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Review

Precast production scheduling in off-site construction: Mainstream contents and optimization perspective

Liang Wang [a,*], Yueqiao Zhao [a], Xianfei Yin [b]

[a] School of Maritime Economics and Management, Dalian Maritime University, Dalian, 116026, China
[b] Department of Construction Management & Engineering, Faculty of Engineering Technology, University of Twente, 7500, Enschede, Netherlands

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ABSTRACT

Precast production scheduling (PPS) is a key factor that enables efficient off-site construction (OSC) and has received considerable attention from researchers. However, there is still a lack of systematic analysis and summary of existing PPS-related studies in the OSC domain to identify current research gaps and predict future research directions. Thus, 75 relevant academic publications were selected for this systematic review. The current research status of PPS was analyzed from four aspects (flow shop scheduling, production rescheduling, internal resource constraints, and external supply chain constraints) to explore the mainstream contents and optimization perspectives of PPS research. The research findings showed that (1) research on flow shop scheduling of precast components (PCs) was dominant in the PPS domain, and the genetic algorithm (GA) was the most applied optimization algorithm; (2) worker allocation strategy, mold grouping, and layout planning of production space were the main starting points for optimizing PPS from a resource perspective; and (3) establishing a collaborative scheduling mechanism by integrating various departments of the OSC supply chain to achieve the just-in-time (JIT) delivery strategy was the main idea for optimizing PPS from the supply chain perspective. This study revealed potential future research focuses in the field of PPS, including PC flow shop scheduling based on carbon emission targets, distributed permutation flow shop scheduling of PCs, layout optimization for intelligent production shops, and production scheduling mechanisms based on digital technology. This study provides theoretical guidance to promote the future development of PPS research in the field of OSC and can help precast production practitioners manage production scientifically and efficiently.

1. Introduction

The construction industry plays an important role in the development of the national economy; however, it is often accompanied by excessive energy consumption and large carbon dioxide emissions, which is one of the main causes of global warming (Lin and Liu, 2015). To solve this problem, the construction industry industrialized in recent decades, and various innovative construction methods have been tested and implemented (Kamali and Hewage, 2016). Consequently, off-site construction (OSC) has been implemented as an improved construction method for several reasons. First, OSC is an efficient construction method. In an OSC project, the overall structure of a building is divided into multiple precast components (PCs) that are manufactured in a factory environment and transported to the construction site for direct assembly (Hussein et al., 2021). Second, OSC is a more sustainable construction method that helps reduce energy consumption and better protects the environment (Z. D. Li et al., 2014). Moreover, OSC provides other advantages over traditional construction methods, including higher productivity (Jang and Li, 2018), improved quality assurance, and fewer construction safety hazards (Tam et al., 2015).

Although OSC offers these advantages, it also poses some difficulties and challenges to the construction industry. For example, each stage of an OSC, including design, production, transportation, and assembly, is closely connected, which may increase the cascading effect when uncertainty occurs (Hussein et al., 2021). Additionally, compared with the traditional construction supply chain, the OSC supply chain is more fragmented, making supply chain management considerably more difficult (Wang et al., 2019). Therefore, formulating a thorough engineering plan for each OSC phase in OSC is essential.

Precast production plays a major role in OSC supply chains. The real-time production status of PCs directly affects their subsequent transportation and on-site assembly. Problems may arise owing to a lack of

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* Corresponding author.
E-mail addresses: liangwang@dlmu.edu.cn (L. Wang), 1120210515.cn@dlmu.edu.cn (Y. Zhao).

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production plans and schedules, such as early or late delivery, large inventory, extended construction duration, and additional costs (Wang et al., 2018a). Precast production involves several closely linked processes. Based on the characteristics of precast production, the production processes can be divided into interruptible and non-interruptible processes (Chan and Hu, 2002a; Wang et al., 2017; Xiong et al., 2021). Interruptible processes include mold assembly and stripping, reinforcement placement, finishing, and repair; workers can start these processes and finish them the next day. For non-interruptible processes, such as casting and curing, workers are not allowed to stop the process until the jobs are completed. Precast production scheduling (PPS) is the key factor in ensuring the orderly operation of production and has received considerable attention from scholars in the OSC field. As a result, the optimization of the PPS mechanism has become an important research topic.

Review articles on OSC topics indicate that PPS-related research will become a future research trend in the field of OSC. Z. Li et al. (2014) conducted a systematic literature review of the research on prefabricated construction management and concluded that production strategy issues are the main research topics in the field of prefabricated construction management and issues such as production control and PPS are the focus of future research. Subsequently, Wang et al. (2019) conducted a mixed review (including scientometric and systematic reviews) of 103 articles focusing on OSC supply chain management and found that while studies on precast production dominate the field of OSC supply chain management, the integration of PPS and resource allocation is only a recommended future research direction. In addition, Hussein et al. (2021) provided a more comprehensive review of 309 articles from the perspective of modeling OSC supply chain management. This study analyzed the research gaps regarding the various stages (including design, production, logistics, and on-site construction) of OSC and concluded that most PPS models are deterministic and future research on the PPS using stochastic models is necessary.

In summary, previous review studies have only briefly discussed PPS from the perspective of OSC supply chain management, and a systematic summary of the theoretical knowledge of PPS (e.g., the mainstream contents of PPS research and the optimization perspective for PPS) is lacking. Meanwhile, the application of OSC methods in the construction industry is gradually increasing, and China's National New Urbanization Plan 2014–2020 has set a target that 30% of new buildings will adopt the OSC method within the next ten years (The State Council, 2016). Therefore, it is necessary to systematically organize and summarize the existing PPS-related literature to help future researchers gain a clear understanding of its status in the OSC domain.

This study aimed to develop a theoretical knowledge framework for PPS through a systematic literature review and determine the current research gaps and future research directions to provide a scientific and valuable reference for future researcher that can help them understand the knowledge domain of PPS and find valuable research topics in the OSC field. The following research questions were answered in this study.

(1) What are the mainstream contents of PPS research in the OSC industry?
(2) What perspectives can be used to optimize PPS and how can it be realized?
(3) What are the potential research directions for PPS in the OSC domain?

The rest of the paper is organized as follows. Section 2 illustrates the method used to collect relevant research papers and extract data. Section 3 summarizes the mainstream content of PPS research, which includes the research scope and methodology. Section 4 introduces how to optimize the PPS from both the resource and supply chain perspectives. Section 5 presents the research directions for PPS in the OSC domain. Finally, Section 6 offers conclusions.

2. Methodology

A systematic literature review method was adopted to explore the answers to these research questions as it has been shown to be an effective tool for establishing the knowledge boundaries of a discipline and exploring future research directions and has been widely used in the field of construction engineering and management (Wuni et al., 2019). This method comprises two main phases: selection and analysis. Selection is the process of choosing a certain number of publications in the desired field that fit the research topic, while analysis is the process of critically reflecting on and narrating these publications to highlight a theme (Sonego et al., 2018). In this study, a three-stage approach was adopted to select PPS-related literature: a literature search, literature screening, and data extraction.

2.1. *Literature search*

This study used the Scopus and Web of Science databases to conduct a comprehensive search of the relevant literature. Scopus is the largest global literature database, covering more than 21,500 peer-reviewed journals (He et al., 2017), while the Web of Science database contains the world's most influential journals and highly cited literature (Neto et al., 2016). By integrating the search results of these two databases, comprehensive and high-quality academic literature can be collected, as evidenced by the many previous review studies that have collected data from these two databases (e.g., Jang et al., 2021; Wang et al., 2019; Liu et al., 2020).

Based on previous research (e.g., Hong et al., 2016; Wuni et al., 2019; Wang et al., 2019; Hussein et al., 2021; Yang et al., 2021), we determined that the synonymous keywords of OSC include: "prefabricated construction," "precast construction," "modular construction, " and "industrialized construction." High-frequency keywords that appear within PPS-related studies include "precast production", "production scheduling", "production planning", "manufacturing", and "supply chain". Subsequently, the above keywords were combined for the literature search. After several attempts and modifications, the following search criteria were determined: TS= ("off site" OR "offsite" OR "off-site" OR "precast" OR "modular" OR "prefabricated" OR "industrialized") AND ("construction" OR "construction industry" OR "architectural engineering" OR "construction engineering" OR "construction management" OR "construction engineering and management") AND ("prefabrication" OR "production" OR "manufacturing" OR "supply chain" OR "productivity") AND ("scheduling" OR "rescheduling" OR "schedule" OR "planning" OR "plan"). After searching the two databases using these search criteria and excluding duplicates and review papers using EndNote, 318 articles were obtained as a preliminary sample.

2.2. *Literature screening*

After the literature search, the acquired preliminary sample may still contain literature that is not relevant to the research topic; therefore, it was necessary to conduct an in-depth review and screen the initial sample of 318 papers. Fig. 1 shows the specific process of literature screening for this study.

As shown in Fig. 1, we first performed an initial screening through the titles, abstracts, and keywords of the 318 retrieved documents. This step focused on screening the article topics, excluding papers with topics irrelevant to off-site construction and management (e.g., hydraulic, electrical, and petroleum engineering). Through the initial screening, 93 papers that met the exclusion criteria were removed, and 225 papers were retained.

The remaining 225 papers were then further screened through full-text reading using the following literature inclusion criteria.

(1) Empirical studies associated with PPS must be included.

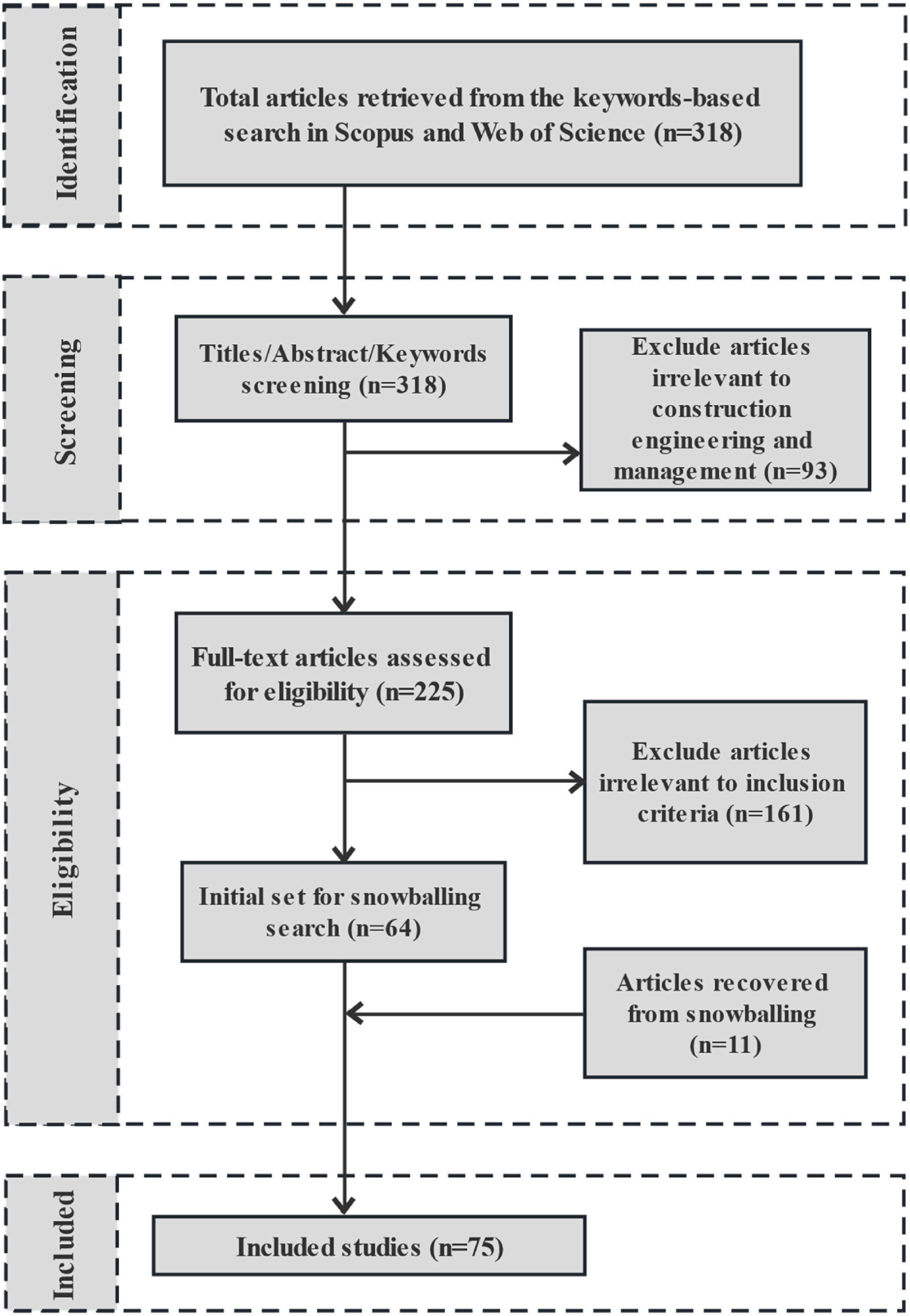

Fig. 1. Flow chart of research literature screening.

(2) Studies on production resource management (e.g., worker allocation, mold grouping, and production layout optimization) must be included because one of the purposes of this study is to explore the optimization perspective of PPS research.
(3) Studies on the research topic of OSC supply chain must be selected. Many of the studies in the OSC domain examined issues from the perspective of the entire OSC supply chain, considering the characteristics of each stage of the OSC to explore the influence mechanism among them, which also provided ideas for this study to explore the optimization perspective of PPS research.

Among the 225 documents, 161 that did not comply with the inclusion criteria were excluded, and 64 were retained. However, searching the literature only through keywords has certain limitations, namely that it may lead to the exclusion of some important papers. Thus, this study also adopted snowballing search strategies to supplement some important papers that were used to collect papers outside the scope of the keyword search that are relevant to the research topic (Greenhalgh and Peacock, 2005; Wuni et al., 2019). Snowball search is a manual search for related papers within the references and citations of an existing literature sample. The most recent collected literature is used as a sample for further snowball searches, and the process is repeated until no new related papers are found (Webster and Watson, 2002). The selected 64 papers served as the initial set for the snowball search, and uncovered an additional 11 papers that met the inclusion criteria. Consequently, a total of 75 papers were used for the next step.

2.3. Data analysis

We conducted a preliminary analysis of the annual publication trends of 75 selected papers to shed light on the current status of PPS research. Fig. 2 provides the details. As shown in the figure, before 2000, the OSC method was in the early stages of development, and issues relevant to the PPS had not received sufficient attention from researchers, as indicated by the small number of publications (two) between 1954 and 1998. During 2000–2017, PPS gradually gained interest among researchers with further promotion of the OSC method. However, the average number of annually published papers was less than two, indicating that the development of PPS research remained flat between 2000 and 2017. After 2018, the development of PPS research gained momentum, and the average number of annually published papers reached ten between 2018 and 2022, which indicates an increasing trend in PPS research.

After analyzing the annual publication trends, the 75 selected papers were further categorized. Based on similarities in the research topics of the selected papers, four major categories were identified: PC flow shop scheduling, PC production rescheduling, internal resource constraints, and external supply chain constraints. Fig. 3 presents the classification logic of the literature selected for this review. As shown in the figure, the mainstream contents of precast production scheduling (PPS) are divided into two clusters as follows: (1) PC flow shop scheduling, which focuses on the static production scheduling mechanism combining the traditional flow shop scheduling model with realistic production scenarios of PCs and (2) PC production rescheduling, which focuses on the dynamic production scheduling mechanism of PCs under the disruptions of different production emergencies, such as rush orders, demand variability, and machine breakdown. Among the 75 selected papers, the numbers of PC flow shop scheduling and PC production rescheduling as research topics were 28 and 8, respectively, occupying the top two positions in the total number of selected studies. In the last five years (2017–2022), the numbers of studies on the two topics were 17 and 5, respectively, indicating that they are still hot research topics in the PPS field. Therefore, it is reasonable to select representative literature on these two research topics to systematically summarize the mainstream content of PPS research.

Furthermore, when researchers conducted studies on PPS optimization, they considered the two main dimensions to be production resources and supply chain-related constraints. Among the selected articles, 48 papers combined internal resource constraints (e.g., worker, mold, and workspace constraints) for production scheduling optimization. In addition, 31 studies considered the impact of OSC supply chain-related factors (e.g., transportation strategy, on-site assembly speed, and supply chain information management) on precast production to improve the production scheduling mechanism. Therefore, this review also adopts the two starting points of PPS optimization research—resource and supply chain—as the classification criteria and

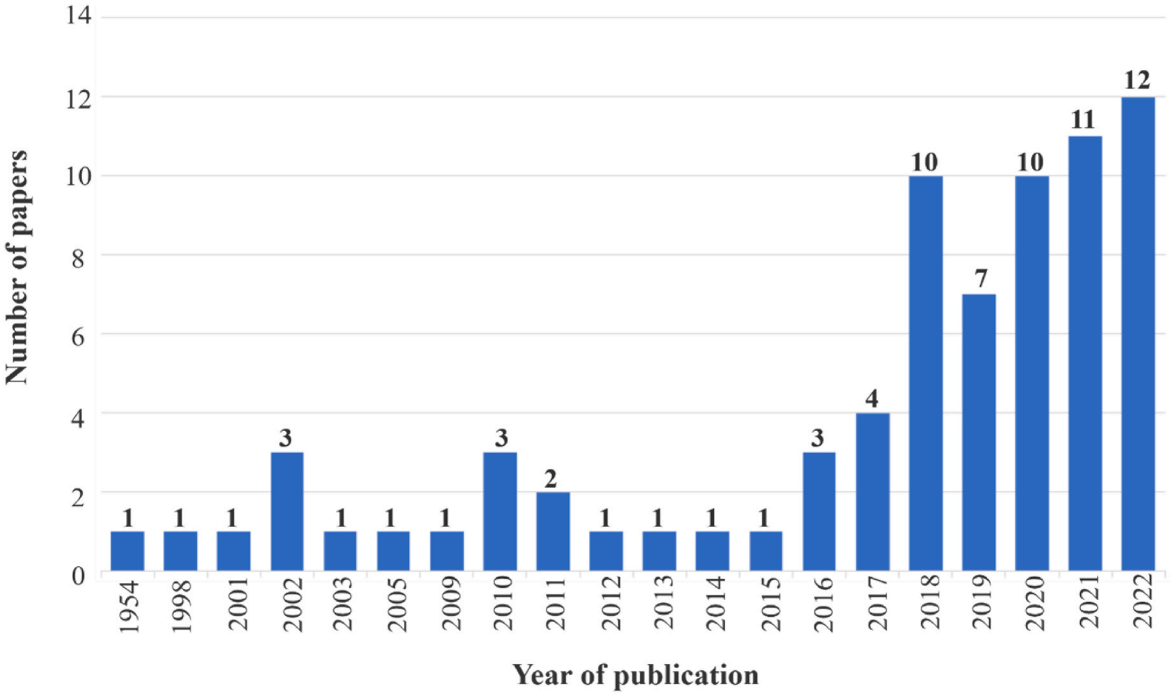

Fig. 2. Annual research publications on PPS.

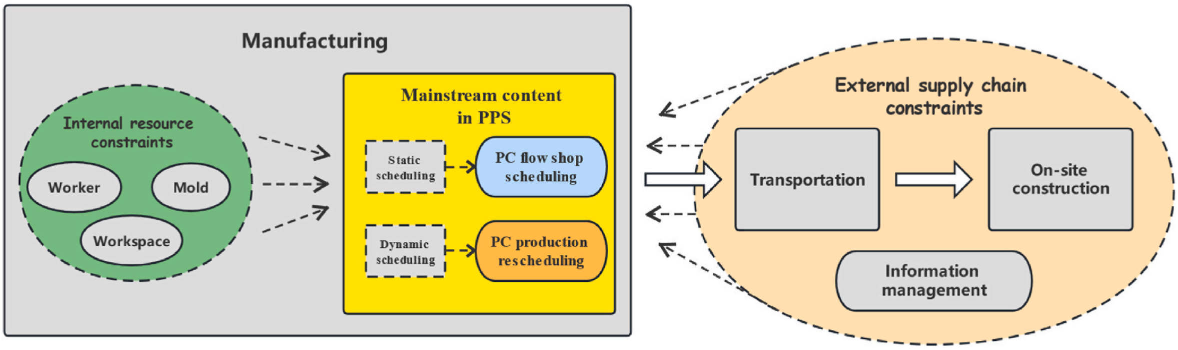

Fig. 3. Classification logic of the selected literature in this review.

discusses how to optimize PPS from the resource and supply chain perspectives.

3. Mainstream contents of PPS research

The mainstream contents of PPS were PC flow shop scheduling and PC production rescheduling. Regarding PC flow shop scheduling, researchers tend to modify the conventional flow shop scheduling model by considering the production characteristics of PCs, and studies have primarily focused on the static production scheduling mechanism (Wang and Hu, 2018; Wang et al., 2021). However, production plant schedules must be coordinated with the on-site assembly schedules. The occurrence of production emergencies, such as rush orders, demand variability, and machine breakdowns, will result in the rescheduling of existing production schedules (Ma et al., 2018). Consequently, dynamic rescheduling mechanism is essential for dealing with disturbances in a scientific and efficient manner, and studies related to PPS have also been conducted on PC production rescheduling. Therefore, this section will systematically summarize the mainstream content in PPS around two research topics: PC flow shop scheduling and PC production rescheduling and discuss the specific content of each research topic from two aspects: the research scope and methodology.

3.1. PC flow shop scheduling

Stationary and traveling production systems are the two basic production systems adopted by prefabrication plants to produce PCs (Chan and Hu, 2001). In a stationary production system, production is usually performed using horizontal or battery molds, and all production activities are performed at one location. In contrast, in the traveling production system (Warszawski,1990; Chan and Hu, 2002a), the entire production system comprises many workstations (see Fig. 4), each of which is responsible for different production activities such as mold cleaning, reinforcement placement, and casting. Generally, after completing the casting process, the mold is sent to the curing chamber for curing, and the PCs are demolded when the curing standard is reached. Finally, after checking and repairing the data, PC production is completed. Production activities are carried out sequentially, and the molds are passed between workstations via conveyors or transport devices, such that the entire production system is in a dynamic mode. The traveling production system is more flexible and productive than the stationary production system; therefore, in practice, more prefabricated factories prefer to adopt the traveling production system (Yang et al., 2016).

In general, the flow shop scheduling problem considers m machines and n jobs; each job is composed of m operations and each operation requires a different machine (Leu and Hwang, 2002). Based on the characteristics of the traveling production system, the PPS problem is

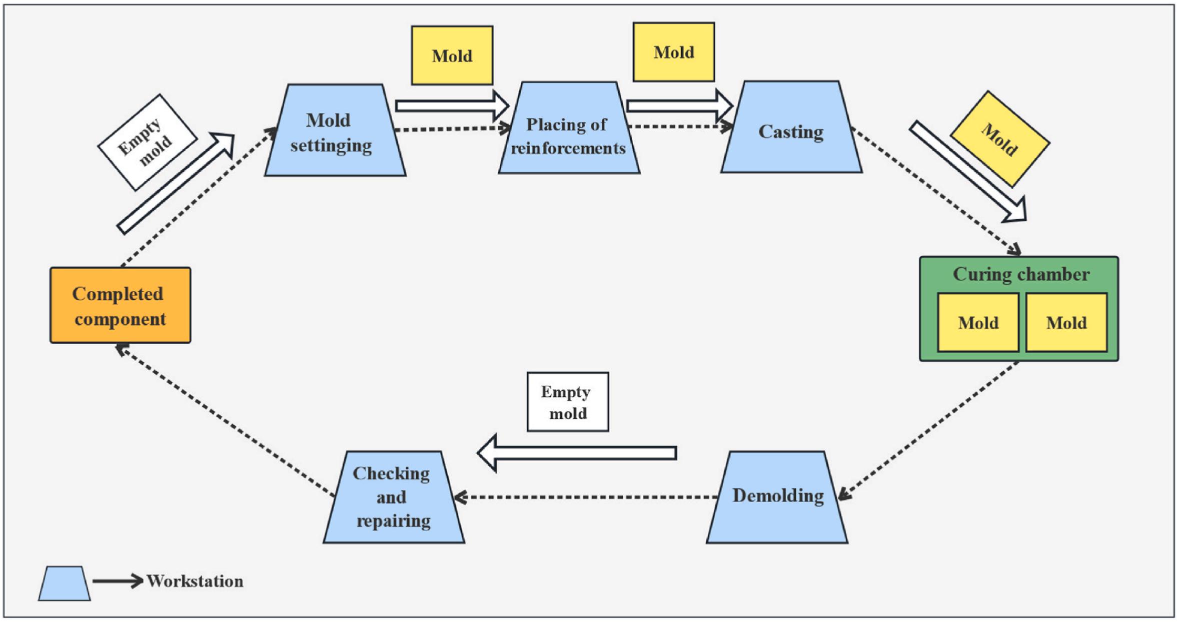

Fig. 4. Traveling production system of PCs [adapted from Warszawski (1990); Chan and Hu (2002a)].

considered to be similar to the traditional flow shop scheduling problem. The appropriateness of the flow shop scheduling model for solving the PPS problem was analyzed in a previous study. Chan and Hu (1998) compared the applicability of several scheduling models to the prefabricated production problem, and their findings showed that the flow shop scheduling model was more suitable for optimizing the PC prefabrication process. Consequently, extensive research has been conducted on PC flow shop scheduling.

3.1.1. Research scope

There are two significant milestones in the research on PC flowshop scheduling. One of the milestones was in 1954 when Johnson conducted a pioneering study on the two-machine flow shop scheduling, the first production scheduling study to minimize the production completion time by optimizing the sequence of production activities. Since then, researchers have paid more attention to the PPS optimization problem and have made efforts to pursue a more applicable production scheduling mechanism for PCs. Another milestone was at the beginning of the 21st century when Chan and Hu (2001, 2002a) presented a flow shop sequencing model for the production problem of PCs to simultaneously minimize the production makespan and delivery penalties. This model is more suitable for precast production systems than other production scheduling models, and some realistic scenarios in the production process of PCs are considered in the model, including interruptible and non-interruptible processes and normal and non-normal working times. Subsequently, researchers have begun to enrich and improve the PC flow shop scheduling model from different perspectives and production contexts.

With in-depth research, scholars have gradually considered the influence of resource factors on PPS in different production scenarios and combined them with production resource constraints to improve scheduling models. For example, when multiple types of precast components (PCs) are produced for multiple construction projects, the utilization of production resources increases. Meanwhile the production scheduling schemes are usually disrupted due to resource limitations. To address this issue, Leu and Hwang (2002) developed a flow shop scheduling model under the resource constraints of workers and production machinery to minimize the completion time for mixed production.

Based on the influence of the mold usage plan on precast production, Benjaoran and Dawood (2005) proposed a multi-objective flow shop scheduling model for bespoke precast concrete products that considered mold quantity constraints, total machine idle time minimization, and tardiness penalty minimization. The model could help decision-makers rationally analyze real-time production conditions, including making a more accurate assessment of mold quantities and processing time.

In practical production, PCs must be produced in a limited space. However, the buffer size between production workstations has been ignored in previous studies, resulting in a lack of practicality in production scheduling. Ko and Wang (2010, 2011) analyzed the effect of buffer size on production time and modified the traditional flow shop scheduling model by integrating buffer size constraints. Consequently, a more rational production sequence can be achieved, which saves production time and expenses. In addition, the blocking of jobs generally occurs in real-world production owing to the product attributes of PCs. For instance, in the process of concrete casting, the concrete cannot be removed from a workstation in time to avoid cracks (Riahi et al., 2018). This situation often blocks jobs and affects production flexibility and efficiency. To solve this problem, Qin et al. (2022a) proposed a novel mathematical model for the blocking hybrid flow shop group scheduling problem, which can help improve the efficiency of PC production under blocking constraints.

Human factors are also key elements affecting PPS. Factors such as worker experience, learning rates, and skill proficiency determine the duration of each production process. Therefore, to further improve the realistic applicability of the scheduling model, Wang et al. (2018b) developed a two-hierarchy scheduling optimization model that considers worker competence to optimize the PPS and simultaneously promote the development of worker resources. Cao et al. (2022) integrated worker fatigue recovery into a production scheduling optimization model to determine the optimal allocation strategy for logistics workers.

In addition to resource factors, researchers have improved the PC flow shop scheduling model from different perspectives. For instance, Yang et al. (2016) proposed a scheduling optimization model that focused on the precast production of multiple production lines. Several practical optimization objectives and constraints were integrated into the scheduling model, such as the objective of minimizing the variation in the type of PCs during the production process and constraining the number of production pallets. Wang and Hu (2017) analyzed the impact of mold manufacturing, PC storage, and transportation on PPS and improved the flow shop scheduling model from a supply chain perspective. Three transportation scenarios—daytime, nighttime, and all-day delivery—were considered to enhance the comprehensiveness of the scheduling model. Xie et al. (2022) constructed a production scheduling model based on the just-in-time (JIT)) strategy, which considers the coordination of precast production and on-site assembly. Wang et al. (2018c) adopted radio frequency identification (RFID) technology to collect real-time production information and integrate the information flow of the OSC supply chain through a multi-agent system to synchronously optimize PPS and resource allocation.

Furthermore, as OSC methods mature, the modularity of building components gradually increases and the precast production of PCs becomes more complex. Optimization studies of PPS have also focused on several production details. For example, Wang et al. (2018a) considered the uncertainty of processing time in realistic production and process waiting time under resource constraints in an optimization model and achieved trade-offs between the conflicting objectives of on-time delivery of PCs and minimization of production costs in their study. Dan et al. (2021) optimized a flow shop scheduling model considering practical constraints, such as process connection and blocking in the production process of PCs, to minimize tardiness and earliness penalty, which could help reduce the probability that the PPS scheme will not be executed efficiently due to the issues of process connection and blocking. For the two types of components produced—make-to-order (MTO) and make-to-stock (MTS)— Jiang and Wu (2021) developed a PC flow shop scheduling model under a hybrid MTO-MTS production environment by considering their production characteristics.

In summary, on the one hand, due to the large impact of changes in production resources on PPS as well as productivity, most studies of PC flow shop scheduling combined production resource constraints to optimize PPS, including the number of molds (Benjaoran and Dawood, 2005), worker competence (Wang et al., 2018b), and production workspace (Ko and Wang, 2010). However, research on PC flow shop scheduling increased with the development of the OSC method, and researchers modified the objectives and constraints of the scheduling model by considering more realistic production factors such as multiple production lines (Yang et al., 2016), the influence of the supply chain (Wang and Hu, 2017), uncertainties with regard to processing times (Wang et al., 2018a), etc., thus continuously improving the performance and practicability of the scheduling model.

Although previous studies have refined production scheduling models by incorporating realistic production factors, they have mainly considered the economic benefit indicators associated with the duration and cost of the precast production phase. However, very few studies have integrated environmental benefit indicators, such as carbon emissions, into the production scheduling mechanisms of PCs. With in-depth research related to carbon emissions in the manufacturing industry, limited studies have incorporated carbon emission targets as optimization objectives in the flow shop scheduling mechanism (Saber and Ranjbar, 2022; Schulz et al., 2022). These studies can be used as basic research to help future scholars combine the carbon emission characteristics of the PC production process to further develop a PC flow shop scheduling mechanism based on carbon emissions.

As technology advances, innovative devices (e.g., automated guided vehicles) have been gradually applied to PC production; therefore, it is necessary to further explore PC flow shop scheduling applicable to intelligent precast production systems in the future. Many manufacturers have gradually transformed single-plant production into multiple-plant production to improve production efficiency and reduce production costs (Naderi and Ruiz, 2010; Xiong et al., 2021). However, most existing PPS studies are based on the single-plant production model, and studies on distributed permutation flow shop scheduling of PCs considering the multiple-plant production model are scarce. Thus, this topic deserves more attention from future scholars.

3.1.2. Research methodology

The flow shop scheduling problem is considered a non-deterministic polynomial (NP), hard problem due to its high complexity, which makes it difficult for decision-makers to find the optimal solution quickly and efficiently (Chan and Hu, 2001; Wang et al., 2018b; Yazdani et al., 2021). For decision-makers, a theoretically optimal production scheduling scheme can be achieved through operations research-related methods. However, from an execution perspective, it is difficult to solve a mathematical model with complex variables and constraints to arrive at a satisfactory solution in a limited time through only operational research (Liu et al., 2021). Heuristic algorithms have been widely adopted to address PPS optimization problems over the past few decades. These are based on a specific analysis of the problem and computational experience and can be used as effective methods to provide near-optimal solutions in a limited time in situations where the optimal solution to the problem is impossible or difficult to acquire (e.g., NP problems). Currently, many heuristic algorithms, such as the ant colony (ACO), simulated annealing (SA), and genetic (GA) algorithms, are inspired by certain natural phenomena.

The GA was found to offer better optimization effects in ensuring on-time delivery as well as in optimizing resource allocation problems; therefore, it has been extensively applied in PPS optimization research in the context of OSC (Li and Love, 1998). Chan and Hu (2001) compared the optimization performance of GA, rapid access (RA), and Gupta, Palmer, Campbell-Dudek-Smith (CDS) algorithms on the flow shop scheduling problem, and the results showed that the optimization performance of the GA was more reliable and stable for generating a set of near-optimal solutions. The GA is also an efficient way to solve scheduling problems in situations with more realistic constraints and complex production environments. For example, Leu and Hwang (2002) demonstrated the flexibility and efficiency of the GA in addressing the PC flow shop scheduling problem by considering resource constraints and mixed production strategies. Ko and Wang (2010) developed a GA-based decision support system to obtain an appropriate PPS scheme. As shown in these examples, GA has demonstrated excellent performance in finding the optimal solution to a problem; thus, such a system

Table 1
Summary of representative research literature on PC flow shop scheduling.

Literature	Research topic	Methodology	Optimization objectives	Main variables considered in scheduling
Johnson (1954)	Two machine flow shop scheduling problem	Simple and correct algorithm	Minimization of production completion time	Operation sequence
Chan and Hu (2001)	Flow shop sequencing model to ensure on-time delivery	GA	Minimization of the tardiness and earliness penalty	Working time and operation types
Leu and Hwang (2002)	Flow shop scheduling model considering resources constraints and mixed production	GA	Minimization of the precast production makespan	Constraints of resources (cranes and labor)
Benjaoran and Dawood (2005)	Flow shop scheduling model for bespoke precast production	GA	Minimization of machine idle time and tardiness and earliness penalties	Constraints of resources (molds)
Ko and Wang (2010)	Decision support system for arranging precast production plans	GA	Minimization of the makespan and tardiness penalties	Buffer size between production stations
Yang et al. (2016)	Flow shop scheduling model of multiple precast production lines	GA	Minimization of the delivery penalty, type change of precast components during production	Multiple production lines
Wang and Hu (2017)	Flow shop scheduling model considering the whole supply chain	GA	Minimization of the tardiness and earliness penalty	Mold manufacturing, PC storing, and transportation processes
Wang et al. (2018b)	Precast production scheduling optimization model considering worker competence	GA	Minimization of production time, maximization of worker competence	Worker competence
Wang et al. (2018c)	Synchronizing precast production scheduling with resource allocation in a multi-agent system environment	GA and multi-agent system	Minimization of the delivery penalty and order waiting and extension time	Constraints of and bidding on resources
Dan et al. (2021)	Flow shop scheduling model considering process connection and blocking	GA	Minimization of the total penalty cost of earliness and tardiness	Process connection and blocking
Liu et al. (2021)	Optimization of flow shop scheduling in precast concrete component production via mixed-integer linear programming	Mixed-integer linear programming model	Minimization of the storage and delay time	Worker overtime hours
Jiang and Wu (2021)	Flow shop scheduling model considering hybrid make-to-order and make-to-stock production	Iterative job insertion algorithm	Minimization of total tardiness and earliness of delivery	Make-to-order and make-to-stock production of PCs
Xiong et al. (2021)	Distributed flow shop scheduling model for precast components	Hybrid tabu search and iterated greedy algorithm	Minimization of the tardiness and earliness penalty	Multiple PC production plants
Du et al. (2022)	Flow shop scheduling model considering the lean construction principle	Biogeography-based optimization algorithm	Minimization of resource idle time and PC storage time	Limitation of mold and buffer size
Xie et al. (2022)	Flow shop scheduling model considering the just-in-time strategy	GA	Minimization of the tardiness and earliness penalty	On-site assembly scheme
Ruan and Xu (2022)	Eight-process flow shop scheduling model considering enterprise decision-making coefficient	GA	Minimization of the error between model output and actual production time	Resource constraints (molds, steel, concrete)
Cao et al. (2022)	Optimization of flow shop scheduling of PCs considering worker fatigue recovery	GA	Minimization of logistic workers in the production line	Worker fatigue levels
Kim et al. (2022)	PC flow shop scheduling with the reinforcement learning approach	Reinforcement learning algorithm	Minimization of the tardiness penalty	Dynamic shop situation

could assist decision-makers in devising better production plans.

For different production scenarios, the GA can be modified or combined with other methods to improve optimization performance. For instance, multi-objective GA have also been used to solve the PC flow shop scheduling problem when multiple objectives need to be optimized (Ko and Wang, 2011; Anvari et al., 2016; Wang and Hu, 2017). Some research has also integrated GA with the branch-and-bound method (Li et al., 2010), multi-agent systems (Wang et al., 2018c; Du et al., 2021), and other methods as optimization methods for PPS problems. In addition, mixed-integer linear programming has the characteristics of high accuracy and long computation time compared to GA. The PPS optimization problem is not a large sample problem. In some cases, the difference in computation time between mixed-integer linear programming and GA is not significant, and studies have been conducted to optimize the PPS by establishing a mixed-integer linear programming model (Khalili and Chua, 2014; Liu et al., 2021). Table 1 summarizes the representative research literature on PC flow shop scheduling, including several aspects: research topic, research methodology, optimization objectives, and the main variables considered in the study.

As shown in Table 1, in terms of the research topic, as the research progressed, researchers successively considered several variables and constraints in realistic production situations and incorporated them to optimize the PPS mechanism. First, PC flow shop scheduling under resource constraints was the most popular research topic among researchers, and the variables that have been considered in scheduling models include the number of molds (Benjaoran and Dawood, 2005; Li et al., 2010), worker competence (Wang et al., 2018b), working hours (Chan and Hu, 2001; Liu et al., 2021), and size of production space (Ko and Wang, 2010; Li et al., 2010; Cao et al., 2022). Second, researchers considered the PPS optimization problem from the perspective of the OSC supply chain and integrated variables that could affect production scheduling at each stage of the supply chain into the scheduling model, such as transportation time (Wang and Hu, 2017), order change (Jiang and Wu, 2021), etc.

In terms of optimization objectives, the most frequent objective was the "minimization of early or late delivery penalties." Early delivery can result in problems, such as inventory accumulation and component damage, and late delivery directly affects the next phase of work; therefore, the goal of on-time delivery could better reflect the significance of PPS optimization research. In addition, some researchers set up multiple optimization objectives simultaneously in the scheduling model to make the study more realistic and provide more theoretical help to the real precast production process of PCs; for example, on-time delivery was set as an optimization objective along with other objectives such as minimization of machine idle time (Benjaoran and Dawood, 2005), maximizing worker competence (Wang et al., 2018b), etc. However, few researchers have considered the environmental impact of the PC production process and incorporated carbon emission targets as optimization objectives in the production scheduling mechanism of PCs, which deserves further study.

In terms of research methods, most studies were based on a single metaheuristic algorithm for model solving, and the search capability of a single algorithm is limited, which can result in poor-quality optimization solutions. Thus, future scholars could attempt to utilize hybrid metaheuristic algorithms to enhance the overall search mechanism of the algorithm. Among these studies on PPS optimization, the GA is the most frequently applied optimization method. Therefore, future research directions could concentrate on other optimization algorithms, such as local search algorithms, exact methods, and swarm intelligence metaheuristics (Hussein et al., 2021). In addition, reinforcement learning has been shown to be a suitable approach for optimizing production scheduling problems (Du et al., 2022a; Kim et al., 2022), and future scholars could use reinforcement learning as an optimization method for PPS research to further improve optimization efficiency. The iterated greedy (IG) algorithm has a simple structure with few parameters and can integrate construction and metaheuristics into its framework, which has been proven to be an effective method for solving flow shop scheduling problems (Qin et al., 2022a, 2022b). In future research, the IG algorithm could be further improved to optimize PC flow shop scheduling under more complex constraints.

Based on an analysis of existing studies on PC flow shop scheduling, the main research findings can be summarized as follows.

1. Most previous studies modified the traditional flow shop scheduling model by considering the impact of factors relevant to the resource and supply chains, including resource allocation and transportation time. However, multiple real-world production scenarios were not considered (e.g., multiple-plant production scenarios, PC production systems based on intelligent devices).
2. Previous studies have mainly focused on optimizing the economic benefit indicators associated with the duration and cost of precast production. However, the influence of precast production on the environment has rarely been analyzed, and very few studies have integrated environmental benefit indicators such as carbon emissions into the PPS mechanism.
3. The GA is the dominant optimization method adopted in the existing research. Other algorithms or hybrid metaheuristic algorithms were rarely adopted for improving the optimization performance (e.g., reinforcement learning algorithms, swarm intelligence metaheuristics).

3.2. PC production rescheduling

The previous section explored the development process of PC flow shop scheduling research and concluded that these studies were conducted around the static scheduling mechanism, and the impact of unexpected emergencies on the production schedule was not considered. However, in the real production of PCs, the scheduling scheme of the production plant is adjusted according to the real-time situation at the assembly site, and precast production is easily affected by sudden events, such as the demand variability of PCs, machine breakdown, urgent orders, and quality problems (Vieira et al., 2003; Ma et al., 2018; Wang et al., 2021). If these interruptions are not properly considered when formulating a scheduling plan, the initial production scheduling scheme will be ineffective in the presence of emergencies, leading to problems such as resource waste, customer dissatisfaction, and loss of market share (Wang and Hu, 2018). Therefore, a dynamic rescheduling mechanism is essential for a more effective response to production emergencies and the minimization of losses. To date, there have been some studies on PC production rescheduling. In the following section, we explore the research and development process.

3.2.1. Research scope

Rescheduling is common in project management, particularly in the manufacturing domain, where the role of rescheduling is to efficiently respond to unexpected situations and rearrange production resources and jobs in a timely manner to minimize losses from changes. In real-life management practices, two issues must be addressed before rescheduling: how and when to respond to unexpected changes: the first is to clarify the concept of the rescheduling policy and the second is to address when to conduct rescheduling (Ouelhadj and Petrovic, 2009).

To address these two issues, Vieira et al. (2003) defined rescheduling as a modification of an existing scheduling scheme to reduce the impact of emergencies on the production system. Aytug et al. (2005) identified rescheduling factors in a production system by analyzing four aspects of risk: cause, context, impact, and inclusion. As for when to perform rescheduling, there are three common rescheduling policies: periodic, event-driven, and hybrid (Vieira et al., 2003). Under this periodic policy, the production scheduling scheme is adjusted and renewed in phases. Under an event-driven policy, rescheduling is conducted when emergencies occur such as urgent orders or machine breakdowns. With a hybrid policy, rescheduling is performed periodically and driven by special events.

PC production rescheduling differs from traditional production scheduling owing to the combination of push and pull production, the high level of coordination between supply and demand, and more complex operations and has unique issues (Wang et al., 2021). Chan and Wee (2003) repaired the PPS scheme under demand variability from the perspective of a heuristic strategy; however, they did not consider the prioritization of PCs or the selection criteria of production lines. Ko (2011) adjusted production scheduling to respond to demand changes based on customer performance; however, the optimization mechanism was not taken into account. Moreover, these studies were limited to the rescheduling of a single production line, whereas in reality, multiple-line production is often used to increase productivity. Accordingly, Ma et al. (2018) developed a PC flow shop rescheduling model for the multiple-line production of PCs, which was proven through cases to help managers deal with production emergencies more efficiently.

More consideration of the real-world production environment is key to enhancing the practicality of scheduling models. Wang and Hu (2018) established a two-hierarchy rescheduling model that considers the selection of product lines and the priority of PCs to reduce production costs. Multiple real-world production scenarios, including multiple production lines, shared mold types, and mold changeover costs, were integrated into the model. Wang et al. (2021) presented a rescheduling optimization model to cope with interruptions in machine breakdowns. In their research, many details of real-world production environments were considered, including the process waiting time, idle time of multiple production lines, and lead time, which increased the feasibility of the rescheduling model in various production scenarios and reduced the gap between theory and reality.

3.2.2. Research methodology

The rescheduling problem is a scheduling problem with more constraints, and it is difficult to find an optimal solution in a short time. Optimization, metaheuristic algorithms, combinations of optimization and simulation, and other artificial intelligence (AI) methods have been the main research approaches used in previous rescheduling studies. Li et al. (2000) proposed an expert simulation system for production rescheduling to solve various production disruption problems by integrating simulation techniques, neural networks, and other methods. Chan and Wee (2003) and Ko (2011) compared the effectiveness of several heuristic strategies in response to demand variability. However, their studies lacked sound optimization mechanisms. Ma et al. (2018) and Wang and Hu (2018) developed a rescheduling optimization model applicable to multiple production lines and adopted the GA as the solution method for the model. However, optimizing the scheduling mechanism using only a mathematical model based on simple assumptions cannot ensure the feasibility of this study. Wang et al. (2021) considered realistic production scenarios and developed a more practical dynamic rescheduling system by combining optimization and simulation methods. Table 2 summarizes the representative research literature on PC production rescheduling.

As shown in Table 2, in terms of the number of studies, there are fewer studies on PC production rescheduling than on PC flow shop scheduling, but the number of studies increased during 2018–2021. In terms of research topics, most studies explored the rescheduling mechanism under demand variability (Chan and Wee, 2003; Ko, 2011; Wang and Hu, 2018), real-world production environments to optimize PC production rescheduling, and several other variables, including multiple production lines (Ma et al., 2018), processing wait time (Wang et al., 2021), and due date (Kim et al., 2020) were integrated into their models.

In terms of research methodology, GA and other heuristic algorithms are still the dominant methods for rescheduling optimization research. Few studies have conducted rescheduling optimization using hybrid metaheuristic algorithms, which deserves the attention of future researchers. Furthermore, in different cases, a flexible combination of optimization and other methods can achieve better solutions, such as optimization, simulation, and multi-intelligent systems. In the future, scholars could attempt more combinations of methods to study PC production rescheduling.

Table 2
Summary of the representative research literature on PC production rescheduling.

Literature	Research topic	Methodology	Real-world production environment	Variables considered in scheduling
Chan and Wee (2003)	Schedule repairing plan subject to demand variability	Heuristic strategies	No	PC type, storage level
Ko (2011)	Demand variability analysis based on customer behaviors	Schedule adjustment principles	No	Lead time
Ma et al. (2018)	Rescheduling model of multiple production lines for flow shop precast production	GA	No	Multiple production lines
Wang and Hu (2018)	Dynamic rescheduling model for precast production to respond to the frequent demand variability of PCs	GA	Yes	Multiple production lines, shared mold types, and mold changeover fees
Kim et al. (2020)	Dynamic production rescheduling model under due date uncertainty	Discrete time simulation	Yes	Due date
Wang et al. (2021)	Hybrid rescheduling optimization model under disruptions of machine breakdown	GA simulation hybrid method	Yes	Multiple production lines, process waiting time, idle time, lead time, and mold utilization

The main findings are summarized below based on the literature review on PC production rescheduling.

(1) Disturbances that cause PC production rescheduling originate in the entire OSC supply chain. While existing studies have mainly considered disturbances within production, few have combined disturbances from other stages of OSC to optimize production rescheduling mechanisms (e.g., traffic congestion and severe weather on construction sites).
(2) Most studies on PC production rescheduling are based on event-driven policies, including PC demand and variability and machine breakdown. However, a PC production rescheduling mechanism under other rescheduling policies, such as periodic or mixed rescheduling policies, has not yet been developed.
(3) Multiple disturbances can occur simultaneously in precast production systems. However, existing studies have primarily focused on production rescheduling that considers a single disturbance. The PC production rescheduling mechanisms under multiple disturbances have rarely been investigated.

4. Optimization perspective for PPS

Section 3 explores the mainstream content of PPS research, from which it can be concluded that researchers have optimized the PPS mechanism by considering more realistic factors in the production environment. From an optimization perspective, PPS optimization studies that combine production resource constraints have received the most attention from researchers, while other studies have been conducted to improve the optimization mechanism from the OSC supply chain perspective by considering the impact of each stage in the supply chain on precast production. Thus, this section explores two optimization perspectives for PPS: internal resources and external supply chain constraints.

4.1. Internal resource constraints

In the prefabrication process, the cost of production resources accounts for more than 50% of the total cost (Li et al., 2010; Yazdani et al., 2021), and production resource management directly affects the productivity of PCs and execution of the PPS scheme (Wang et al., 2020a). Consequently, many researchers have incorporated production resource management strategies in PPS optimization studies, including worker allocation strategies (Al-Bazi and Dawood,2010; Wang et al., 2018b; Hyun et al., 2021), usage plans for production molds (Benjaoran and Dawood, 2005; Li et al., 2010; Khalili and Chua, 2014), and workspace layout plans (Ko and Wang, 2010; Li et al., 2010). In the next sections, we discuss how to optimize the PPS from the resource perspective in terms of workers, molds, and workspaces.

4.1.1. Workers

After reviewing previous academic publications, we can conclude that PPS optimization research incorporating worker factors has mainly focused on two starting points: worker allocation strategy and worker competence.

One of the starting points is worker allocation strategy. PCs are produced through several production processes and multiple workstations that require a high degree of coordination between workstations. If workers within the workstation cannot match the corresponding workload, it will lead to bottlenecks in the entire production flow, which, in turn, affects productivity (Ahmadian Fard Fini et al., 2017; Nasirian et al., 2019a). Therefore, there are related studies linking worker allocation strategies to PPS optimization from the perspective of production workers.

Chan and Hu (2001) considered workers' normal working hours and overtime and combined the characteristics of interruptible and non-interruptible processes to formulate a PPS plan with a reasonable worker allocation strategy. In response to the shortage of skilled labor in real production processes, Leu and Hwang (2002) developed a scheduling optimization model considering the allocation of limited workers. Al-Bazi and Dawood (2010) proposed a crew allocation system for the manufacturing industry of prefabricated buildings that could reduce resource costs and idle time. Hyun et al. (2021) developed a multi-objective optimization model for modular building production that focused on worker allocation and production performance to minimize the production completion time and worker costs.

Another worker-related starting point is competence. In the construction industry, workers' skill proficiency significantly affects project productivity (Tai et al., 2021). At the same time, the experience, competence, and learning rate of each worker differs significantly. Cross-training of production workers can ensure worker productivity and reduce heterogeneity among workers (Arashpour et al., 2018; Nasirian et al., 2019b). Cross-training refers to the training of workers with multiple skills and abilities to enable them to be assigned when and where they are needed (Hopp and Oyen, 2004).

For instance, Tai et al. (2021) collected the training time datasets of 4352 workers for 14 prefabricated production activities over a five-year period (2016–2021) and used the learning curve model to explore workers' learning rates and the threshold for proficiency for each production activity. The findings show that for different production activities, 3.8–26.15 days were required for workers to reach the proficient levels. Nasirian et al. (2019b) compared the operational performance of worker management strategies such as no cross-training, employing single-skilled workers, and employing multi-skilled workers in the presence of production bottlenecks, thus providing insights for managers in the prefabricated construction production industry in terms of workforce planning and management. In addition, Wang et al. (2018b) analyzed the influence of worker competence on the time of each production process and systematically integrated worker-relevant factors in the PPS optimization model to achieve simultaneous optimization of production scheduling and human resource management. Table 3 summarizes the representative literature on optimizing precast production from the perspective of workers, including research topics, optimization starting points for workers, and research contributions. As shown in the table, in terms of research topics, many studies integrated worker-related factors such as worker allocation and worker competence in the traditional flow shop scheduling model to optimize PPS (Chan and Hu, 2001; Leu and Hwang, 2002; Wang et al., 2018b; Hyun et al., 2021). Other research topics include worker allocation mechanisms for PC production (Al-Bazi and Dawood, 2010; Nasirian et al., 2019a; Cao et al., 2022) and worker training times based on worker abilities (Tai et al., 2021).

In terms of research contributions, in general, researchers have done

Table 3
Summary of the representative literature on optimizing precast production from the perspective of workers.

Literature	Research topic	Optimization starting points for workers	Contributions
Chan and Hu (2001)	Flow shop sequencing model to ensure on-time delivery	Worker allocation strategy	Considers workers' normal working hours and off-normal working hours in the PPS optimization model
Leu and Hwang (2002)	Flow shop scheduling model considering resource constraints and mixed production	Worker allocation strategy	Considers the impact of limited skilled workers on precast production
Al-Bazi and Dawood (2010)	Crew allocation system that can appropriately allocate prefabrication workers	Worker allocation strategy	Provides an efficient worker allocation strategy that can minimize production costs and idle time
Wang et al. (2018b)	Precast production scheduling optimization model considering worker competence	Worker competence	Models worker competence to synchronize the production scheduling with workforce development
Nasirian et al. (2019b)	Operational benefits of different labor skill set structures to address bottlenecks in precast production	Worker competence and allocation strategy	Reveals the performance and sensitivity of different labor skill sets in different production situations
Hyun et al. (2021)	Multi-objective optimization model for modular unit production lines considering crew allocation	Worker allocation strategy	Integrates the optimization of the unit production line design with the type and number of workers
Tai et al. (2021)	Worker training time and proficiency threshold for each activity in precast component production	Worker competence	Determines the thresholds (in days) of worker training time and the learning curve slope

a good job of combining worker quantity constraints and worker allocation strategies with the PPS optimization mechanism, which has provided references on how to optimize PPS from the perspective of workers. Moreover, research since 2018 has preferred to take worker competence as an optimization starting point. However, there are still many opportunities in PPS research combining worker competence, and research issues, such as how to achieve an effective trade-off between minimizing production costs and maximizing worker competence, deserve further attention from future researchers (Wang et al., 2018b).

4.1.2. Molds

A mold is a tool used for shaping PCs and is the main production equipment employed throughout every precast production process. In reality, production molds are very expensive, and the quantity of molds is limited by the factory space. Mold changeover is needed for the production of different types of PCs; however, this process often requires a long preparation time of up to one day (Chan and Hu, 2002b; Khalili and Chua,2014). Therefore, to ensure that production can be completed on time, making full use of production molds during the life cycle of molds has become an important issue that managers must consider when formulating production scheduling plans.

Among PPS optimization studies, the mold usage plan is also a key consideration for researchers. For example, as the production of bespoke PCs, which consumes a large number of customized molds, Benjaoran and Dawood (2005) took this feature into account in their production scheduling mechanism and conducted a sensitivity analysis of the number of available production molds to determine the appropriate number of production molds for different types of bespoke products. Li et al. (2010) incorporated internal resource constraints to develop a scheduling scheme with lower total production costs and fewer molds required, while also providing insights into issues such as reducing mold idle time.

Furthermore, most previous studies only considered the processes directly related to production, such as mold and reinforcement setting, pouring, and maintenance, but ignored the actual process of mold manufacturing. To fill this gap, Wang and Hu (2017) integrated the mold manufacturing process into a scheduling optimization model, which improved the practicality of the obtained production scheduling scheme. Meanwhile, some researchers have investigated the usage plans of molds for special production situations in the PPS optimization mechanism, such as the mold allocation strategy for multiple production line modes (Yang et al., 2016), selection criteria for mold quantity under rescheduling (Wang et al., 2021), and the mold cost control plan (Wang and Hu, 2018). These studies can help production decision-makers develop more appropriate mold usage plans and provide ideas for future scholars to explore how to optimize PPS from a mold perspective.

With the increasing number of prefabricated buildings, the complexity of PCs has also increased. The PC configuration directly affects the planning, scheduling, and cost of each phase of an OSC project (Khalili and Chua, 2013). For example, the size and weight of PCs significantly affect transportation and handling costs. In the production stage, the number of molds in the production plant is limited, and frequent mold changeovers consume considerable time and costs when facing various PC types. Thus, component grouping plays an important role in the efficient use of production molds. Fig. 5 shows the specific application form of the component grouping (Chan and Hu, 2002b). As shown in the figure, only a single type of mold is required for the production of a single-type component. Multiple-type production molds are required for the production of multiple components, and frequent mold changes are required to achieve production. Component grouping is an appropriate approach for producing multiple components as the mold group is responsible for the production of the components in the corresponding component groups. For instance, complex molds in a mold group can produce both complex and simple components in the corresponding component group. Rational component grouping can reduce mold changes, thereby optimizing production scheduling and reducing production costs (Chan and Hu, 2002b; Li et al., 2010; Khalili and Chua, 2014; Wang and Hu, 2018; Dan et al., 2021).

Some researchers have also optimized PPS from the perspective of component grouping. Chan and Hu (2002b) illustrated the relationship between the components and mold groups and explored how to obtain a production scheduling plan with a suitable assignment plan for components and molds using a scheduling model based on a constraint programming approach. Khalili and Chua (2013) developed a system based on the industry foundation class (IFC) to determine the appropriate component grouping; the production costs of various component groups and mold groups at different construction cycle times were verified through experiments, which could help decision-makers formulate efficient production scheduling schemes in conjunction with mold grouping. In addition, one year later, Khalili and Chua (2014) proposed a mixed-integer linear programming model integrating two new concepts—prefabricated configuration and component groups—to optimize precast production, which could help address problems in the production of complex components, including the utilization of complex molds and production cost control. Table 4 summarizes the representative literature on optimizing precast production from the perspective of molds, including the research topic, optimization starting points for molds, and research contributions. As shown in the table, in terms of the research topic, some researchers integrated the mold quantity constraints under different production scenarios in the PPS optimization model to obtain the PPS scheme with a proper mold usage plan; production scenarios, such as the production of customized components (Benjaoran and Dawood, 2005); multiple-line production (Yang et al., 2016), and production rescheduling (Wang et al., 2021). Moreover, an

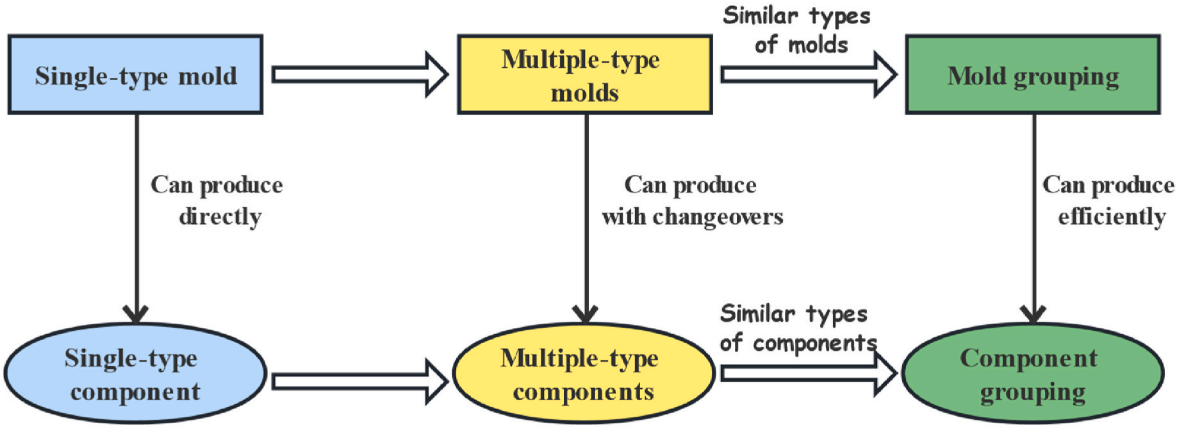

Fig. 5. Application form of component grouping [adapted from Chan and Hu (2002b)].

Table 4

Summary of the representative literature on optimizing precast production from the perspective of molds.

Literature	Research topic	Optimization starting points for molds	Contributions
Chan and Hu (2002b)	Constraint programming approach to precast production scheduling	Mold grouping	Introduces the relationship between the component group and the mold group
Benjaoran and Dawood (2005)	Flow shop scheduling model for bespoke precast production	Number of molds	Provides a suitable mold allocation plan for bespoke precast concrete products
Li et al. (2010)	Production scheduling scheme considering internal resource constraints	Mold grouping	Develops a scheduling scheme with lower total production cost and less mold quantity
Khalili and Chua (2013)	Industry foundation class (IFC)-based framework to arrange the grouping of precast components	Mold grouping	Determines a configuration of components with fewer components and molds for the different construction cycle
Khalili and Chua (2014)	Integrating prefabrication configuration and component grouping to create an optimal production plan	Complex mold grouping	Provides the mold allocation plan for precast production with more complex molds
Yang et al. (2016)	Flow shop scheduling model of multiple precast production lines	Number of molds	Discusses the allocation of molds and production pallets under multiple production lines
Wang and Hu (2017)	Optimizing precast production scheduling from the perspective of the entire supply chain	Process of mold manufacturing	Considers the process of mold manufacturing in the scheduling optimization model, thereby improving the applicability of the model
Wang and Hu (2018)	Dynamic rescheduling model for precast production to respond to the frequent PC demand variability	Mold type and mold grouping	Considers the shared mold types and mold changeover fees in the model to minimize the mold changeover
Wang et al. (2021)	Hybrid rescheduling optimization model under disruptions of machine breakdown	Number of molds	Obtains the mold configuration under rescheduling

appropriate mold grouping can effectively reduce the number of mold changeovers, thereby saving time and controlling production costs. Many studies have been conducted to optimize PPS from the perspective of component grouping and mold grouping (Li et al., 2010; Khalili and Chua, 2013; Khalili and Chua, 2014).

In terms of research contributions, researchers have considered the use of molds under various production situations in the scheduling mechanism. Future researchers can continue to improve the PPS optimization mechanism based on these studies in conjunction with practical mold use strategies. Simultaneously, as the variety of building components becomes increasingly complex, the optimization of the PPS from the perspective of mold grouping remains valuable for future research.

4.1.3. *Workspace*

The workspace is also an essential resource for building construction projects and impacts the schedule, cost, and safety of the project. In reality, because the workspace is limited, multiple construction activities often need to be conducted in the same space, and workspace interference occurs when project scheduling is poorly planned, directly reducing engineering efficiency and impairing worker safety (Tao et al., 2020).

In OSC projects, workspace interference can affect the fluidity of the precast production, preventing PCs from being produced on time. First, owing to the different durations of each production process, PCs form a queue in the limited buffer between production stations to wait for the next process. As a result, production congestion sometimes occurs (Ko and Wang, 2010). Furthermore, PCs produced early must be stored in the staging area of the plant to await transportation, which can easily result in workspace interference if there are no well-established guidelines for PC storage (Chen et al., 2019).

Optimal production scheduling is considered an effective solution for reducing workspace interference (Tao et al., 2018). Researchers have also conducted studies on optimizing PPS from the perspective of production workspaces. For example, Li et al. (2010) compared production behavior and cost loss under different production space constraints and improved the production scheduling scheme accordingly. Ko and Wang (2011) considered the effect of the buffer size between production workstations on precast production and integrated the waiting time of PCs in the buffer zone into the PPS optimization model to increase the practicality of the scheduling model.

Additionally, proper production layout planning is crucial to ensure the smooth production of PCs. Workspaces in construction projects have been classified into multiple categories in previous studies, including building component, equipment, and labor spaces (Akinci et al., 2002). The layout planning of each type of workspace has a large or small impact on the precast production process; thus, scholars have also pursued efficient precast production by researching the layout planning of the production space. For instance, Wang et al. (2018d) developed a mold layout optimization model considering the constraints of PC and pallet sizes to reduce the space wastage of production pallets and thus increase productivity.

In Industry 4.0, AI-based devices, such as automated guided vehicles (AGV) that transfer PCs between workstations, are used within prefabricated factories. However, the key to the successful incorporation of AGV in precast production systems is a thorough layout planning of the production space. Based on this situation, Chen et al. (2019) proposed a layout optimization model for an AGV-based manufacturing system in which the size arrangement of workstations and storage areas was considered in the model to make full use of the production space. Table 5 summarizes the representative literature on optimizing precast production from the perspective of workspaces, including research topics, optimization starting points for workspaces, and research contributions. Regarding the research topic, some studies have analyzed the direct effects of production space factors on the precast production process, such as the overall production space size (Li et al., 2010) and the buffer size between workstations (Ko and Wang, 2010, 2011; Du et al., 2022), and integrated these space constraints to improve the PPS mechanism. Other studies have also been conducted on the production space layout of precast factories, such as the layouts of PCs and production pallets (Wang et al., 2018d), workstations, and storage areas (Chen et al., 2019). These studies explored the layout plans of production spaces with lower space wastage and higher productivity using layout optimization models.

In terms of the optimization starting points for the workspace, previous studies have adapted building component (Li et al., 2010; Wang et al., 2018d), facility (Ko and Wang, 2010; Reisinger et al., 2022), and storage (Li et al., 2010; Chen et al., 2019) space as the starting point for optimization of prefabrication production. However, few studies have considered the influence of labor space on the production process. Future researchers could attempt to conduct research on production layout planning as well as production schedules from the workspace

Table 5

Summary of the representative literature on optimizing precast production from the perspective of workspaces.

Literature	Research topic	Optimization starting points for workspace	Contributions
Li et al. (2010)	Production scheduling scheme considering internal resource constraints	Building component and storage space	Analyzes the influence of different production space constraints on precast production
Ko and Wang (2011)	Precast production scheduling optimization model considering the buffer size between workstations	Facility space	Considers the waiting time before the component enters the buffer in the optimization model to improve the practicability of the model
Wang et al. (2018d)	PC layout optimization model for production pallet during mold setting process	Building component and facility space	Provides a production plan with higher pallet utilization and less production time
Chen et al. (2019)	Facility layout optimization model for AGV-based precast production system	Storage and facility space	Provides a better layout plan for the storage area and workstation area to reduce space wastage
Reisinger et al. (2022)	A new parametric evolutionary technology method for automated production layout generation and optimization	Facility space	Presents a production layout plan that can ensure production efficiency and reduce the probability of collision of building components

perspective. Furthermore, to allow intelligent production devices (such as AGV) to be applied more efficiently within a prefabricated production system, it is necessary to conduct more in-depth theoretical research on certain issues, such as the size configuration of intelligent production devices and layout planning of intelligent production systems.

Based on the aforementioned literature review, the main findings of optimizing the PPS from a resource perspective are as follows.

(1) In current PPS optimization studies that consider worker factors, the worker allocation strategy and worker competence are the prime starting points. Certain realistic factors related to workers were not considered; for example, whether the processing time of each operation was subject to the impact of worker fatigue and recovery.
(2) Mold grouping directly affects the duration and costs of mold changeover; therefore, it serves as the main starting point for optimizing PPS from the perspective of molds in previous studies. With the development of the OSC approach, the complexity of component types has increased gradually; however, few studies have optimized PPS in combination with complex mold grouping strategies.
(3) Workspace constraints, such as buffer and storage space size and production pallet layout, were integrated into the PPS mechanism in previous studies. However, the influence of multiple workspace factors on PPS, such as the layout of the labor space and transportation route plan of the AGV, has rarely been considered.

4.2. External supply chain constraints

As we all know, the OSC supply chain is composed of multiple stages, including PC production, transportation, and on-site assembly, all of which affect each other and require collaboration to maximize the overall efficiency of the supply chain. The PC transportation strategy, construction situation at the assembly site, and information sharing across the supply chain influence the formulation and execution of the PC production plan (Fang and Ng, 2019). From a macro perspective, it is logical to optimize the PPS from the supply chain perspective, and relevant studies on PPS optimization have been conducted from this perspective. Therefore, this study discusses how to optimize PPS from three aspects of the OSC supply chain: transportation, on-site assembly, and information management.

4.2.1. Transportation

PC transportation connects the prefabrication plant and construction site, which is a crucial step in ensuring the efficient completion of the OSC project. Fig. 6 shows the general flow of OSC logistics transportation. As shown in the figure, building components are first produced in the factory through the design scheme, and according to the requirements of the construction site, PCs are transported to the staging area for temporary storage or directly to the assembly site for installation (Yang et al., 2021; Luo et al., 2020). From this process, it can be seen that transportation plays a tandem role and directly affects the inventory levels of PCs in prefabrication plants, staging areas, and assembly sites, which consequently affects the schedule and cost of the entire OSC project.

In the PPS optimization studies considering PC transportation, many researchers have integrated the transportation speed, transportation time, and cost of PCs as constraints within the production scheduling mechanism. For example, Wang and Hu (2017) improved the production scheduling model by considering three PC transport scenarios—daytime, nighttime, and all-day transportation—which facilitate the on-time delivery of PCs. When a single factory is responsible for the production of multiple OSC projects, a combination of more accurate production scheduling and transportation strategies is necessary to ensure on-time delivery of PCs. Based on this situation, the scheduling optimization model proposed by Lee and Hyun (2019) considered the distance from the factory to each project location and the transportation rate, thus improving the accuracy of PPS.

The JIT delivery strategy, which means that the required number of PCs is delivered to the assembly site for installation at the required point in time, is also widely applied in the field of OSC (Si et al., 2021; Du et al., 2022). The application of the JIT delivery strategy can enable OSC projects to be completed on time, but for it to be successfully applied, collaborative operations between precast production and transportation are essential (Wang et al., 2019). However, most previous studies have only focused on production as the main object of study to achieve a JIT delivery strategy, and the impact of subsequent transportation stages on PC delivery has not yet been considered (Benjaoran and Dawood, 2005; Ko and Wang, 2010; Yang et al., 2016). To fill this gap, Kong and Luo (2017) viewed the three stages of production, transportation, and assembly as a whole. Several variables, such as production batches and transportation time of each component, were integrated into the proposed production scheduling model, which allowed the JIT delivery theory to be applied more effectively and provided ideas on how to optimize the PPS in conjunction with PC transportation.

In summary, most studies in the OSC field based on the JIT delivery strategy have focused only on optimizing the process of precast production. A few studies have developed collaborative scheduling mechanisms for production and transportation to achieve a JIT delivery strategy. Future researchers can consider this as the starting point for optimizing PPS from a transportation perspective. Some studies have also incorporated variables such as transportation time (Wang and Hu, 2017; Kong and Luo, 2017) and transportation distance (Lee and Hyun, 2019) into the PPS optimization model to enhance the availability of the scheduling scheme, which can provide insights for future PPS optimization studies. In addition, for OSC projects with single or multiple plants corresponding to the construction of multiple sites, the complexity of transportation is higher and a high degree of coordination

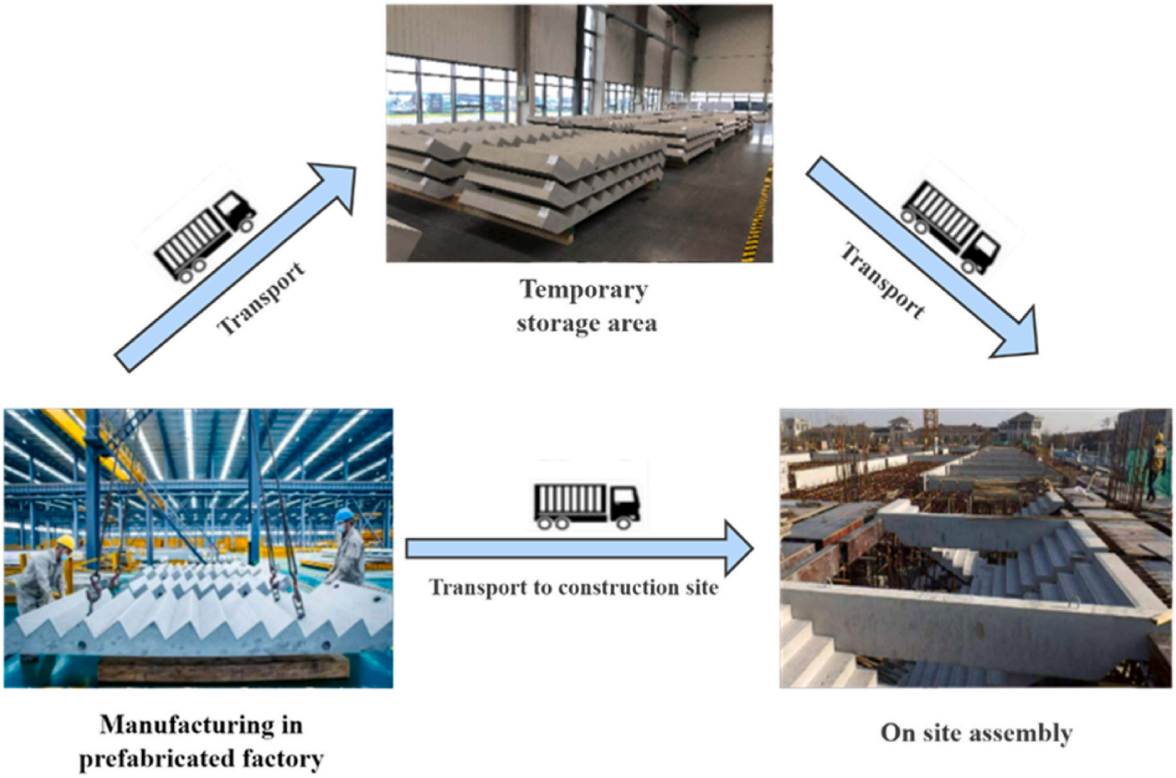

Fig. 6. General flow of OSC logistics transportation.

between production scheduling and transportation is required, which deserves further research by future scholars.

4.2.2. *On-site assembly*

PC assembly activities are conducted after production and transportation, and thus are at the end of the OSC supply chain. Early or late delivery of PCs leads to unsuccessful on-site assembly work, and the status of the assembly work influences production scheduling in the prefabrication plant. The production sequence of PCs in the plant is affected by the installation sequence at the construction site; thus, it is necessary to establish a collaborative scheduling mechanism between the construction site and production plant to enhance the efficiency of the OSC project (Chen et al., 2020). Furthermore, some uncertainties in the assembly phase may change the construction schedule and due date of PCs, so production plants must conduct production rescheduling to address this situation (Kim et al., 2020).

Owing to the close relationship between on-site assembly and precast production, researchers have combined them to optimize engineering scheduling mechanisms. Kong and Luo (2017) improved the production scheduling model by linking the production and assembly times of each batch of components, thereby enhancing the production efficiency and resource utilization. Simultaneously integrating the constraints of production, transportation, and assembly when developing a production scheduling scheme can enhance the applicability of the scheduling scheme and reduce the duration of installation work (Lee and Hyun, 2019). Chen et al. (2020) established a collaborative scheduling mechanism for on-s and off-site construction activities to mitigate the risk of construction delays and demonstrated the practicality of their scheduling approach through a multi-supplier OSC project case. Xie et al. (2021) not only considered the linkage between precast production and on-site assembly and their respective characteristics but also incorporated renewable resource constraints in the scheduling model to achieve an efficient engineering scheduling scheme and a reasonable resource allocation plan.

At the construction site, the demand for PCs varies as the project progresses; for instance, if the PC is damaged owing to installation errors, weather conditions, etc. the production plant will receive urgent orders. To address this issue, Wang and Hu (2018) developed a dynamic rescheduling model to respond to the impact of PC demand variability on precast production, which can promote the on-time delivery of PCs and reduce production cost losses due to demand variability. Additionally, the uncertainty of construction site scheduling leads to subsequent changes in PC due dates; Kim et al. (2020) considered production scheduling under due date uncertainty and integrated the magnitude of the due date change and the receipt time of the changed order into the production scheduling model, which allowed for a better combination of production and on-site scheduling, thus increasing engineering efficiency. Based on the literature review, Fig. 7 depicts the influence mechanism between off-site production and on-site assembly. As shown in the figure, two starting points for optimizing the PPS can be identified from the perspective of on-site assembly. First, because PPS and on-site construction scheduling are mutually implicated and jointly determine the efficiency of OSC, many scholars have combined them to explore their collaborative scheduling mechanisms (Kong and Luo, 2017; Lee and Hyun, 2019; Chen et al., 2020; Xie et al., 2021), which will help future researchers generate new ideas for PPS optimization research. Second, various uncertainties exist at the assembly site, such as PC demand variability (Wang and Hu, 2018) and due date uncertainty (Kim et al., 2020), which directly cause production rescheduling. Accordingly, future researchers could continue to investigate the production rescheduling mechanism under the influence of other uncertainties from the assembly site.

4.2.3. *Information management*

The OSC supply chain, which involves many sectors, relies on collaboration between various departments. Effective information sharing among stakeholders guarantees the on-time completion of a project (Hussein et al., 2021). However, the OSC supply chain is highly uncertain. If each department lacks real-time information, it cannot properly respond to unexpected situations, which negatively impacts the

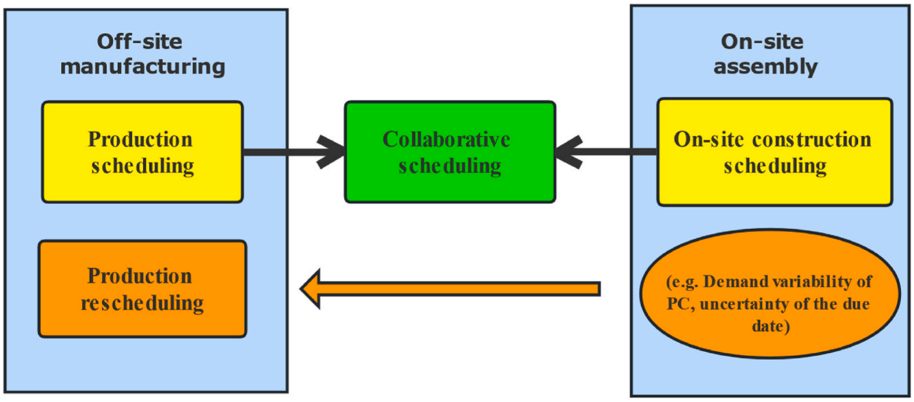

Fig. 7. Influence mechanism between off-site production and on-site assembly.

project schedule, cost, and work quality (Wang et al., 2019). Therefore, based on the importance of supply chain information management, many scholars have researched how to improve OSC project performance, while some studies have also focused on PPS optimization issues.

Production tracking for PCs is key to helping production managers evaluate real-time production status and adjust production schedules and is also one of the dominant research topics among scholars. Arashpour et al. (2015) proposed a customized production tracking mechanism for OSC that can be used to detect production shortages in a short time to facilitate swift remediation. In the long run, this can help evaluate production capacity and adjust production schedules. Yan et al. (2022) developed an intelligent monitoring and evaluation system for precast construction schedules based on computer vision-based (CVB) technology that could help production managers efficiently track the real-time status of PC and workers. With the advancement of information technology, the Internet of Things (IoT) technologies, such as RFID, have been applied in the OSC domain to facilitate the tracking of PCs' real-time status (Li et al., 2017; Mohsen et al., 2022), Luo et al. (2020) collected and managed real-time information of PCs through an information platform combining building information modeling (BIM) and RFID, which was proven to help managers manage risks and adjust project schedules more efficiently through a case study.

Simulation methods, such as discrete event simulation (DES), can help precast production managers simulate and evaluate diverse production situations within a virtual environment (Altaf et al., 2018; Yuan et al., 2020). The application of simulation models to production processes requires large amounts of accurate real-time production data. However, the process of data collection often suffers from problems and obstacles (e.g., inappropriate application of information technology and incompatible data selection criteria) and a sound planning and control system is considered to be key to data processing and engineering planning (Arashpour et al., 2015; Yang et al., 2021). The automated production planning and control system proposed by Altaf et al. (2018) for the OSC production process incorporates RFID technology, data mining technology, and simulation-based optimization models. This system can help monitor and manage real-time production information, thereby allowing PPS to be adjusted and optimized in time.

Furthermore, some studies considered the information transfer mechanism between the various sectors of the OSC supply chain to optimize the PPS; for instance, Wang et al. (2018c) analyzed the information flow of the OSC project with the help of a multi-agent system and developed a two-hierarchy scheduling optimization model to synchronously optimize the PPS and resource allocation plan. In light of scheduling changes, timely information sharing between plants and general contractors is required to adjust the scheduling scheme. To this end, Si et al. (2021) proposed a dynamic compensation mechanism to promote the more active sharing of information and resources between precast plants and other sectors, thereby facilitating the timely delivery of PCs.

In summary, tracking and monitoring real-time production information can identify risks and promptly adjust PPS (Arashpour et al., 2015). Production planning and control systems aid in the rational application of information technology and data collection (Altaf et al., 2018). Currently, RFID is a common information technology for collecting production data, and studies have been conducted to optimize PPS by combining RFID with other methods, including RFID and BIM (Li et al., 2017; Luo et al., 2020; Zhao et al., 2022), RFID, and multi-agent systems (Wang et al., 2018c), among others, from which future scholars can consider optimizing PPS from the perspective of supply chain information management. Blockchain, a newly emerging IoT technology, has also been applied in the OSC field for data processing (Wang et al., 2020b). However, problems with the application of blockchain technology in the prefabrication domain persist. For example, the blockchain platform is excessively rigid, which reduces the flexibility of production scheduling (Yang et al., 2021). Thus, future researchers could explore more effective ways of combining blockchain technology with precast production systems.

Based on the aforementioned literature review, the main findings on optimizing PPS from the supply chain perspective are as follows.

(1) Previous studies optimized PPS in combination with PC transportation strategies to improve the delivery efficiency of PCs. However, some realistic transportation scenarios have not been considered in the PPS mechanism, such as the PC transportation strategy under multiple plants or construction sites.
(2) From the perspective of on-site assembly, developing collaborative scheduling between precast production and on-site assembly is the main approach for optimizing the PPS. However, few studies have combined disruptions at construction sites to optimize collaborative scheduling mechanisms, such as variable due dates and rush orders.
(3) RFID and BIM are common information technologies that have been adopted in previous studies on PC production tracking and risk management. Meanwhile, the combination of multiple information technologies, such as the IoT and blockchain, has been demonstrated to be suitable for application in precast production systems; however, the number of studies is limited.

5. Discussion

What has been done and what remains to be done were identified from the systematic review of OSC-PPS in the previous sections. Future research directions for mainstream content and optimization perspectives can be derived based on the research gaps identified in previous studies, as presented in Fig. 8.

As shown in Fig. 8, this study summarizes the research gaps in PPS

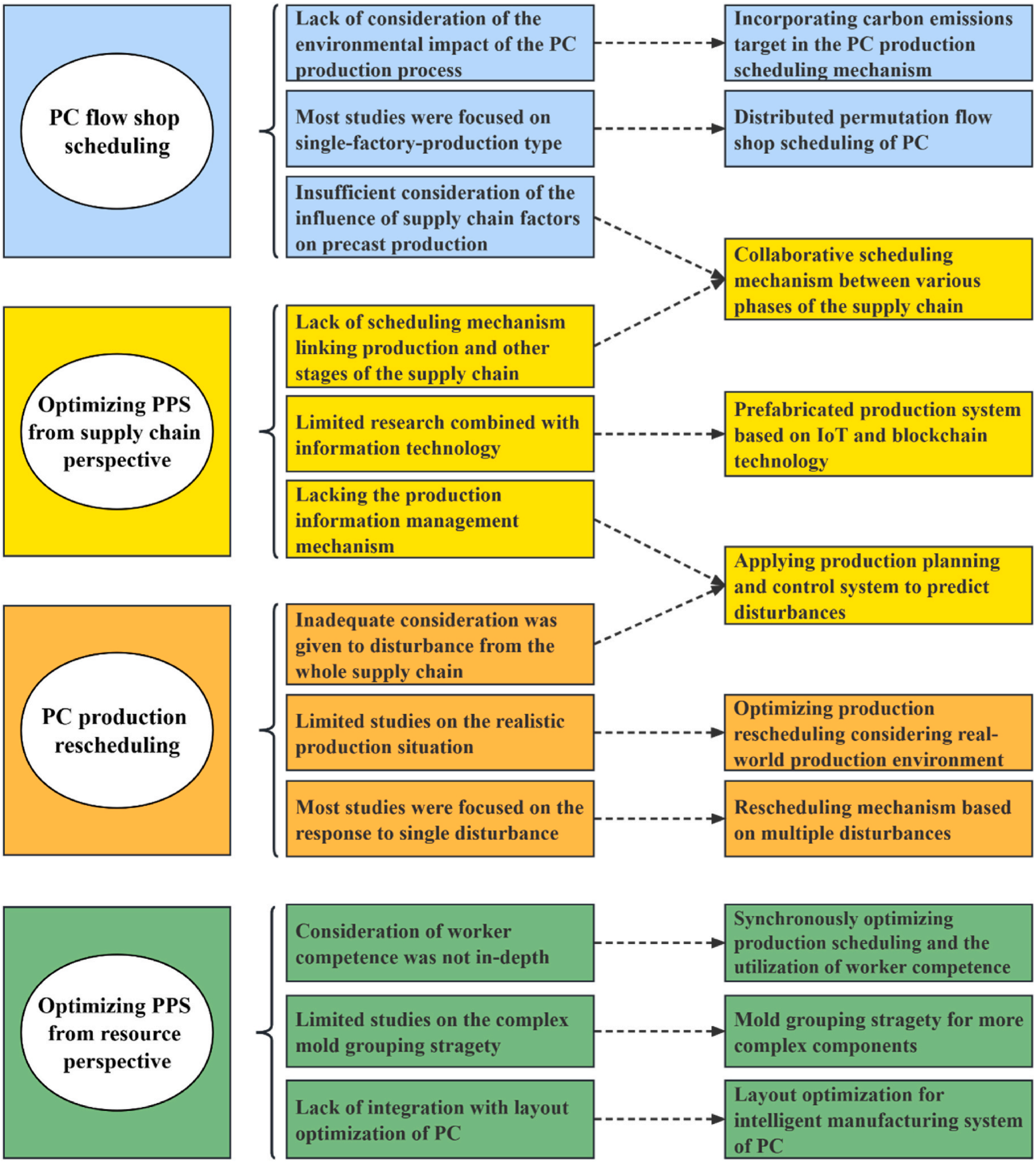

Fig. 8. Future research directions for PPS optimization.

optimization from four dimensions: PC flow shop scheduling, PC production rescheduling, resource optimization, and supply chain optimization. The contents of the panels indicated by dotted arrows represent future research directions for the corresponding research gaps, which are discussed below.

(1) *PC flow shop scheduling research in the OSC industry.* In most previous studies, economic benefit indicators, such as production duration or cost, were used as optimization targets. However, the environmental impact of PC production has been ignored, which may lead to a decrease in the environmental benefits of precast production. Therefore, it is necessary to incorporate carbon emissions targets as optimization objectives in the PC production scheduling mechanism to improve the realistic applicability of scheduling models. In addition, most studies on PC flow shop scheduling are based on a single-plant production model, but many OSC projects adopt a production model with multiple plants simultaneously, which is more complicated than a single-plant production model. Therefore, proper production scheduling is critical for the timely delivery of components (Xiong et al., 2021). The distributed permutation flow shop scheduling problem of PCs could be addressed with more research efforts in the future.

(2) *Research on PC production rescheduling in the OSC industry.* Future research could consider the risk factors that commonly occur in production factories (e.g., the uncertainty of processing time for each process) to optimize production rescheduling instead of making straightforward assumptions with uncertainties. Several disturbances in the OSC supply chain can cause production rescheduling, such as PC demand variability (Ko, 2011; Wang and

Hu, 2018), machine breakdown (Wang et al., 2021), and urgent orders. Future researchers could continue to explore the production rescheduling problem under different disturbances from a supply chain perspective. Moreover, most previous studies focused on production rescheduling under the influence of a single disturbance; however, production rescheduling mechanisms based on multiple disturbances have rarely been considered and deserve further investigation.

(3) *Optimizing PPS from a supply chain perspective in the OSC industry.* First, previous PPS optimization studies have not considered the impact of supply chain-related factors on precast production. Scheduling mechanisms linking production and the various stages of the supply chain have rarely been studied. Therefore, it is necessary to establish a collaborative scheduling mechanism between each stage of the supply chain to ensure efficient execution of production activities and improve the comprehensiveness and practicality of the production scheduling mechanism. Second, future research can increase the application of production planning and control systems to manage real-time production information, predict obstacles in production, and adjust the production schedule in time. Furthermore, there is considerable room for improvement in research on combining information technologies (e.g., the IoT and blockchain) to optimize precast production, and future scholars can make more attempts to adopt these information technologies to enhance precast production systems.

(4) *Optimizing PPS from a resource perspective in the OSC industry.* First, PPS optimization research that combined factors such as worker competence and learning time was insufficiently thorough; for instance, the issue of how to achieve the maximum utilization of worker competence in coordination with PPS still needs further exploration. Furthermore, the mold grouping strategy requires further refinement as the variety and complexity of the components increase, thereby reducing the time and costs consumed in the mold changeover. Suitable layout planning of production facilities is key to integrating smart devices into the production system, which also helps improve productivity and optimize PPS (Chen et al., 2019). However, the relevant theoretical research is currently limited, and the layout optimization of PC production systems based on smart devices needs to be further explored. Finally, the influence of crane-related factors on precast production (e.g., the crane layout plan in the factory and crane lift path) has rarely been considered and deserves further consideration by future scholars. Studies have been conducted to optimize the flexible job shop scheduling mechanism with crane transportation (Du et al., 2022b; Li et al., 2022), which could provide ideas for future scholars to optimize the PPS from a crane perspective.

6. Conclusion

With the continuous development of OSC methods, PPS has become a major research topic for scholars and practitioners. Researchers have made significant efforts to improve production scheduling mechanisms. However, from the existing review studies in the field of OSC, most studies only provide a macroscopic generalization of PPS, and a systematic summary of the theoretical knowledge related to PPS is lacking. Therefore, this study conducts a comprehensive and systematic review of 75 research papers related to PPS and provides an in-depth analysis of the mainstream content of PPS research and how to optimize PPS from the perspectives of resources and supply chains. Research gaps and directions for future research are summarized, and the study findings are as follows.

First, in terms of mainstream content in PPS research, PC flow shop scheduling and PC production rescheduling are the mainstream contents in PPS research, representing the static and dynamic scheduling of PCs, respectively. In future research, additional environmental and social sustainability factors such as carbon emissions could be considered to improve the practicality of the scheduling mechanism. Second, in terms of the optimization perspective for the PPS, workers, molds, and workspaces were the prime resource perspectives considered by researchers to optimize the PPS, including the worker allocation strategy, mold grouping, and production line layout. Third, developing collaborative scheduling in conjunction with transportation or on-site assembly to achieve a JIT delivery strategy was the main focus of optimizing the PPS from the supply chain perspective. Finally, RFID and BIM are the main information technologies adopted in existing studies for intelligent monitoring and evaluation of PPS. In future research, multiple combinations of information technologies (e.g., the IoT and blockchain) could be suitable for devising intelligent PC production systems.

This study offers a valuable reference for scholars interested in PPS and industry practitioners in the OSC domain. More specifically, it could help scholars gain a deeper understanding of the current status of PPS research in the field of OSC and enable them to grasp the theoretical knowledge related to PPS more systematically. Furthermore, this study can help precast production practitioners adopt more efficient methods and technologies to improve production management performance. However, although the selected papers reflected the overall trend of the PPS discipline, not all related studies were considered.

CRediT authorship contribution statement

All the authors contributed to the study conception and design.

Material preparation, data collection and analysis carried out by all author.

All authors read and approved the final manuscript.

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.

Data availability

Data will be made available on request.

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