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Cyber-physical system-based real-time monitoring and visualization of greenhouse gas emissions of prefabricated construction

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ABSTRACT

The excessive emissions of greenhouse gases (GHGs) from the construction industry are currently receiving global attention. Many breakthroughs have been made in assessing GHG emissions, including pre- and post-evaluation methods. However, the real-time monitoring of GHG emissions has not been studied on a large scale. The real-time GHG emissions of construction sites must be monitored, and the use of clean energy and technologies must be facilitated by comparing real-time GHG emissions under different mechanical and energy use conditions. Thus, this study proposes a cyber-physical system (CPS)-based real-time monitoring and visualization of the GHG emissions of prefabricated construction, which is widely practiced in the construction industry. In this system, acceleration sensors monitor the operational status of tower cranes, barometric sensors monitor the running state of construction elevators, and a Global Positioning System module records the travel time of on-site transfer vehicles to detect and transmit the running time of construction machineries to a remote server via a preinstalled Wi-Fi or General Packet Radio Service module. Furthermore, the database can store the model number, quantity, and power of each element of construction machinery and GHG emission factors. Thus, GHG emissions from prefabrication sites can be calculated in real time using the specified quantitative model in the remote server. In addition, GHG emission data can be displayed using a visual model and 2D charts on fixed and mobile devices. The development process of each part of the CPS-based system is also described in this paper.

1. Introduction

The European Institute of Architects reported that construction-related industries consume 50% of the Earth's energy, contributes 50% of air pollution, and emits 42% of greenhouse gases (GHGs) worldwide, making the construction industry a major contributor to global GHG emissions (Ge et al., 2010). GHG emissions from the construction industry will continue to increase as urbanization progresses. To control the GHG emissions of the construction industry, many studies have been conducted on the GHG emissions of buildings. Seo and Hwang found that GHG emissions during the operation stage are higher than those during the other stages (Seo and Hwang, 2001). Hence, numerous studies have focused on reducing GHG emissions during the operation stage (Davies et al., 2013; Guo et al., 2017), and several methods have been developed for this purpose (Dixit et al., 2010). GHG emissions also occur during the construction stage due to the use of considerable amounts of materials and energy (Sandanayake et al., 2016). The density of GHG emissions during the construction stage is higher than that during the operation stage (Xiaodong et al., 2014). However, GHG emissions during the construction stage of buildings are occasionally not considered due to the complexity and time consumed in data collection (Sandanayake et al., 2017). Thus, studying GHG emissions during the construction stage of buildings has become important. The prefabricated construction method has been adopted in many countries because it is an environment-friendly alternative to the traditional construction method (Dong et al., 2015; Jaillon and Poon, 2008). In China, a series of policies

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was proposed to promote prefabricated construction at the national and industrial levels (Zhu et al., 2018). Thus, studying the GHG emissions of prefabricated construction is important.

Most traditional GHG emission assessment methods focus on pre- or post-analysis, which are not useful for monitoring and studying GHG emissions during the construction stage (Fu et al., 2014; Luo et al., 2016). An automatic and real-time method for monitoring GHG emissions during the construction stage remains nonexistent due to the lack of reliable inventories and models (Sandanayake et al., 2017). Thus, the real-time monitoring of GHG emissions is highly significant. First, such method can reduce GHG emissions during the construction stage and improve environmental performance (Seo et al., 2016). Second, the collection and analysis of GHG emission data are helpful in the government's formulation of energy conservation and emission reduction policies (Tao et al., 2018). Third, the GHG emission database collected by the system will facilitate the use of clean energy or technology by comparing real-time GHG emissions under different mechanical and energy use conditions to optimize the "cost, quality, schedule, and GHG emissions" of the construction industry. Thus, a real-time GHG emission monitoring system must be developed.

To address this research gap, this study presents an automatic and real-time GHG emission monitoring and visualization system for the construction stage of prefabricated buildings. In recent decades, the advent of new technologies, such as the cyber-physical system (CPS), has provided theoretical and practical bases for such system. Research has shown that CPS has been applied to the manufacturing industry (Kaihara and Yao, 2012), smart power grids (Wen et al., 2012), the transportation industry (Yan et al., 2013), and the healthcare industry (Shi et al., 2011) for intelligent monitoring and control. In the construction industry, CPS has been used in temporary structure monitoring (Lu et al., 2011) and project delivery (Anumba et al., 2010), which involve the acquisition, transmission, storage, and processing of a huge amount of information. Thus, CPS is applicable to monitoring GHG emissions in real time.

Three types of machinery used in construction sites were selected for the preliminary study based on the literature. The GHG emissions of construction sites were calculated through the energy consumption of these machineries. The first-order parameters of the model were divided into electricity, gasoline, and diesel consumption. Through the analysis of machineries, second-level parameters were divided into the running time of machineries and GHG emission factors. The energy consumption of the machineries was obtained from running time and converted into GHG emissions.

The remainder of this paper is arranged as follows. Section 2 reviews previous studies on the GHG emissions of the construction industry and examines the applicability of CPS. Section 3 details the methodology adopted in this study. Section 4 describes the development of a quantitative model. Section 5 introduces the CPS-based configuration and the development process of each part. Section 6 presents several considerations for the system's application. Section 7 draws conclusions from the study.

2. Literature review

The knowledge and importance of studying GHG emission reduction in the construction industry have resulted in many studies on GHG emission assessment methods for buildings. Life cycle assessment (LCA) is the most frequently used method for building systems at multiple levels, including building materials, building products, and the entire building (Peng, 2016). Intelligent methods, such as simulation, information (e.g., machine learning), and visualization, have also been applied to GHG emission assessment to improve computational efficiency and establish effective management platforms, achieving satisfactory results (Li et al., 2017; Macorini and Beccaria, 2010).

The current methods for GHG emission assessment are summarized in Table 1.

2.1. Traditional LCA approach

ISO 14040 defines LCA as the compilation and evaluation of the input, output, and potential environmental impact of a product system throughout its life cycle (Finkbeiner et al., 2006). In accordance with different principles, LCA can be divided into the following categories: process-based LCA (PLCA), input–output LCA (I–O LCA), and hybrid analysis (HA) (Omar et al., 2014).

At the micro level, PLCA is a bottom-up method that calculates the environmental impact of each process by defining the corresponding required energy consumption and materials (Mao et al., 2013; Yan et al., 2010). Thus, PLCA is a relatively accurate method for assessing GHG emissions. Table 1 indicates that PLCA can be adopted to evaluate the GHG emissions of one stage of a building's life cycle and its entire life cycle. Furthermore, PLCA can be used to select environment-friendly building schemes (Balasbaneh and Bin Marsono, 2018; Fu et al., 2015).

By contrast, I–O LCA is a top-down evaluation method (Huang et al., 2009) that adopts economic transactions instead of physical flows as the driving factor for the supply chain of GHG emissions (Algarin et al., 2017). Following the principle that input equals output, I–O LCA summarizes the GHG emission intensity of relevant economic sectors involved in each construction process. Thereafter, it converts materials and other consumables involved in the construction process to monetary terms to calculate carbon emissions (Acquaye and Duffy, 2010; Nassen et al., 2007; Zhang and Wang, 2016).

To address the shortcomings of the two methods, HA is developed for assessing the GHG emissions of the construction industry by combining the reliability of the PLCA approach and the integrity of the I–O LCA framework to provide reliable computing and cover a wide range of system boundaries (Dixit, 2017; Dixit and Singh, 2018; Stephan and Stephan, 2016). Depending on the characteristics of the specific case, PLCA is adopted if the system boundary is clear; otherwise, I–O LCA is used (Hawkins et al., 2015). HA also demonstrates its usefulness in the GHG emission assessment of buildings (Aye et al., 2012; Omar et al., 2014; Zhan et al., 2018; Zhang and Wang, 2016).

2.2. Intelligent approaches

The development of various information technologies has led to the emergence of intelligent approaches. These approaches, which are based on LCA, optimize data collection and processing during GHG emission assessment. Table 1 classifies intelligent approaches into visualization, virtual and simulation, and mathematical methods.

Visualization methods: Visualization methods have been introduced to GHG emission assessment in various studies (Hajibabai et al., 2011). For example, Mao et al. proposed a new decision-making tool that combines building information modeling (BIM) with GHG emission analysis on the basis of LCA theory, making decision-making in the design stage easier through visualization (Mao et al., 2013). Hajibabai proposed a new method for graphically representing GHG and other harmful gas emissions from construction activities (Hajibabai et al., 2011). Other studies have also focused on the visualization method (Heydarian and Golparvar-Fard, 2011; Macorini and Beccaria, 2010; Wong et al., 2013).

Virtual and simulation methods: To improve the efficiency of

Table 1
Current methods for GHG emission assessment.

Reference	Method	Research stage	Construction type
(Sandanayake et al., 2017), (Fu et al., 2014), (Luo et al., 2016)	PLCA	Construction	Traditional
(Li and Chen, 2017), (Yan et al., 2010), (Zhang et al., 2013)	PLCA	Life cycle	Traditional
Dong et al. (2015)	PLCA	Construction	Traditional and prefabricated
(Nassen et al., 2007), (Acquaye and Duffy, 2010)	I–O LCA	Construction	Traditional
(Zhang and Wang, 2016), (Zhan et al., 2018)	HA	Life cycle	Traditional
(Aye et al., 2012), (Zhang and Wang, 2016), (Omar et al., 2014)	HA	Construction and operation	Traditional and prefabricated
(Mao et al., 2013), (Hajibabai et al., 2011)	Visualization	Construction	Traditional
(Li et al., 2017), (Heydarian et al., 2012), (Ou et al., 2017)	Virtual and simulation	Construction	Traditional
(Davies et al., 2013), (Wu et al., 2013), (Wu and Feng, 2014)	Mathematical method	Construction	Traditional and prefabricated

data collection, Heydarian et al. introduced a motion recognition technology into the GHG emission assessment of earthworks in buildings (Heydarian et al., 2012). Virtual construction during the design stage (Ou et al., 2017) and on-site simulation and optimization (Li et al., 2017) have also demonstrated potential in GHG emission assessment.

Mathematical methods: To achieve the lean calculation of GHG emissions, several mathematical methods have been introduced for GHG emission assessment (Wu et al., 2013). For example, Davies proved that a linear regression model that combines historical environmental performance indicator data and staff opinions collected through interviews can be applied to GHG emission assessment through energy practice (Davies et al., 2013). Wu et al. developed a weighted factor model to study the production process of prefabricated components and analyzed the amount of GHG emissions that can be reduced using lean production (Wu and Feng, 2014).

2.3. Limitations

Although the three aforementioned LCA methods have been widely used in GHG emission assessment, they exhibit limitations with respect to integrity, reliability, and specificity (Rauf and Crawford, 2015). For example, PLCA requires the collection of processed data, which can be labor- and time-intensive; moreover, the truncation errors of PLCA can reach 50%–90% (Aye et al., 2012). I–O LCA also has many potential limitations (Omar et al., 2014). First, its calculation accuracy is less than that of PLCA (Zhan et al., 2018). Moreover, the assumption of architectural homogeneity limits its applicability to independent architectural design decisions (Moncaster and Symons, 2013), implying that it cannot be used to analyze individual buildings or compare different buildings (Hondo et al., 2002). The HA method lacks relevant statistical data to precisely calculate GHG emissions (Zhang and Wang, 2016).

The introduction of intelligent methods has improved the calculation efficiency of GHG emission evaluation and the visualization degree of evaluation results. However, most of these methods intend to simulate and predict carbon emissions from different dimensions immediately before or after the construction of a project instead of conducting on-site real-time monitoring. In addition, most methods use quota or bill of quantities in calculating GHG emissions (Jeong et al., 2017; Li and Chen, 2017; Zhang and Wang, 2015); this practice can induce deviations in the calculation results. Lastly, more studies have focused on traditional buildings than on prefabricated buildings, as indicated in Table 1. Therefore, the real-time monitoring of GHG emissions in prefabrication sites is necessary.

A few studies have been conducted on the real-time monitoring of GHG emissions. However, several of these studies have focused only on traditional sites without visualization (Seo et al., 2016), and others are not useful due to the high cost and difficulty of installing sensors (Lewis et al., 2011). Therefore, a real-time GHG emission monitoring and visualization system for prefabrication sites that uses a number of practical sensors must be developed.

2.4. Applicability of CPS

CPS is a physical and engineering system with operations that are monitored, coordinated, controlled, and integrated by the computing and communication cores (Rajkumar et al., 2010). It can improve information and knowledge processing by implementing bidirectional coordination between the virtual model and the physical structure (Akanmu et al., 2013). CPS is applicable and beneficial for meeting the demands of the real-time GHG emission monitoring and visualization of prefabricated sites because it can provide theoretical and practical bases for this process.

CPS has been applied in many fields, including the construction industry. Yuan et al. (2015) established a security monitoring system in a temporary building structure by using wired sensors, a wireless network, mobile devices, and a data collection platform; the results showed that CPS demonstrates good applicability (Yuan et al., 2015, 2016). Akanmu et al. used radio-frequency identification technology and various wireless sensors to build a CPS and achieve real-time monitoring of architectural lamps (Akanmu et al., 2014). These applications can be referred to as real-time monitoring of GHG emissions because such monitoring is also realized by collecting and processing data information from field equipment operation. To date, however, only a few studies have used CPS in the real-time monitoring of GHG emissions at prefabrication sites. Therefore, CPS exhibits necessity and applicability in the development process of the proposed system.

3. Methodology

The development and implementation of the system require addressing the following essential issues: (1) building a quantitative calculation model for the GHG emissions of prefabrication sites, (2) developing a CPS-based real-time GHG emission monitoring and visualization system for prefabrication sites, and (3) improving system practicability during the engineering process. To deal with these challenges, research was conducted in three parts, as shown in Fig. 1: quantitative model development, CPS-based system configuration, and consideration for application.

3.1. Quantitative model development

System boundary definition: In prefabrication sites, many construction or related activities can produce GHGs due to energy consumption. However, previous studies have shown that GHG emissions generated by construction machineries account for the largest proportion of the total GHG emissions of construction sites. Thus, the system boundary of this study is limited to the GHG

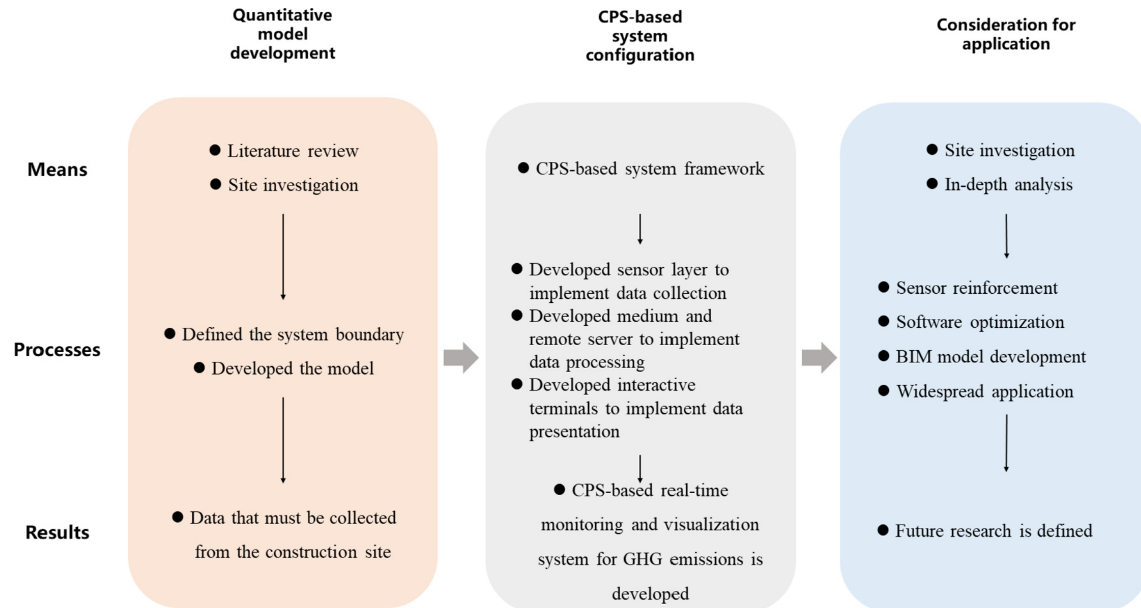


Fig. 1. Framework of the methodology.

emissions of construction machineries.

Model development: The quantitative calculation model of the GHG emissions of construction machineries can guide the development of the CPS-based system. From the analysis of the operation characteristics, this study establishes quantitative models for three types of machinery commonly used in construction sites: tower cranes, construction elevators, and transfer vehicles. The specific calculation formula is found in Section 4.

3.2. CPS-based system configuration

Data collection: In accordance with the quantitative calculation model of GHG emissions, the running time of construction machinery must be collected in real time. Thus, three types of wireless sensors were selected: (1) acceleration sensors, which were adopted to collect the running time of tower cranes; (2) barometric sensors, which were used to collect the running time of construction elevators; and (3) Global Positioning System (GPS) sensors, which were applied to collect the running time of transfer vehicles.

Data processing: After data were collected, they were transmitted within the system through certain media, and the system calculated and stored real-time GHG emissions in accordance with the existing quantitative model in a remote server.

Data presentation: To allow management personnel to view GHG emission data and the working state of construction machinery, the system displays GHG emission data visually on a desktop and a portable device. In addition, users can input relevant information through these terminals to interact with the system.

3.3. Consideration for application

Sensor reinforcement: Real-time data acquisition requires a highly stable hardware system. To achieve this goal, sensors must be continuously strengthened to ensure a stable application process.

Software optimization: The software system plays a key role in real-time data processing and presentation. The actual application process frequently includes a large amount of data from the construction site. This condition is a good test for the capacity and stability of the software system. Therefore, the software system must be constantly optimized to ensure the smooth progress of the application process.

BIM model development: The data visualization results of a BIM model are typically better than those of other lightweight models. Therefore, a BIM model for displaying the data must be developed to further assist management personnel in their work.

Widespread application: To accelerate the development of prefabricated buildings and the realization of low-carbon construction, the CPS-based system must be extensively applied. Therefore, the widespread application of the system must be considered.

4. Quantitative model development

Quantitative models must be established to calculate the GHG emissions of construction sites. Two studies were conducted to achieve this objective. First, several GHG emission sources were selected for the research by defining the system boundary. Second, a number of formulas and related parameters were utilized to establish quantitative models for the GHG emissions of construction sites.

4.1. System boundary definition

A construction site has many GHG emission sources because it is typically the most complex stage in the construction life cycle. Sandanayake divided GHG emissions into direct and indirect emissions. Direct GHG emissions refer to emissions associated with construction activities, such as the fuel consumption of equipment and transport vehicles; indirect GHG emissions refer to emissions associated with the consumption of materials and electricity (Sandanayake et al., 2017). By contrast, Hong classified emissions due to electricity consumption as direct emissions and indicated that on-site electricity consumption by machineries and building material production are two major factors of direct and indirect emissions, respectively (Hong et al., 2015). For prefabricated buildings, however, the production of components is conducted in a factory, but component assembly is performed at the construction site. Hence, GHG emissions related to building materials (e.g., concrete and steel reinforcements) should be considered within the industrial sector rather than at the construction site. The present study considers direct GHG emissions generated by construction activities. Furthermore, CO_2 is the most common and the major GHG, and other GHG emissions in several studies have been converted into their CO_2 equivalent to assess GHG emissions (Fu et al., 2014; Li and Chen, 2017; Luo et al., 2016). In this study, other GHGs were also converted into their CO_2 equivalent for real-time monitoring. The corresponding GHG emission coefficient unit was kg CO_{2-e}/kWh (or kg).

As shown in Fig. 2, a construction site can be typically divided into construction, living, and office areas (Li and Chen, 2017). The living and office areas of a construction site can also produce GHG emissions due to the use of various electrical appliances. However, these GHG emissions can be reduced by referring to research conducted on GHG emissions during the building operation stage. Moreover, these areas only account for a small percentage of the total GHG emissions of a construction site. Therefore, this study only considers GHG emissions from construction areas.

Electricity and fuel consumption by machineries in construction areas produce a considerable proportion of GHGs (Li and Chen, 2017). Electricity consumption, which accounts for the highest proportion of GHG emissions, exhibits the highest potential for emission reduction (Hong et al., 2015). Thus, this study focused on GHG emissions from construction machineries, as shown in Fig. 2. On the basis of relevant data and previous studies (Guggemos and Horvath, 2006; Hong et al., 2015; Li and Chen, 2017; Zhang and Wang, 2015), the major machineries used during the construction phases of prefabricated buildings are listed in Table 2. In this study, the calculation boundary included GHG emissions emitted by all machineries.

4.2. Model development

Once the system boundary is determined, the calculation model for GHG emissions can be developed using GHG emission factors based on process analysis. This method has been adopted in many studies to calculate the GHG emissions of various construction machineries, equipment, and activities (Hong et al., 2015; Li and Chen, 2017; Zhang et al., 2013). GHG emissions during a certain period can be calculated by multiplying fuel or electricity consumption during that period with the corresponding GHG emission factors (Zhang and Wang, 2015). An electricity measurement method has also been adopted in several studies on the GHG emissions of construction sites (Seo et al., 2016); however, the consumption of other energy sources (gasoline and diesel) at the construction site also produces GHGs. Thus, the calculation method for GHG emissions that involves sensing the running time of machineries has a wider range of applications. Determining mechanical running time will also facilitate the scheduling of various construction processes. Thus, this method was adopted in the current study.

In the CPS-based system proposed in this work, sensors are used to perceive the running state of machinery. Therefore, electricity and fuel consumption can be determined through the rated power or energy consumption of machinery. Subsequently, GHG emissions can be calculated through GHG emission factors. Lastly, the GHG emissions of each piece of equipment are summarized to obtain the total GHG emissions.

Theoretically, GHG emissions generated by all types of machinery used during the construction process can be calculated using the aforementioned methods. However, due to limitations concerning development cycle and experimental conditions, simultaneously developing sensors for all types of machinery is unrealistic and unreasonable. As a preliminary attempt, this study selected three types of machine used during major structure assembly in the engineering stage for CPS-based real-time monitoring and visualization, namely, tower cranes, construction elevators, and transfer vehicles.

The development of a quantitative model involves establishing a computational formula and selecting GHG emission factors, which can be found in the supplementary materials of this paper. The development of a calculation model for GHG emissions provides calculation logic for the CPS-based monitoring system and highlights the methods for system development.

5. CPS-based system configuration

The CPS-based system proposed in this study is mostly for the automatic collection, rapid processing, and visual presentation of GHG emission data from construction sites. The overall framework of the system should be built to ascertain the functions of each part and the interactive logic between each part. This condition is beneficial for realizing system functions.

The system consists of three major parts: the sensing, computing, and interaction layers (Fig. 3). The sensing layer includes three types of sensors used to collect data in real time. The computing layer includes a remote server and a database that process data (calculation, storage, and transmission). The interaction layer includes a desktop and a mobile phone that present data to enable users to interact with the system. In addition, General Packet Radio Service (GPRS) and wireless local area networks (WLANs), which are the basic media for the coupling and

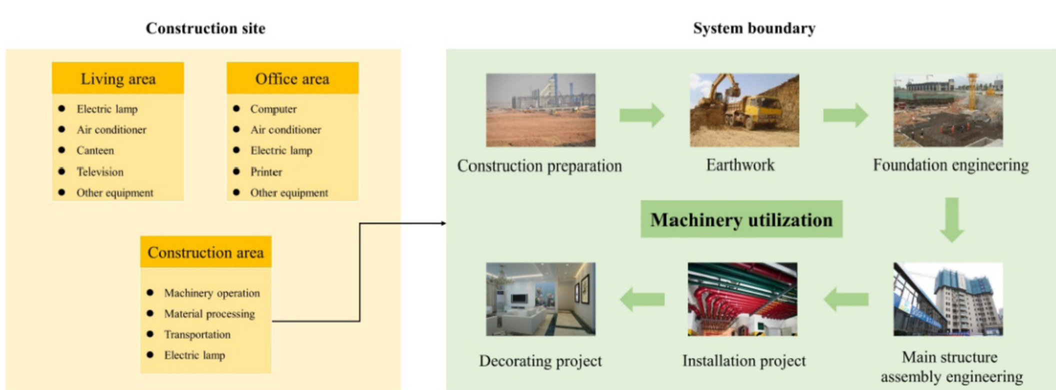


Fig. 2. Calculation boundary of the proposed system.

Table 2
Major machineries used in prefabricated buildings.

Construction phases	Major construction machineries
Construction preparation	Dozer, excavator, road roller, truck
Earthwork	Dozer, excavator, truck
Foundation engineering	Piling machine, concrete mixer, concrete pump, welder, cutter, truck
Main structure assembly engineering	Tower crane, construction elevator, truck, concrete mixer, concrete pump, welder, cutter
Installation project	Truck, miscellaneous small equipment
Decorating project	Mortar mixer, truck, miscellaneous small equipment

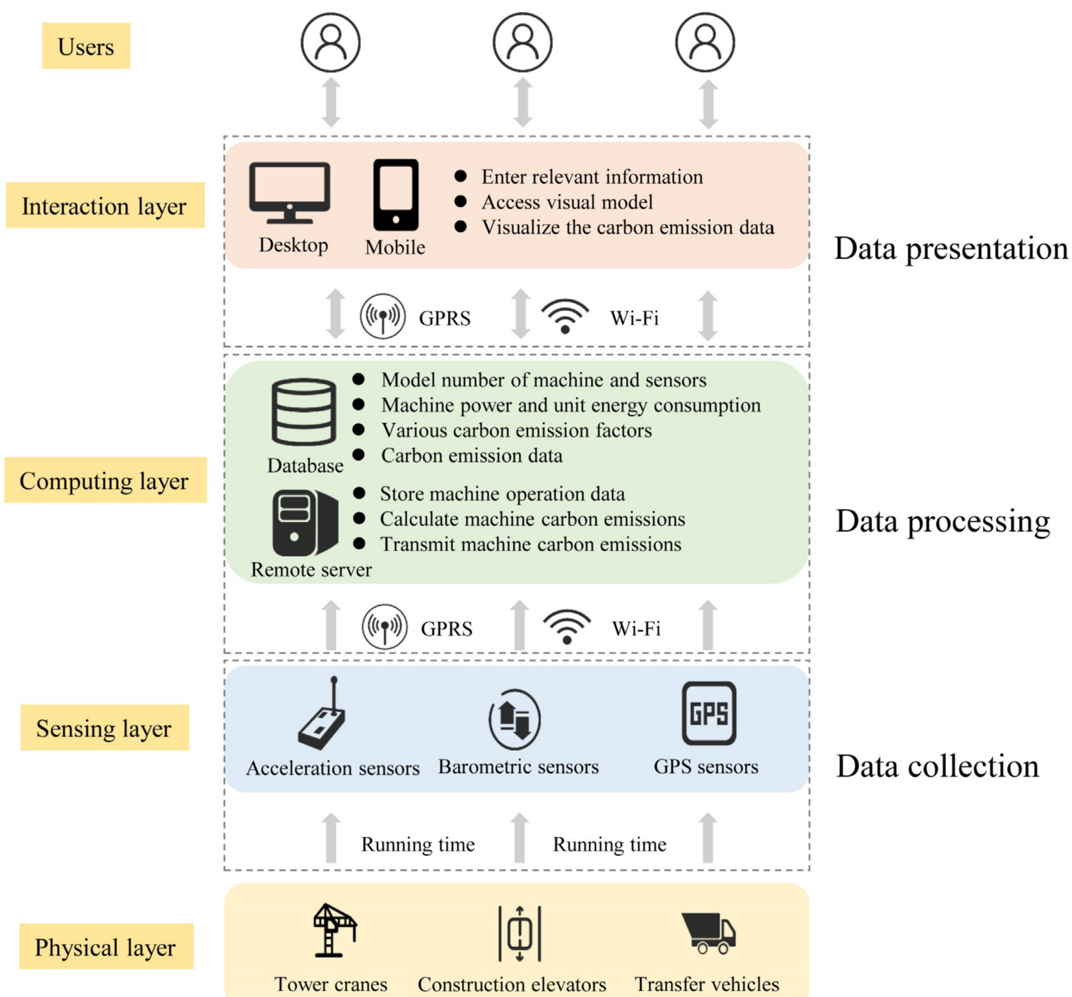


Fig. 3. System framework.

interaction of the entire system, are adopted to effectively connect all parts of the system.

The following sections describe the development process of each part of the CPS-based system.

5.1. Data collection

A wireless sensor network is an important part of the sensing layer in CPS (Darwish and Hassanien, 2018). When it is attached to the physical architecture, a wireless sensor can collect the corresponding monitoring data and transmit them to the central controller through a certain path to collect real-time data (Petroulakis et al., 2015). Thus, wireless sensors are used in various industries, such as agriculture (Guo et al., 2018), human health monitoring (Darwish and Hassanien, 2018), emergency response to landslides (Estrela et al., 2018), and gait measurement analysis, to collect data for CPS (Arafsha et al., 2018). The application of these sensors provides a useful reference for this study.

In the CPS-based monitoring system, wireless sensors exhibit the following characteristics: (1) sufficient stability and anti-interference ability, (2) high accuracy, (3) high reaction speed, and (4) easy to install and maintain.

Three types of wireless sensor were selected for this study on the basis of the aforementioned principles. First, acceleration sensors were attached to the crane boom or hook. While the tower crane was operating, the acceleration sensors captured the motion state of the crane boom or hook, identifying the running time of the tower crane and sending relevant data to the remote server.

Second, barometric sensors attached to the inner wall of the construction elevators identified the operation of these elevators by sensing changes in the surrounding air pressure, and the running state of the construction elevators could be sent simultaneously to the remote server. Third, GPS sensors were attached to the on-site transfer vehicles. Thus, the running state of the vehicles was sensed by the GPS module and sent to the remote server. All the running states were sent to the remote server via GPRS or Wi-Fi at certain time intervals for the subsequent processing of GHG emissions. In addition, a one-to-one correspondence between the sensor and the construction machine was created to facilitate the statistics of the running time of each machine.

To apply practical engineering, sensors were assembled in the sensor box integrated with other components. As shown in Fig. 4, a LED screen outside the box displays the working status of the sensor box. Several corresponding operation buttons were used to control the working status of the sensor. Various components were connected inside the box through the main board: an acceleration sensor module, a power module, a USB charging port, a Wi-Fi module for data transmission, a single-chip microcomputer for data information processing, and a buzzer for giving sound alerts to the user when the sensor acts abnormally.

5.2. Data processing

The computing layer of the proposed system includes a remote server and a database. Data processing (transmission, calculation, and storage) is achieved through the tight coupling of these parts.

5.2.1. Remote server

The remote server performs the following functions: (1) determine and store the running time data of the machine, (2) calculate the GHG emissions of the machine, and (3) transmit the GHG emissions of the machine. In particular, the running time of the machine is identified by the server and stored first in the server, denoted as T_t, T_e, and T_v. Thereafter, the required data, including machine power, energy consumption index, and GHG emission factors, are automatically extracted from the database to the server. Thus, the server can calculate GHG emissions through the pre-written calculation model. Lastly, GHG emission data are transmitted and stored in the database and can be transmitted to the interaction layer through the remote server when necessary.

The proposed system adopts the Apache server. Given its high cross-platform support and security features, Apache has become one of the most popular web servers. When the sensing layer collects relevant data, the server can receive data in real time, as shown in Fig. 5(a). In addition, the system has a display window to show the running status of the server and control buttons to allow the administrators or maintenance staff to conveniently control the server, as shown in Fig. 5(b).

5.2.2. Database

The database acts as a data warehouse that stores the following data: (1) model numbers of machine and corresponding sensors, (2) machine power and unit energy consumption, (3) various GHG emission factors, and (4) GHG emission data. After the remote server calculates the GHG emissions of machine, the database receives and stores emission data transmitted from the remote server. The emission data can also be accessed using the interaction layer.

The MySQL database, which is an open-source relational database management system that is preferred due to its favorable speed, reliability, and adaptability, was selected for this study. MySQL is the best choice for managing data content in the absence of transaction processing. It stores each data set in the platform as a list to allow its retrieval at any time, as shown in Fig. 6. The database access interface clearly shows the stored data in the form of a data classification menu and a data information table. A functional area is also provided at the top of the interface where users can import, modify, search, and perform a series of other operations on the data.

5.3. Data presentation

After data collection and processing, GHG emission data can be presented in the interaction layer, which includes a desktop and a portable device (mobile phone). As a major channel for users to interact with the CPS-based system, the primary functions of the interaction layer are as follows: (1) entering relevant information or data, (2) accessing the visual model, and (3) visualizing the GHG emission data.

5.3.1. Desktop

Users can interact with the system using an application on the desktop. In the application, three basic interfaces are utilized to enable interaction, namely, machine information entry interface, visual monitoring interface, and data analysis interface, as shown in

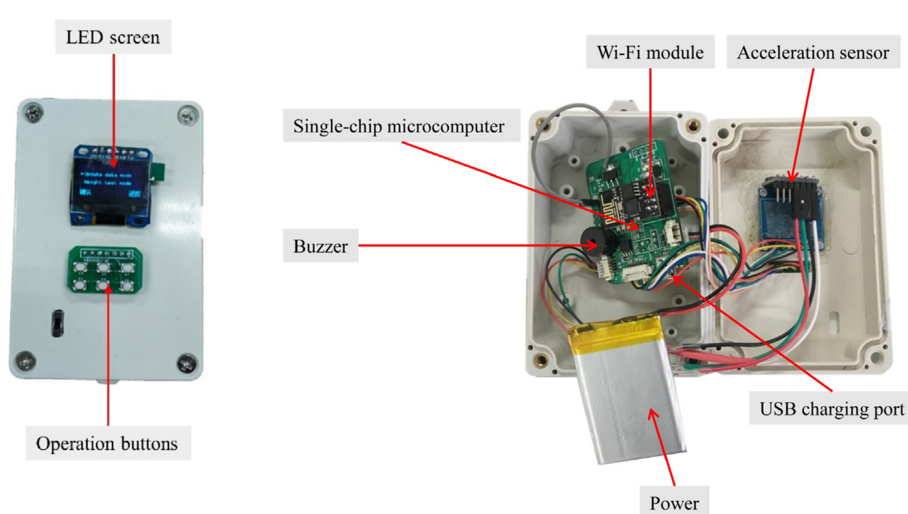


Fig. 4. Sensor appearance.

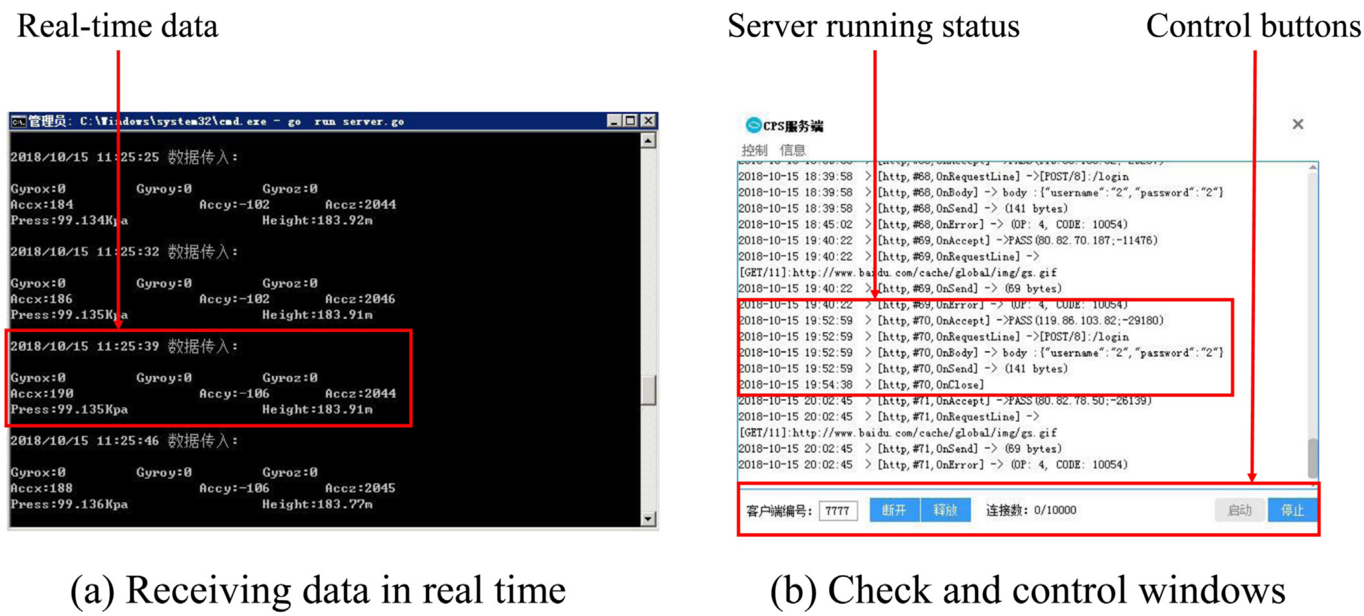


Fig. 5. Apache server.

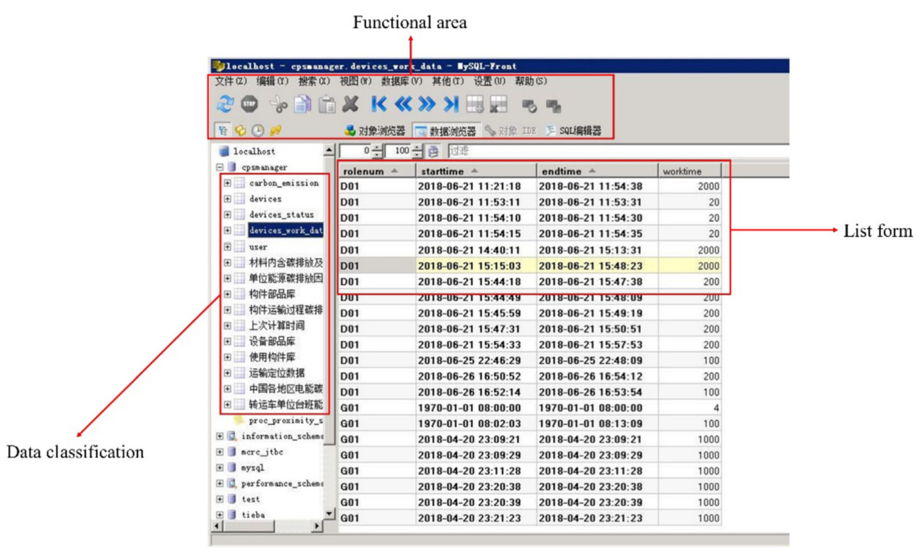


Fig. 6. Database access interface.

Fig. 7.

In the machine information entry interface, users can manually input the type, model, power, or unit of energy consumption of machinery and the number of corresponding sensors into the system before the system works through the manual input bar. Thereafter, the data are shown in the display area and transmitted to the database through the remote server. In addition, users can enter device information into a table and import the data automatically through the "Import from Excel" button in the interface. Users can also switch to the visual monitoring interface or data analysis interface through the function switch button placed at the left side of the interface.

In the visual monitoring interface, users can access the visual model of construction machinery, which is embedded into the desktop applications, as shown in Fig. 8. Lightweight visual models are adopted and accessed through this interface in the primary edition. This method connects the physical world to the digital world, creating a visual model of GHG emission data for a construction site. The interface can show the running state, running duration, and accumulated GHG emissions of construction machinery in the status bars, marked in Fig. 8. When the GHG emissions of construction machinery exceed the preset value, the visual model will issue a text warning, which can be used by construction personnel to take appropriate management measures. Figs. 8, 9 and 11 present the results of the preliminary test of the proposed system, but only the display effects of the system (e.g., GHG emission data, mechanical types, and real-time data changes) are shown. The data in Figs. 8, 9 and 11 have no reference value.

In the data analysis interface, the system provides another means to connect the physical world to the digital world, wherein 2D charts display GHG emission data. First, the rectangular coordinate system displays the cumulative GHG emissions of the

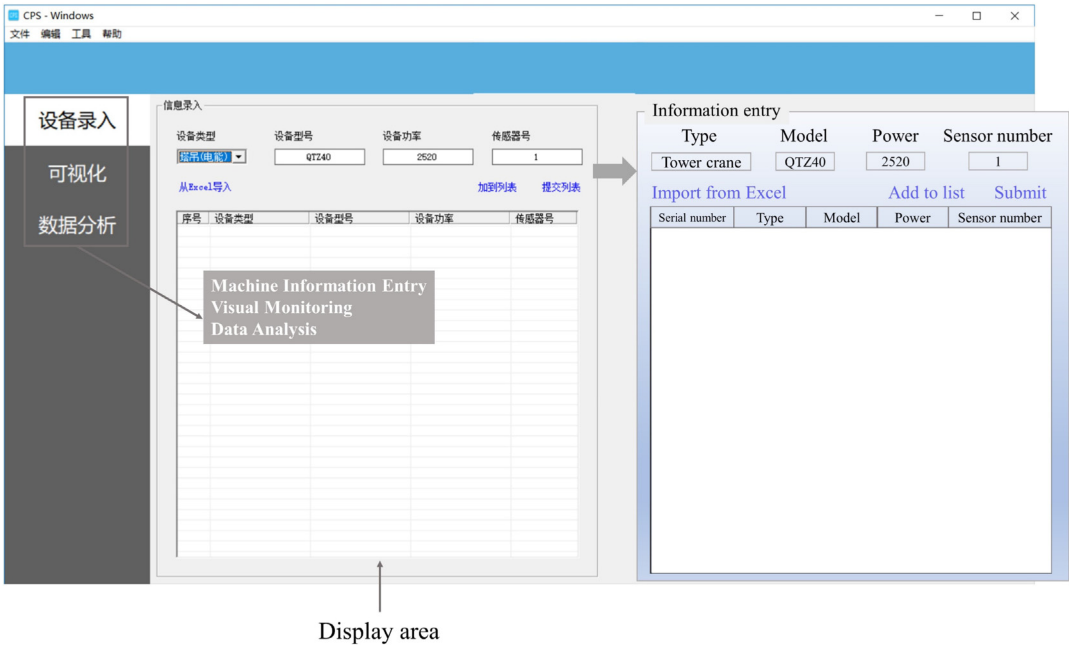


Fig. 7. Information entry interface.

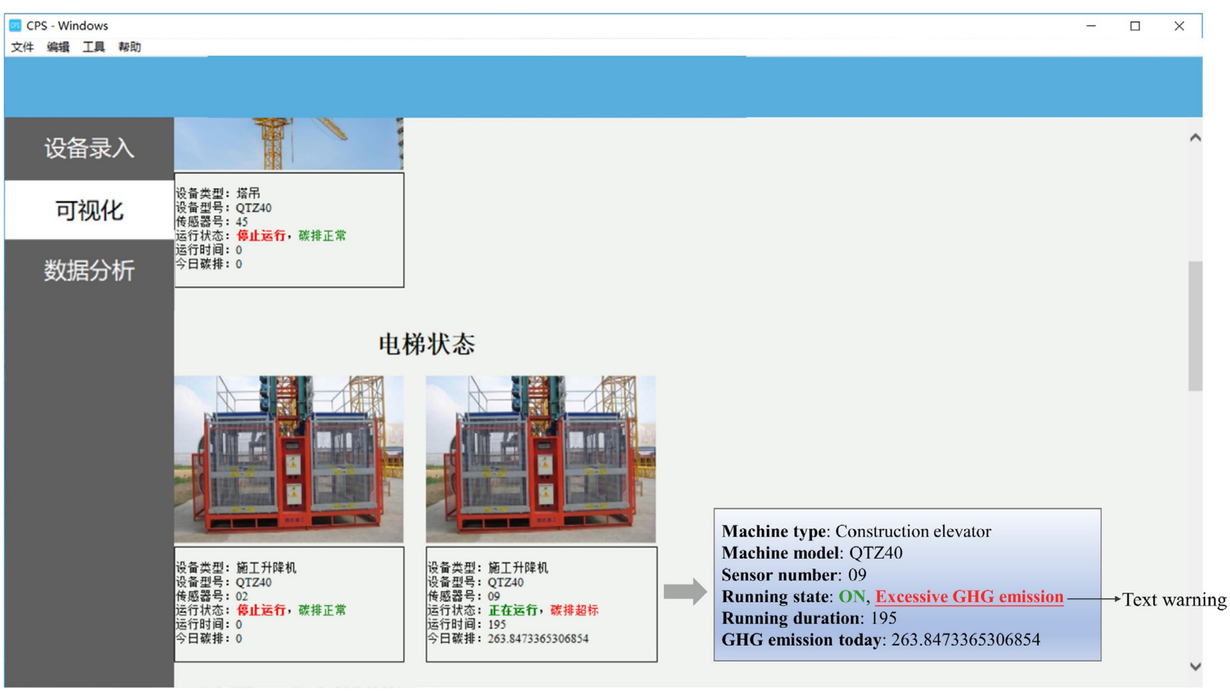


Fig. 8. Visual monitoring interface.

construction site, as shown in Fig. 9(a). In this coordinate system, the horizontal axis represents time and the vertical axis represents GHG emissions. When construction machinery attached with sensors emits GHG, a cluster of fluctuating curves will appear in the coordinate system, showing the cumulative GHG emissions per machine. Moreover, the horizontal axis can be stretched and compressed to allow users to observe the changing GHG emissions at any time. On the right side, the pie chart of the accumulated GHG emissions at a particular time is set, wherein accumulative GHG emissions are classified by mechanical type. Second, another rectangular coordinate at the bottom of the page shows the real-time change in the GHG emissions of each construction machine. Here, the horizontal and vertical coordinates remain the same as the previous ones, as shown in Fig. 9(b). Furthermore, a pie chart on the right side analyzes the composition of real-time GHG emissions. Third, the interface provides historical data for query function, allowing users to access historical data. At the top of the page in Fig. 9(a), when users enter a date into the query bar in a given format and click the “Query” button, the corresponding GHG emission data will be displayed on the interface.

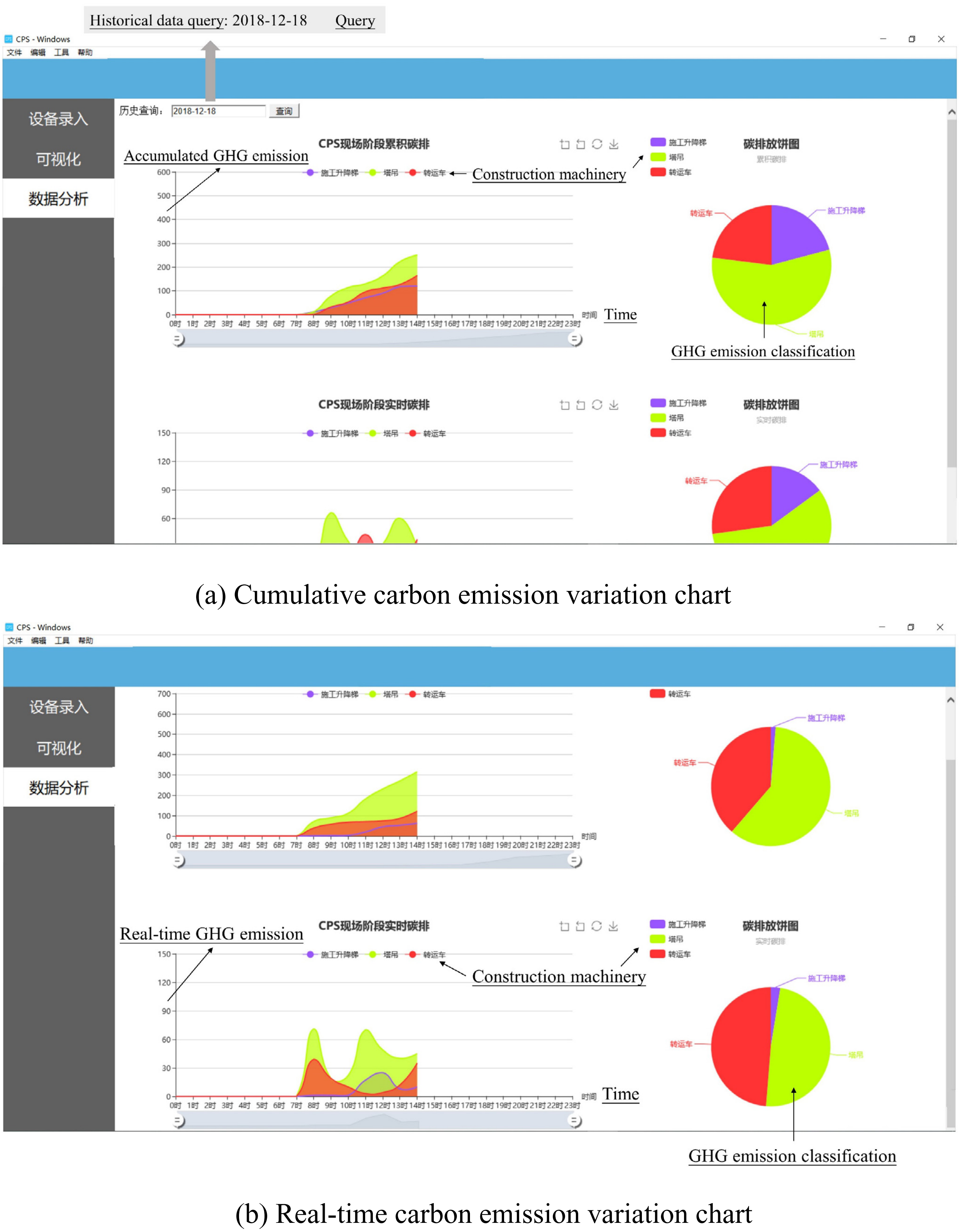


Fig. 9. Data analysis interface.

5.3.2. Portable device

The development of a portable device enables users to access the system anytime and anywhere. In the CPS-based system, mobile devices with specially developed applications are adopted. As shown in Fig. 10, users must first enter a password to log in to the system for security. In the main interface, two interfaces, which are the same as those in the desktop, are available for users to operate. They present the same data monitoring and analysis results as those on the desktop, as shown in Fig. 11.

5.4. Communication network

As a basic medium for information and data transmission, the communication network is essential for the effective integration of all parts of a system. In this study, the communication network must exhibit the following characteristics: (1) favorable stability, (2) fast transmission speed, and (3) high data transmission capacity. WLAN was selected to implement the communication network on the basis of the aforementioned characteristics.

In the sensor-integrated box, the WLAN module was applied to sense the WLAN signal. The sensors can transmit the mechanical operation data collected by the remote server in real time until WLAN is connected.

For the remote server, database, and interaction layer, WLAN was also adopted to implement data access and transmission functions. Given the particularity of the mobile phone terminal, it can access the system through GPRS to ensure convenient access for users. Thus, all parts of the CPS-based system were effectively integrated.

The system developed in this study can be used for the real-time monitoring of GHG emissions in construction sites. Moreover, GHG emission intensity can be conveniently obtained for each on-site construction activity under different construction machinery conditions. These GHG emission intensities can also be compared with several clean technologies in the future.

6. Considerations for application

The proposed system was developed with a full understanding of the actual conditions prevailing at a construction site. The feasibility of the system was verified preliminarily, but its complete application remains lacking. Therefore, two or three complete construction projects are required in our experimental plan to verify the persistent stability of the system, and a GHG emission database can be built through several construction projects. With the progress of the experiment plan, the following aspects of optimization must also be implemented.

First, the operational method of all types of sensors must be improved. Favorable fastening devices to reliably achieve fixation are currently unavailable for the sensor-integrated box, easily leading to the instability of the GHG emission monitoring system or making it dangerous to use in actual projects. Therefore, the sensor-integrated box must be improved in the future by adding a magnetic device, such as a strong clamp or a rivet reinforcement device.

Second, the sensors, servers, and databases used in the current system are relatively common versions. When the experimental data become extremely large, the bearing capacity of the servers and databases may reach a limit, and system coupling may be considerably affected, resulting in system failure. Therefore, the software components of the system will be optimized in the future to cope with complex situations. For example, powerful servers and databases must be selected, renovation measures must be implemented to strengthen system coupling and make the system widely utilized, and the system must be upgraded.

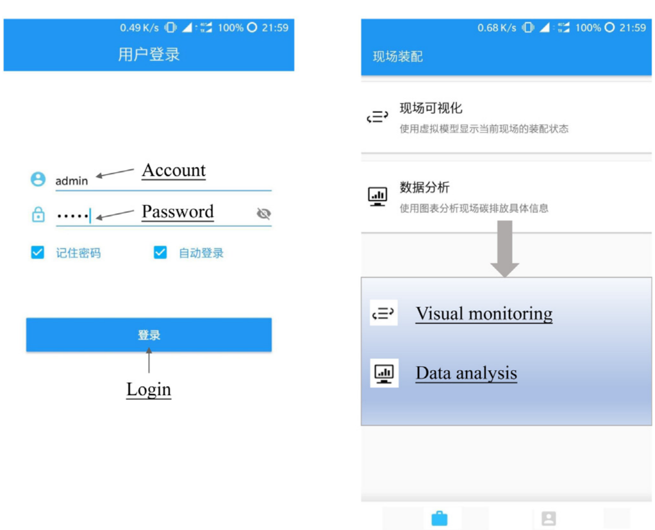
Third, the BIM model should be effectively applied as an improved visualization tool to present GHG emission data. Thus, the next step is to establish a BIM model for the construction site to achieve 3D visualization of GHG emission data and simultaneously enhance the two-way interaction between the physical and virtual world.

Moreover, the widespread application of the CPS-based system will be highly significant for the development of energy-saving and prefabricated buildings in China. Therefore, after verifying the practicability and stability of the system, mass production of sensors and corresponding software platforms should be conducted to extensively apply the system.

7. Conclusion

This study proposed developing a CPS-based real-time monitoring and visualization system for GHG emissions from prefabrication sites based on the analysis and comparison of previous GHG emission assessment methods. First, through the analysis of the GHG emissions of a prefabrication site, the system boundary was defined to limit the research scope to GHG emissions generated by machineries in construction sites. As a preliminary attempt, three types of machinery commonly used in the engineering of the main structure in a construction site were selected, namely, tower cranes, construction elevators, and transfer vehicles. These machineries were used to establish the GHG emission calculation model and determine the corresponding GHG emission factors to determine the calculation logic of the CPS-based system. Thereafter, the entire framework of the CPS-based system was constructed, the functions and interactions of each part were designed, and the specific development process of each part was described.

The system provides the following innovations. The first is the novelty of the research object. At present, only a few studies have been conducted on the real-time monitoring of GHG emissions during the on-site installation stage of prefabricated buildings. This study adds to the research on this aspect. The second is the innovative research method. CPS technology is introduced to monitor GHG emissions. This practice has rarely been done in the past. Through the coupling of multiple subsystems, the real-time monitoring and visual presentation of GHG emission data in a construction site is preliminarily achieved. Third, compared with the direct measurement method of electricity consumption



(a) Login interface (b) Main interface

Fig. 10. Mobile app interface.

(a) Visual monitoring on mobile app

(b). Data analysis on mobile app

Fig. 11. Data monitoring and analysis results on mobile app.

adopted in several studies, GHG emissions were calculated by measuring the operation time of machinery, which cannot only measure widespread GHG emissions but can also help optimize and schedule the construction process to a certain extent.

Furthermore, this study presents the following management results. First, the ability of the system to record the GHG emissions of various construction activities enables the formation of a GHG emission database. This database can be utilized when making construction scheduling arrangements to achieve the multi-objective optimization of cost, schedule, quality, and GHG emissions. Second, the mechanical operation in a construction site can be intuitively understood using the real-time change of system data, and the system can present the real-time virtual model of a construction site if combined with BIM.

However, the system proposed in this study must be further strengthened in terms of the visual presentation of GHG emission data and two-way interaction between the physical and virtual world. These issues will be addressed in future studies. Moreover, additional optimization and debugging work are required before the system can be used at a wider scale.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

In this study, three types of machine in a precast construction site were considered to establish the calculation model: tower cranes, construction elevators, and transfer vehicles. E_0, E_t, E_e, and E_v represent the total GHG emissions monitored by the system and the GHG emissions generated by tower cranes, construction elevators, and transfer vehicles, respectively.

$E_0 = E_t + E_e + E_v$ (1)

For construction tower cranes, the operation of each tower crane was perceived through the acceleration sensor; thus, the operation time of a tower crane was recorded. Combined with the rated power of tower cranes and GHG emission factors, the GHG emissions of tower cranes can be calculated as follows:

$$Et = \sum_{i=1}^{kt}(Pt, i \times Tt, i \times fe / 3600) \quad (2)$$

where k_t represents the total tower cranes in the site; $P_{t,i}$ represents the rated power of the ith tower crane (kW), which can be obtained from the construction plan; $T_{t,i}$ represents the running time of the ith tower crane(s), and f_e represents the electricity GHG emission factor (kg CO_{2-e}/kWh).

Similarly, the GHG emissions of construction elevators can be calculated as follows:

$$Ee = \sum_{i=1}^{ke}(Pe, i \times Te, i \times fe / 3600) \quad (3)$$

where k_e represents the number of construction elevators in the site; $P_{e,i}$ represents the rated power of the ith construction elevator (kW), which can be obtained from the construction plan; and $T_{e,i}$ represents the running time of the ith construction elevator(s).

The computational formula of transfer vehicles is more complex due to the diversity of types and energy consumption. In this study, the transfer vehicles that consume gasoline and diesel oil were considered. Thus, the computational formula is as follows:

$$Ev = \sum_{i=1}^{kv}[Tv, i \times EUv, i \times fi / (8 \times 3600)] \quad (4)$$

where k_v represents the number of transfer vehicles in the site; $EU_{v,i}$ represents the energy use of the ith transfer vehicle during one work shift which can be gasoline or diesel oil (kg) and can be obtained from the construction plan; $T_{v,i}$ represents the running time of the ith transfer vehicle(s); and f_i represents the fuel GHG emission factor (kg CO_{2-e}/kg). The choice of f_i depends on the type of energy consumed by the transfer vehicle. When the transfer vehicle consumes gasoline, $f_{i,g}$ is used; otherwise, $f_{i,d}$ is used.

As an important parameter in the computational formula of GHG emissions, the selection of GHG emission factors will affect the accuracy of calculation. Therefore, this study summarizes the relevant GHG emission factors on the basis of the current situation of the construction industry in China and previous studies, as shown in Table 3, Table 4, and Table 5.

Table 3
Regional electricity GHG emission factors

Region	Relevant provinces	f_e(kg CO_{2-e}/kWh)
North China	Beijing, Tianjin, Hebei, Shanxi, Shandong, Inner Mongolia Autonomous Region	1.0416
Northeast China	Liaoning, Jilin, Heilongjiang	1.1291
East China	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian	0.8112
Northwest China	Shaanxi, Gansu, Qinghai, Ningxia Autonomous Region, Xinjiang Autonomous Region	0.9457
Central China	Henan, Hubei, Hunan, Jiangxi, Sichuan, Chongqing	0.9515
South China	Guangdong, Guangxi Autonomous Region, Yunnan, Guizhou, Hainan	0.8959

Note: The factor library is derived from the **Baseline Emission Factors for Regional Power Grids in China** published by the Department of Climate Change, National Development, and Reform Commission of China in 2015 (Department of Climate Change, 2015). The factors calculated using the operating margin method are adopted in this study.

Table 4
Energy consumption of transfer vehicle per work shift

Model of transfer vehicles	EU_v (kg/work shift)	
	Gasoline	Diesel
4t	25.48	–
6t	–	33.24
8t	–	35.49
15t	–	56.74

Note: The factor library is based on (Li and Chen, 2017).

Table 5
GHG emission factors of energy consumption

Energy type	f_i (kg CO_{2-e}/kg)
Gasoline	3.51
Diesel	3.68

Note: The factor library is based on (Li and Chen, 2017).

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