierarchical mapping among orders, products, models, and components. This enables order-driven production management at the component level.

In integrated management, the system incorporates business modules for personnel, security, and vehicle control; material entry and exit management; finished and defective product management; and logistics and warehousing, thereby supporting coordinated management and dynamic status updates of various business information throughout factory production and operations.

In the carbon emission monitoring and allocation stream, the system applies the emission-factor method and integrates emission factors for materials, energy consumption, transportation, and carbon sinks. It calculates carbon emissions associated with materials, factory operations, and transportation, respectively, and dynamically allocates carbon emissions arising from material losses based on production-related business data, thereby enabling life-cycle carbon emission monitoring and refined carbon management.

3. BIM-driven Order-Product-Component Mapping Mechanism

BIM integrates digital modeling, information integration, and collaborative management [32], enabling the unified representation of component information, visualization of production status, and sharing of production-related information. In this study, BIM is applied to the production and processing of timber components by establishing relationships between model components and actual production objects in the factory, while linking production progress, quality details, and finished-product delivery information at the component level. This approach enhances the visualization, traceability, and management accuracy of the production process.

This study establishes a progressive mapping mechanism among orders, products, BIM models, and components, as illustrated in Fig. 2. Products are divided into two categories: complex products and simple products. For complex products, BIM models are associated with the corresponding products. Managers upload BIM models through the model upload interface, after which the system automatically performs model lightweighting and stores the extracted component information in the backend database, ensuring a consistent correspondence between each product and its model components. For simple products, component information is added directly through user-defined

component entries. During order management, managers establish one-to-many relationships between orders and products according to customer production requirements, thereby creating a clear mapping between orders and their associated products.

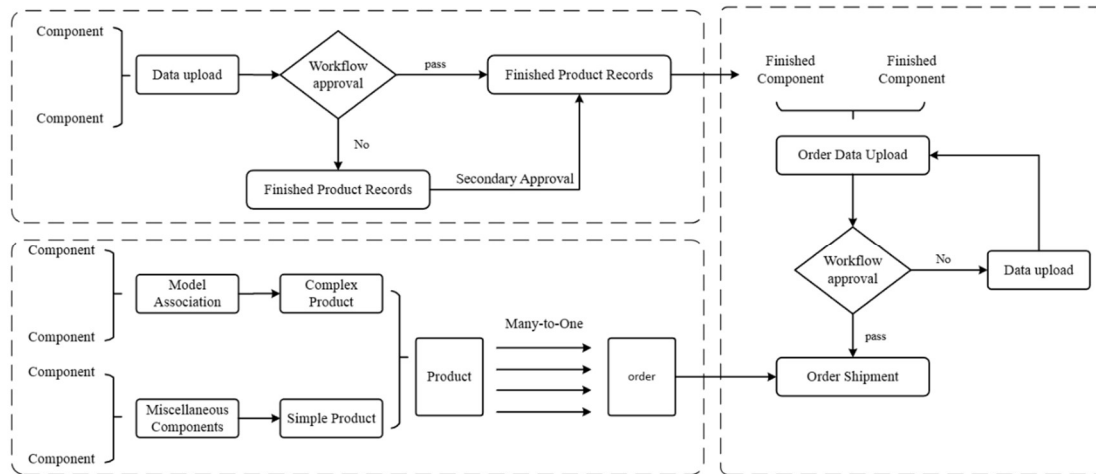


Fig. 2 Object Mapping and Order-Driven Production Workflow

During production management, the progress upload module serves as the sole entry point for daily production records. Production personnel upload the daily production progress, and the system identifies the submitted data using the order ID. For components of complex products, the corresponding components and quantities are selected through BIM-based model visualization. All uploaded production records are then subject to an approval process. Components that pass the review are transferred to the finished-product inventory, whereas those that fail the review are classified as defective products. Defective products can be transferred to the finished-product inventory only after passing a second review, thereby ensuring product quality. In addition, the system establishes associations between orders and finished components, allowing managers to track order progress and the completion status of finished products in real time and providing a basis for organizing subsequent shipments by order.

4. Carbon Emission Monitoring Module

To clarify the carbon accounting boundary of the timber factory, this study defines the system boundary in accordance with the Standard for Building Carbon Emission Calculation^[33]. For the building operation stage, the boundary is limited to carbon emissions associated with purchased energy consumption and other minor emission sources, such as refrigerants. For the timber component production stage, the boundary includes carbon emissions from factory operation, raw material production, and material transportation. The carbon accounting boundary of the timber factory is shown in Fig. 3.

The carbon accounting boundary in this study is divided into five categories: energy, materials, transportation, emission reduction, and others. The energy category includes carbon emissions from purchased electricity consumption and fossil fuel combustion. The materials category represents carbon emissions associated with material losses during factory production. The transportation category covers carbon emissions generated during transportation. The emission reduction category accounts for the reduction in emissions attributable to the factory's carbon sinks. The others category includes carbon emissions arising from activities such as wastewater treatment and refrigerant consumption.

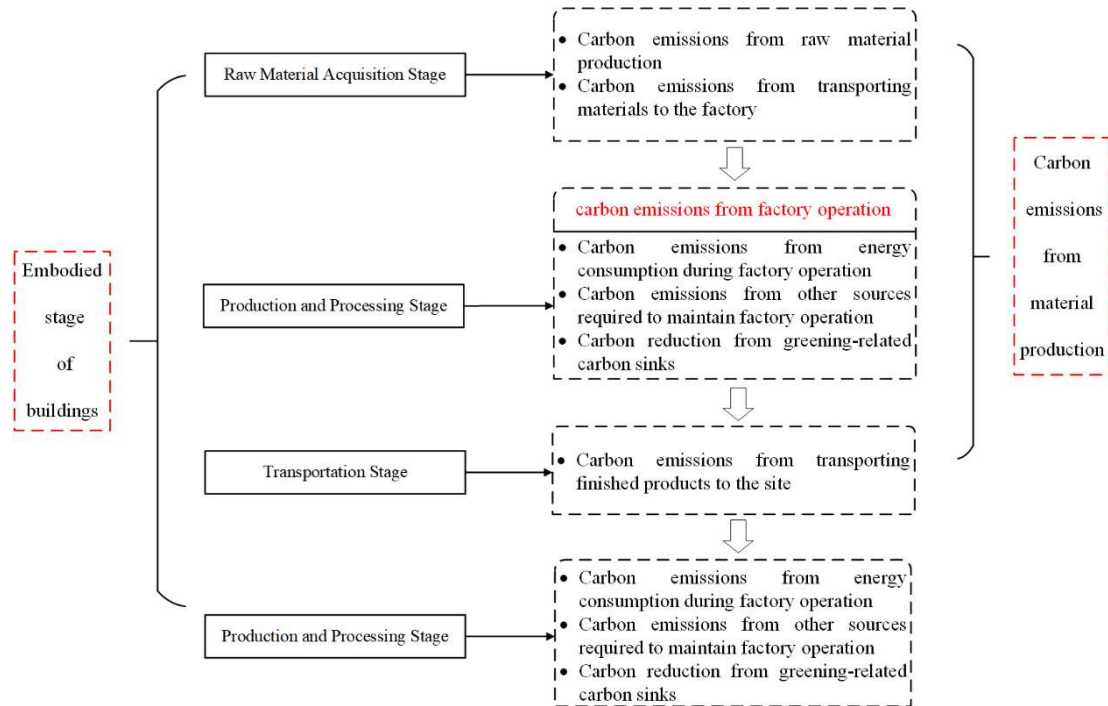


Fig. 3 Carbon emission accounting boundary of the building

Carbon emissions in each category are calculated by multiplying activity data by the corresponding emission factor. The total carbon emissions of the timber factory are obtained by summing all categories, with the emission-reduction category treated as a negative value. The carbon emission calculation formula is given in Eq. (1).

$$C = C_e + C_m + C_t + C_o + S \quad (1)$$

C —total carbon emissions of the factory;

C_e —carbon emissions from the energy category;

C_m —carbon emissions from the materials category;

C_t —carbon emissions from the transportation category;

C_o —carbon emissions from the other category;

S —emission reduction associated with the factory's carbon sinks.

The carbon emissions from the energy category are calculated according to Eq. (2).

$$C_e = (SD - RD) \times FD + \sum_{i=1}^n SH_i \times FH_i \quad (2)$$

SD —total electricity consumption of the factory;

RD —self-generated electricity of the factory;

FD —electricity carbon emission factor;

SH_i —consumption of the i -th type of fossil fuel;

FH_i —carbon emission factor of the i -th type of fossil fuel.

The carbon emissions from the materials category are calculated according to Eq. (3).

$$C_m = \sum_{i=1}^n SM_i \times FM_i \quad (3)$$

SM_i —consumption of the i -th material;

FM_i —carbon emission factor of the i -th material.

The carbon emissions from the transportation category are calculated according to Eq. (4).

$$C_t = \sum_{i=1}^n LT_i \times WT_i \times FT_i \quad (4)$$

LT_i —travel distance of the i -th transportation mode;

WT_i —transported load of the i -th transportation mode;

FT_i —carbon emission factor of the i -th transportation mode.

The carbon emissions from the other category are calculated according to Eq. (5).

$$C_o = \sum_{i=1}^n SO_i \times FO_i \quad (5)$$

SO_i —engineering quantity of the i -th carbon emission source;

FO_i —carbon emission factor of the i -th carbon emission source.

The carbon emissions from the emission-reduction category are calculated according to Eq. (6). In this study, only carbon sequestration during the factory operation stage is considered, while the 40-year baseline CO₂ fixation value of greening is excluded.

$$S = \sum_{i=1}^n S_i \times A_i \quad (6)$$

S_i —carbon sequestration quota of the i -th category, namely the expected amount of CO₂ fixed per unit area within 40 years;

A_i —occupied area of the i -th carbon sequestration category.

In the Carbon Emission Monitoring Module, the data center mainly manages data related to energy, materials, transportation, emission reduction, and other carbon-related categories. Through this module, the system provides centralized entry and management of various carbon emission source data and their corresponding emission factors, while allowing users to add or modify relevant data according to actual requirements. An approval workflow is also integrated into the system to standardize the review process, and all uploaded data must be approved through the designated procedure.

For the acquisition of carbon emission source data, the system includes both an automated data interface module and a manual input module. The automated data interface exchanges data with the green operation and maintenance system, warehouse management system, and vehicle management system to obtain carbon-related data associated with materials and transportation. Energy-related carbon emission data are collected through external sensors and monitoring devices. Other scattered data that cannot be automatically acquired are entered manually. The emission reduction module calculates the annual carbon reduction of the factory based on the carbon sequestration quota and occupied land area. The carbon emission calculation process is shown in Fig. 4.

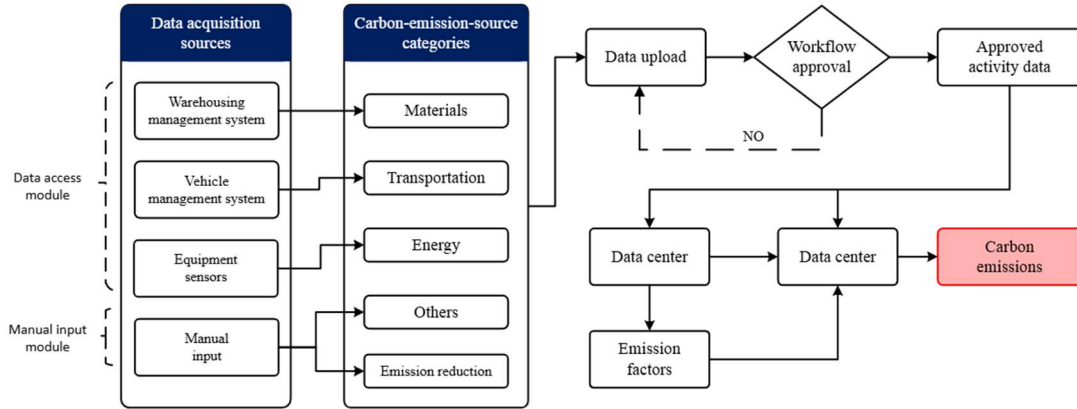


Fig. 4 Carbon emission calculation workflow

Considering the operational complexity, cost-effectiveness, and data management convenience in practical system applications, performing an independent full-stage carbon accounting for each order is not an optimal solution. To address this issue, this study proposes a BIM-driven weighted proportional allocation method for estimating order-level carbon emissions. In this method, carbon emissions are divided into two categories. The first is the traceable portion, which mainly corresponds to carbon emissions caused by material losses. The second is the shared portion, which mainly includes emissions from factory energy consumption, transportation processes, and carbon-sink-related effects. For the traceable portion, the system automatically extracts component information from the BIM model and performs precise calculations. For the shared portion, dynamic weighted allocation is conducted based on the proportion of BIM component volume represented by each order in the total production volume during the corresponding period. The calculation procedure is presented in Eqs. (7)–(9).

$$C_{order} = C_{material} + \left(\frac{V_{order}}{\sum V_{factory}} \right) \times C_{shared} \quad (7)$$

$$C_{shared} = C_e + C_t + C_o \quad (8)$$

$$C_{material} = (M_{out} - M_{in}) \times FM \quad (9)$$

C_{order} —total carbon emissions of a given order;

$C_{material}$ —carbon emissions of that order caused by material losses;

C_{shared} —total shared carbon emissions of the factory;

V_{order} —total volume of the components in that order, as automatically extracted from the BIM model;

$\sum V_{factory}$ —total volume of all components produced by the factory during the current period;

M_{out} —the quantity of material issued from storage;

M_{in} —quantity of material procured for production;

FM —carbon emission factor of the material;

C_e, C_t, C_o —carbon emissions from factory energy consumption, vehicle transportation, and other sources, respectively.

5. System Design and Implementation

5.1 Architecture Modules of the Proposed System.

As illustrated in Fig. 5, the system architecture comprises five layers: the user service layer, business application layer, data storage layer, network transmission layer, and infrastructure layer. The system is designed to serve factory workers, security personnel, warehouse staff, and managers. The business application layer integrates a business management platform and a 3D visualization platform. Specifically, the business management platform incorporates a workflow engine and a lightweight engine, while the 3D visualization platform is developed based on the Unreal Engine. System data are acquired through both manual entry and interface-based import, and are subsequently stored in the database. The infrastructure layer consists of various sensor devices that collect physical information and transmit it to the cloud platform via IoT.

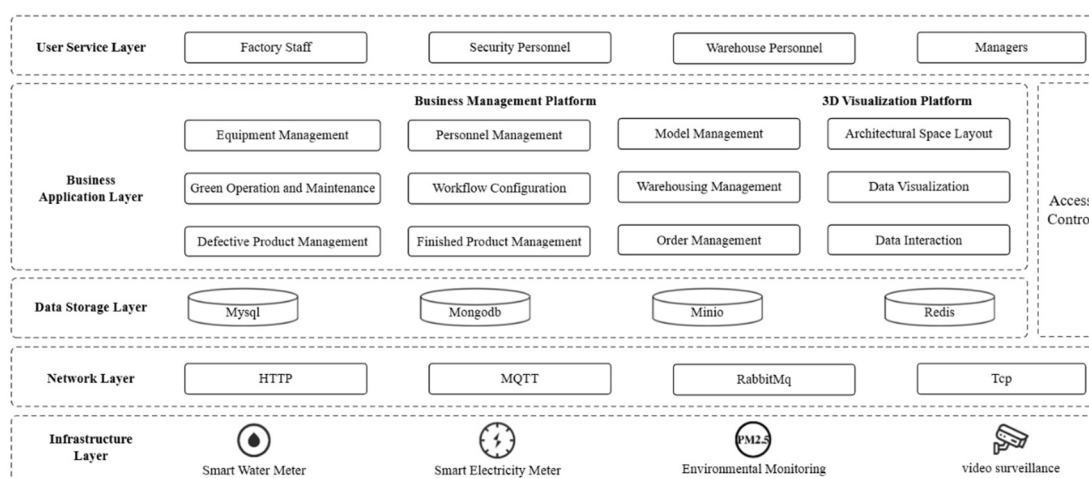


Fig. 5 Architecture Modules of the Proposed System

5.2 Functional Modules of the System.

According to the system's functional division, the proposed integrated management system for intelligent timber construction factories consists of three subsystems: the production and processing subsystem, the integrated operation and maintenance subsystem, and the green and low-carbon subsystem. These three subsystems address the needs of production organization, operational support, and low-carbon management, respectively, and jointly support the digitalized, coordinated, and green operation of timber factories.

The production and processing subsystem covers the entire manufacturing process of timber products and includes functional modules for model management, product management, order management, progress reporting, workflow configuration, warehouse management, finished-product management, defective-product management, and the management dashboard. The subsystem adopts an order-driven production approach and uses model components as the smallest management unit. By establishing relationships among orders, products, and components, it enables end-to-end management from material warehousing, production and processing, and quality inspection to finished-product storage and order shipment.

The integrated operation and maintenance subsystem includes modules for personnel management, equipment management, vehicle management, and security management. It provides unified management and status monitoring of key operational elements, including personnel, equipment, vehicles, and security, thereby supporting the orderly operation of factory production activities.

The green and low-carbon subsystem is mainly used to monitor carbon emissions from factory operations and includes modules related to materials, equipment, transportation, and carbon emission factors. The system integrates and calculates data on energy consumption, materials, transportation,

and emission reduction, enabling the statistical analysis and dynamic monitoring of carbon emissions across different production stages.

In summary, the three subsystems jointly establish an integrated management framework for timber construction factories, covering production and processing, operational support, and green and low-carbon management. Through business data integration and information sharing, the framework enables coordinated management of production, operation and maintenance, and carbon emissions, providing a basis for the digital and refined management of timber construction factories.

5.3 Case Study.

This section presents the prefabrication factory in Xingtang County as a practical application case. Figure 6 shows the overview page of the management dashboard, which provides an integrated visualization of factory energy consumption and carbon emissions, material consumption, and finished-product processing.

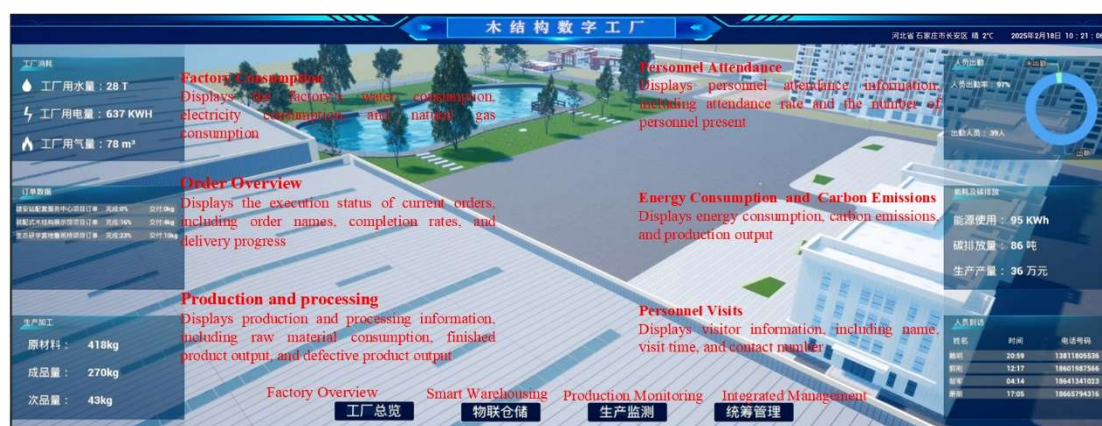


Fig. 6 Overview interface of the dashboard.

As shown in Fig. 7, in terms of production management, the application of the platform reduced the average component verification time from 20 min to 8 min, the average order progress feedback time from 30 min to 13 min, the average raw material traceability time from 20 min to 7 min, and the average issue response time from 20 min to 6 min, corresponding to improvements of 60.0%, 56.7%, 65.0%, and 70.0%, respectively. These results indicate that the platform can effectively improve the efficiency of production-management-related tasks, including order coordination, component verification, raw material traceability, and issue response.

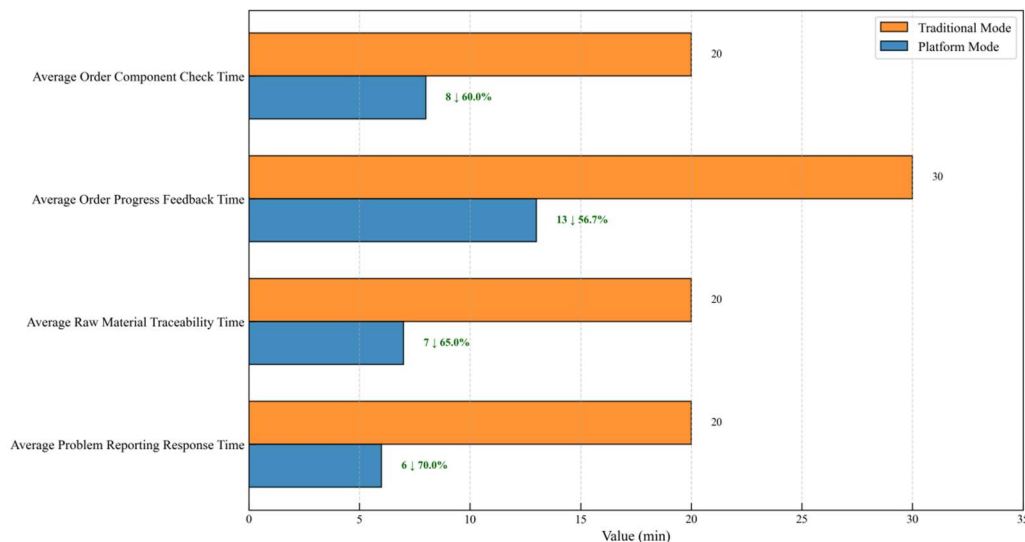


Fig. 7 Comparison of production management efficiency indicators

As shown in Fig. 8, in terms of carbon management, the application of the platform reduced the average carbon report preparation time from 40 min to 7 min, the average order-level carbon verification time from 60 min to 15 min, the average carbon data traceability time from 30 min to 10 min, and the average abnormal energy-use localization time from 15 min to 6 min, corresponding to improvements of 82.5%, 75.0%, 66.7%, and 60.0%, respectively. These results indicate that the platform performs effectively in carbon-related data processing, including statistical reporting, verification, traceability, and abnormal energy-use identification.

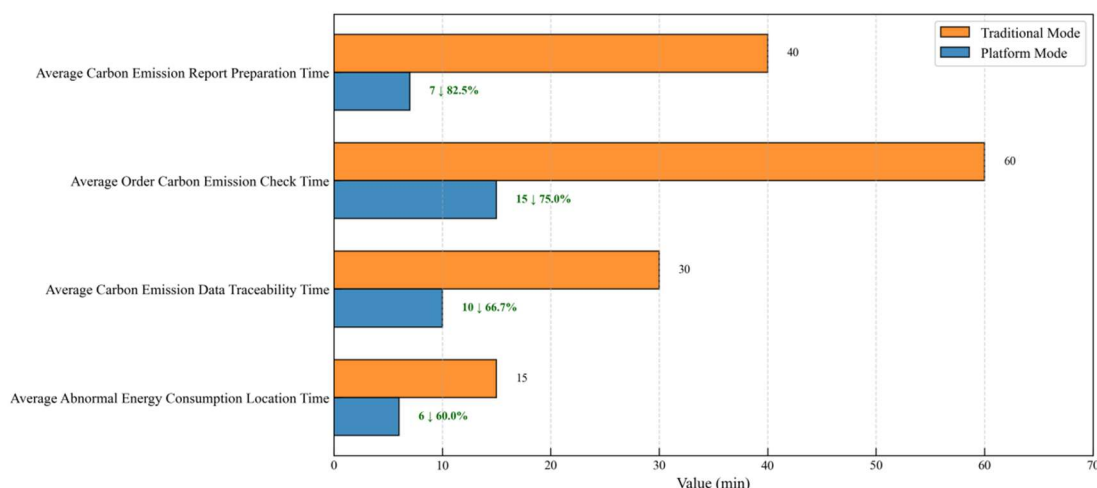


Fig. 8 Comparison of carbon management efficiency indicators.

Overall, the case trial results verify the feasibility of the proposed platform for both production management and carbon management in timber factories, indicating its promising potential to support the digitalized, refined, and low-carbon management of timber factory operations.

6. Conclusion

This study developed a BIM-based integrated management platform for production and green operation in timber factories and validated its application through a case study conducted in a prefabrication factory. The main conclusions are as follows.

- (1) A BIM-based application method for production management in timber factories was proposed, in which design components were transformed into production objects with business attributes, thereby providing a foundation for the refined management of the entire production process.
- (2) The integration of production management information and green operation information was achieved, enabling the system to support order-level and factory-level carbon emission statistics and visualization.
- (3) An integrated management platform for timber factories was designed and developed, realizing the unified organization and collaborative management of component information, business information, and carbon emission information.
- (4) The case study results demonstrated that the proposed platform could support order inquiry, component verification, progress feedback, and carbon emission accounting within a unified platform environment, showing good engineering feasibility and application value.

Overall, the proposed BIM-based integrated platform for production and green operation provides a feasible pathway for the digitalized, visualized, and green management of timber factories. Future research may further focus on the integration of multi-source real-time data, the enhancement of applicability across projects and factories, and the development of intelligent analysis and decision-support functions, so as to strengthen the engineering value and scalability of the system.

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