

Process Monitoring with Support of IoT in Prefabricated Building Construction

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This paper focuses on how to use IoT technologies to monitor the project implementation process in prefabricated building (PB) construction, which will help optimize the construction schedule and ensure the quality and safety of PB construction. Although IoT monitoring can obtain a large amount of data during construction, the challenge is how to convert these data into intelligent information needed for feasible decision-making. Therefore, we need to clarify the key factors requiring monitoring during construction and how to use these data to make decisions. In this paper, we analyze the whole process of PB construction, comprising five phases: pre-construction, off-site manufacturing, delivery, on-site assembly, and finishing. Through mathematical model formulation to discover the key factors that affect the construction implementation process, we clarify the monitoring data that need to be obtained by IoT technologies. Using these monitoring data, it is possible to make judgments on process abnormalities, promptly give alarms, make proactive adjustments, and optimize the construction implementation process, thus achieving the goal of ensuring project quality and construction safety.

1. Introduction

Engineering projects are operating in an ever-changing environment and are vulnerable to a myriad of risks at all levels. To survive in such a complex environment, companies need to be extremely agile and build a high level of resilience with high risk mitigation capability and structural flexibility to allow a rapid response to these challenges. Information technology (IT) has been, and continues to be, an essential enabler for effective project management (PM). Internet of Things (IoT) technologies, as one of the latest IT developments, provide a paradigm shift in several areas including PM and process control. IoT systems allow the possibility of human-to-things communication and autonomous coordination among ‘things’ when they are being stored in a facility or being transported to different operations.^(1–3)

A prefabricated building (PB) consists of factory-made components or units that are transported and assembled on-site to form the complete building. PBs are characterized by

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standardized design, industrial production, assembly construction, integrated decoration, and information management, with the integration of various fields including R&D design, off-site manufacturing, and on-site assembly.

The PB construction method has become a generally recognized advanced construction method.⁽⁴⁾ Different from traditional construction methods (on-site operations), in the PB construction method, most of the materials are not directly supplied to the construction site. The construction site mainly assembles the components, and these components are processed and produced by professional suppliers. With the development of PBs, various types of professional suppliers have gradually come into existence such as precast concrete component suppliers and pipeline component suppliers. These suppliers have their own independent manufacturing and processing sites, do not provide original materials to building construction enterprises, but provide pre-assembled semi-products with certain functions. As shown in Fig. 1, owing to its industrialized method, compared with the traditional construction process, more complex supply and demand relationships need to be considered in the PB construction process.

An IoT monitoring system consists of smart sensors, transmission devices, service platforms, and so forth. As shown in Fig. 2, smart sensors are platforms with onboard technologies such as

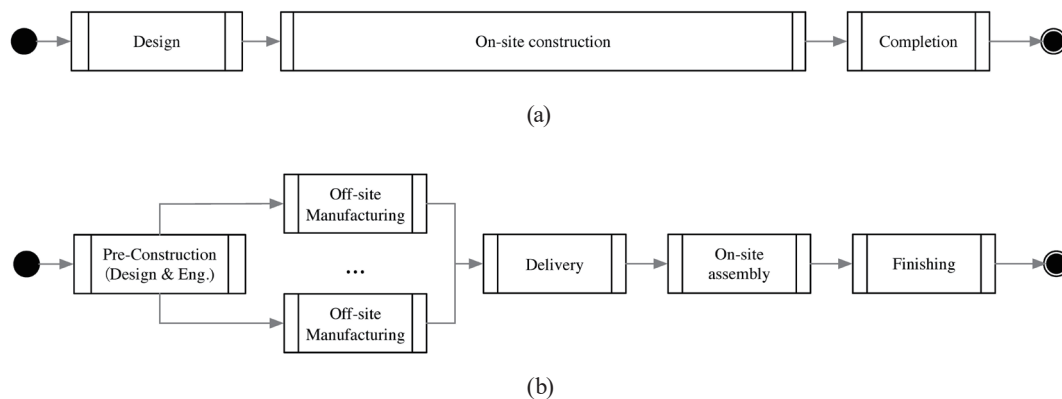


Fig. 1. Comparison of the processes of traditional construction and PB construction. (a) Traditional construction process. (b) PB construction process.

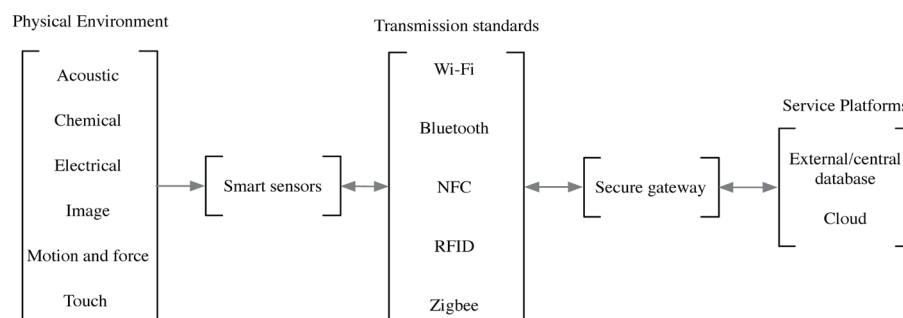


Fig. 2. IoT monitoring system.

microprocessors, storage, diagnostics, and connectivity tools that transform traditional feedback signals into true digital insights. These smart sensors can obtain timely and valuable data that are sent to the service platform through transmission devices. A service platform with analytical insights can drive improvements in cost, performance, and customer experience.^(3,5,6)

An IoT monitoring system increases the level of automated collection and processing of data and broadens management visibility across the whole project process. Integrating an IoT monitoring system into PM and process control can

1. increase operational efficiency through automation,
2. reduce repair costs and maintenance downtime through better monitoring,
3. perform real-time inventory tracking with improved demand planning,
4. inform product development and strengthen product life cycle management,
5. enhance customer service by connecting more closely to the customer.

As discussed above, a more complex construction process must be considered for PBs. The construction process is affected by many factors, such as the productivity of off-site manufacturing and the type of transportation. Design changes affect component production, and many quality and safety risk control issues must be faced during on-site assembly. Applying IoT technologies to managing the whole process of PB construction will greatly improve construction efficiency. Therefore, we need to clarify the key factors affecting the construction process and how to use monitoring data obtained through the IoT to make decisions.

Firstly, we decompose the whole process of PB construction into five phases: pre-construction, off-site manufacturing, delivery, on-site assembly, and finishing, as shown in Fig. 3. Then, we formulate the mathematical model for each phase to discover and define the key factors that affect the construction implementation process. Lastly, through the use of the IoT to monitor the changes in these key factors, we propose a design optimization algorithm to reduce operating costs, improve efficiency, and ensure project quality and construction safety.

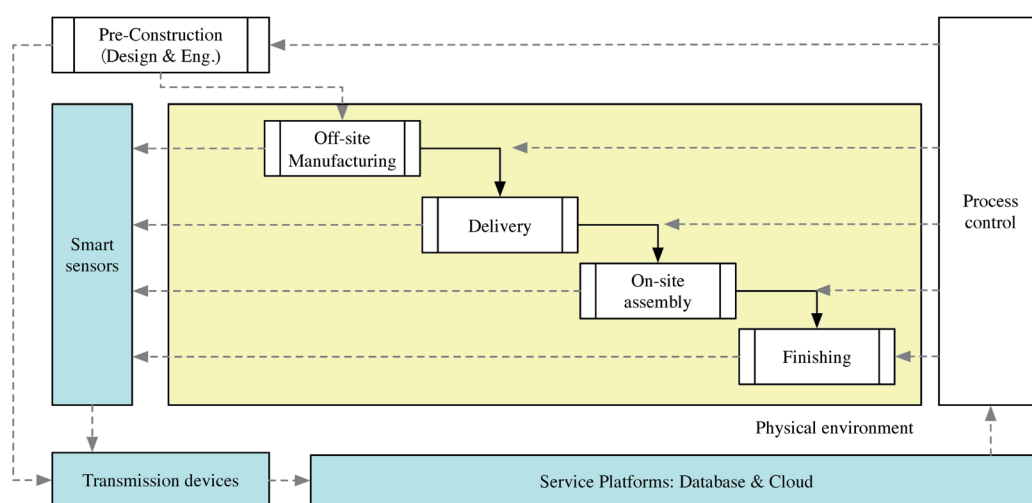


Fig. 3. (Color online) Process monitoring and control system.

The rest of this paper is organized as follows. Section 2 presents a comparison of the features of PB construction, traditional construction, and the manufacturing industry. The mathematical modeling of project planning and control in PB construction is introduced in Sect. 3. Smart sensor applications for the whole process of a PB construction project are discussed in Sect. 4. Section 5 concludes this paper and outlines future research.

2. PB Construction

As shown in Table 1, different from traditional construction, the construction of a PB mainly involves assembling the components, which are processed and produced by professional manufacturers and suppliers.⁽⁷⁾ The PB construction company cooperates with multiple suppliers and manufacturers and optimizes the delivery of components, services, and information from the suppliers to the construction site.

An illustration of PB construction is shown in Fig. 4. Complex parts of buildings traditionally produced on site, such as columns, slab beams, exterior walls, and verandas, are produced by manufacturers. All components can be pre-manufactured, avoiding on-site pouring. Many on-site manual operations are replaced by assembly operations. PB construction has the characteristics of prefabrication in advance, increasing the construction speed, reducing the construction period, and reducing the influence of weather. Traditional on-site construction requires cross-working with a complex operation process. In PB construction, mechanized hoisting is mainly used. The assembly operation is similar to that of assembling automobile components in a factory. This reduces the number of on-site manual operations, improves construction efficiency, and ensures safety and quality.

Because simple mechanized hoisting is widely used on site, a lot of physical labor is eliminated, and constructors only need to master simple prefabricated assembly and hoisting skills after simple training. This reduces the demand for labor and the requirement for professional skills. Furthermore, scaffolding, site masonry, site plastering, and other issues

Table 1
Comparison of features of PB construction, traditional construction, and manufacturing industry.

	PB construction	Traditional construction	Manufacturing industry
Production features	Batch production of components	Customized, non-copiable	Batch production, large-scale
Production process	Pre-assembled semi-products, on-site assembly, geographical restrictions	On-site manufacture, geographical restrictions	Component manufacture, assembly, no geographical restrictions
Cooperation	Select multiple suppliers of industrial components	Select suppliers based on customized order	Select multiple suppliers based on components
Collaboration relationship	Long-term collaboration with suppliers, manufacturers	Temporary	Long-term collaboration with suppliers
Core enterprise	Suppliers, off-site manufacturers, delivery company, on-site construction contractor	Construction contractor	Manufacturers
Objectives	Quick response to uncertain environmental changes, agile response to customer needs	Quality, safety, due date, environmental protection, cost	Quality, cost, etc.

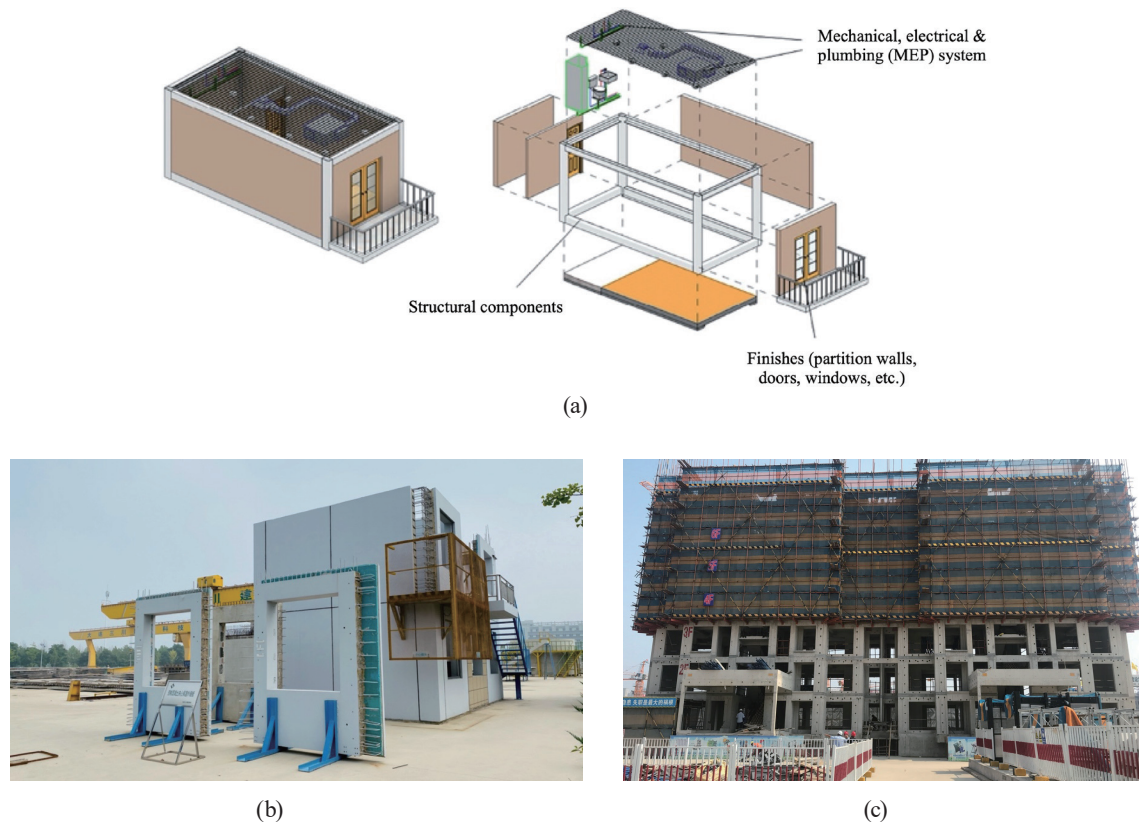


Fig. 4. (Color online) Illustration of PB construction. (a) Example of PB component design.⁽⁸⁾ (b) Example of PB component assembly. (c) PB construction site.

associated with traditional on-site construction can be avoided in PB construction. PB construction can reduce water consumption by at least 80%, energy by 70%, material use by 20%, and working space by 20%, effectively reducing the noise and environmental impact of construction.

3. Project Process Control (PPC) Model for PBs

The concept of PPC comes from production process control in the manufacturing industry. PPC refers to the completion of the complex processes of a project according to the duration plan with reasonable control of the progress. The project plan involves choosing an appropriate strategy and achieving the desired objectives (such as progress, cost, quality, safety, and environmental impact). PPC is an iterative process that constantly predicts progress, analyzes deviations, and adjusts plans during the execution of the project. A basic model of PPC includes the following assumptions:

- A1. A single project consists of a number of activities with known processing times.
- A2. The start time of each activity is dependent upon the completion of some other activities (precedence constraints).

- A3. Resources are available in limited quantities and they are non-renewable during a period.
- A4. There is no substitution between resources.
- A5. Activities cannot be interrupted.
- A6. There is only one execution mode for each activity.

We consider a single project that consists of $\{j = 1, 2, \dots, J\}$ activities performed by $\{r = 1, 2, \dots, R\}$ non-renewable resources with non-preemptive processing time $\{p_j\}$. Each activity j requires n_{rj} resources of type r . The maximum number of available resources $\{b_r\}$ is given. The definition of an activity is illustrated in Fig. 5. In addition, $Suc(j)$ is the set of successors of activity j and $Pre(j)$ is the set of predecessors of activity j . In the precedence graph shown in Fig. 6, the nodes denote the activities and direct arcs denote the precedence constraints. Taking the example of minimizing the makespan, i.e., the total length of the schedule (that is, until all activities have finished processing), the objective function can be formulated as

$$\min f_M = \max_j \{t_j^F\}, \quad (1)$$

where t_j^F is the finish time of activity j . The activities $\{j\}$ are interrelated by two types of constraints. Firstly, the precedence constraints prevent an activity j from being started before all its predecessors $\{j'\}$ have been finished, which is formulated as

$$t_j^S - t_{j'}^S \geq p_{j'}, \forall j' \in Suc(j), \quad (2)$$

where t_j^S is the starting time of activity j . We can see that the key factor affecting the makespan of the project is the processing times $\{p_j\}$ of the activities.

Secondly, any activity j needs to be completed using the resources $R_j = \{r_{jk}\}$ required. During every time period t of its processing time p_j , the processing of activities is constrained by resources, such as the amount, capability, and usability. The constraint on activities is formulated as

$$\sum_{j=1}^J r_{jk} x_{jkt} \leq b_k, \forall t, k, \quad (3)$$

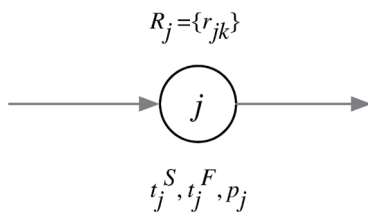


Fig. 5. Illustration of definition of activity.

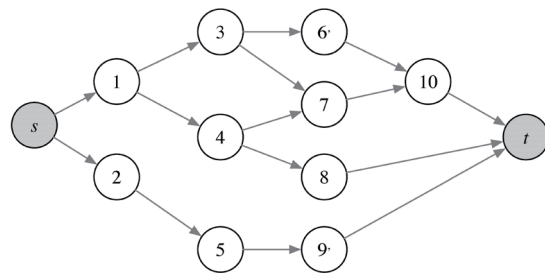


Fig. 6. Precedence graph of PPC.

where b_k is the constraint of resource type k and x_{jkt} is the decision variable, which is the resource assignment {0 or 1} of resource type k for activity j at time period t .

We can see that PPC is affected by two types of factors: the arrangement of activities for process optimization and the assignment of resources to meet the system constraints. Owing to the characteristics of PB construction, the structure and engineering technology are more complicated than traditional construction. To effectively control the progress of PB construction, it is necessary to conduct a detailed analysis of the whole process. Different from traditional construction, PPC in PB construction can be divided into five phases: pre-construction, off-site manufacturing, delivery, on-site assembly, and finishing. Each phase can be regarded as an independent project, and these phases are related, as shown in Fig. 7.

The advantage of PB construction is that it minimizes the operation time on the construction site. PB construction projects can achieve simultaneous off-site manufacturing and on-site assembly as a parallel process. PB construction allows multiple subcontracting teams to perform different tasks in the project. In addition, manufacturers can manufacture components separately and integrate them by on-site assembly. Therefore, a PB construction project is different from traditional single PM, consisting of multiple projects involving a number of activities with known processing times and multiple resources. Such a model is called a multiple project process control (mPPC) model, as shown in Fig. 8. An mPPC model can be defined by the following assumptions:

- A7. When a specific project is initiated, it must be finished without changing to another project (precedence constraints of multiple projects).
- A8. The starting time of each activity is dependent upon the completion of some other activities (precedence constraints of activities).
- A9. Multiple resources are available in limited quantities but are renewable from period to period.
- A10. Activities cannot be interrupted; there is only one execution mode for each activity.
- A11. The managerial objective is to minimize the total project time and the total tardiness penalty for all projects.

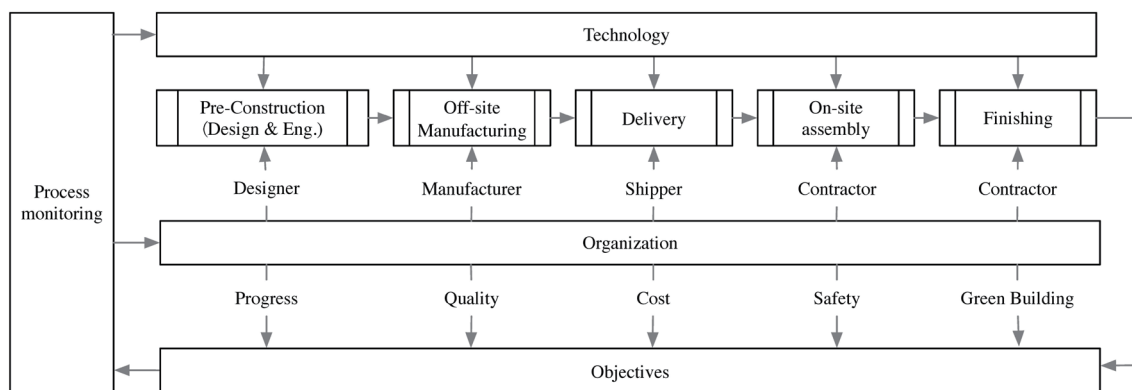


Fig. 7. PPC with multiple objectives in PB construction.

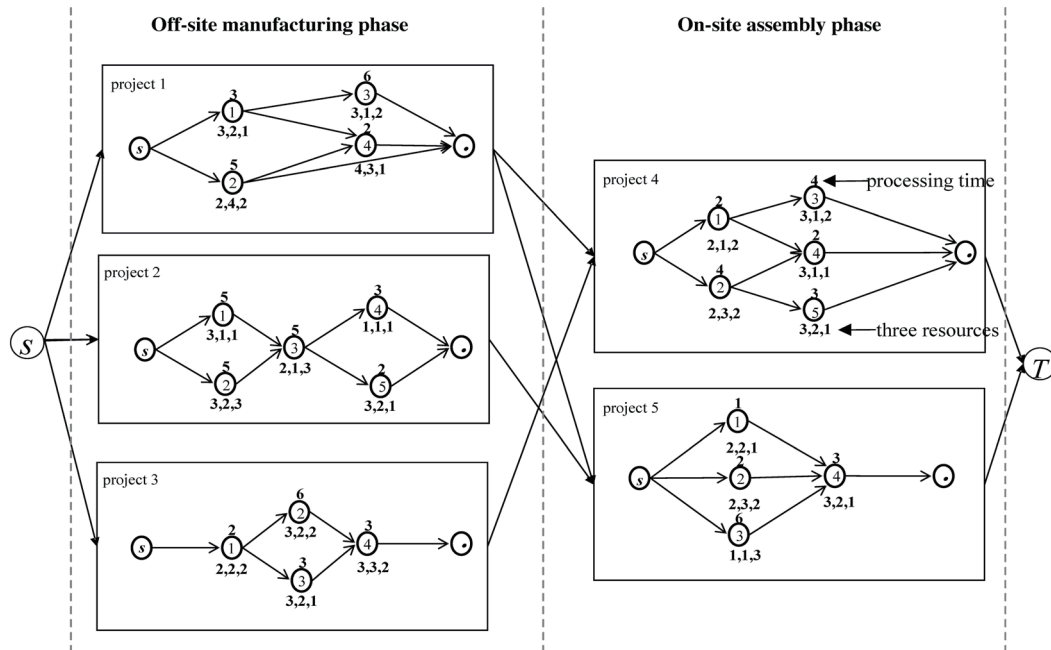


Fig. 8. Precedence graph of mPPC.

We consider an mPPC model that consists of $\{i = 1, 2, \dots, I\}$ projects and $\{j = 1, 2, \dots, J\}$ activities with a non-preemptive processing time $\{p_{ij}\}$ of periods. Additionally, the precedence relations between the pair of projects (i, m) , where i immediately precedes m , are taken into consideration. In each model, the activities are interrelated by two types of constraints. As the first type of constraint, the precedence constraints that are known from a single PPC prevent an activity from being started before all its predecessors have been finished. As the second type of constraint, activity j in project i requires l_{ijr} units of resource $r \in R$ during every period of its processing time p_{ij} . (Resource r is only available with a constant period availability of b_r units for each period. Each activity is scheduled at the feasible earliest start time when its resources have not reached the resource limit.

4. Process Monitoring with Support of IoT

Usually, there are many factors that affect the project implementation process, such as technical factors, human factors, equipment factors, materials, component factors, environmental factors, and funding factors. The critical factors of the PB construction process are shown in Table 2.

As shown in Fig. 9, IoT technologies extend the geographical space of PPC from on-site construction to the whole process of PB construction. The currently fragmented and highly dynamic PB construction with PPC can be more robust and productive with real-time information retrieval and dissemination, structured and efficient communication, and embedded intelligence.⁽⁹⁾

Table 2
Process control of PB construction project.

Construction processes	Critical factors
Pre-construction process	Structural design, split design, construction process design, hoisting step design, resource allocation, project process arrangement
Off-site manufacturing process	Mold reuse, equipment operation error, component accuracy deviation, component quality, manufacturing capacity, just in time
Delivery process	Transport capacity, damaged components
On-site assembly process	Construction worker assignment, construction worker training, component loading and storage, assembly accuracy, hoisting process
Finishing process	Impact on natural environment, component quality

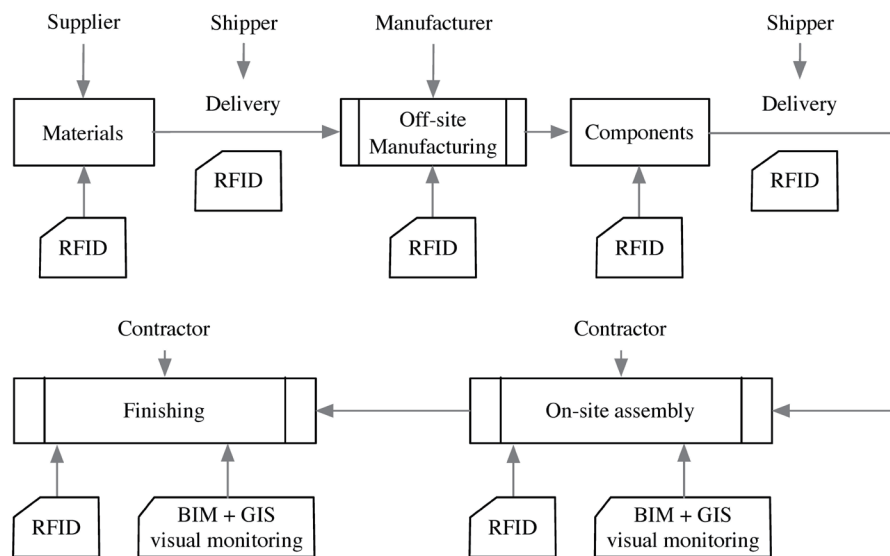


Fig. 9. IoT monitoring in the whole process of PB construction.

4.1 Process optimization in pre-construction phase

The importance of different influencing factors depends on the PB construction project. When implementing a construction project, the manager needs to fully consider the uncertain factors that affect its implementation process, so as to achieve project scheduling. A general optimization strategy is cost optimization. The cost of a PB construction project mainly includes direct costs, indirect costs, profits, taxes, and so forth. The construction cost is dominated by direct costs, the main ones being listed in Table 3.

As discussed in Sect. 3, using the mathematical model of PPC, we can solve the problem through optimization algorithms and obtain an effective cost control solution. The key issue is how to monitor the changes of uncertain factors and how to dynamically adjust the project process according to the changes.

In the pre-construction phase, the activity processing time is defined as a deterministic variable based on experience. However, in the project implementation process, the actual processing time is affected by various uncertain factors, which prevent the project from being

Table 3
Direct construction costs of PB construction project.

Direct costs	Critical factors
Manufacturing costs	Material cost, production cost, maintenance fees, taxes, and other costs
Shipping costs	Supplier to manufacturer, supplier to construction site, manufacturer to construction site, storage fees
Assembly costs	Labor costs, special tools

completed as planned. Therefore, we can monitor the activity process using IoT technology. When the activity cannot be processed normally and the project plan is interrupted, we can adjust the time of the project process. The processing time is defined as an uncertain value, and the finishing time can be formulated as

$$\xi t_j^F = \xi t_j^S + \xi p_j. \quad (4)$$

The uncertainty of the processing time is the critical factor to ensure the successful completion of the project. IoT technology focuses on monitoring the processing time ξp_j .

In addition, in the project implementation process, activity processing is affected by the constraints on resources. However, the actual resources are dynamically changing and are also critical factors to ensure the successful completion of the project. Equation (3) can be reformulated as

$$\sum_{j=1}^J \tilde{r}_{jk} x_{jkt} \leq b_k, \forall t, k, \quad (5)$$

where resource \tilde{r}_{jk} is an uncertain value of resource type k for activity j . The sensing technology focuses on monitoring the resources, which are dynamically changing.

In the pre-construction phase, we design and arrange the project implementation process. On the basis of the above description of uncertain factors, we convert the traditional model of PPC [Eqs. (1)–(3)] into an uncertainty model. We adopt the expected model as follows:

$$\min E[f_M] = E \left[\max_j \left\{ \xi t_j^F \right\} \right], \text{ where } \xi t_j^F = \xi t_j^S + \xi p_j, \quad (6)$$

$$\text{s.t. } \xi t_j^S - \xi t_{j'}^S \geq \xi p_{j'}, \forall j' \in \text{Suc}(j), \quad (7)$$

$$\sum_{j=1}^J \tilde{r}_{jk} x_{jkt} \leq b_k, \forall t, k, \quad (8)$$

$$x_{jkt} = \{0, 1\}. \quad (9)$$

4.2 Process monitoring in off-site manufacturing phase

In the off-site manufacturing phase, the manufacturing capability determines the efficiency of PPC for a PB construction project. This capability is defined as the variation of the resource constraints in the above PPC model. As shown in Fig. 10, a component C_i starts at a dummy node s and ends at a dummy node t , where directed arcs present the operation precedence. The variables $e_{jj'} = [e_{jj'}^1, e_{jj'}^2, \dots]$ on the arcs represent the idle time and other specialized variables between operations o_{ij} and $o_{ij'}$. The precedence constraints of each operation o_{ij} , and A_{ij} can be defined as an adjacency list $\{o_{ij'}\}$.

Each operation o_{ij} can be defined as a node similar to that in Fig. 11, where $M_{ij} = \{m_k\}$ denotes the machines required. The start time of operation j is t_{ij}^S , the finish time of operation j is t_{ij}^T , and the operation time of operation j is p_{ijk} .

Generally, we can consider the minimization of the makespan g_M of the components as follows:

$$\min g_M = \max_{i,j} \{t_{ij}^T\}. \quad (10)$$

According to the above description, we can define two types of critical factors that affect the manufacturing process: operation time and manufacturing capability. The uncertain operation time is defined as ξp_{ijk} and the manufacturing capability at time period t is defined as $\tilde{m}_{jt} \in \{0,1\}$. The objective of manufacturing can be converted into the following expected equations:

$$\min E[g_M] = E \left[\max_{i,j} \{ \xi t_{ij}^T \} \right], \text{ where } \xi t_{ij}^T = \xi t_{ij}^S + \sum_k \xi p_{ijk} \cdot x_{ijk} + \sum_{\xi t_{ij}^S \leq t \leq \xi t_{ij}^T} \overline{\tilde{m}_{jt}}, \quad (11)$$

$$\text{s.t. } \xi t_{ij}^S - \xi t_{ij'}^S \geq \xi p_{ij'k} \cdot x_{ij'k}, \forall i, k, j' \in \text{Suc}(j), \quad (12)$$

$$\left(\sum_{i,j} \xi t_{ij}^S \cdot x_{ijk} \leq \sum_{i,j'} \xi t_{ij'}^S \cdot x_{ij'k} \right) \wedge \left(\sum_{i,j} \xi t_{ij}^T \cdot x_{ijk} \leq \sum_{i,j'} \xi t_{ij'}^S \cdot x_{ij'k} \right), \forall k. \quad (13)$$

Equation (12) states the precedence constraint of the operations within each job i , i.e., all of the successors $\{j'\}$ need to start after their predecessor j has been finished. Equation (13) states that each operation cannot be interrupted, i.e., any operation j in process on machine k cannot be interrupted by another operation j' .



Fig. 10. Illustration of a component operation sequence.

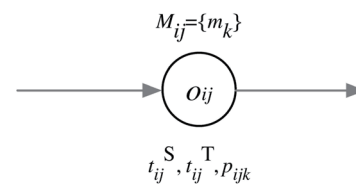


Fig. 11. Definition of operation.

Therefore, the IoT monitoring in the off-site manufacturing phase focuses on increasing the visibility of the manufacturing process and monitoring the manufacturing capabilities. Manufacturing capabilities include the material supply capability, shelf replenishment capability, inventory accuracy, and out-of-stock capability. As shown in Table 4, information sharing is one of the key technologies to protect order and inventory management, helping to make efficient adjustments of the supply capacity and manufacturing capacity. Bowman *et al.* discussed the challenges of having different IoT technologies and measurement standards across a supply chain.⁽¹⁰⁾ Abdel-Basset *et al.* explored the role of IoT and its impact on the supply chain through an extensive literature review.⁽¹¹⁾ Data visualization is an important means of assisting decision-making for project control. Da Silva *et al.* pointed out that the visibility of the real-time operational data plays a very important role in the interaction between suppliers and manufacturers.⁽¹²⁾ Fan *et al.* focused on the impact of radio frequency identification (RFID) technology adoption on supply decisions with shrinkage and misplacement problems in the IoT.⁽¹³⁾ Cui *et al.* proposed an RFID-based investment evaluation model to adopt an effective multistage delivery policy in replenishment cycles that can result in delivery cost savings.⁽¹⁴⁾ Metzger *et al.* developed an inventory control policy based on shelf stock information generated by RFID.⁽¹⁵⁾ Goyal *et al.* explored the use of RFID-enabled visibility to decrease the inventory record inaccuracy and the out-of-stock level for inventories held both in the backroom and on the sales floor.⁽¹⁶⁾ Cui *et al.* explored the effectiveness of RFID in decreasing inventory inaccuracies in a supply chain containing one retailer and two suppliers.⁽¹⁷⁾

4.3 Process monitoring in delivery phase

In PB construction, delivery has changed from centralized delivery at the construction site to a distributed delivery network. A distributed delivery network model describes the discipline of optimizing the delivery of components, services, and information from the supplier/manufacturer to the construction site. The goals of PPC include transportation, supplier/manufacturer location and allocation, and efforts to improve the response to orders. The capability of a distributed delivery network is affected by the uncertainty of the delivery capacity of manufacturers.

Consider the delivery capacity $E = (e_1, \dots, e_j, \dots, e_J)$ and the demand type $M = (m_1, \dots, m_l, \dots, m_L)$ of a construction site. The relationship between the delivery capacity and the demand type can be defined as

Table 4
Impact of IoT monitoring on off-site manufacturing phase.

Critical success factor	Impact of smart sensor	Sensor technology	References
Material supply capability	Information sharing	IoT	10, 11
	Supply visibility	RFID tags	12
Manufacturing capability	Shelf replenishment	RFID tags	13–15
	Inventory accuracy and out-of-stock level	RFID tags	16, 17

$$G \subseteq E \times M = \{(j, l) : j \in E, l \in M\}. \quad (14)$$

The delivery capability constraint of a manufacturer for demand d_k can be defined as

$$\Omega = \left\{ \mathbf{x} \left| \sum_{j:(j,l) \in G} x_{jk} = d_k, \forall j, (j, l) \in G \right. \right\}. \quad (15)$$

Suppose that different distributed delivery network structures can satisfy the constraint in Eq. (15), as shown in Fig. 12. If the delivery capacity of manufacturer 1 changes, manufacturer 1 cannot provide the component to meet demand d_2 . Although the existing solution [in Fig. 12(a)] cannot continue to provide services for construction site 2, another solution [in Fig. 12(b)] can continue to provide services by adjusting the delivery process of manufacturer 2. Therefore, we need to consider the flexibility of the network structure. A measure of the structural flexibility of a distributed delivery network can be defined as

$$Z(d_k) = \max_{\mathbf{x} \in \Omega} \left\{ \sum_{l \in M} U_l \left(\sum_{j \in E} x_{jk} \right) \right\}, \quad (16)$$

where manufacturer j processes x_{jk} components of component type l , and U_l is a structural flexibility function.

As shown in Table 5, barcodes, RFID, and wireless sensor networks (WSNs) are attached to physical items, which transform objects into smart items. This helps monitoring and control throughout the delivery process involving the manufacturer, contractor, and shippers. Decker *et al.* analyzed different types of IoT systems within a typical delivery scenario. They developed a quantification cost model to evaluate the different viewpoints of the supplier, customer, and shipper.⁽¹⁸⁾ Abdel-Basset *et al.* tracked the flow of products at each stage in a delivery network through RFID technology.⁽¹¹⁾ Lang *et al.* presented an “intelligent container”,

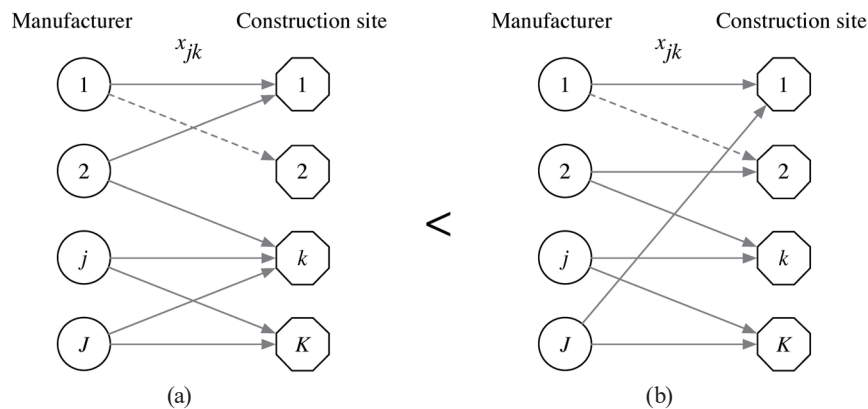


Fig. 12. Different delivery capabilities based on different distributed delivery network structures.

Table 5

Impact of IoT monitoring on delivery phase.

Critical success factor	Smart sensor impact	Sensor technology	References
Delivery capacity	Delivery visibility	WSNs	11, 18
	Intelligent containers	RFID tags, WSNs, barcodes	19, 20
	Autonomous decision-making product conditions	RFID tags, WSNs	21–23
	Accurate and timely delivery	Sensor-enabled RFID	24, 25
	Quality-controlled logistics	RFID tags, WSNs	26

which was a sensor network used for the management of delivery processes.⁽¹⁹⁾ Papert *et al.* proposed an IoT ecosystem to support logistics companies with recommendations for the design of their own IoT ecosystem and the realization of IoT services.⁽²⁰⁾ Ferreira *et al.* reviewed the smart sensor technologies associated with automated support of business processes in delivery, which can exchange data in the business processes and make decisions based on business delivery.⁽²¹⁾ Tu *et al.* proposed an IoT-based production logistics and supply chain system that reduces the complexity of system development and increases system portability.⁽²²⁾ Hsu *et al.* focused on a methodology that applies IoT technology to improve the material procurement process of a manufacturer.⁽²³⁾ Yao introduced the physical internet into the one-stop delivery mode as an important means of delivery and technical support. They analyzed the operating mechanism of the physical internet and discussed the operating conditions of one-stop delivery.⁽²⁴⁾ Zhu proposed an IoT- and big-data-based cooperative delivery scheduling method. After obtaining the big data of delivery resources and requirements from delivery companies through the IoT and/or Internet, they established a map of delivery routes based on the big data of delivery resources.⁽²⁵⁾ Karakostas and Bessis proposed how IoT brokers can be introduced in delivery environments and discussed issues of trust and security that arise when using the IoT in delivery contexts.⁽²⁶⁾

4.4 Process monitoring in on-site assembly phase

The on-site assembly process is mainly limited by the component quality and construction resources. The whole process of tracking the component quality is shown in Fig. 13. Firstly, the on-site assembly phase of PB construction has a greater need for a complete quality evaluation mechanism than traditional construction. The component quality should be tracked throughout the design, manufacturing, shipping, and assembly. Considering the characteristics of PB construction, the on-site assembly process should involve proposing a construction quality evaluation system and rules, along with systematic and comprehensive detection and control. Critical factors of quality control in the on-site assembly phase are shown in Table 6. An example of quality monitoring of PB construction based on the IoT is shown in Table 7.

Zhong *et al.* introduced a multidimensional IoT-enabled building information modeling platform (MITBIMP) to achieve real-time visibility and traceability in PB construction. MITBIMP ensures the quality visibility and traceability of components through their design, manufacturing, shipping, and assembly.⁽²⁷⁾ Louis and Dunston provided a framework for

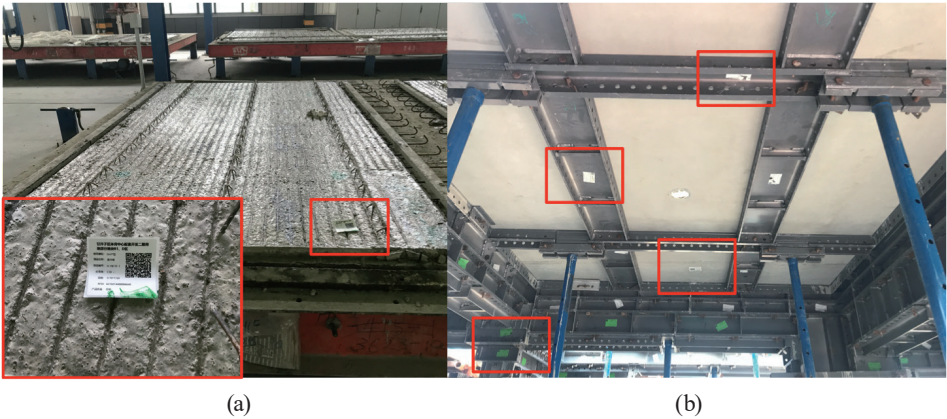


Fig. 13. (Color online) Whole process of tracking component quality. (a) Component identification in manufacturing phase. (b) Component identification in assembly phase.

Table 6
Quality control in on-site assembly phase.

Quality control	Critical factors
Design quality	Unreasonable component design, design changes, description insufficiently detailed
Manufacturing quality	Component accuracy, mold quality, production quality
Shipping quality	Transport damage, insufficient component accessories, inconvenient transportation
Assembly quality	Installation size deviation, pouring quality, product protection, component connection quality

Table 7
Example of quality monitoring of PB construction based on IoT.

Mold size	length, board thickness distortion, warpage, surface unevenness, bending diagonal error, embedded parts, lateral twist	Sensor technology: infrared sensor, camera
Embedded parts and reserved holes	embedded steel plate position of embedded pipe and reserved hole (centerline position, exposed length) embedded rings reserved hole embedded connector	Sensor technology: infrared sensor, camera
Quality tracking	Sensor-enabled RFID, sensor networks	

leveraging the growing ubiquity of devices that can be considered part of the IoT to inform real-time decision-making on a construction site.⁽²⁸⁾ An IoT-enabled platform has been designed for PB construction projects by integrating the IoT and BIM. Smart construction objects and smart gateways are defined and designed to collect real-time data throughout the on-site assembly of PB construction using RFID technology. The captured data are uploaded to the cloud in real time for processing and analysis to ensure quality control.⁽²⁹⁾ Xu *et al.* proposed an integrated cloud-based IoT platform exploiting the concept of a cloud asset. They developed an IoT service-sharing module to support different levels of service sharing on the platform.⁽³⁰⁾ Wang *et al.* proposed a conceptual framework of an intelligent construction system for PBs based on the

IoT (ICSPB-IoT). This framework provides quality control and decision-making support in the design, manufacturing, and on-site assembly stages.⁽³¹⁾

In addition, the on-site assembly process is also delayed by uncertainties due to safety issues. Currently, safety issues mainly focus on on-site construction work space monitoring and safety risk management. Different from traditional construction, the main safety risk factors in the on-site assembly process of PB construction are the component installation risk, environmental risk, hoisting risk, and technology risk, as shown in Table 8.

To prevent the component installation risk, binding columns and wall steel bars should be operated with special high stools. Workers should not walk on top of component walls. Workers also need to wear safety devices in some special construction environments. Haddad *et al.* presented a framework for safety monitoring and management in the context of complex dynamic spatial environments, such as ports.⁽³²⁾ The framework combines IoT and multiagent geo-simulation techniques to build a realistic replication of the complex situation in a real port and to use this replication to assess worker safety from different user-defined safety perspectives. To reduce the environmental risk, PB components are not allowed to be hoisted in rain, snow, fog, or when the wind is stronger than level 6. Thus, weather-monitoring devices are necessary. In addition, to reduce the hoisting risk, when carrying out hoisting operations, workers are not allowed to stand underneath. Construction environment monitoring is also necessary, and when the hoisting object is within 1 m from the ground, the workers' behavior needs to be monitored. Chen *et al.* proposed a proactive worker safety risk evaluation framework, in which position and posture are identified as two key quantitative features. They proposed a principle fusing position and posture for evaluating the safety risks of construction worker behavior.⁽³³⁾ Awolusi *et al.* evaluated the potential applications of wearable sensing devices and the IoT for the continuous collection, analysis, and monitoring of construction worker safety metrics to mitigate safety hazards and health risks on construction sites.⁽³⁴⁾ They reviewed wearable sensors and systems that can be used for physiological monitoring, environmental sensing, proximity detection, and location tracking of a wide range of construction hazards and vital signals to provide early warning signs of safety issues to construction workers. Finally, to reduce the technology risk, PB components are installed individually piece by piece, the length of the wire rope used for hoisting is fixed, and the two ends are strictly prohibited from having different heights. During the PB construction process, it is essential to monitor the status of equipment. Aernouts *et al.* proposed a multimodal localization framework for IoT applications. They applied this framework to monitor the usage and location of large construction tools.⁽³⁵⁾

Table 8
Safety risk monitoring based on IoT in on-site assembly phase.

Safety risk		Critical factors
On-site safety risk	Component installation risk	Use of special tools, wearing safety devices, worker behavior
	Environmental risk	Weather
	Hoisting risk	Worker behavior, construction environment
	Technology risk	Construction status

5. Conclusions

In this paper, we provided an account of developments in the application of IoT technologies to PPC in PB construction. As such, we explored the processes of PB construction and formulated them into a multiple PPC model. We analyzed the key factors that affect PPC with PB characteristics. We introduced related IoT technologies to monitor the changes in these key factors. On the basis of monitoring data, a decision maker can make judgments on process abnormalities, give prompt alarms, and proactively adjust and optimize the construction implementation process to achieve the goal of ensuring project quality and construction safety. In the future, we will design and develop optimization algorithms based on the models described in this paper and consider how to provide effective solutions when these key factors of PM are changing in an uncertain environment.

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