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Inventory Management of Concrete Components on Construction Sites

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Abstract: The construction industry in Thailand has proliferated over the past 20 years, leading to high competition. Reducing avoidable costs is one solution for staying competitive in the market. In a construction project, material costs comprise over half of the total cost. Concrete is a key onsite material with high annual consumption and inventory cost. Therefore, appropriate concrete management is essential for construction project economic efficiency. This study develops a system dynamics (SD) model to examine concrete component inventory management on site to minimize long term total inventory costs. Key criteria affecting total inventory cost include order quantity, demand, lead time, safety stock, reorder point, storage area, transportation, holding, ordering, and material. Simulation results show that with appropriate inventory management, specifically in order quantity, cement price, storage space, and rework percentage, construction companies may reduce total inventory cost and achieve effective long-term inventory planning. The SD model developed is validated by sensitivity analysis. However, study results should be implemented on sites to further validate the developed model and adjust parameters to suit current practices.

Keywords: Concrete component, construction site, inventory management, system dynamics modeling.

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1. Introduction

Construction is one of Thailand's largest industries, playing an essential role in national economic growth, with a gross domestic product (GDP) increase of 6.5% from 2016 to 2020 (Mordor Intelligence, 2022). The industry was not severely affected by the Novel Coronavirus 2019 (COVID-19) pandemic and remains strong, with annual value-added increasing by 8.6% during the first half of 2021 (Global Information, 2021). This leads to high industrial competitiveness, with construction companies obliged to implement marketing practices to reduce cost overruns and achieve highest profits. Different costs associated with construction projects include land acquisition, machine and equipment, labor, administration, material, and inventory (Gerasimova, 2020). According to Nanaware et al. (2017), 60% of construction costs include material and inventory management costs. Appropriate inventory management, supply unit efficiency, and timely deliveries are key factors influencing construction work efficiency (Rzepecki, 2019).

Company inventory management systems affect profits directly and indirectly (Rose and Ondara, 2020). Inventory management covers the areas of finance, procurement, and selling, which must be harmonized to achieve effective inventory management. Generally, materials are ordered in big lots and kept onsite to meet unexpected demands and avoid price increments. High inventory holding costs may be incurred and construction productivity reduced due to immoderate storage area requirements. Good inventory management makes materials available when needed at the right time and place. It also facilitates work planning, increases work productivity, improves space utilization, and reduces total inventory cost. Diverse methods may be used to manage construction site inventory, such as ABC analysis, first-in, first-out (FIFO), just-in-time (JIT), and cycle counting (Chinda, 2021). For example, Zeb et al. (2017) used ABC analysis to manage inventory of Pakistani construction companies, concluding that concrete and steel are categorized in group A and should be procured accordingly. Patil and Dhawale (2018) examined the significance of, and obstacles to, JIT adoption in construction projects and concluded that executing the JIT technique diminished stock level, capacity space, and cost issues. Pro Crew Schedule (2021) suggested using ABC analysis with cycle counting to identify the most profitable and essential construction inventory and ensure no inventory loss on sites. Jakkraphobyothin et al. (2018) concluded four key factors affecting inventory management: performance, cost, strategy, and inventory policy, to achieve high competitiveness in the Thai construction industry.

Although many research studies have been conducted in construction inventory management, interactions among key factors influencing inventory management and their long-term impact have yet to be explored. Dynamic changes in those key factors, such as price changes, delivery delays, and fluctuating demand, require methodical planning for effective inventory management to cope with potential feedback loops. For example, lower unit pricing of cement may generate larger order quantities to achieve the economy of scale. This in turn may affect delivery time and storage space required to stock cement. If onsite space available is insufficient, order quantities must be adjusted, and unit costs may increase. Therefore, this study develops a system dynamics (SD) model to examine and manage inventory on construction sites in Thailand. The study focuses on inventory management of concrete as a significant material on sites, deemed a class A item (Zeb et al., 2017). Concrete considered in this study is based on batching or mixing on sites by hand, concrete mixer, or batching plant. It is typical for construction in many developing countries, including Nigeria and Bangladesh (Chakraborty and Farhan, 2022; Aguwa, 2010). The goal is to better understand key factors influencing inventory management of concrete components in construction companies and formulate inventory management plans for concrete components to achieve the best long-term economic output.

2. Literature Review

Concrete is an important material described as a class A item in construction sites. Strict inventory control, efficient consumption forecasting, and accurate storage allotment are needed to properly manage onsite concrete component inventory. Ravanshadnia and Ghanbari (2014) agreed that concrete is a principal material in construction projects, so that meeting sought-after quantity and quality is vital. Berry (2022) mentioned that concrete is used in many steps of construction work: foundation, piling, slab construction, and architectural features. It is composed of sand, rubble, and cement with a standard mix ratio of 1:2:4, respectively (CMU, 2022; Pro Crew Schedule, 2020; MT Copeland, 2020). To ensure availability of concrete when needed, inventorying sand, rubble, and cement is essential. Inventory control for these materials should lead to optimal use of materials, economizing production energy, reducing material loss, and saving ordering and warehousing costs. Low inventory may not meet unexpected demands and severely impact project schedule. By contrast, surplus inventory may increase costs and decrease construction productivity due to excessive storage areas.

Different studies identify factors influencing inventory management on construction sites. Ravanshadnia and Ghanbari (2014) mentioned that economic order quantity (EOQ) and reorder point (ROP) were crucial in effectively planning inventory management on sites in Tehran. Xu (2016) used EOQ, demand, and costs of ordering, holding, and material for inventory management in Chinese construction projects. Lu and Chen (2015) identified key factors of inventory cost of an engineering project in China, including productivity, material supplier inventory, lead time, EOQ, demand, storage, site storage, transportation, procurement, ordering, and inspection. In this study, nine factors influencing concrete component inventory management on sites are extracted from the construction-related literature: 1) order quantity; 2) lead time (LT); 3) ROP; 4) material demand; 5) delay; 6) storage area; 7) holding; 8) ordering; and 9) material cost.

- Order quantity: It is used to determine volume and frequency of orders required to satisfy a given demand on a construction site while minimizing cost per order. It is designed to help companies to reduce ordering and holding costs and balance stock. It depends on annual demand, ordering cost, holding cost (represented by percentage of unit price), and discount, if any (Chinda, 2021); see Eq. (1) where Q = order quantity (units/order), D = annual demand (units/year), S = ordering cost (baht/order), I = holding cost (%), and P = price (baht/unit). The best order quantity is the amount providing the lowest total cost, including annual ordering, holding, and product costs.

$$Q = \sqrt{2DS/IP} \tag{1}$$

- Lead time: It is the time from order release to reception. It should be concised as delivery delays may hold back work scheduling (Multanen, 2011; Lu et al., 2016). In this study, material delivery lead time is set at one day, as orders are usually made and delivered from local shops near construction sites, with safety stock unnecessary.

- ROP: the point at which action is taken to replenish the stocked item. It provides information on when to place the order and depends on daily demand and lead time; see Eq. (2) where ROP = reorder point (units), d = daily demand (units/day), and LT = lead time (days) (Chinda, 2021).

$$ROP = d \times LT \tag{2}$$

- Material demand: As construction work differs periodically, material demand is nonstationary or dynamic in practice (Lu et al., 2016). Rework could delay work progress and may result in higher material demand.

- Rework: It causes construction delays, resulting in time overruns and interrupting schedules of subsequent projects. After workers are experienced with learning processes, rework and delay may be reduced (Upkeep, 2020). In this study, a learning curve of 80% is used, so that rework should decrease by 20% each time repeated projects are doubled (Martin, 2022; Faithful and Gould, 2015).

- Storage area: Construction projects vary according to site conditions and sizes, storage spaces, and project sizes. A good layout planning strategy may produce high productivity in material storage (Misron et al., 2018).

- Holding cost: It is associated with holding inventory over time and may include warehouse rental, labor, transportation, depreciation, and damage (Callarman, 2020). It can range from 15-40% of inventory value (Chinda, 2021). Overstocking causes high holding costs; stockout, however, increases the risk of lost sales.
- Ordering cost: It includes supplies, order processing, and purchasing (Chinda, 2021). Large order quantities may lower this cost. This, however, increases the holding cost (Kumar et al., 2018).
- Material cost: It accounts for over 40% of total cost. Saving material costs by efficient material management may lead to considerable savings in total cost (Deepa et al., 2019). According to Chinda (2021), suppliers usually offer discounts for high order quantities. These bring high annual holding costs, but low annual ordering costs. Management must trade off reduced product cost and increased holding cost to achieve the lowest total cost.

3. Research Methods

In this study, the literature review is conducted to understand better inventory management in the construction industry, including inventory management methods, key construction site materials, and factors influencing inventory management. Key inventory management factors are extracted for data collection and SD model development. An SD model of construction company inventory management is developed and simulated. Sensitivity analysis is performed to validate the developed SD model and suggest long-term construction company inventory management plans.

3.1. System Dynamics Modeling Approach

Diverse instruments may be used to examine and simulate construction industry perspectives, including building information (BIM), agent-based (ABM), and system dynamics (SD) modeling (Uddin et al., 2021; Ding et al., 2018, Mohamed and Chinda, 2011). According to Uddin et al. (2021), BIM saves time, improves performance, economizes human resources, and boosts communication, profitability, accuracy, planning and design, visualization and advanced data. Building performance must be simulated under realistic conditions to attain more performance precision. ABM is an approach for behavioral prediction from the occupant individual to group levels. In ABM, global behavior is not directly defined, but expressed through individuals or occupant behaviors. By contrast, SD modeling can reproduce structures and relationships, underlying system behavior without factoring in the disposition of decision makers (Uddin et al., 2021; Ding et al., 2018). It is used in this study as it allows policies and processes to be included in the model. One example is reducing cement price to lower total inventory cost. The SD model also considers dynamic relationships between system variables, making outcomes realistic. In addition, qualitative and quantitative data can be input in the equations (Chinda, 2022).

SD is a tool to solve dynamic problems related to complex social, managerial, economic, and engineering systems considering mutual interactions, information feedback, and circular causalities (Sterman, 2018). Peterson et al. (2019) stated that SD model can facilitate the understanding of dynamic aspects of industrial development from lab to commercial scales. Mohamed and Chinda (2011) mentioned that SD focuses on long-term structure and behavior with multiple feedback loops (cause-and-effect relationships), where results of actions are fed back to generate future actions. It is performed in many construction-related studies. For example, Mohamed and Chinda (2011) investigated long-term construction safety culture improvement in Thailand using SD modeling. Hao et al. (2007) investigated waste-generating factors and waste levels onsites in Hong Kong through SD modeling. Nasir and Hadikusumo (2018) examined contractual relationships between construction project owners and contractors. Jing et al. (2019) used SD modeling to evaluate local construction project cost and time performance and its variation from internal and external factors.

In this study, an SD model is developed to plan for long-term inventory management of construction site concrete components. The developed SD model is validated to establish confidence in the developed model (Forrester and Senge, 1980). Rodrigues and Williams (1998) mentioned that model validation is performed to ensure that the model captures the dynamics of system behavior and produces results close to actual practices. A model is validated if simulation results display similar behavior in a real system. Sensitivity analysis is performed to validate the developed SD model for total concrete component inventory cost by varying key parameters. This validation method is used in many construction-related studies (Sun et al., 2019; Tang and Ogunlana, 2003; Mohamed and Chinda, 2011). If only model magnitude, and not behavior, is changed, then the model is valid for real practices.

3.2. Data Collection

Data collection is made from construction-related literature. For example, sand price ranges from 400 to 500 baht/cubic meter (m^3), while rubble costs from 500 to 600 baht/m^3 (Baanlaesuan, 2022). A typical concrete formula contains sand, rubble, and cement with a mix ratio of 1:2:4 (CMU, 2022; Pro Crew Schedule, 2020). Data is collected from observations at ten building construction sites in Pathum Thani Province, Thailand. They have an average site area of 1350 m^2 and are scheduled to be completed within one year. Data gathered includes space usage, working days, and concrete demand. For instance, concrete use in early construction stages (phase 1), such as foundation and construction, and the final construction stage (phase 2) of decoration, are 80% and 20% of the total amount, respectively. About 60% of the schedule is used in phase 1 of construction. Storage space is from 2% to 10% of site space. Lead time for sand, rubble, and cement is set at one day, as these materials are generally delivered from local shops near construction sites (see Table 1).

4. SD Model for Construction Site Concrete Component Inventory Management

The SD model is developed to examine long-term construction site concrete component inventory management and to suggest effective construction company inventory management plans. SD model development procedures are shown in Fig. 1. For this study, three key materials used in the concrete mixture are sand, rubble, and cement. For each material, order quantities are calculated based on material demand, ordering cost, holding cost, and different discounts.

Table 1. Data used in SD model development

Data	Value	Reference
Concrete demand	• 438 m^3 per project • Phase 1 (foundation, piling, and construction): 80% of project demand • Phase 2 (architectural features): 20% of project demand	Krungsri (2021), site observation
Working day	• Project duration: 1 year • Phase 1 (foundation, piling, and construction): 213 days • Phase 2 (architectural features): 152 days	Diez (2022), site observation
Daily concrete demand	• Phase 1: 1.65 m^3, on average • Phase 2: 0.58 m^3, on average	Diez (2022), Krungsri (2021), site observation
Percentage of holding cost	• Sand: 35% of unit price • Rubble: 15% of unit price • Cement: 15% of unit price	Baanlaesuan (2022), Krungsri (2021), site observation
Lead time	• Sand: 1 day • Rubble: 1 day • Cement: 1 day	Site observation
Material cost	• Sand: 400 baht/m^3 for an order of at least 5 m^3, 500 baht/m^3 for an order of less than 5 m^3 • Rubble: 500 baht/m^3 for an order of at least 5 m^3, 600 baht/m^3 for an order of under 5 m^3 • Cement: 120 baht/bag of 50 kg for an order of at least 10 bags, 130 baht/bag of 50 kg for an order of fewer than 10 bags	Baanlaesuan (2022), Krungsri (2021), site observation
Ordering cost	• Sand: 50 baht/order • Rubble: 50 baht/order • Cement: 20 baht/order	Baanlaesuan (2022), Krungsri (2021), site observation
Concrete mixture ratio	• Sand: rubble: cement = 1:2:4 (equivalent to 0.57m^3 of sand: 1.14 m^3 of rubble: 6.5 bags of cement)	CMU (2022), Pro Crew Schedule (2020)
Rework	• 15% of the work (in phase 2) • Range of rework: 15-35% • Learning curve: 80%	Martin (2022), Faithful and Gould (2015), Dougherty et al. (2012), Site observation
Site space	• 1350 m^2 on average	Site observation
Storage space	• 2% of site space (about 27 m^2) • Range of storage space: 2-10% • Sand storage space: 3.86 m^2 • Rubble storage space: 7.72 m^2 • Cement storage space: 15.42 m^2	Alavi and Rizk (2021), site observation

Note: 1$ = 35.66 baht (BOT, 2022)

Rework and delay in earlier projects, if pertinent, increase material demand for later projects to conclude previous projects. The best order quantity with lowest total cost is considered with space allocated to confirm storage availability. If storage space is adequate, the order quantity is finalized; otherwise, the order quantity is adjusted to fit space availability. The order is scheduled for delivery based on lead time, and the new order is initiated when inventory reaches the ROP. The SD model of construction site concrete component inventory management is developed based on the assumption that supplier capacity is unlimited, and safety stock is not considered. It comprises five sub-models: demand, order quantity, storage, cost, and inventory.

4.1. Demand Sub-Model

Concrete demand is separated into two phases: phase 1 requires about 80% of concrete for use in foundation and construction work. Concrete required for rework and delays in previous projects is added to the phase 1 demand; see Eq. (3) and Eq. (4). This is based on the assumption that the construction company must complete the previous project before starting a new one, and rework cost is added to the new project. The percentage of rework is reduced through learning processes and work experience with an initial 15% of phase 2 work in the first project; see Eq. (5) (Martin, 2022; Faithful and Gould, 2015). The demand for concrete for each phase is used to calculate average daily demand and demand for each construction material based on a mixing ratio of sand, rubble, and cement of 1:2:4, see Eq. (6) (CMU, 2022; Pro Crew Schedule, 2020). It is noted that D1 = concrete demand in phase 1 (m^3), DC = concrete demand (m^3/project), RW = concrete demand to rework previous projects (m^3), RWP = Rework percentage (%), D2 = concrete demand during phase 2 (m^3), CY

= Counted year, LC = Learning curve (%), and d1 = Daily concrete demand during phase 1 (m^3), and DAY1 = Working days in phase 1 (days).

$$D1 = (DC \times 0.8) + RW \tag{3}$$

$$RW = RWP \times HISTORY\ (D2,1) \tag{4}$$

$$RWP = 0.15 \times CY^{lnln\ LC/lnln\ 2} \tag{5}$$

$$d1 = D1/DAY1 \tag{6}$$

4.2. Order quantity sub-model

Order quantities for each construction material are calculated based on different discount prices offered by suppliers; see Eq. (1). Optimum order quantity minimizes total cost. For example, two order quantities of sand for phase 1 are calculated based on two discount conditions (see Table 1 and Eq.(7) and Eq. (8)). Order quantity is adjusted, if necessary, to match the minimum order amount for a price discount. Total cost of each order quantity is then calculated, and the best sand order quantity is selected based on lowest total cost (see Eq. (9)). It is noted that OQ1SS = sand order quantity during phase 1 with original price (m^3), D1S = sand demand for phase 1 (m^3), OS = sand ordering cost per order (baht/order), IS = holding cost percentage (%), PSS = original sand price (baht/m^3), OQ1SL = sand order quantity during phase 1 with discount price (m^3), PSL = discounted sand price (baht /m^3), OQ1SF = final sand order quantity (m^3), TC1SS = total sand inventory management cost in phase 1 at original price (baht), and TC1SL = total sand inventory management cost for phase 1 with price discount (baht).

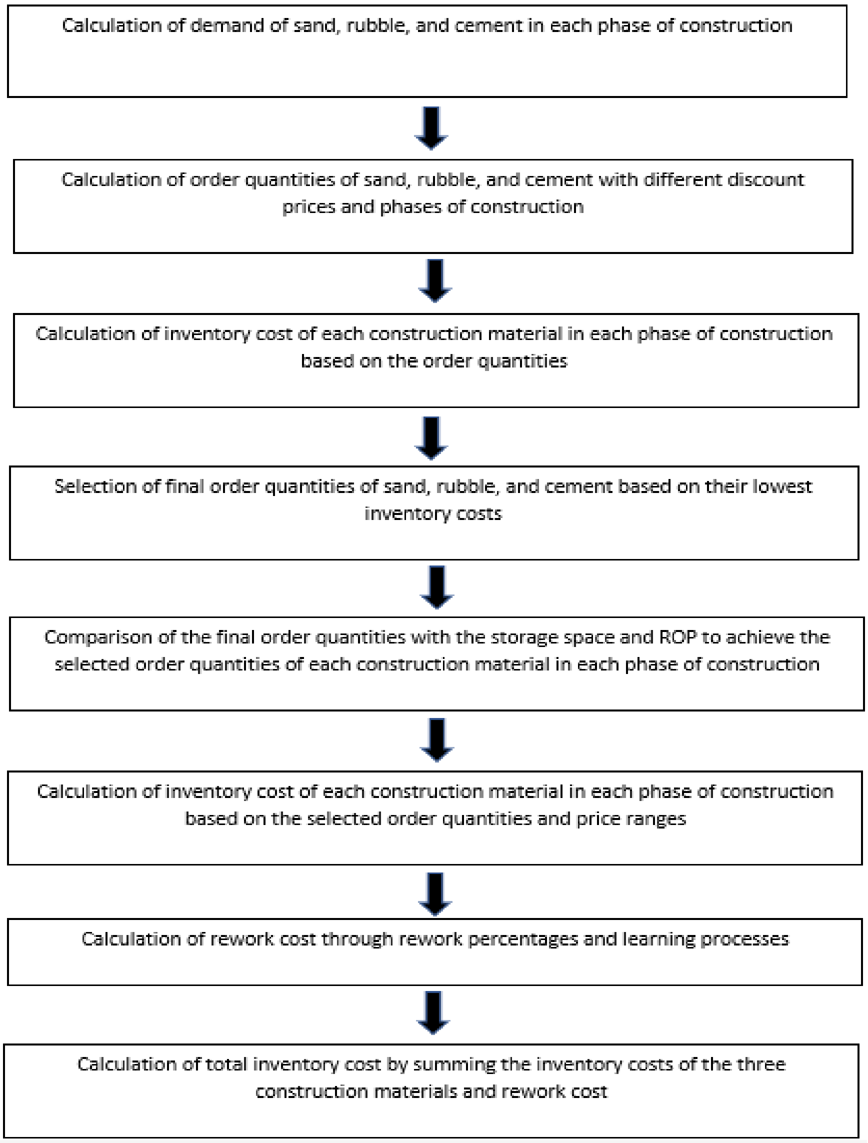

Fig. 1. SD model development steps

$$OQ1SS = ROUND\ (\sqrt{\frac{(2 \times D1S \times OS)}{(IS \times PSS)}}) \tag{7}$$

$$OQ1SL = MAX\ (ROUND\ \left(\sqrt{\frac{(2 \times D1S \times OS)}{(IS \times PSL)}}\right), 5) \tag{8}$$

$$OQ1SF = IF\ (TC1SS > TC1SL) THEN\ OQ1SL\ ELSE\ OQ1SS \tag{9}$$

4.3. Storage Sub-Model

Construction site storage space is 2% of the total space. Final construction material order quantities (such as sand, rubble, and cement) must be checked with available space onsite before orders are finalized (see Eq. (10) where OQ1SSL = selected sand order quantity for phase 1 (m^3), INV1S = sand inventory during phase 1 (m^3), and STS = sand storage space (m^3)). The ratio of space for three construction materials follows the mixing ratio of 1:2:4. For safety reasons, cement bags are stacked up to 10 bags.

$$OQ1SSL = IF\ \big((OQ1SF + INV1S) > STS\big)\ THEN\ (STS - INV1S)\ ELSE\ OQ1SF \tag{10}$$

4.4. Cost Sub-Model

Total cost of concrete component inventory management (see Eq. (11)) is a sum of total costs of sand, rubble, and cement inventory management used during construction phases 1 and 2. For example, total sand cost in phase 1 includes ordering, holding, material, and rework (in percentages of total cost of the previous project), see Eq. (12) through Eq. (17). Based on RHLB (2021), sand, rubble, and cement prices are constant in this study. It is noted that TC = total concrete inventory management cost (baht/project), TC1S = total phase 1 sand inventory management cost (baht); TC1R = total phase 1 rubble inventory management cost (baht); TC1C = total phase 1 cement inventory management cost (baht); TC2S = total phase 2 sand inventory management cost (baht); TC2R = total phase 2 rubble inventory management cost (baht); TC2C = total phase 2 cement inventory management cost (baht); RC = rework cost (baht/project); OC1S = phase 1 sand ordering cost (baht); HC1S = phase 1 sand holding cost (baht); MC1S = phase 1 sand material cost (baht); and P1S = final phase 1 sand price (baht/m^3).

$$TC = TC1S + TC1R + TC1C + TC2S + TC2R + TC2C + RC \tag{11}$$

$$TC1S = OC1S + HC1S + MC1S \tag{12}$$

$$RC = RWP \times HISTORY\ (TC, 1) \tag{13}$$

$$OC1S = (D1S \times OS)/OQ1SSL \tag{14}$$

$$HCS1 = (OQ1SSL \times IS \times P1S)/2 \tag{15}$$

$$MC1S = D1S \times P1S \tag{16}$$

$$P1S = IF\ (OQ1SS < OQ1SSL \leq OQ1SF)\ THEN\ PSL\ ELSE\ PSS \tag{17}$$

4.5. Inventory Sub-Model

The inventory sub-model tracks inventory for each onsite construction material. In this study, the initial stock of each material is set at half its order quantity. After inventory diminished below the ROP, a new order should be placed to avoid stockout. For example, Eq. (18) and Eq. (19) demonstrate phase 1 sand ROP and reorder action. ROP1S = phase 1 sand reorder point (m^3); d1S = phase 1 daily sand demand (m^3); LTS = sand lead time (days); and INV1S = phase 1 sand inventory (m^3).

$$ROP1S = d1S \times LTS \tag{18}$$

$$RO1S = IF\ (INV1S \leq ROP1S)\ THEN\ 1\ ELSE\ 0 \tag{19}$$

5. Research Results

5.1. Simulation Results

The SD model of concrete component inventory management is simulated for 10 years, reflecting 10 one-year projects. Simulations are separated into two scenarios: 1) no rework and construction delay considered; and 2) rework and construction delay considered. In the first scenario, rework and construction delays are not considered, meaning that concrete demand is constant for all projects (see Table 2 and Table 3). Results reveal selected order quantity for each construction material and total project inventory cost, where 80% of total cost is for phase 1 work. Total inventory cost is the same for all 10 projects, as concrete demand is constant. Due to limited onsite space, selected sand and rubble order quantities are smaller than final ones. Total project inventory cost is 687211.65 baht, with cement inventory cost the highest (49.84%).

When rework and construction delays are considered, concrete demand in each project varies, depending on amount of rework and the learning process. Table 4 to Table 6 show the rework percentage, selected order quantity for each construction material and additional concrete demand, and total project inventory cost, respectively. Reworking a former project, if necessary, affects the work schedule and concrete demand of subsequent projects, adding to total inventory costs for the latter. For instance, a 15% rework of a prior project (see Table 4) results in additional concrete demand of 13.14 m^3 added to project number 2. This boosts total second project inventory cost in phases 1 and 2 by 67855.14 and 17075.74 baht, respectively, due to additional rework cost (see Table 6). These results are consistent with Fashina et al. (2021) who state that rework causes project delays and cost overruns. Table 4 shows that when rework occurs, demand for concrete increases. However, this does not alter the final selected order quantities for three construction materials, as big lot sizes with discounts are chosen for final order quantities, and site space limits selected order quantities (see Table 5). The results also show that total inventory cost diminishes (through learning processes) when rework lessens (see Table 6 and Table 7). Most total concrete inventory cost is from cement, representing almost half of the total (see Table 7). Therefore, good cement inventory management is essential for minimizing total construction project inventory cost. For example, Malik and Sharma (2022) suggested using EOQ to minimize cement bag stockout. Thrishna and Harish (2018) utilized EOQ and ABC analysis concepts to define key construction materials and concluded that cement and steel are "A" class materials requiring strict ordering and purchasing controls. In addition, onsite space management is necessary to achieve optimum order quantities of construction materials and reducing total onsite concrete component inventory costs.

Table 2. Selected concrete component order quantities for each construction phase with rework and construction delay not considered

Phase	Sand (m^3/order)		Rubble (m^3/order)		Cement (bags/order)	
	Final OQ	Selected OQ	Final OQ	Selected OQ	Final OQ	Selected OQ
1	12	9	23	8	72	72
2	6	6	12	9	36	36

Table 3. Total concrete component inventory cost with rework and construction delays not considered

Material	Phase 1 (baht)	Phase 2 (baht)	Total (baht)	Portion (%)
Sand	81630.8	20808.9	102439.7	14.91
Rubble	193655.1	48609.97	242265.07	35.25
Cement	273749.76	68757.12	342506.88	49.84
Total	549035.66	138175.99	687211.65	100

Table 4. Rework percentage and total concrete demand as a result of the learning process

Project No.	Rework (%)	Additional concrete demand (m^3)	Total project concrete demand (m^3)
1	15	0	438
2	12	13.14	451.14
3	10.53	10.83	448.83
4	9.6	9.45	447.45
5	8.93	8.59	446.59
6	8.43	7.98	445.98
7	8.02	7.51	445.51
8	7.68	7.14	445.14
9	7.39	6.84	444.84
10	7.15	6.58	444.58

Note: Rework in previous projects adds to concrete demand for subsequent projects.

Table 5. Selected concrete component order quantity for each construction phase with rework and construction delay considered

Project No.	Phase	Sand (m^3/order)		Rubble (m^3/order)		Cement (bags/order)	
		Final OQ	Selected OQ	Final OQ	Selected OQ	Final OQ	Selected OQ
1	1	12	9	23	8	72	
	2	6	6	12	9	36	36
2	1	12	9	23	8	72	72
	2	6	6	12	9	36	36
3	1	12	9	23	8	72	72
	2	6	6	12	9	36	36
4	1	12	9	23	8	72	72
	2	6	6	12	9	36	36
5	1	12	9	23	8	72	72
	2	6	6	12	9	36	36
6	1	12	9	23	8	72	72
	2	6	6	12	9	36	36
7	1	12	9	23	8	72	72
	2	6	6	12	9	36	36
8	1	12	9	23	8	72	72
	2	6	6	12	9	36	36
9	1	12	9	23	8	72	72
	2	6	6	12	9	36	36
10	1	12	9	23	8	72	72

2	6	6	12	9	36	36

Table 6. Total concrete component inventory cost with rework and construction delays considered

Project No.	Phase	Sand (baht)	Rubble (baht)	Cement (baht)	Rework (baht)	Net (baht)	Total (baht)
1	1	81630.8	193655.1	273749.76	0	549035.66	687211.65
	2	20808.9	48609.97	68757.12	0	138175.99	
2	1	81630.8	193655.1	273749.76	67855.14	616890.80	772142.53
	2	20808.9	48609.97	68757.12	17075.74	155251.73	
3	1	81630.8	193655.1	273749.76	59247.25	608282.91	761368.85
	2	20808.9	48609.97	68757.12	14909.95	153085.94	
4	1	81630.8	193655.1	273749.76	53841.78	602877.44	754603.28
	2	20808.9	48609.97	68757.12	13549.85	151725.84	
5	1	81630.8	193655.1	273749.76	50013.32	599048.98	749811.48
	2	20808.9	48609.97	68757.12	12586.51	150762.50	
6	1	81630.8	193655.1	273749.76	47097.97	596133.63	746162.53
	2	20808.9	48609.97	68757.12	11852.91	150028.90	
7	1	81630.8	193655.1	273749.76	44771.14	593806.80	743250.18
	2	20808.9	48609.97	68757.12	11267.39	149443.38	
8	1	81630.8	193655.1	273749.76	42851.68	591887.34	740847.71
	2	20808.9	48609.97	68757.12	10784.38	148960.37	
9	1	81630.8	193655.1	273749.76	41228.96	590264.62	738816.64
	2	20808.9	48609.97	68757.12	10376.03	148552.02	
10	1	81630.8	193655.1	273749.76	39830.85	588866.51	737066.70
	2	20808.9	48609.97	68757.12	10024.20	148200.19	

Note: Reworking of previous projects augments subsequent project concrete demand and total inventory cost.

Table 7. Total concrete component inventory cost percentages with rework and construction delays considered

Project No.	Sand (%)	Rubble (%)	Cement (%)	Rework (%)
1	14.91%	35.25%	49.84%	0.00%
2	13.27%	31.38%	44.36%	11.00%
3	13.45%	31.82%	44.99%	9.74%
4	13.58%	32.10%	45.39%	8.93%
5	13.66%	32.31%	45.68%	8.35%
6	13.73%	32.47%	45.90%	7.90%
7	13.78%	32.60%	46.08%	7.54%
8	13.83%	32.70%	46.23%	7.24%
9	13.87%	32.79%	46.36%	6.98%
10	13.90%	32.87%	46.47%	6.76%

5.2. Model Validation and Sensitivity Analysis

5.2.1. Model verification and validation

The developed SD model must be validated for construction industry usage. Verification tests model behavior using logical, extreme-value, and mass-balance methods are commonly used for model verification (McLucas, 2005). A logical test, commonly used in model verification, ensures dimensional integrity, unit consistency, and stochastic/statistical character (Mohamed and Chinda, 2011). Model validation ensures that the model captures the dynamics of system behaviour and produces reliable results. According to Forrester and Senge (1980), three common validation tests include model structure, model behavior (or sensitivity analysis), and policy implications. The sensitivity analysis is widely used in many research studies (Barlas et al., 2007; Tang and Ogunlana, 2003; Huy, 2002). In this study, the logical test and sensitivity analysis are performed to verify and validate the developed SD model for total concrete component inventory management to ensure utility and practical applicability. The logical test is confirmed through the consistency of units in SD model development, including the baht as currency unit; one year interval per project; m^2 for storage space; and m^3 for concrete demand. Sensitivity analysis is also done by varying parameters significantly impacting total inventory cost, including cement unit costs, storage space percentages, and rework percentages. Details are in the next section.

5.2.2. Sensitivity analysis

To validate the developed SD model of total concrete component inventory management and ensure its practical applicability, sensitivity analysis is performed by varying parameters significantly impacting total inventory cost (Barlas et al., 2007). In this study, different cement unit costs, storage space percentages, and reworking percentages are selected in sensitivity analysis. Cement unit cost is chosen as the material requiring the highest expenditure (see Table 7). According to Baanlaesuan (2022), cement unit cost ranges from 100-120 baht/bag of 50 kgs with an order quantity of at least 10 bags. In sensitivity analysis, cement unit cost is changed from a minimum of 100 baht/50 kg bag to a maximum of 120 baht/50 kg bag to discern total inventory cost changes. Simulation results depicted in Fig. 2 indicate that model behavior does not alter, with the amount of total inventory cost changing when cement unit cost does; this validated the developed SD model for concrete component inventory management. Results show that when the cement unit cost decreases to 100 baht/50 kg bag, total inventory cost decreases by about 6.8% for the next 10 projects (or from about 740000 baht to 690000 baht by the end of the project number 10. Therefore, construction companies should maintain business relationships with suppliers to reduce long-term cement and total inventory costs. This is consistent with Lazzerini (2020), who underlined that maintaining strong working relationships with suppliers and vendors is critical to company success.

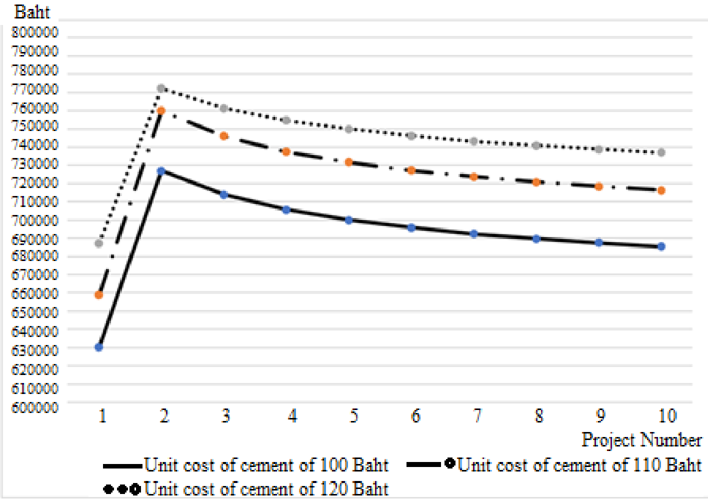

Fig. 2. Sensitivity analysis for total concrete component inventory cost with altered cement unit cost

Based on Table 2, the selected sand and rubble OQs are inferior to final OQ due to limited onsite space. According to Alavi and Rizk (2021), construction site storage space could be up to 10% of site space. Therefore, sensitivity analysis is performed in this study by varying storage spaces from 2% to 10% of site space. As shown in Fig. 3, simulation results validate the developed SD model, as solely magnitude, rather than model behavior, alter. Results reveal that when storage space expands from 2% to at least 6% of site space, total inventory cost is minimized, as selected OQs of the three construction materials are the same as their final OQs. This is consistent with Misron et al. (2018) who argued that effective construction material storage management is required to ensure site productivity, security, and cost reduction.

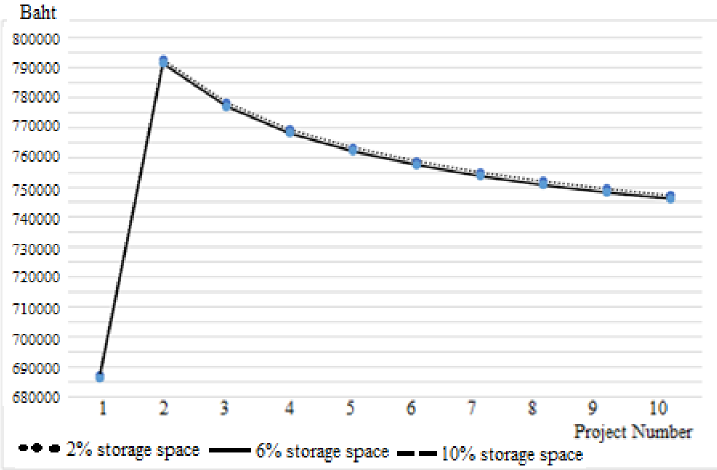

Fig. 3. Sensitivity analysis of total concrete component inventory cost if storage space percentage alters

Based on Table 4 and Table 6, rework causes higher concrete demand, resulting in higher total inventory cost. Dougherty et al. (2012) mentioned that rework could be up to 35% of total work. Sensitivity analysis is performed by varying rework percentages from 15% (base simulation) to a maximum of 35%. Simulation results in Fig. 4 show that when rework increases, so does total inventory cost. With a high rework percentage and no work experience (for example, project no. 2 in Fig. 4), total project inventory cost increases by almost 20% (from about 790000 baht to 940000 baht at the end of project no. 2). With more work experience through learning processes, total inventory cost of 35%-rework exceeds the 15% rework by about 11%. Therefore, management must closely supervise work and monitor rework regularly to minimize total inventory cost.

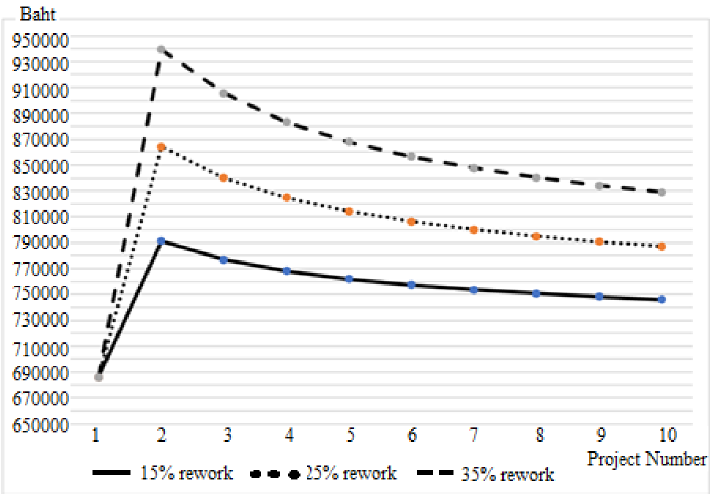

Fig. 4. Sensitivity analysis of total concrete component inventory cost with altered rework percentage

6. Conclusion

Effective construction site inventory management is necessary for avoiding stockout, increasing productivity, and reducing total project inventory cost. This study develops an SD model of total concrete component inventory cost to examine total cost over several projects. Three construction materials (sand, rubble, and cement) are vital components of concrete; inventory management of them is essential for minimizing total inventory cost. Simulation results reveal that optimum order quantities of the three construction materials are those with price discounts. Therefore, long-term relationships with suppliers are needed to achieve the best price per unit matching construction project demands. Results also indicate that cement constituted the majority of total inventory cost. Sensitivity analysis is performed by varying cement cost per unit to examine total project inventory cost over time. Results confirm that total inventory cost may be reduced by almost 7% when cement unit cost drops from 120 to 100 baht/unit (see Fig. 2). Sensitivity analysis is also performed by varying storage space and rework percentages, respectively. Results suggest that at least 6% of site space should be provided for material storage to ensure space availability for selected large order quantities at discounted prices. Increasing storage space helps companies achieve optimum order quantities with lowest total inventory cost (see Fig. 3). Rework should also be controlled, as increasing rework by 20% (such as from 15% to 35%, see Fig. 4) increases total construction project inventory cost by about 20% (with no work experience) to 11% (with work experience through learning processes). Construction industries, especially those in developing nations, may use these findings to effectively plan for concrete component inventory management to achieve the lowest total long-term inventory cost. This may include selecting construction materials to be stored onsite and suitable order quantities for achieving an economy of scale and lowest total inventory cost. Onsite storage space allocation, including location and size, may affect total inventory cost. Long-term relationships with suppliers are also essential for reducing unit costs of construction materials to achieve the lowest total inventory cost.

This study has some limitations. Data used in the SD model development are from secondary and primary sources, not limited to the context of construction in Thailand. Construction site space and project scheduling are fixed in this study. Daily construction material consumption rates are constant in each construction project phase. The construction company may implement strategies from onsite study results to validate and adjust the developed SD model to suit company practices. The concrete considered in this study is mixed onsite and might not apply to pre mix concrete mostly used in developed nations.

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Author Contributions

Thanwadee Chinda contributes to conceptualization, methodology, technical data, model development and simulation, manuscript preparation, and manuscript editing. Ratinan Chinda contributes to model adjustment, manuscript preparation, and manuscript editing. All authors have read and agreed with the manuscript before its submission and publication.

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Institutional Review Board Statement

Not applicable

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