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Review

Solutions to Address the Low-Capacity Utilization Issue in Singapore's Precast Industry

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Abstract: Singapore has established six Integrated Construction and Prefabrication Hubs with the goal of meeting ambitious productivity targets and building a resilient precast supply chain by 2024. These factories are equipped with high levels of mechanization and automation. However, they are currently operating far below their designed capacity due to a storage bottleneck. In land-scarce Singapore, finding large spaces for precast storage is a challenge. One possible solution is to implement a just-in-time approach. To achieve this, a systematic approach is required to plan, monitor, and control the entire supply chain effectively, utilizing various strategies, methods, and tools. This paper aims to conduct a comprehensive literature review in related areas, believing that knowledge transfer is a faster way to develop solutions to new problems. The main idea of the proposed solution is to implement an integrated supply chain system model with a central decision-maker. It is recommended that the factories take a more active role in decision-making. Establishing this integrated system relies on trust and information sharing, which can be facilitated by cutting-edge digital technologies. The results of this paper will provide valuable insights for future research aimed at completely solving this issue.

Keywords: precast supply chain; just-in-time; inventory; literature review

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1. Introduction

Precast concrete prefabrication technology supports the transformation of the entire built environment sector [1]. Singapore is the first country in the Southeast Asian region to utilize this technology to enhance efficiency and quality in construction projects. The precast concrete market in Singapore is expected to see significant revenue growth, with a predicted compound annual growth rate (CAGR) of 9.2% from 2024 to 2030 [2]. This positive market outlook is driving the establishment of highly automated precast concrete factories. In July 2021, the sixth Integrated Construction and Prefabrication Hub (ICPH) was launched in Punggol Barat Lane, Singapore.

Given Singapore's limited land area, there is a growing emphasis on maximizing land use, resulting in the emergence of multi-level industrial buildings throughout the country. These ICPHs are multi-level advanced manufacturing facilities representing the industry's highest level of mechanization and automation. They play a crucial role in supporting the transformation of the entire built environment sector and have attracted significant attention from the government, industry, and academia.

The latest ICPH spans an area approximately the size of seven football fields and can produce up to 100,000 cubic meters of precast components annually, catering to the full range of components required for public Housing Development Board (HDB) projects. The facility is equipped with 54 loading bays, 26 production lines, and state-of-the-art technology systems, including a smart storage and retrieval system for building components. With these capabilities, it can construct about 17 blocks of HDB flats per year, leading to faster delivery of build-to-order (BTO) flats because more precast building components can be made locally. This ensures a more stable supply chain and minimizes disruptions. The efficiency and resilience of the ICPH are championed by the Building and Construction Authority (BCA), especially after the COVID-19 pandemic. A master plan has been formulated for the development of ICPHs with a 30-year lease term.

However, during a recent visit to the ICPH, the authors learned from the plant manager that the ICPHs are currently operating well below their planned capacity. When the authors asked the manager why, the manager pointed to the trucks parked on the roadside, which were loaded with finished precast components. The shortage of storage space for finished products was so severe that paying traffic fines for illegal parking could become a temporary choice for some ICPH runners. This situation seems ridiculous, but it is understandable in this island country where land resources are scarce. It is very obvious that the shortage of storage yards is causing a bottleneck in ICPH production when achieving just-in-time (JIT) delivery is impossible at present. In order to prevent the overloading of their storage yards, ICPHs are currently being utilized at only 30% of their design capacity. With a 30-year lease term, recouping the hundreds of millions in investment capital expenditure is a significant challenge. For example, Soilbuild recorded a gross profit of approximately SGD 22.13 million in 2023, with its prefabricated and precast supply constituting 15.6% of the total [3]. An investment of SGD 100 million in a precast production plant would take at least 30 years to break even.

In addition to using their internal storage yards within the plants, ICPHs rented vacant state lands through temporary occupation licenses (TOLs) from the Singapore Land Authority (SLA). But per the manager, obtaining them has become increasingly difficult these days. The lack of space is the biggest headache issue for ICPH runners, pushing them to consider moving production to neighbouring regions like Johor, Malaysia. However, doing so would go against the original purpose of establishing ICPHs in Singapore. To embrace change and drive successful transformation truly, ICPHs should not just be a display of cutting-edge technologies; their value must be proven in real business scenarios.

Responding to these challenges, the Singapore government initiated the development of Integrated Construction Parks (ICPs) to co-locate construction facilities and resources for improved collaboration. The first ICP site was in Jurong Port and began operations gradually at the end of 2022. Another ICP site is planned for the Pulau Punggol Barat area. Although the logistics distance within the supply chain has been reduced, the primary issue remains with inventory, which is associated with uncertainties at construction sites. Unless JIT delivery is achieved, the inventory problem can be eliminated.

In academia, researchers have explored better production methods to handle the uncertainty of due dates in precast construction; for example, Kim et al. [4] proposed a dynamic production scheduling model that uses a discrete-time simulation method to adapt to real-time changes in due dates and a new dispatching rule that considers the uncertainty of due dates to minimize tardiness.

Generally, finished product inventory is crucial to supply chain management, bridging upstream and downstream systems. Inventory issues should be tackled with a holistic view of the entire system rather than solved in isolated segments. While current solutions primarily focus on planning and scheduling on the factory side, the authors believe that the inventory issue cannot be fully resolved without addressing downstream uncertainty, such as construction uncertainty.

To systematically address these challenges, this research aims to review relevant methods and techniques in the existing literature, believing that knowledge transfer to new contexts is a faster way to develop solutions to problems. The goal is to propose a systematic methodology that can effectively reduce the inventory levels of finished products in the precast supply chain by managing uncertainties. This requires a combination of various strategies, techniques, and tools. The research results are expected to offer valuable insights for future studies aimed at fully resolving this issue. Reducing finished product inventory is not only a crucial step toward JIT delivery but also a key enabler for achieving leanness.

The value of ICPHs can only be fully realized by reaping economies of scale through mass production. Only businesses operating at a lower cost can succeed in a fully competitive market. Therefore, solutions to reduce inventory waste in precast production are imperative and meaningful.

2. Prefabrication and Modular Construction

Before delving into this research, let us gain a general idea of prefabrication and modular construction. The terms prefabrication and modular construction are often used interchangeably [5]. Prefabrication refers to manufacturing building components off-site in a controlled environment and assembling them on the site. Modular construction takes prefabrication to the next level and involves the fabrication of entire building modules offsite, including plumbing, electrical systems, and finishes.

ICPHs can produce prefabricated individual components such as precast columns, beams, and staircases, as well as prefabricated integrated sub-assemblies like prefabricated bathroom units (PBU), modular prefabricated mechanical, electrical, and plumbing (MEP), and prefabricated prefinished volumetric construction (PPVC) modules [6].

2.1. Brief of the Precast Production System

An ICPH often comes with an automated production line for precast production. This can be a fully automated carousel or a semi-automated pallet circulation system. Molds are placed on steel production pallets and moved from one station to another. The manufacture of precast components involves several steps: (1) mold assembly; (2) reinforcement placement; (3) concrete casting; (4) curing; (5) mold stripping; and (6) product finishing. Optimizing precast production can be modeled as a flow shop scheduling (FSP) problem, where a set of n jobs have to be processed with identical flow patterns on m machines. However, unlike traditional FSP, precast production features both interruptible and uninterruptible activities. The interruptible tasks can be paused if they cannot be finished within working hours but can be resumed the next day, for example, mold assembly, reinforcement placement, mold stripping, and product finishing. Uninterrupted tasks, such as concrete curing and casting, cannot be paused until they are finished. Some ICPHs also feature a robotic warehousing system that allows precast components to be stored and retrieved automatically without the need for manual labor.

In contrast to the automated precast production, the modular fitting out is still a manual assembly line. Once the carcass is erected, it remains in place until delivery. Workers have to carry materials and tools to locate the target jobs in a maze of rows and columns. The modular fitting-out process involves a long series of sequential stages. For example, in the case of PBU, the stages include (1) WC chair bracket and cistern installation; (2) mechanical and electrical piping installation; (3) pressure testing; (4) partition box installation; (5) ceiling access panel installation; (6) ceiling skim coat; (7) waterproofing (first coat); (8) curing (first coat); (9) waterproofing (second coat); (10) curing (second coat); (11) water ponding test; (12) marble/tile installation; (13) tiling pointing; (14) ceiling painting; (15) cabinet installation; (16) vanity top installation; (17) shower screen installation; (18) sanitary wares and accessories installation; (19) functionality check; (20) water flow and final control; and (21) wrapping. Figure 1 shows examples of the main facilities mentioned above in an ICPH.

(**a**) (**b**)

(**c**) (**d**)

Figure 1. ICPH main facilities: (**a**) carousel system; (**b**) pallet circulation system; (**c**) modular fitting out; (**d**) robotic warehousing system (photos taken by Chen Chen in Singapore ICPHs).

2.2. Severe Overstock Problem

Precast production currently operates on a confirmed order basis, following a make-to-order (MTO) approach to meet individual customer requirements precisely. While make-to-stock (MTS) supports agility, MTO supports JIT. Moreover, raw materials are purchased in advance and ready when production starts. Moreover, production time variances are minimized in a highly controlled, automated environment. When demand, raw material supply, and process time are all fixed, the output becomes more predictable. For precast fabricators, customer satisfaction is determined by their ability to deliver on time.

JIT models with limited inventory and reliance on partners to deliver products can create a very fragile supply chain that is especially vulnerable to disruptions. Thus, maintaining some inventory is beneficial for absorbing uncertainties in the supply chain system. However, precast fabricators face challenges in determining a proper safe inventory level for their finished products [7]. Due to limited space at a construction site, the customer may sometimes adjust delivery dates to align with the actual construction progress on the site. The delayed delivery of finished products may quickly deplete storage yard space due to their large volumes and heavy weights. Overstocking is a common scene in the precast industry [8].

In fact, precast fabricators clearly comprehend their issues, and they deploy drones to construction sites regularly to monitor construction progress. The issue is that current estimations and predictions rely solely on human experience and cognitive abilities, which are imprecise and have not been relied upon for decision-making. Deciding the optimal float between an early start and a late start for precast production remains a serious question.

The storage problem faced by ICPH is unique to Singapore, where land is limited, but inventory issues are common in the precast industry globally. Uncertainties in the supply chain lead to high inventory levels, despite the availability of land in other countries. High inventory levels go against the lean principle. This research is important as it provides a systematic approach to lean transformation in the precast industry.

3. Research Methodology

Elsevier's Scopus database, the largest abstract and citation database of peer-reviewed literature, was searched for relevant literature in production- and construction-related research. Compared to Web of Science, Scopus covers a more significant number of journals and includes most journal articles from the former. The search methods and results are listed in Table 1. The search field was sometimes narrowed down to "Article title" to reduce the large number of irrelevant articles. The search was categorized into four sections to find literature on the production–inventory system, construction progress prediction, supply chain collaboration, and precast supply chain review. The authors' brainstorming generated the search keywords.

Table 1. The search methods.

Category	Keywords	Search Field	Search Result	Selected Result
Production–inventory system	"inventory level" + "production"	Article title	98	4
	"JIT delivery" + "uncertain" + "production"	Article title, Abstract, Keywords	424	2
	"vendor purchase cooperation"	Article title, Abstract, Keywords	111	2
Construction progress prediction	"construction schedule" + "impact"	Article title	23	5
	"schedule" + "risk" + "precast construction"	Article title, Abstract, Keywords	24	2
	"construction schedule" + "delay"	Article title	29	8
	"construction" + "duration"+ "prediction" + "site"	Article title, Abstract, Keywords	103	7
Supply chain collaboration	"4D BIM" + "collaboration"	Article title, Abstract, Keywords	72	9
	"supply chain" + "visibility" + "construction"	Article title, Abstract, Keywords	62	6
Precast supply chain review	"review" + "precast supply chain"	Article title, Abstract, Keywords	14	2
	"review" + "offsite construction supply chain"	Article title, Abstract, Keywords	25	8

Initially, 985 articles were found. By screening the titles and abstracts of these articles, 55 articles were selected based on their relevance to the research topic and typicality. Their distribution with the source of publication is shown in Table 2. The authors aim to answer the following research questions from the review results:

1. How should the minimum finished product inventory level be calculated?
2. How should production be scheduled when the due date is uncertain?
3. How can the progress of the construction be predicted?
4. How can stakeholder collaboration be improved in the precast supply chain?

Table 2. Distribution of the literature with the source of publication.

No.	Journal	Quantity
1	Automation in Construction	6
2	Construction Innovation	4
3	Journal of Cleaner Production	4
4	Journal of Construction Engineering and Management	4
5	Journal of Management in Engineering	3
6	Buildings	2
7	Journal of Building Engineering	2
8	International Journal of Production Economics	2
9	Construction Management and Economics	1
10	Engineering, Construction and Architectural Management	1
11	International Journal of Construction Management	1
12	Building and Environment	1
13	Smart and Sustainable Built Environment	1
14	Built Environment Project and Asset Management	1
15	Advances in Civil Engineering	1
16	Journal of Information Technology in Construction	1
17	Journal of Civil Engineering and Management	1
18	KSCE Journal of Civil Engineering	1
19	Journal of Financial Management of Property and Construction	1
20	CivilEng	1
21	International Journal of Production Research	1
22	International Journal of Operations & Production Management	1
23	Supply Chain Forum: An International Journal	1
24	Advanced Engineering Informatics	1
25	ARPN Journal of Engineering and Applied Sciences	1
26	Computers in Industry	1
27	Applied Mathematical Modelling	1
28	Sustainability	1
29	Conference	8

Addressing the above questions aims to decrease inventory levels in the production system, thus eliminating the need for extensive storage and resolving the bottleneck of mass-producing ICPHs.

4. Research Findings

The following section summarizes the main findings from the literature review. It describes relevant models, algorithms, methods, and techniques. The discussion is divided into three areas: (1) the production–inventory system; (2) construction progress prediction; and (3) supply chain collaboration. By gaining an understanding of the current state of relevant research and progress, it is hoped that a systematic methodology can be developed, and future research directions can be identified.

4.1. Production–Inventory System

A pull system is a lean technique and a prerequisite for JIT. The following subsections explain the necessity of buffers, methods to reduce them, and the significance of vendor–buyer cooperation.

4.1.1. Strategic Buffers

Maintaining a specific level of safety inventory is beneficial for agility, customer satisfaction, and preventing disruptions in construction progress. Betts [9] used simulation to calculate the amount of safety inventory required to meet customer demand with a certain probability. The demand follows a specific distribution, and production is limited to a maximum capacity per period. Because demand is random, there will be periods with a shortfall. Betts estimated the shortfall distribution to address inefficiencies in simulation-based approaches. Once the shortfall distribution is known, the service level obtained with a certain inventory target level can be calculated directly. Computational experiments demonstrate that the model's accuracy only slightly decreases when the production system faces increased production constraints or demand variability.

To deal with the impact of delivery uncertainty, a supply chain can adopt the time buffer policy and emergency borrowing policy in addition to the inventory buffer policy. JIT is managed through logistic triggers and work-in-process (WIP) inventory levels using Kanban. Demand information flows through all processes using Kanban, while logistics operate in the opposite direction, supplying necessary parts from the first production process to meet the needs of the next process. In a JIT environment, Chiu and Huang [10] suggested using an emergency borrowing policy along with a time buffer policy. In the precast industry, this implies that multiple precast factories collaborate. In the event of a shortage, a factory can borrow products from nearby ones. Today, multi-factory operations are a hot topic in precast supply chain research [11].

4.1.2. Buffer Reduction

Though buffers are necessary in the lean concept, they are a kind of waste, and minimizing them is the optimization goal. To reduce inventory, a strategy involves delaying production as much as possible. In research by Ko [7], fuzzy logic is used to evaluate a time buffer to prevent the fabricator from reaching full capacity. Production due dates are then adjusted to synchronize the erection schedule with lower inventory based on the evaluated buffer. This adjustment results in the production curve moving closer to the erection curve (see Figure 2). Once the production due dates are set, the final challenge is to complete products according to the due dates. A multi-objective genetic algorithm (MOGA) is used to develop schedules simultaneously minimizing cost and production duration. In the literature, precast production is often modeled as a flow shop scheduling problem, and GA is the most commonly used optimization algorithm for solving it [12].

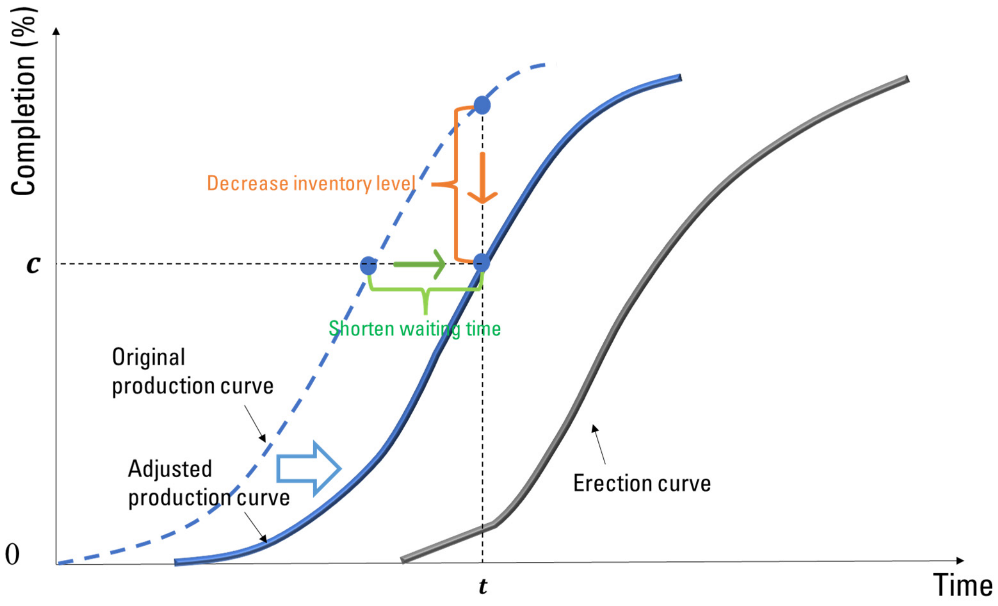

Figure 2. Production strategy used to reduce inventory level.

Meanwhile, orders with the same due dates can have different priorities. For example, production for orders with high due date uncertainty and orders from construction sites with high uncertainties can be started later than similar due date orders. Since traditional dispatching rules such as earliest due date (EDD), critical ratio (CR), and shortest processing time (SPT) do not consider the due date uncertainty, Kim et al. [4] have proposed a new dispatch rule based on EDD that considers the uncertainty of due dates and the penalty for tardiness. The rule is designed for precast production, which often suffers frequent due date changes.

Having a dynamic rescheduling mechanism is also essential for a more effective response to due date changes and production emergencies. Two issues must be addressed before rescheduling: how and when to respond to unexpected changes. Rescheduling is defined as modifying an existing scheduling scheme to minimize the impact of emergencies on the production system. There are three common rescheduling policies: periodic, event-driven, and hybrid. Wang et al. [12] summarized the representative research literature on precast production rescheduling. While a static production scheduling mechanism improves leanness, a dynamic rescheduling mechanism enhances agility. Finally, the combination of the two creates a "leagile" system.

In summary, methods to reduce inventory can be summarized as follows: first, evaluate buffers to account for demand uncertainty; second, shift the production schedule closer to the assembly date; third, optimize production scheduling to align with inventory planning [13].

4.1.3. Integrated Production–Inventory Model

JIT is characterized by small lot sizes, frequent delivery, short lead time, and a close relationship between vendor and buyer. In order to achieve JIT, researchers have proposed integrated production and inventory models to allow the vendor and the buyer to form a strategic alliance for profit sharing, assuming a central decision-maker for total system optimization. The integrated inventory model is created for a vendor's production scenario, where production begins once an order is placed. Instead of using a lot-for-lot production policy, the vendor may find combining multiple lots into one production batch more cost-effective due to the relatively high set-up cost. The results of the experiment show that when an optimal joint inventory replenishment policy is implemented, it leads to a reduction in the vendor's production batch size. When setup costs decrease at the same time, shipment sizes also decrease, eventually creating a true pull production–delivery system. This leads to significant economic benefits for both parties [14].

Jha and Shanker [15] looked into this problem. During one production cycle, a constant number of units are added to the inventory over a certain number of times to meet the demands of all the buyers. The cost of crashing lead time is borne by the buyer. Once the optimal value of shipment size is established, the optimal order quantity for all the buyers can be determined. Jha and Shanker used a Lagrangian multiplier technique to evaluate the limited number of combinations of lead time of the buyers to find, simultaneously, the optimal lead time, the order quantity, the buyer's safety factor, and the number of shipments between the vendor and the buyer in a production cycle. The model could be applied to precast production for long-term building projects with many similar designs.

When the vendor is the decision-maker who determines the order size to meet the customer's predetermined inventory range, this is known as vendor-managed inventory (VMI). It includes a service level constraint for each buyer, and orders are placed whenever the inventory level drops. Accurate and timely forecasts of customer needs can help organize inventory management better. Researchers commonly employ the so-called rolling horizon framework to account for uncertainty in future demand. The idea is to address the problem within a defined planning period based on current knowledge of the future. Only the most immediate decisions are set, while the updated information re-evaluates subsequent decisions at later optimization stages. As such, the problem is solved periodically throughout the planning horizon based on regularly updated information about customer orders and due dates.

Ghasemi et al. [16] categorized the customers as MTS, MTO, and VMI and implemented different strategies for each category. They formulated the problem as a mixed-integer linear programming (MILP) model, aiming to minimize total costs while improving the overall system efficiency. This involved ensuring the timely satisfaction of all VMI customers, maintaining the service level target for MTO customers, and controlling the acceptance rate for MTS customers. The model could be applied to future precast production systems when building components become more standardized, as Chen et al. [17] discussed.

Even though the vendor and buyer may collaborate, they may also have personal reasons not to follow the agreement, which can lead to a situation where they are not cooperating. When the buyer's cost of holding inventory is higher than the vendor's, it is not possible to instantly distribute final products from the vendor's stock to the buyer's stock. The buyer keeps receiving shipments just to run out of stock, like the situation in the precast industry. Then, the size of the batches transferred between the vendor and the buyer becomes a competitive dynamic. In each production cycle, the sizes of successive shipments from the vendor to the buyer either increase by a factor equal to the ratio of the production rate to the demand rate (the vendor dominates the buyer) or are equal in size (the buyer dominates the vendor). Bylka [18] examined the problem from a game theory perspective and constructed Nash equilibrium strategies. Game theory models have been popularly applied to optimize coordination between stakeholders in the precast supply chain [19].

Tennakoon et al. [20] addressed the limitations associated with current procurement methods used in construction projects. These methods include design-build (DB), integrated project delivery (IPD), negotiated-bid (NB), management contracting (MC), and engineering–procurement–construction (EPC). They emphasized the necessity of adjusting the procurement strategy to account for the increasing importance of precast manufacturers in shaping industry behavior. The lack of an appropriate strategy increases business risk and results in imbalanced risk distribution with other stakeholders, which also affects long-term relationships [21].

4.2. Construction Progress Prediction

The construction industry is experiencing project delays. Many factors affect construction project performance, and frequent delays disrupt upstream precast production schedules. If project activities on the critical path are delayed, it will impact the overall project completion date. Researchers have dedicated significant effort to studying the delay problem from various perspectives in recent decades. The following subsections cover the reasons for delays, how delays are analyzed, and methods for preventing delays.

4.2.1. Delay Causes

Amarkhil et al. [22] summarized fourteen inherent delay causes in construction project activities: (1) communication and coordination; (2) corruption and bureaucracy; (3) decision-making and approval; (4) design and specification; (5) experience and knowledge; (6) financial and price escalation uncertainty; (7) management and performance; (8) planning and scheduling; (9) political and security problems; (10) regulation and contract requirements; (11) risk assessment and uncertainty; (12) resources availability; (13) scope change and work variation; and (14) weather and climate.

Hwang and Leong [23] categorized the schedule delay causal factors into eight groups based on the literature review. These groups are as follows: (1) project-related factors; (2) client-related factors; (3) design-team-related factors; (4) consultant-related factors; (5) contractor-related factors; (6) labor-related factors; (7) equipment- and material-related factors; and (8) external factors. From a survey, they further identified the top five factors causing delay in green construction projects are as follows: (1) speed of decision-making by the client; (2) speed of decision-making involving all project teams; (3) communication and coordination between key parties; (4) level of experience of consultants; and (5) difficulties in financing the project by contractors.

In addition, Larsen et al. [24] identified the five main causes of delay in public construction projects as follows: (1) unsettled or lack of project funding; (2) delay or long process times caused by other authorities; (3) unsettled or lack of project planning; (4) errors or omissions in construction work; and (5) lack of identification of needs.

Moreover, Won et al. [25] discovered that the top five risk factors with a high impact on the schedule performance of high-performance group (HPG) projects are as follows: (1) overall construction method difficulties; (2) design accuracy provided by the employer; (3) weather and climate uncertainty; (4) administrative approval and licensing delays; and (5) corruption, collusion, and underground deal practice. On low-performance group (LPG) projects, the top five risk factors with a high impact are as follows: (1) insufficient period for construction completion; (2) IT-based project management difficulties; (3) weather and climate uncertainty; (4) insufficient project management capability of the employer; and (5) insufficient organizational management capability. Construction projects were categorized as either HPG or LPG based on profitability, calculated as the difference between the contract amount and actual execution cost.

According to Li et al. [26], schedule risks associated with precast construction primarily stem from project scale, resources, and management. Project scale refers to the specific quantities of housing construction. Changes in project scale would lead to changes in resource demand. Precast construction can only be executed smoothly with adequate resources. Meanwhile, management is related to operational efficiency and quality issues. In addition, Xie et al. [27] identified seventeen reasons for schedule delays in precast construction projects through a literature review. They classified these reasons as owner-related, general-contractor-related, and external-environment-related. Moreover, Cho et al. [28] identified that one of the main problems leading to schedule delays in precast construction is the lack of using building information modeling (BIM) for schedule management, in addition to the insufficient experience of the contractor in precast construction.

In summary, schedule risks are diverse and can arise at any project stage [29]. Tennakoon et al. [30] revealed that insufficient up-to-date knowledge of skilled labor, poor readiness for uncertainties, absence of a suitable procurement model, lack of end-to-end visibility of the supply chain, and the absence of national or government standards are key issues in the current precast supply chain. Wuni et al. [31] also mentioned stakeholder fragmentation and management complexity.

4.2.2. Delay Analysis

Construction projects generate a significant amount of data that can be used to predict future activity durations and gain insights into the project. Previous researchers [32–34] have relied on regression methods for construction time prediction. However, recent studies now use data mining technologies to identify and measure key factors influencing construction progress. This is achieved by analyzing contract documents, bills of quantities, requests for information, site instructions, and meeting minutes. Among various data mining algorithms, random forest (RF) has been found to have superior prediction accuracy for construction duration compared to algorithms such as k-nearest neighbor (KNN), logistic regression, decision tree, neural network, support vector machine (SVM), and naïve Bayes [35].

It was found that more accurate prediction models were created by using raw data [35]. However, the lack of data standardization is a common issue in the construction industry. Project documents vary from one project to another. Even when projects were completed for the same client, and the basic formats were the same, the level of recorded information varied. By providing a standardized information model, digital twins allow for more powerful data mining. It was found that data from radio frequency identification (RFID) and BIM significantly improved the accuracy of RF prediction [36]. Alongside machine learning, the predictive ability of computationally expensive simulation models can also be enhanced in a data-driven fashion [37].

Successful experience and valuable information from previous projects can be leveraged to address delay problems in current projects. Although each project may have its own unique features, the approaches and procedures for addressing problems in construction projects are generally similar. Case-based reasoning (CBR) has emerged as a promising technique for this purpose [27]. CBR is a reasonable technique that uses past solutions to solve similar new problems.

Various methods have been developed to measure delay-based losses and apportion the responsibility for these losses to each contracting party. These methods include global impact, net impact, impacted as-planned, as-planned versus as-built, windows analysis (WA), time impact analysis (TIA), collapse analysis, as-planned but-for daily window analysis, daily WA with multiple baseline updates, modified but-for, isolated delay type, isolated collapsed but-for, delay analysis method using delay section, accumulated delay analysis method, effect-based delay analysis method, and stochastic delay analysis and forecast method (SDAF). However, these methods have many drawbacks, as criticized by Cevikbas et al. [38]. Based on the drawbacks identified, Cevikbas et al. proposed a new method, namely, modified schedule versus modified updated schedule (MSvsMUS).

With BIM providing a comprehensive data-rich digital representation of the building, many researchers are developing progress evaluation methods to quantify the risk of schedule delays in an automated way, enabling project managers to take proactive measures to minimize potential delays and ensure successful project delivery. For example, Zhang and Wang [39] developed a second-order reliability method (SORM) for progress evaluation. They assumed that the task duration follows a PERT-Beta distribution characterized by three parameters. This approach allows for the analysis of the likelihood of the actual project duration exceeding a specified project duration using probabilistic methods. The SORM utilizes Newton's method to locate the most probable point within the failure domain. To address the time constraints associated with iterative computation, a differentiable surrogate function was utilized to improve the efficiency and accuracy of estimation.

4.2.3. Delay Prevention

Floats are meant to absorb local delays and safeguard the project timeline. The term "float" includes periods of idleness and planned buffers, which are limited consumable time periods. The contract float is the contract due date minus the project finish date. Su et al. [40] investigated the fair allocation of contract floats at the activity level through Monte Carlo simulations. They devised an algorithm inspired by political apportionment methods to allocate floats to activities according to their delay risk scores. Since sequential activities are likely to be affected by common factors, the correlations between them are represented using a Gaussian copula. Since the deterministic critical path method (CPM) cannot quantify the influence of float loss in noncritical activities that is within the total float values, Sakka and El-Sayegh [41] tackled this problem through stochastic analysis using Monte Carlo simulations.

Researchers [42] have found that reducing variability in task durations and resource/information availabilities is beneficial for generating a reliable construction schedule. Recently, takt planning has been proposed with the last planner (LP) implementation [43]. Takt refers to the pace at which work progresses. Unlike using time buffers in the schedule, takt planning concentrates on the project's overall delivery performance and capacity buffers. This involves underloading production resources to less than 100% utilization so that there can be standby capacity to promptly address any negative impacts of variation.

Song et al. [44] suggested involving contractors in both early design and construction to improve construction schedule performance. It is crucial to incorporate construction knowledge and experience into the design process. Neglecting to consider how a contractor will execute the design can lead to scheduling issues, delays, and disputes during construction, ultimately impacting the overall project performance. The Singapore construction industry also adopts the design for manufacturing and assembly (DfMA) concept to promote precast construction. DfMA is a key pillar of Singapore's construction industry transformation map (ITM).

4.3. Supply Chain Collaboration

Various digital technologies support an efficient, agile, and resilient supply chain. Cheng et al. [45] conducted a thorough review of them. The following subsections discuss four-dimensional (4D) BIM (3D plus time) technologies and radio frequency identification (RFID)-enabled visualization.

4.3.1. 4D BIM

BIM, with its virtual and centralized information model, has the potential to reduce fragmentation and promote better collaboration within the construction industry. This allows stakeholders such as architects, engineers, constructors, and clients to work together more efficiently. Sampaio et al. [46] highlighted several advantages of BIM implementation, including the ability to overlay different models (architectural, structural, and MEP), the elimination of potential conflicts between disciplines, the creation of realistic visualizations of the interior and exterior, easier quantity-take-off of materials, and the facilitation of construction activity planning through 4D modeling.

Successful BIM implementation requires the timely sharing of the latest information among stakeholders. This involves keeping information in a centralized database. Along with the 3D BIM model, additional information in the added dimensions should also be maintained in a centralized manner. Web and database technologies can support this. However, web-based BIM model visualization often requires a significant amount of time to load the BIM model files. To overcome this file-loading challenge, various methodologies, including the use of the web graphics library (WebGL) for sharing daily BIM information in construction, have been tried. Park et al. [47] also proposed an automated update mechanism based on progress status information to ensure the daily 4D BIM models are updated to reflect the actual project's progress.

As construction projects become larger and supply chains more complex, logistics has quickly become critical in ensuring project success. Construction logistics management involves strategically storing, handling, transporting, and distributing resources. It also includes planning the layout of a building site and actively managing and adjusting the site layout as construction progresses. Utilizing 4D BIM can significantly improve the management of construction logistics [48]. The successful implementation of 4D BIM in construction logistics management requires highly accurate and updated 3D models as a prerequisite. Effective clash detection can only be achieved through meticulous plotting, accurate modeling, and an up-to-date logistics plan.

Because individual observations and text-based documentation can cause information delay and inconsistent data, studies [49] have suggested using photogrammetric 3D mapping with unmanned aerial vehicles (UAVs) equipped with attached cameras, such as drones, for construction progress monitoring. Researchers [50] have shown that it is feasible to automate spatial data collection fully, as well as registration from various locations using UAVs without human intervention. By providing improved visualization and process transparency, this approach reduces non-value-adding activities and defects, aligning with lean construction principles [51].

Extended reality (XR) and its subcategories, such as virtual reality (VR), augmented reality (AR), and mixed reality (MR), can serve as media that enable stakeholders to access, present, and exchange information for multi-hub and multi-platform collaborative meetings [52]. The integration of XR into BIM goes beyond visualization, with some research exploring the two-way link between BIM and XR using OpenBIM technology [53]. The BIM collaboration format (BCF) is a key tool, leveraging the Industry Foundation Classes (IFC) data as one of the main components of OpenBIM.

Although a centralized repository supports the common data environment (CDE), making data management and sharing easier, it also poses cybersecurity risks due to data manipulation. Recent studies suggest that data can be distributed across multiple nodes, eliminating the need for a central authority. Integrating BIM with blockchain, a decentralized database technology emerges as the solution [54]. OpenBIM processes need to be managed by the blockchain to ensure that all changes are traceable.

4.3.2. RFID-Enabled Visualization

Tracking a wide range of construction resources in challenging work environments is both difficult and time-consuming. In the past, simple information technology tools such as Microsoft Excel and Project, as well as enterprise resource planning (ERP) systems like SAP or Oracle were used to help with coordination. However, their use was often unsystematic and sporadic and required considerable amounts of time to share information. An industry survey by Dharmapalan et al. [55] showed that the overall visibility in the offsite construction supply chain was low. Nowadays, BIM and RFID technologies are being widely used to improve the visibility and coordination of construction supply chains [56]. Improved supply chain visibility enables the development of practical future plans. Furthermore, automated tracking relieves site superintendents and construction engineers from manual observations.

RFID systems are composed of three main components: an RFID tag, a reader, and a back-end database. RFID tags are available in three types: active, semi-active, and passive. Of the three, passive tags are the cheapest. Passive tags can be further classified into two distinct groups: chipped and chipless. Among the two, chipless tags are cheaper. Additionally, they are more durable in harsh environments due to their lack of a microchip. Therefore, chipless RFID tags are recommended for use in the offsite construction system [57].

Passive tags have neither a power source nor an antenna, limiting their reading range and data capacity. Consequently, one of the main challenges associated with this kind of RFID system is precision in localization. The determination of tag locations depends on geometric relationships. The spatial arrangement of tags is used for localization. However, these methods are sensitive to environmental factors, requiring complex algorithms and often experiencing accuracy issues due to multipath effects. Many researchers have studied this problem. Recent research endeavors have introduced innovative concepts, such as virtual reference tags and machine-learning algorithms [58].

With RFID technologies, digital twins are developed for various physical objects in the construction supply chain. Greif et al. [59] distinguished digital twins into three levels of complexity: lightweight digital twins, which reflect simple structures and do not contain unnecessary details; multi-physics, multi-scale simulation systems, which combine models, data, and information; and autonomous systems, which enable decision automation without reconfiguration even for unexpected situations. The lightweight digital twin is recommended for non-high-tech industries such as our construction industry to integrate into the decision support system for regular logistics operations involving pickups, deliveries, and replenishments. Ontology allows key concepts and terms relevant to a given domain to be identified and defined in an open and unambiguous way [60]. Building a supply chain ontology is the solution to providing consistent information for digital twins.

5. Proposed Solution

Based on the literature review's findings, Figure 3 shows the proposed solution to address the low-capacity utilization issue at Singapore's ICPHs. The main concept of the proposed solution is to implement an integrated supply chain system model with a central decision-maker. It is recommended that precast factories play a more active role in decision-making. Establishing this integrated system relies on trust and information sharing, which cutting-edge digital technologies can facilitate.

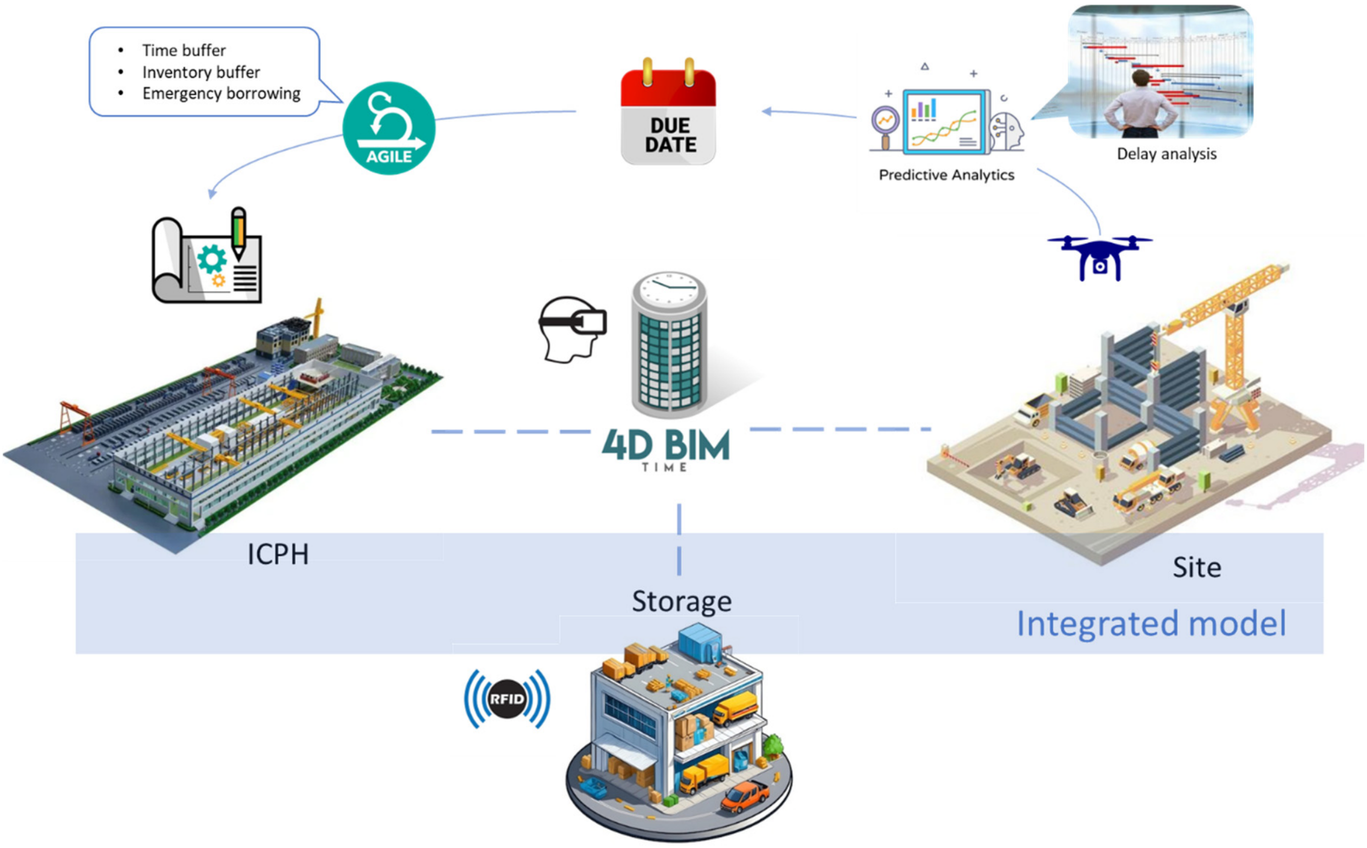

Figure 3. The proposed solution.

First, a close vendor–buyer relationship should be established to facilitate adopting an integrated production and inventory management model. It is better to have a central decision-maker who can optimize the performance of the entire supply chain. When both sides make independent decisions, the outcome is less effective than when a central decision-maker is involved. Since factories clearly understand their production constraints and are highly motivated to minimize inventory levels, it is recommended to have the central decision-maker come from the vendor side. As such, rather than buyers setting due dates for their orders and vendors arranging production accordingly, vendors are to decide when they should deliver their products to meet the customer needs based on their predictions of customer progress schedule. As a prerequisite, buyer trust in the vendor is essential, and this trust is established through information sharing and transparency. The growing importance of vendors in supply chain management necessitates the re-engineering of business processes, new contract arrangements, and updated regulations and guidance.

Second, a 4D-BIM platform is needed to provide a clear vision for project execution. 4D-BIM-enabled XR improves project perception through visual, auditory, tactile, and other senses so as to easily detect scheduling deviations. Creating a 4D model requires complementing BIM with specific planning software. However, the lack of interoperability between BIM authoring tools (e.g., Revit, ArchiCAD, Bentley), BIM management tools (e.g., Navisworks, Syncro Pro), and legacy scheduling tools (e.g., Primavera, MS Project) results in a lot of extra work when modifying any activity or 3D elements, leading to numerous manipulations, adjustments, and repeated planning process. Additionally, updating daily progress information and performance data regarding the construction work, as well as context-specific information and documents on scheduled tasks, requires a tedious routine and considerable responsibility. Due to the complexity of 4D planning methods, the use of 4D BIM is currently limited to small projects with few activities.

Third, it is suggested that an agile production planning strategy be implemented to better accommodate changes in due dates. The precast factory can improve its flexibility by implementing appropriate time buffers, inventory buffers, and emergency borrowing policies. Orders can be categorized (e.g., VMI, MTS, MTO) and managed using different strategies: VMI focuses on timely satisfaction, MTO focuses on service level, and MTS focuses on acceptance rate. Also, orders with the same due dates can be prioritized based on the level of uncertainty. Orders from construction sites with high uncertainties can be started later than orders with similar due dates. Moreover, a rolling horizon framework can be applied to handle uncertainty in demand. It is important to develop scheduling models that consider realistic scenarios to optimize production in line with the buffer plan. A shorter makespan enables a swifter response to changes. Along with the static scheduling mechanism, a dynamic rescheduling mechanism is also essential to mitigate the negative impacts of unexpected events.

Fourth, it is advisable for precast factories to proactively anticipate customers' actual demand to assist with their production decisions. By clearly understanding their customers' construction schedule and actual progress, factories can plan and schedule their production activities accordingly to satisfy their customers. Demand prediction can be based on delay analysis, as deviations from the original plans matter. Since delay schedule risks are diverse and can arise at any project stage, data-driven delay management depends on a data lifecycle viewpoint. Despite the differences in each building project, they all face common causes of delays. Using knowledge from past cases is generally easier than creating predefined rules, which can be difficult and time-consuming. It is feasible to reuse results from similar cases. Therefore, it is possible to develop an automated tool for identifying and assessing delay risks by leveraging machine learning and simulation technologies on project data and historical case databases.

Lastly, automated data collection is essential to accomplish the above. Drones make automating progress tracking and remotely monitoring construction sites easier than ever. Singapore's ICPHs have regularly applied drone surveys on their customers' sites. However, the data collected by the drone are currently only used for the factory's internal reference and not for decision-making. Without a mutually accepted reliable technology to interpret customer demands from the data, factories have no power to argue about due date issues with their customers. Additionally, the VMI policy has not yet been implemented.

Meanwhile, RFID technology improves visibility throughout the supply chain by providing real-time information on the movement and status of various resources, including labor, materials, and tools. Nowadays, Singapore government agencies such as the HDB and the Land Transport Authority (LTA) have mandated using RFID in their projects. In the early days of RFID, there was a misconception that it was a proprietary technology without standards. However, today, there are numerous standards that ensure diverse frequencies and applications. Singapore adheres to ISO standards as the national standard for RFID data construct requirements. The remaining issues concern how to utilize the RFID data to create a digital twin that enables levels of detail in terms of visibility.

6. Conclusions

Singapore has made significant investments in ICPHs with the aim of transforming the construction industry from labor-intensive to high-tech. These ICPHs are equipped with the latest technologies and represent the industry's highest level of mechanization and automation. However, the ICPHs are currently operating well below their intended capacity, contrary to the initial expectations of mass production. The reason for this is the shortage of storage yards for finished products on the island, which disrupts continuous production in the factories. Therefore, this paper aims to address the problems faced by ICPHs by conducting a comprehensive literature review. Based on the literature review's findings, a solution is proposed, aiming at solving this problem completely.

The literature review covers the production–inventory system, construction progress prediction, and supply chain collaboration. As shown in Figure 3, the proposed solution involves implementing an integrated production–inventory model, a 4D BIM, an agile production planning strategy, a machine-learning-based prediction for delays, and utilizing UAV and RFID technologies. Then, the initial research questions are addressed as follows:

How should the minimum finished product inventory level be calculated? The minimum level of finished product inventory can be calculated using the simulation method. Because demand is random, there will be periods with a shortfall. Once the shortfall distribution is known, the service level obtained with a certain inventory target level can be calculated directly. Orders are classified and handled using different strategies to meet customer satisfaction. A new dispatch rule is suggested to be designed that considers the uncertainty of due dates and the penalty for tardiness.

How should production be scheduled when the due date is uncertain? An agile production planning strategy should be implemented to adapt to changes in deadlines quickly. This agility can be achieved by incorporating time buffers, inventory buffers, and emergency borrowing from other factories. The uncertainty in customer demands is dealt with using a rolling horizon approach. The precast supply chain system is designed as an integrated production–inventory system, assuming a collaborative vendor–buyer relationship. A central decision-maker is responsible for optimizing the entire system. By clearly understanding customer demands, we can determine the expected values of the optimal lead time, order quantity, buyer's safety factor, and the number of shipments between the vendor and the buyer in a production cycle.

How can the progress of the construction be predicted? Machine learning algorithms can predict the progress of construction projects by analyzing the variance between actual progress and the initial schedule. They can identify and assess the risks of delays by mining project data. The reasons for construction project delays are usually similar regardless of the specific nature of each project. Therefore, successful experiences and valuable information from previous projects can be used to address delay issues in current projects.

How can stakeholder collaboration be improved in the precast supply chain? Digital tools can enhance stakeholder collaboration. The 4D BIM enables the visualization of each project stage by integrating 3D models with the project schedule. This allows stakeholders to gain a comprehensive overview of the entire process and stay informed about everything happening (or about to happen) on-site. RFID systems can track and identify the location and movement of personnel, materials, and tools at any time point. Drone photogrammetry enables automated progress tracking and the remote monitoring of construction sites. The implementation of these digital technologies improves visibility in the supply chain, fostering trust and building strong relationships among stakeholders.

Future research should prioritize interoperability and ontology in 4D BIM, integrated production–inventory management, agile planning buffers, and data-powered delay analysis through machine learning. Continuous digital transformation efforts are appreciated to achieve the proposed solution's success. ICPH's performance improvement can be measured by monitoring on-time delivery rates and inventory levels, which directly impact customer satisfaction—the factory's primary objective.

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