Optimizing Material Procurement and Storage on Construction Sites

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Abstract: Efficient planning of materials procurement and storage on construction sites can lead to significant improvements in construction productivity and project profitability. Existing research studies focus on material procurement and storage layout as two separate planning tasks without considering their critical and mutual interdependencies. This paper presents the development of a new optimization model for construction logistics planning that is capable of simultaneously integrating and optimizing the critical planning decisions of material procurement and material storage on construction sites. The model utilizes genetic algorithms to minimize construction logistics costs that cover material ordering, financing, stock-out, and layout costs. The model incorporates newly developed algorithms to estimate the impact of potential material shortages on-site because of late delivery on project delays and stock-out costs. An application example is analyzed to demonstrate the capabilities of the construction logistics planning model in simultaneously optimizing material procurement decisions and storage layout plans. **DOI:** 10.1061/(ASCE)CO.1943-7862.0000307.

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Introduction

Material procurement and storage on construction sites need to be properly planned and executed to avoid the negative impacts of material shortage or excessive material inventory on-site. Deficiencies in the supply and flow of construction material were often cited as major causes of productivity degradation and financial losses (Thomas et al. 2005). Ordering smaller quantities of material more frequently minimizes the locked-up capital in material inventories; however, it increases the probability of material shortages and project delays. On the other hand, ordering larger quantities of material less frequently minimizes the probability of material shortage and project delays; however, it increases the cost of locked-up capital in large inventory buffers on-site. Construction planners need to consider this critical trade-off during the planning of material procurement and storage on-site.

A number of research studies were conducted to investigate the procurement and storage of construction material on-site. Existing material procurement studies focused on: (1) investigating the impact of material procurement and supply decisions on construction labor productivity (Thomas et al. 1989; Thomas et al. 1999; Thomas and Horman 2005); (2) formulating the principles of site material management and storage (Thomas et al. 2005); (3) applying "just-in-time" strategy in construction projects (Akintoye 1995; Bertelsen and Nielsen 1997; Pheng and Hui 1999; Shmanske 2003; Polat and Arditi 2005); (4) implementing 4 dimensional (4D) visualization to manage and control material supply and storage on-site (Subsomboon et al. 2003); (5) developing decision support systems for economical material supply chains (Tserng et al. 2006; Polat et al. 2007); and (6) developing data exchange and integration standards in onstruction supply chains (Danso-Amoako et al. 2004). Other research studies investigated material storage on-site as part of construction site layout planning assuming predetermined sizes of material storage areas (Zouein and Tommelein 1999; Osman et al. 2003; Elbeltagi et al. 2004; AbdelRazig et al. 2005; El-Rayes and Said 2009).

Despite the significant contributions, these studies did not investigate the critical and mutual interdependencies between (1) material procurement planning; and (2) dynamic material storage and site-layout planning. As shown in Fig. 1, existing material procurement models focus on procurement decisions without considering the availability of material storage space on dynamic construction site layouts. On the other hand, existing dynamic site layout planning models focus on-site layout decisions without considering the impact of material procurement decisions on inventory levels and storage space needs. Overlooking these critical interdependencies between material procurement and site-space availability can lead to serious project problems including material shortages, improper storage, poor and unsafe site layout, and productivity losses (Bell and Stukhart 1987; Thomas et al. 1989; Jang et al. 2007). Accordingly, there is a pressing research need to investigate and model the critical interdependencies between material procurement and material storage decisions. The objective of this paper is to present the development of a construction logistics planning (CLP) model that is capable of integrating and optimizing critical planning decisions of material procurement and material storage on construction sites.

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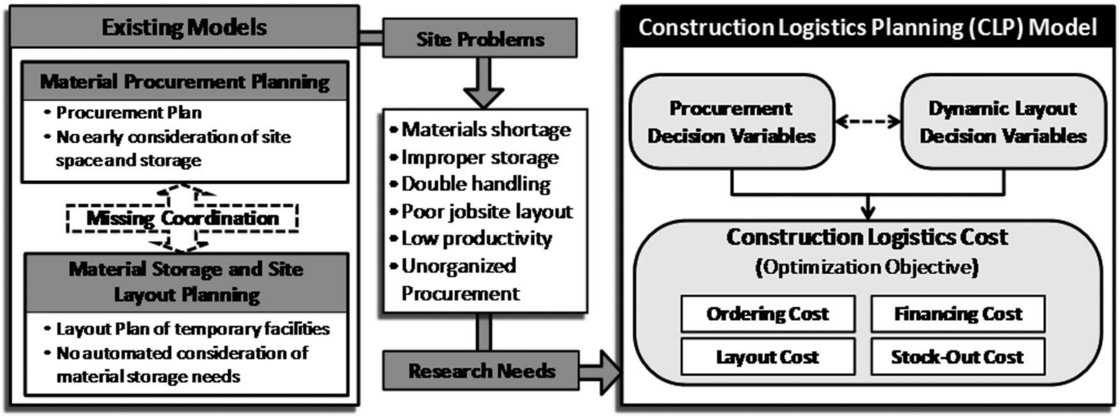

Fig. 1. Construction logistics planning model

Construction Logistics Planning Model

The present CLP model is designed to help contractors minimize material logistics costs by using an integrated approach (see Fig. 1) that simultaneously optimizes two categories of decision variables: (1) material procurement decisions that affect materials inventory levels and storage needs; and (2) dynamic layout decisions that identify the dynamic locations of material storage areas and other temporary facilities over the project duration. Both categories of decision variables have a direct impact on the objective function that is designed to minimize the construction logistics costs, which include: (1) materials ordering cost; (2) financing cost; (3) stock-out cost; and (4) layout cost. The present CLP model is implemented by using genetic algorithms (GA) because of its unique capabilities in solving complex nonlinear optimization problems with large search space (Deb et al. 2000). GA has been widely used in optimizing different construction planning applications such as time-cost tradeoff analysis, resource utilization, and site layout planning (Li and Love 1997; Kandil and El-Rayes 2005; Khalafallah and El-Rayes 2008). GA is an iterative algorithm in which a population of abstract representation of decision variables (called chromosome) that evolves toward a better solution of decision variables utilizing natural processes such as selection, crossover, mutation, and elitism (Goldberg 1989). The algorithm starts by an initial population of chromosomes randomly generated that evolves by applying the following steps iteratively: (1) evaluating the fitness of each chromosome by using the objective function; (2) selecting a group of chromosomes based on their fitness to produce a more fit offspring; and (3) generating a new population by using various genetic operators (crossover, mutation, and elitism). The following sections describe in more details the two categories of decision variables and the optimization objective function of the present CLP model.

Procurement Decision Variables

The planning of material procurement and supply in the present model is accomplished by identifying the optimal ordering period of each material that is changing dynamically to consider the fluctuating demand over the project duration. In the present model, the construction duration is divided into T stages that can be specified by project planners to account for the changing demand rate of materials and site space availability. As shown in Fig. 2, material procurement in each stage (t) is formulated as a fixed-ordering-period (FOP) system that replenishes the inventory at the beginning of fixed intervals when new orders are acquired to cover the demand for the succeeding intervals (Magad and Amos 1995).

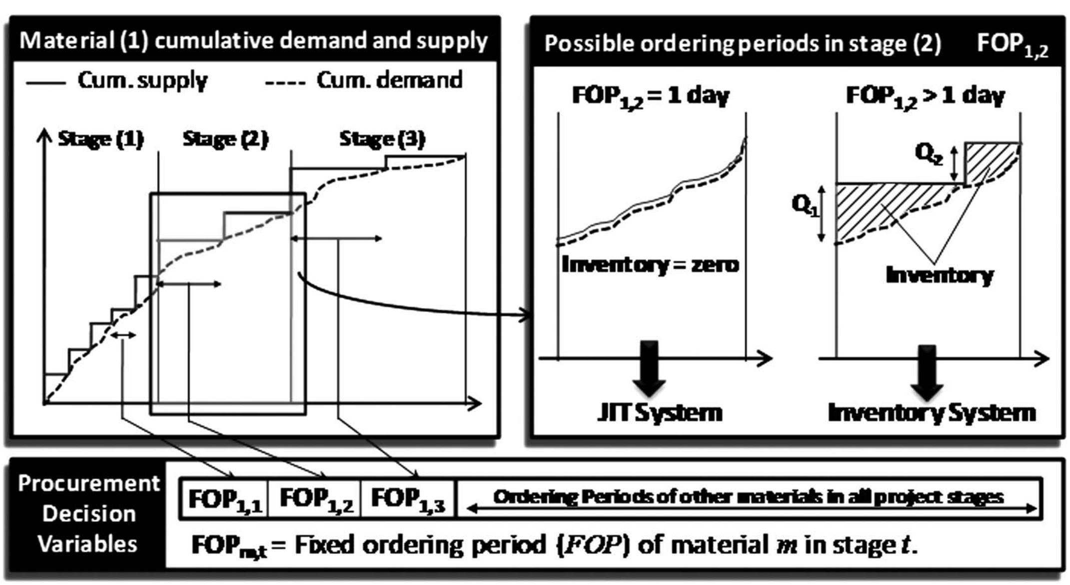

Fig. 2. Procurement decision variables in the CLP model

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Accordingly, procurement decision variables in the present model are represented by the fixed-ordering period ($FOP_{m,t}$) of each material (m) in every construction stage (t). A preliminary set of these procurement decisions is generated by the present model during the planning phase established on the initial construction plan. During the construction phase, the model can also be used to update the generated optimal logistics plans to consider any changes in schedule, site layout, or procurement decisions that may occur during the actual progress of construction operations.

In the present model, ordering quantities are unequal with uniform replenishment periods ($FOP_{m,t}$) that can take any duration starting from one day in the case of just-in-time (JIT) system to longer durations in the case of traditional inventory systems, as shown in Fig. 2. By considering the shortest ordering period (one day), the inventory is eliminated by having daily material procurement that satisfies the day-to-day material demand. On the other hand, considering longer fixed-ordering periods creates inventory stocks that are replenished over uniform intervals, as shown in Fig. 2. The values of the procurement decisions in the present model are constrained by the supplier capacity to ensure that the quantities of the generated orders do not exceed the maximum amount that the supplier can provide in a single order.

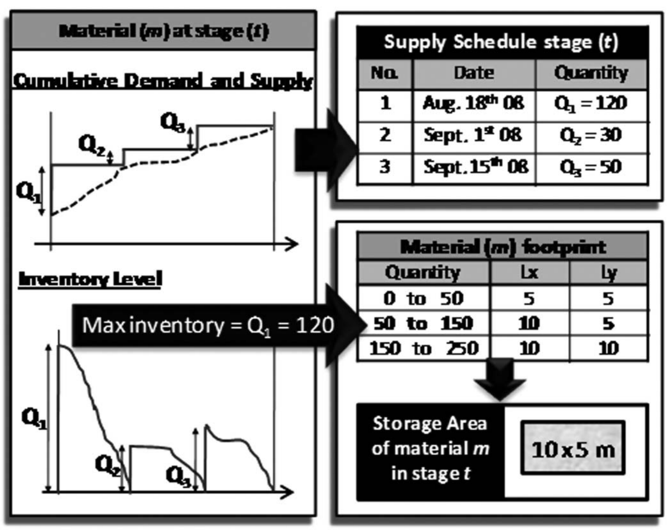

Fig. 3. Impact of procurement decisions on material storage needs

The present model is designed to consider the impact of the previously mentioned procurement decisions ($FOP_{m,t}$) on material storage space needs in two main steps. First, the supply schedule of each material m (i.e., delivery quantities and dates) is generated for construction stage (t) based on the values of the fixed-ordering periods ($FOP_{m,t}$). For example, the inventory of material (m) in stage (t) shown in Fig. 3 is replenished by three unequal-quantity orders over three equal periods. The last replenishment interval in a stage is the minimum of the selected fixed-ordering period and the remaining time in the corresponding stage. Second, storage space needs are identified by the maximum inventory level and materials footprint schedules. The maximum inventory level is the largest quantity of the material stored on-site during the corresponding stage, which is determined in the present model by the largest order quantity in the generated procurement plan. The identified maximum inventory level is then used to estimate the material storage needs on the basis of the "materials footprint schedules," as shown in Fig. 3. In the present model, materials footprint schedules are specified by construction planners to define the dimensions (Lx and Ly) of materials storage areas for different inventory quantities (see Fig. 3).

Dynamic Layout Decision Variables

In the present model, dynamic layout decision variables are designed to identify the dynamic layout (i.e., locations and orientations) of (1) material storage areas; and (2) temporary facilities on-site, as shown in Fig. 4. First, the model identifies the optimal layout decisions of material storage areas on the basis of their space needs that are estimated by using the previously mentioned procedure that considers the impact of procurement decisions (Fig. 3). The number of decisions variables representing material storage areas in the present model depends on the number of stages and the number of materials m required in each stage t, as shown in Fig. 4. For example, the following 10 decision variables are needed to represent the layout of material storage areas for the example in Fig. 4: (1) two decision variables for the location and orientation of storage area of Material 1 in the first stage; (2) four decision variables for the locations and orientations of Materials 1 and 2 in the second stage; and (3) four decision variables for the locations and orientations of Materials 1 and 2 in the third stage. Possible site locations are generated based on a grid of locations that depends on a grid pitch defined by planners, whereas the orientation angle can be either 0 or 90°, as shown in Fig. 4.

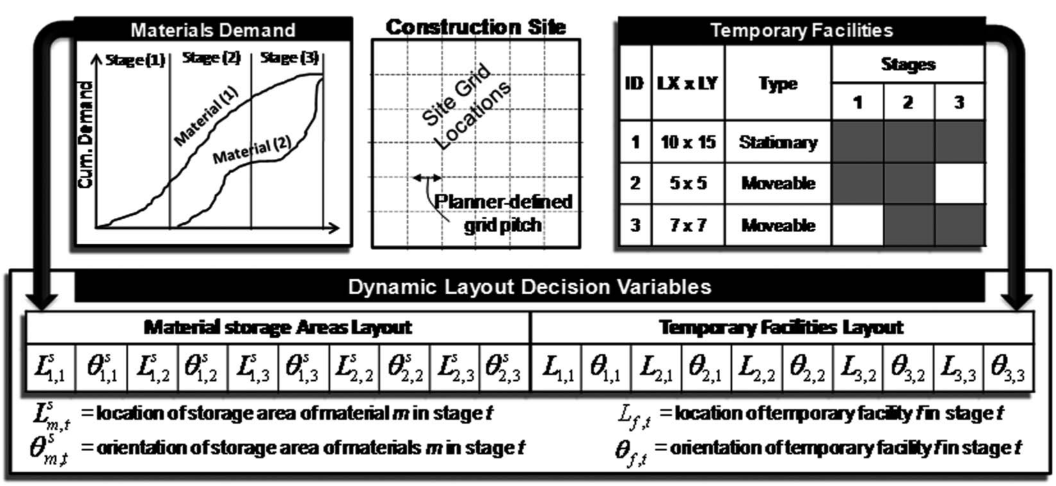

Fig. 4. Dynamic layout decision variables in the CLP model

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In addition to material storage areas, the model also identifies the optimal layout of other temporary facilities on-site such as office trailers and batch plants, as shown in Fig. 4. The present CLP model categorizes construction temporary facilities into moveable and stationary facilities (El-Rayes and Said 2008). Moveable facilities can be relocated at the beginning of each construction stage with additional relocation cost, such as office trailers and fabrication areas. Stationary facilities cannot be relocated after they are positioned because of the significant time and cost required for their relocation, such as a tower crane and batch plants. Accordingly, the layout decision variables of temporary facilities are the location and orientation of: (1) every moveable facility in each stage during which the facility exists on site; and (2) every new stationary facility in each construction stage. For example, the layout of temporary facilities shown in Fig. 4 includes the following 10 decision variables: (1) two decision variables for the location and orientation of the first facility (stationary) that will exist for the whole project duration; (2) four decision variables for the locations and orientations of the second facility (moveable) in the first and second stages; and (3) four decision variables for the locations and orientations of the third facility (moveable) in the second and third stages. The layout of both storage areas and temporary facilities should comply with a set of geometric constraints to: (1) position all facilities and storage areas within the boundaries of the construction site; (2) prevent overlaps between any pair of facilities and storage areas; (3) maintain operational or safety distance between facilities and storage areas; and (4) consider the existence of any exclusion zones on-site (Zouein and Tommelein 1999; El-Rayes and Said 2008).

Construction Logistics Cost

The present CLP model is designed to minimize construction logistics costs that are affected by the previously mentioned procurement and layout decision variables. As shown in Eq. (1), construction logistics costs (CLC) in the present model include four primary cost components: (1) ordering cost (OC) that represents the cost to physically acquire the materials from suppliers and transport them to the construction site; (2) financing cost (FC) that includes interest on the locked-up capital in materials inventories; (3) stock-out cost (SC) that estimates project delay costs because of material shortages, if any; and (4) layout cost (LC) that accounts for material handling costs, travel costs of construction resources moving among site facilities, and the relocation costs of temporary facilities.

$$\mathrm{CLC} = \mathrm{OC} + \mathrm{FC} + \mathrm{SC} + \mathrm{LC} \tag{1}$$

The present model seeks to minimize these construction logistics costs by identifying optimal solutions for the previously mentioned procurement and layout decision variables. The following subsections describe each of these four cost components and how they are affected by procurement and layout decisions.

Ordering Cost

Ordering cost (OC) represents the purchase cost of materials and their delivery from suppliers to the construction site (Blanchard 2007). As shown in Eq. (2), both material purchase and delivery costs depend on the number of material orders and the quantities which are identified by the previously mentioned procurement decisions. Small-order quantities result in high purchase cost because of the loss of potential discounts provided by suppliers for large-order quantities. Moreover, small-order quantities may result in high delivery costs because of underutilized trucks with loads below their maximum capacities. Fig. 5 illustrates the impact of procurement decisions on ordering cost in a simplified example in which 600 units of material m need to be supplied in stage t. In this example, procurement plan options are considered: (1) twelve equal deliveries of 50 units; or (2) two deliveries of 300 units. The first option leads to a higher ordering cost because it supplies the required 600 units by using more deliveries with smaller quantities. The calculation of the material ordering cost with Eq. (2) considers the potential fluctuations of material purchase cost rate $[PCR_m^t(Q_n)]$ and delivery costs $[DLC_m^t(Q_n)]$ that may change from one construction stage (t) to another.

$$\mathrm{OC} = \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{n=1}^{NOR_m^t}[Q_i \times PCR_m^t(Q_n) + DLC_m^t(Q_n)] \tag{2}$$

where T = number of project stages; M = number of project materials; NOR_m^t = number of orders of material m in stage t; Q_n = order quantity of order n; $PCR_m^t(Q_n)$ = purchase cost rate of material m in stage t with Q_n order quantity; and $DLC_m^t(Q_n)$ = delivery cost of material m in stage t with Q_n order quantity.

Financing Cost

Financing cost (FC) is the cumulative interest on working capital of the contractor tied up in the purchased inventories of materials stored on-site (Polat et al. 2007). Financing cost represents: (1) the lost interest on the contractor's money because it is tied up in materials inventory rather than invested elsewhere such as

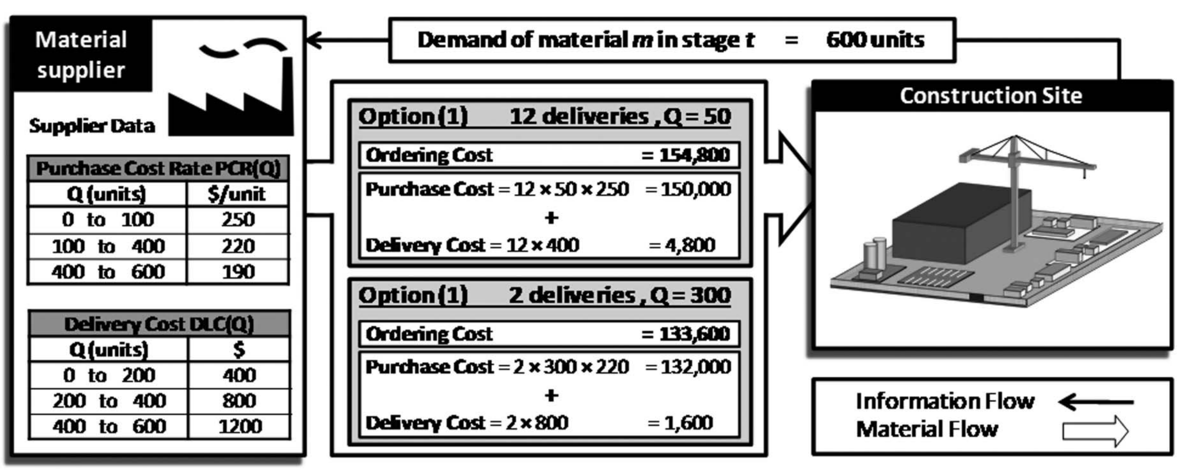

Fig. 5. Impact of procurement decisions on ordering costs

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a savings account; or (2) the amount of interest that the contractor pays if this tied capital is secured from a loaning institution. As shown in Eq. (3), the present CLP model calculates the cumulative financing cost as the sum of the interest paid on the monetary value of the daily inventory of each material over the project duration by using a daily interest rate defined by the planner. The inventory level of material m in a calendar day d is calculated as the difference between the cumulative supply (CS_d^m) and cumulative demand (CD_d^m) of the corresponding material and day. The cumulative supply is solely affected by the previously mentioned procurement decision variables ($FOP_{t,m}$), where longer $FOP_{t,m}$ leads to larger materials inventories (see Fig. 2). The present CLP model and Eq. (3) focus only on evaluating and optimizing the impact of procurement decisions on financing costs. The model does not consider the impact of other finance-related factors, such as the timing of owner payments to the contractor, which are beyond the scope of the model (Magad and Amos 1995; Pooler and Pooler 1997; Neale et al. 2006; Polat et al. 2007; Jung et al. 2007).

$$\mathrm{FC} = \sum_{d=1}^{NCD}\left[\sum_{m=1}^{M}(CS_d^m - CD_d^m) \times PCR_m^{avg} \times DIR\right] \tag{3}$$

where NCD = number of project days; CS_d^m = cumulative supply of material m in day d; CD_d^m = cumulative demand of material m in day d; PCR_m^{avg} = average purchase cost rate of material m; and DIR = project daily interest rate.

Stock-Out Cost

Stock-out cost (SC) represents project delay costs that may occur as a result of delayed materials delivery and depleted materials inventory (Magad and Amos 1995). The present model utilizes a newly developed algorithm of estimating materials-related project delay (MRPD) considering the following input: (1) number of the project's working days (NWD); (2) number of construction activities (I); (3) project baseline schedule that includes activities' early start and finish times (ES_i and EF_i); (4) number of construction materials (M); (5) delivery average delays of construction materials (DAD_m) that are estimated on the basis of historical delivery records or suppliers input; (6) materials assignments to project activities ($MA_{m,i}$); and (7) quantities of materials deliveries on every working day ($MD_{m,d}$), which are generated by the previously mentioned procurement decision variables ($FOP_{m,t}$).

The new algorithm of estimating materials-related project delay costs (MRPD) comprises three nested loops, as shown in Fig. 6. The first loop iterates over all construction activities ($i = 1$ to I) to check if a delay occurs for each activity i on day d because of late delivery of material m. Activity i is considered delayed on day d because of late delivery of material m if the following four conditions are satisfied simultaneously: (1) activity i is in progress on day d (i.e., $ES_i \leq d$ and $EF_i \geq d$); (2) material m is utilized by activity i and therefore, has a nonzero assignment value to activity i (i.e., $MA_{m,i} > 0$); (3) a delivery of material m is scheduled on day d on the basis of the generated procurement decision variables ($FOP_{m,t}$); and (4) delivery average delay of material m (DAD_m) is greater than the current estimated delay ($Delay_i$) caused by late delivery of other materials. If all previous conditions are satisfied, the estimated delay of activity i is set to the delivery average delay of material m (DAD_m). The second loop repeats the first loop for all construction materials ($m = 1$ to M) to estimate activities delays because of the combined delay of all materials on specific day d. The third loop progressively iterates the second loop for all project working days ($d = 1$ to D), where project schedule is updated at the end of each iteration established on estimated activities delay ($Delay_i$) by using critical path method (CPM)

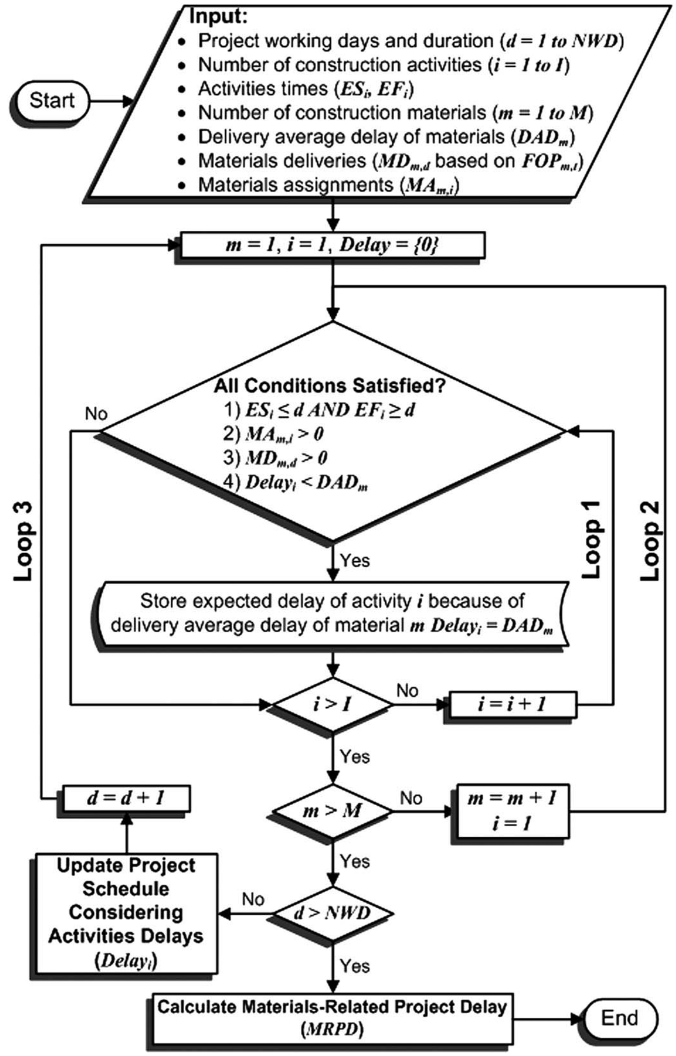

Fig. 6. Algorithm for computing MRPD

calculations. This algorithm ends by calculating the materials-related project delay (MRPD) as the difference between (1) the estimated delayed finish time of the project which is calculated as the latest finish time of all project activities owing to the late delivery of materials ($\max_i(\overline{EF_i})$); and (2) the project baseline finish time, which is calculated as the latest finish time of all project activities [$\max_i(EF_i)$], as shown in Eq. (4). Accordingly, stock-out cost (SC) is calculated, as shown in Eq. (5), by using this estimated materials-related project delay (MRPD) and the project liquidated damage (LQD) and/or time-dependent indirect costs (TDIC).

$$\mathrm{MRPD} = \max_i(\overline{EF_i}) - \max_i(EF_i) \tag{4}$$

$$\mathrm{SC} = \mathrm{MRPD} \times (\mathrm{LQD} + \mathrm{TDIC}) \tag{5}$$

where EF_i = early finish of activity i in the baseline project schedule; and $\overline{EF_i}$ = expected early finish of activity i after considering late delivery of materials.

Layout Cost

Layout cost (LC) represents the travel costs of resources between site facilities and storage areas and the costs of site layout reorganization over the project duration. As shown in Eq. (6), the layout

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cost in the present CLP model is composed of three main cost components: materials handling cost (MHC), resources travel cost (RTC), and site reorganization cost (SRC). First, materials handling cost represents the travel cost of site handling equipments or laborers that cyclically transport construction materials from storage areas to buildings under construction or site temporary facilities (e.g., a fabrication area). As shown in Eqs. (7) and (8), the materials handling cost is calculated by using: (1) the estimated quantity of materials that needs to be transported from each storage area to every site facility in all stages ($Q^t_{m,f}$); (2) the travel cost rates of handling crews that are represented by their handling capacity ($q^r_{m,f}$) and identifies the quantity of material that can be transported in one crew trip, crew hourly cost rate (HCR_r), and crew travel speed (v_r); and (3) the Euclidian traveling distances ($D^t_{m,f}$). Second, the resource travel cost is calculated for other nonmaterial handling resources (e.g., equipment, labor, and supervision personnel) moving between temporary facilities and buildings under construction [see Eq. (9)]. The resource travel cost is calculated by: (1) the travel cost rates between each pair of site facilities in every stage ($C^t_{f,g}$); and (2) the Euclidian traveling distances ($D^t_{f,g}$). Third, the site reorganization cost represents the extra cost paid by the contractor to change site layout at the beginning of each construction stage by relocating some or all moveable facilities. Moveable facilities can be relocated at the beginning of each stage if needed to create space for new temporary facilities or material storage areas. As shown in Eq. (10), the reorganization cost occurs for a moveable facility if it is either moved from its location in the preceding stage (i.e., $D^{t,t-1}_f > 0$) or if its orientation angle is changed (i.e., $\theta^t_f \neq \theta^{t-1}_f$). The present CLP model is designed to consider and control the cost of these potential relocations of moveable facilities [Eq. (10)] and to generate optimal dynamic site layouts that minimize their negative impacts and additional costs.

$$\text{LC} = \text{MHC} + \text{RTC} + \text{SRC} \tag{6}$$

$$\text{MHC} = \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{f=1}^{NF_t} C^t_{m,f} \times D^t_{m,f} + \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{f=1}^{NB_t} C^t_{m,f} \times D^t_{m,f} \tag{7}$$

$$C^t_{m,f} = \frac{2 \times (Q^t_{m,f}/q^r_{m,f}) \times HCR_r}{v_r} \tag{8}$$

$$\text{RTC} = \sum_{t=1}^{T}\sum_{f=1}^{NF_t-1}\sum_{g=f+1}^{NF_t} C^t_{f,g} \times D^t_{f,g} + \sum_{t=1}^{T}\sum_{f=1}^{NF_t}\sum_{g=1}^{B_t} C^t_{f,g} \times D^t_{f,g} \tag{9}$$

$$\text{SRC} = \sum_{t=1}^{T}\sum_{f=1}^{NF^M_t} E_f \times RC_f \times IF\{D^{t,t-1}_f > 0 \quad \text{OR} \quad \theta^t_f \neq \theta^{t-1}_f\} \tag{10}$$

where T = number of project stages; M = number of project materials; NF_t = number of temporary facilities used in stage t; NB_t = number of buildings under construction in stage t; $C^t_{f,g}$ = travel cost rate of resources moving between facilities f and g in stage t; $D^t_{f,g}$ = Euclidian distance between facilities f and g in stage t; $D^{t,t-1}_f$ = Euclidian distance between facility $f's$ positions in stages t and $t-1$; $Q^t_{m,f}$ = estimated quantity of material m required in facility f in stage t; $q^r_{m,f}$ = handling capacity of handling crew r handling material m to facility f; HCR_r = hourly cost rate of handling crew r (\$/h); v_r = speed of handling crew r (m/h); E_f = facilities existence factor equals to 1 if the moveable facility f exists in previous stage $t-1$, and 0 otherwise; RC_f = relocation cost of moveable facility f; θ^t_f = orientation angle of facility f in stage t; and IF{condition} = a conditional function that returns 1 if the inside condition is satisfied, and 0 otherwise.

Application Example

An application example is used to demonstrate the capabilities of the present CLP model in integrating and optimizing the critical planning decisions of material procurement and material storage on construction sites. As shown in Fig. 7, the example involves the construction of two office buildings over three stages in which the construction of the first building (B1) is planned to be completed in a duration that covers the three stages while the construction of the second building (B2) is planned to start in the second stage. For the purpose of illustration, three materials are considered in this example, which include reinforcing steel (rebar), autoclaved cellular concrete (ACC) blocks, and glass curtain walls. Cost rates of materials and handling crews are estimated by using RSMeans building construction cost data (RSMeans 2001). Fig. 7 depicts the cumulative demand of the three considered materials in which the reinforcing steel is required in all stages whereas the concrete block

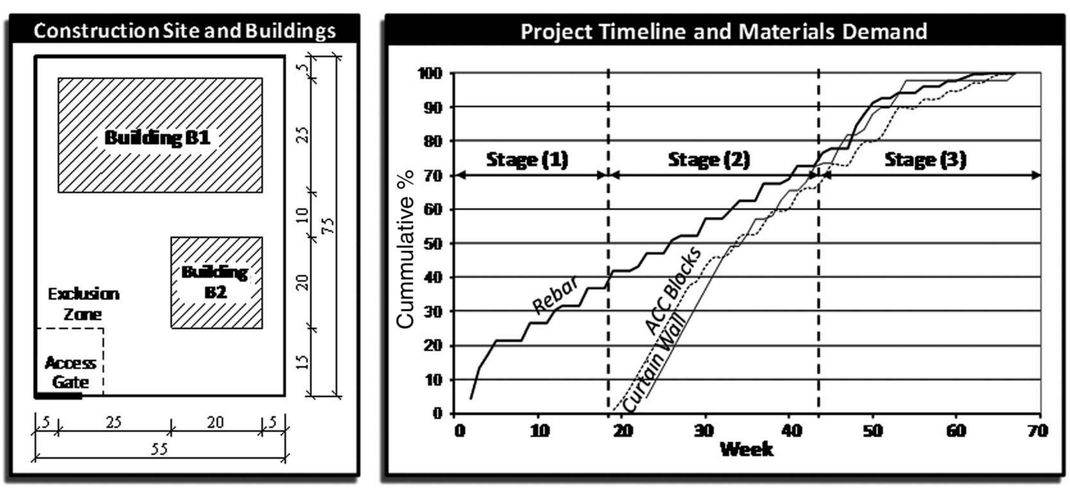

Fig. 7. Geometry and time data of the application example

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Table 1. Geometry and Time Data of Site Facilities

Fixed facilities	ID	Description	Dimensions Lx	Dimensions Ly	Time on-site T1	T2	T3	Fixed position x	y
	B1	Building (1)	45	25	√	√	√	27.5	57.5
	B2	Building (2)	20	20	—	√	√	40	25
	G	Site gate	10	1	√	√	√	5	0

Temporary Facilities	ID	Description	Dimensions Lx	Dimensions Ly	Time on-site T1	T2	T3	Type[a]	Relocation cost
	F1	Tower crane	8	8	√	√	√	S	Not applicable
	F2	Site office trailer (1)	14	4	√	√	√	M	6,000
	F3	Site office trailer (2)	11	3	—	√	√	M	4,000
	F4	Fabrication area	15	10	√	√	√	M	2,000
	F5	Dump area	15	15	√	√	—	M	0
	F6	Lay-down area	10	10	√	√	√	M	3,000
	F7	Labor rest area	5	5	√	√	√	M	500

[a]S = stationary; M = moveable.

Table 2. Travel Cost Rates ($/m) among Facilities for All Construction Stages

Facility (i)	Facility (j) B1	B2	G	F1	F2	F3	F4	F5	F6	F7
B1	0	0	0	150	50	50	90	20	70	15
B2	—	0	0	100	40	40	60	15	40	15
G	—	—	0	0	2	2	1	30	0	0
F1	—	—	—	0	0	0	30	4	25	0
F2	—	—	—	—	0	20	5	0	5	0
F3	—	—	—	—	—	0	5	0	5	0
F4	—	—	—	—	—	—	0	0	30	0
F5	—	—	—	—	—	—	—	0	0	0
F6	—	—	—	—	—	—	—	—	0	0
F7	—	—	—	—	—	—	—	—	—	0

masonry and curtain walls are required in the second and third stages. In this example, the construction project requires the utilization of seven temporary facilities such as office trailers and fabrication areas as shown in Table 1. The present CLP model is used in this example to generate the optimal procurement and layout decisions to minimize total logistics cost.

To optimize the planning of material procurement and storage in this example, the present CLP model requires construction planners to provide the following input data: (1) the construction site geometry including the dimensions and locations of buildings under construction and site boundaries, as shown in Fig 7; (2) the project stages and cumulative demand of each material over time, as shown in Fig. 7; (3) the dimensions and relocation costs of each temporary facility as shown in Table 1; (4) the travel cost rates between site facilities (C_{ij}^t) as shown in Table 2; (5) the purchase cost, delivery cost, and storage footprint data of each material, as shown in Table 3; (6) on-site materials handling quantities and cost data as shown in Table 4; (7) the layout constraints imposed on temporary facilities and material storage areas as shown in Table 5; (8) layout grid pitch, which is specified to be 1 m in this example; (9) daily project interest rate (DIR), which is estimated to be 0.03%; (10) project liquidated damage (LQD), which is estimated to be $25,000/day; (11) time-depended indirect cost (TDIC), which is estimated to be $5,000/day; (12) possible values of fixed-ordering period (FOP), which are 1, 7, 14, or 21 days; and (13) delivery average delay (DAD_m) of each material, which is estimated to be 0.7, 0.3, and 2 for the rebar, AAC blocks, and curtain walls, respectively.

The present CLP model was used to analyze the previously mentioned input data to generate an integrated optimal material procurement and layout plan for the application example. By using a population size of 1,500, the present model generated an optimal plan with a total cost of $2,349,646 established by the identified optimal procurement decision variables shown in Table 6 and the optimal layout decision variables illustrated by the dynamic layout plan in Fig. 8. The model was used to evaluate the fitness (construction logistics cost) by performing the following steps for each solution examined by the GA optimization tool to calculate: (1) the order quantities of each material during every stage because of the generated FOP and the material's demand in that stage, as shown in Table 6; (2) the ordering costs from the order quantities identified in step 1 and the suppliers purchase and delivery costs listed in Table 3; (3) the financing cost calculated with Eq. (3) for the cumulative materials demand (shown in Fig. 7) and the cumulative supply, which is dependent on the generated FOP values; (4) the stock-out cost calculated with Eq (5) and the previously mentioned algorithm (see Fig. 6) for calculating material-related project delay (MRPD); (5) the maximum inventory for each material m in every stage t on the basis of the generated $FOP_{m,t}$

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Table 3. Ordering Costs and Storage Footprints of Construction Materials

ID	Material	Unit	Purchase cost ($/unit)			Delivery cost ($)		Storage footprint		
			Stage (t)	Quantity (Q)	Rate [$PCR^t(Q)$]	Quantity (Q)	Cost [$DLC^t(Q)$]	Quantity (Q)	Lx (m)	Ly (m)
M1	Rebar	Ton	1	$0 \rightarrow 100$	650	$0 \rightarrow 25$	600	$0 \rightarrow 32$	15	2
			1	$100 \rightarrow 200$	550	$25 \rightarrow 50$	1,200	$32 \rightarrow 64$	15	4
			2,3	$0 \rightarrow 100$	750	$50 \rightarrow 75$	1,800	$64 \rightarrow 96$	15	6
			2,3	$100 \rightarrow 200$	650	$75 \rightarrow 100$	2,400	$96 \rightarrow 128$	15	8
						$100 \rightarrow 125$	3,000	$128 \rightarrow 160$	15	10
						$125 \rightarrow 150$	3,600	$160 \rightarrow 192$	15	12
						$150 \rightarrow 175$	4,200	$192 \rightarrow 224$	15	14
						$175 \rightarrow 200$	4,800			
M2	AAC blocks	1,000 blocks (M)	$1 \rightarrow 3$	$0 \rightarrow 10$	1,100	$0 \rightarrow 3$	600	$0 \rightarrow 1$	2.5	2.5
			$1 \rightarrow 3$	$10 \rightarrow 30$	950	$3 \rightarrow 6$	1,200	$1 \rightarrow 2$	5	2.5
						$6 \rightarrow 9$	1,800	$2 \rightarrow 4$	5	5
						$9 \rightarrow 12$	2,400	$4 \rightarrow 6$	7.5	5
						$12 \rightarrow 15$	3,000	$6 \rightarrow 9$	7.5	7.5
						$15 \rightarrow 18$	3,600	$9 \rightarrow 12$	10	7.5
						$18 \rightarrow 21$	4,200	$12 \rightarrow 16$	10	10
						$21 \rightarrow 24$	4,800	$16 \rightarrow 20$	12.5	10
						$24 \rightarrow 27$	5,400	$20 \rightarrow 25$	12.5	12.5
						$27 \rightarrow 30$	6,000	$25 \rightarrow 30$	15	12.5
M3	Curtain wall	m^2	$1 \rightarrow 3$	$0 \rightarrow 1500$	210	$0 \rightarrow 250$	1,000	$0 \rightarrow 250$	5	5
						$250 \rightarrow 500$	2,000	$250 \rightarrow 500$	10	5
						$500 \rightarrow 750$	3,000	$500 \rightarrow 750$	10	10
						$750 \rightarrow 1{,}000$	4,000	$750 \rightarrow 1{,}000$	15	10
						$1{,}000 \rightarrow 1{,}250$	5,000	$1{,}000 \rightarrow 1{,}250$		
						$1{,}250 \rightarrow 1{,}500$	6,000	$1{,}250 \rightarrow 1{,}500$		

Table 4. Materials On-Site Handling Quantities and Cost Data

Material (m)	Unit	Facility (i)	Stage (t)	Required quantity (Q^t_{mi})	Handling equipment (r)	Handling quantity (q^r_{mi})	Travel speed [v_r (m/hr)]	Hourly cost [HCR_r ($/hr)]	Travel cost rate [C^t_{im} ($/m)]
Rebar	Ton	B1	1	286.5	Tower crane	2	5,000	200	11.46
		B1	2	280					11.20
		B1	3	88					3.52
		B2	3	124					4.96
AAC blocks	M	B1	2	97.5		0.5			15.60
		B1	3	30.5					4.88
		B2	3	17.83					2.85
Curtain wall	m^2	B1	2	4,541.67		4.5			80.74
		B1	3	1,998.33					35.53
		B2	3	140					2.49

and material's demand; (6) the storage space needs and dimensions for each material in every stage (see Table 6) established by the planner-defined footprint schedules and the value of the FOP; and (7) the layout costs calculated with Eqs. (6)–(10) considering the values of layout decision variables (locations and orientations) for all storage areas and temporary facilities.

Analyzing the generated optimal results for this example reveals that material procurement decisions are greatly affected by the criticality of construction activities consuming the material and by site space availability. First, materials for construction activities on the critical path required long fixed-ordering periods (FOP) as shown in the optimal procurement decisions in Table 6. Longer material FOP values were generated for these critical activities to ensure the availability of larger inventories to minimize materials-related project delays. For example, the optimal FOP for the rebar material was identified by the model to be 21 days in the three stages because all the rebar activities in this example were on the project critical path resulting in zero delivery slacks. Second, the site space availability also had a significant impact on the generated optimal procurement decisions in Table 6. For example, shorter FOP values for the AAC blocks and curtain walls (1 and 7 days, respectively) were generated in the second stage because of the limited site

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Table 5. Site Layout Planning Constraints

Distance constraints			
Purpose	Type	Facilities	Distance (m)
Safety	Min	B1, F2	5
	Min	B1, F3	5
	Min	B1, F7	5
	Min	B2, F2	5
	Min	B2, F3	5
	Min	B2, F7	5
	Min	F1, F2	15
	Min	F1, F3	15
	Min	F1, F7	15
Operational	Max	F1, F2	30
	Max	F1, F3	30
	Max	F1, B1	30
	Max	F1, B2	30
	Max	F1, F4	30
	Max	F1, F6	30
	Max	F1, M1	30
	Max	F1, M2	30
	Max	F1, M3	30
	Max	F2, B3	5
	Min	M3, M1	5
	Min	M3, M2	5
	Min	M3, B1	5
	Min	M3, B2	5

Exclusion zone constraints (operational)				
Facility	X1	X2	Y1	Y2
All site facilities	0	15	0	15

space. On the other hand, longer FOP values were generated for the same materials in the third stage because more site space became available as facility F5 (dump area) was no longer needed. The present CLP model considers and optimizes the trade-offs among all logistics cost items (i.e., ordering, financing, and stock-out costs) in identifying the optimal material procurement and site layout decisions.

Analyzing the generated optimal results as shown in Fig. 8 reveals also that dynamic site layout decisions are affected by the procurement decisions and their storage space needs, as shown in Table 6. Similarly, the dynamic site layout decisions are affected by the distance and zone constraints shown in Table 5 that are imposed to represent safety or operational issues such as: (1) positioning the site office trailers (F2 and F3) and labor rest areas (F7) at least 5 m away from building B1 and B2 and 15 m away from the tower crane (F1) to mitigate the hazards of falling objects; (2) positioning the tower crane (F1) as shown in Fig. 8 to comply with operational distance constraint of having buildings B1 and B2 within the crane jib reach (30 m); and (3) positioning all temporary facilities and storage areas out of the gate exclusion zone to prevent blocking site access point.

Summary and Conclusion

A new model of construction logistics planning was developed to enable the integration and optimization of the critical planning decisions of material procurement and material storage on construction sites. The procurement decision variables in the developed model are designed to identify the fixed-ordering periods of each material in every construction stage to consider the changing demand rates of materials over the project duration. The layout decision variables are designed to identify the locations and orientations of material storage areas and other temporary facilities in each construction stage to consider the dynamic site space needs.

Table 6. Optimal Values of Procurement Decision Variables and Resulting Logistics Costs

Material (m)	Stage (t)	$FOP_{m,t}$ (days)	Procurement plan: Date	Procurement plan: Quantity	Max inventory	Storage area (m × m)	Logistics cost: Ordering	Logistics cost: Financing	Logistics cost: Stock-out
Rebar	1	21	8/19/2008 — 11/14/2008	156.25 — 40	156.25	15 × 10	178,400	699.85	
	2	21	12/22/2008 — 5/18/2009	60 — 40	60	15 × 4	218,400	586.65	
	3	21	6/8/2009 — 11/2/2009	40 — 2.5	105.5	15 × 8	155,650	393.02	
AAC blocks	2	1	12/25/2008 — 6/2/2009	0.833 — 1.25	Not applicable (JIT)		156,950	0	
	3	21	6/8/2009 — 11/2/2009	10 — 4.08	13	10 × 10	63,213	127.71	
Curtain wall	2	7	1/9/2009 — 6/5/2009	60.56 — 60.56	423.89	10 × 5	977,750	939.73	
	3	21	6/8/2009 — 11/2/2009	726.67 — 140	726.67	10 × 10	459,050	1,724.68	60,000 (2 days delay)

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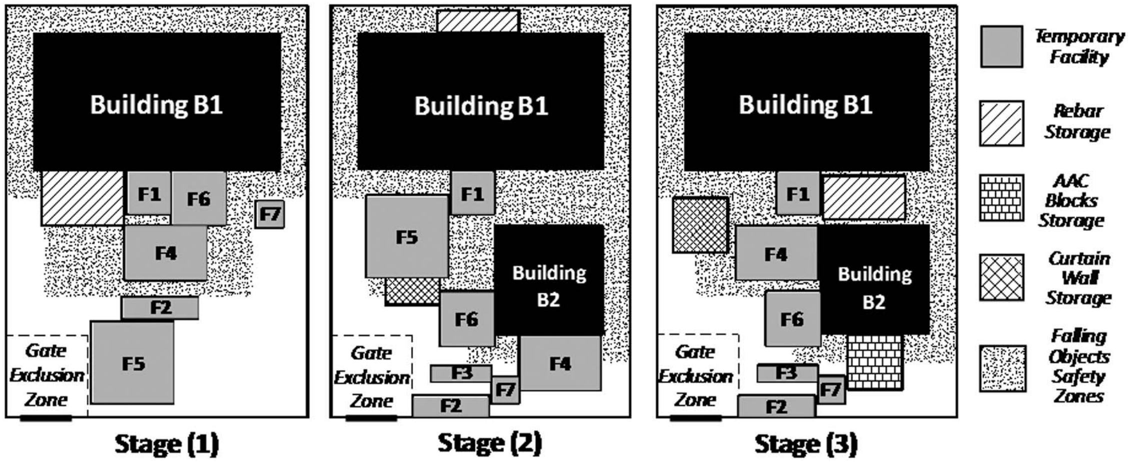

Fig. 8. Generated dynamic layout plan considering material procurement decisions

The present model utilizes genetic algorithms to generate optimal material procurement and layout decisions to minimize construction logistics costs that include material ordering, financing, stock-out, and layout costs. An application example was analyzed to demonstrate the capabilities of the present CLP model in integrating and optimizing procurement and layout decisions while considering their mutual interdependencies. The results of this analysis also illustrate that the material procurement decisions are affected by the criticality of construction activities consuming the material and site space availability, whereas the dynamic site layout decisions are affected by the material procurement decisions and material storage space needs and other site layout constraints. These new capabilities of the developed model should prove useful in the challenging tasks of planning and optimizing material procurement and storage decisions, especially for long-lead items, in construction projects. Future research to expand the present CLP model include: (1) developing an online collaboration system to enable early involvement of all project parties (i.e., owner, designers, contractors, and suppliers) and seamless data collection and sharing; (2) considering the impact of equipment and personnel routes of movement on the generated site layout plans; (3) utilizing building's indoor spaces for material storage areas; (4) developing a graphical user interface that facilitates interaction with users and informative visualization of the generated plans; and (5) performing sensitivity analysis to examine the impact of different planning parameters (such as the number of project stages or materials) on the performance of the developed model.

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Notation

The following symbols are used in this paper:

$C^t_{f,g}$ = travel cost rate of resources moving between facilities f and g in stage t;
CD^m_d = cumulative demand of material m in day d;
CS^m_d = cumulative supply of material m in day d;
$D^t_{f,g}$ = Euclidian distance between facilities f and g in stage t;
$D^{t,t-1}_f$ = Euclidian distance between facility $f's$ positions in stages t and $t-1$;
$DLC^t_m(Q_n)$ = delivery cost of material m in stage t with Q_n order quantity;
E_f = facilities existence factor equal to 1 if the moveable facility f exists in previous stage $t-1$, and 0 otherwise;
EF_i = early finish of activity i in the baseline project schedule;
$\overline{EF_i}$ = expected early finish of activity i after considering late delivery of materials;
HCR_r = hourly cost rate of handling crew r ($/hour);
IF{condition} = a conditional function that returns 1 if the inside condition is satisfied, and 0 otherwise;
M = number of project materials;
NB_t = number of buildings under construction in stage t;
NF_t = number of temporary facilities used in stage t;
NOR^t_m = number of orders of material m in stage t;
PCR^{avg}_m = average purchase cost rate of material m;
$PCR^t_m(Q_n)$ = purchase cost rate of material m in stage t with Q_n order quantity;
Q_i = quantity of order i;
$Q^t_{m,f}$ = estimated quantity of material m required in facility f in stage t;
$q^r_{m,f}$ = handling capacity of handling crew r handling material m to facility f;
RC_f = relocation cost of moveable facility f;
T = number of project stages;
θ^t_f = orientation angle of facility f in stage t; and
ν_r = speed of handling crew r (m/h).

Subscripts and Superscripts

d = project days counter (from 1 to D);
f, g = counter of site facilities in stage t (from 1 to NF_t);
i = project activities counter (from 1 to I);
m = materials counter (from 1 to M);
n = counter of material m orders in stage t (from 1 to NOR^t_m); and
t = construction stage counter (from 1 to T).

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