

Representation of Construction Logistics Planning Model

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Abstract – Construction field has the strongest ability for occupational hazard events among all Asian industries. Planning the site layout of construction projects is a critical task that has a conservative impact on construction cost, productivity, and safety. It involves the placing and standard relocation of temporary facilities that are needed to support various construction activities on site such as offices, logistics industries, hotels, and parking areas. One of the major causes is construction employers or employees' negative attitudes toward safety requirements imposed by different construction safety documents, such as construction safety regulations and project safety plans. Such attitudes towards safety requirements include ignorance, negligence and disobedience and the first two can be dealt with by raising construction project participants' awareness of safety requirements through better construction safety planning. Due to the complexity of the site layout planning problem, construction managers often perform this task using old experience and first-come-first-serve basis which leads to ambiguity and even to inaccuracy. Accordingly, a number of site layout scheduled models have been developed over the past three decades to support this dynamic planning task. The large number of precautionary requirements from different construction safety documents may hinder project participants from carefully looking through them for identifying applicable precautionary requirements. In accordance with that, present approaches and tools for increasing awareness of safety requirements are not enough. Despite of the contributions of existing site layout planning models, they have a number of rules and regulations that require advance research in five main areas in order to: (1) establish international optimization of dynamic site layout planning; (2) integrate material procurement and site layout planning in a construction logistics planning model; (3) enable the usage of interior building spaces for logistics areas on congested construction sites; (4) involve automated retrieval and integration of all necessary data of construction logistics and site layout planning from already installed design and planning documents; and (5) consider security needs and constraints during the construction of critical infrastructure projects.

For the analysis of construction safety requirements, the Ordered Hierarchy of Content Object (OHCO) approach is adopted to build the representation model; Extensible Markup Language (XML) is used in this research to implement the OHCO-based model. First, two novel optimization models are developed that are capable of generating international optimal solutions of standards site layout planning in order to reduces resources transportation and facilities relocation costs while complying with various site geometric constraints. The first model, DSLP-GA, is implemented using Genetic Algorithms while the second model, DSLP-ADP, is formulated using Approximate Dynamic Programming. Ontological modeling, on the other hand, is leveraged to model semantically-rich concepts that describe construction contexts. In addition, the developed reasoning mechanisms utilize the ontological relationships between modeled concepts to automatically evaluate each concept's applicability. Construction safety requirements' applicability then can be evaluated by reasoning about the requirements' applicability conditions and exceptions, which are represented using concepts defined in the concept ontologies. Safety requirements can be classified according to their evaluated applicability. Second, a novel model of construction logistics planning (CLP) is developed to establish the integration and simultaneous optimization of critical planning solutions of material procurement and material storage on construction sites. Procurement solution variables are designed to identify the fixed-ordering-periods of each material in every construction stage, while dynamic layout decision variables are designed to identify the locations and orientations of material storage areas and other temporary facilities in each construction stage. The expected developments of this research study contribute to enhancing the current practices of site layout and material logistics planning and can lead to: (1) raising the efficiency and international optimality of construction site layout planning; (2) developing construction productivity that can be realized as a result of the early coordination between material procurement

and site space planning; (3) enhancing the utilization of interior building spaces for material storage areas while minimizing its possible negative impacts on construction operations and schedules; (4) increasing the security level on the construction sites of critical infrastructure projects; and (5) reducing contractors site costs that cover the travel cost of resources on construction sites, material logistics, and site security systems.

Keywords – logistics planning (CLP), DSLP-ADP.

I. INTRODUCTION

The main objective of this chapter is to present the development of a new construction logistics planning (CLP) model that is capable of integrating and optimizing critical planning decisions of material procurement and site layout planning on construction sites considering existing interdependencies and mutual impacts. As shown in Figure 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).

The present CLP model is designed to help contractors minimize material logistics costs using an integrated approach (see Figure 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 using Genetic Algorithms (GA) (Deb et al 2001). GA has been widely used in many construction planning applications to find near optimal solutions to complex and large scale optimization problems by mimicking natural evolution (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 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 using various genetic operators (crossover, mutation, and elitism). The following sections describe in more details the two categories of decision variables as well as the optimization objective function of the present CLP model.

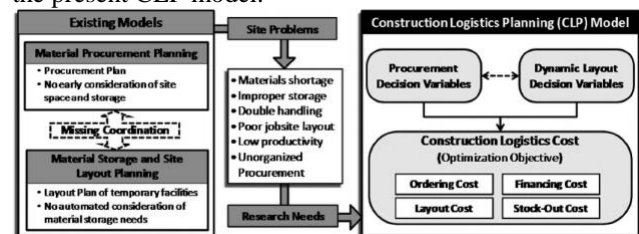


Fig. 1. Construction Logistics Planning Model.

II. 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 Figure 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). 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). 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 Figure 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 Figure 2. It should be noted that 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. The present model is designed to consider the impact of the aforementioned 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 Figure 2 is replenished by three unequal-quantity orders over three equal periods. It should be noted that the last replenishment interval in a stage is the minimum of the selected fixed-ordering-period and the remaining time in the corresponding stage.

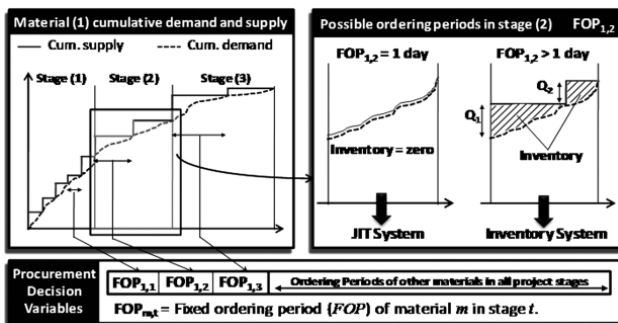


Fig.2. Procurement Decision Variables.

Second, storage space needs are identified based on 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 based on the largest order quantity in the generated procurement plan. The identified maximum inventory level is then used to estimate the material storage needs based on the materials footprint schedules, as shown in Figure 3. In the present model, materials footprint schedules are specified by construction planners to define the dimensions (L_x and L_y) of materials storage areas for different inventory quantities (see Figure 1.2).

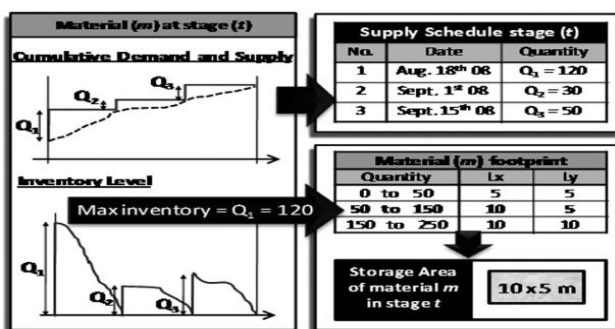


Fig.3. Impact of Procurement Decision on Material Storage Needs.

III. 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 Figure 4. First, the model identifies the optimal layout decisions of material storage areas based on their space needs that are estimated using the aforementioned procedure that considers the impact of procurement decisions (see Figure 4). 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 Figure 4. For example, the following ten decision variables are needed to represent the layout of material storage areas for the example in Figure 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, while the orientation angle can be either 0 or 90 degrees, as shown in Figure 4.

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 Figure 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 stages 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 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 Figure 4 includes the following ten 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. It should be noted that the layout of both storage areas and temporary facilities should comply with a set of geometric constraints in order to: (1) position all facilities and storage areas within the boundaries of the construction site; (2) prevent overlaps between any pair of facilities

and/or storage areas; (3) maintain operational or safety distance between facilities and/or storage areas; and (4) consider the existence of any exclusion zones onsite (Zouein and Tommelein 1999; El-Rayes and Said 2008).

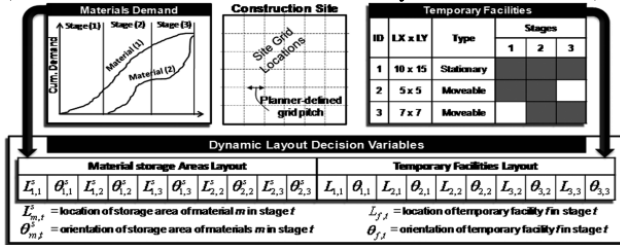


Fig.4. Dynamic Layout Decision Variables in the CLP Model.

IV. CONSTRUCTION LOGISTICS COST

The present CLP model is designed to minimize construction logistics costs that are affected by the aforementioned procurement and layout decision variables. As shown in Equation 1, construction logistics costs in the present model (CLC) include four main 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 due to material shortages, if any; and (4) layout cost (LC) that accounts for material handling costs and resource travel costs on site. The present model seeks to minimize these construction logistics costs by identifying optimal solutions for the aforementioned 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.

$$CLC = OC + FC + SC + LC$$

Where,

CLC = construction logistics costs;

OC = ordering cost;

FC = financing cost;

SC = stock-out cost; and

LC = layout cost.

1. 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 Equation 2, both material purchase and delivery costs depend on

the number of material orders and their quantities which are identified based on the aforementioned procurement decisions. Small order quantities results in high purchase cost because of the loss of potential discounts provided by suppliers for larger order quantities. Moreover, small order quantities may result in high delivery costs because of under-utilized trucks with loads less than their maximum capacities. As shown in Figure 5, a simplified example is provided to illustrate the impact of procurement decisions on ordering cost, where it is required to supply 600 units of material m in stage t. In this example, two options of procurement plan are considered: (1) twelve equal deliveries of 50 units; or (2) two deliveries of 300 units. The example illustrates that the first option leads to a higher ordering cost because it supplies the required 600 units using more deliveries with smaller quantities.

$$OC = \sum_{t=1}^T \sum_{m=1}^M \sum_{n=1}^{NOR_m^t} (Q_t \times PCR_m^t(Q_n) + DLC_m^t(Q_n))$$

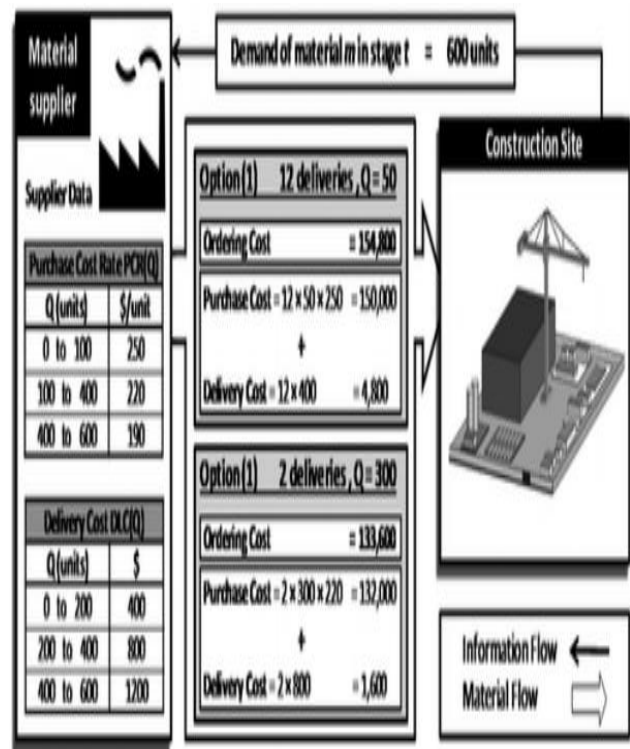


Fig.5. Impact of Procurement Decisions on Ordering Costs.

2. 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 return on the contractor's money tied up in materials inventory if it is invested elsewhere such as 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 Equation 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 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. It should be noted that the cumulative supply is solely affected by the aforementioned procurement decision variables ($FOPt,m$), where longer $FOPt,m$ leads to larger materials inventories (see Figure 2).

$$FC = \sum_{i=1}^{NCD} \sum_{m=1}^M (CS_{d^m} - CD_{d^m}) \times PCR_m^{avg} \times DIR \quad (3)$$

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 ;

d

PCR_m^{avg} = average purchase cost rate of material m ; and

DIR = project daily interest rate.

V. MODEL EVALUATION

An application example is used to evaluate and 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 Figure 6, the example involves the construction of two office buildings over three stages where 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 using RSMeans Building Construction Cost Data (RSMeans 2001). Figure 6 depicts the cumulative demand of the three considered materials where the reinforcing steel is required in all stages while the concrete block 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 in order to minimize total logistics cost.

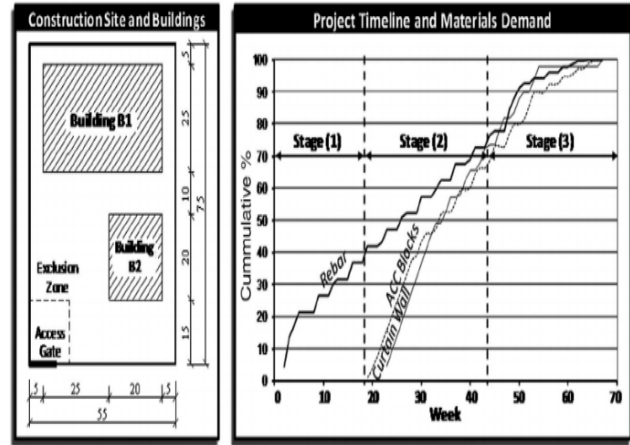


Fig.6. Geometry and Time Data of the Application Example.

Table –II: Geometry and Time Data of Site Facilities

ID	Description	dimensions		Time on site			Fixed position	
		Lx	Ly	T1	T2	T3	X	Y
B1	Building (1)	45	25	v	v	v	27.5	27.5
B2	Building (2)	20	20	-	v	v	40	25
G	Site Gate	10	1	v	v	v	5	0

ID	Description	dimensions		Time on site			Type	Relocation
		Lx	Ly	T1	T2	T3	*	Cost
F1	Tower Crane	8	8	v	v	v	S	N.A.
F2	Office trailer (1)	14	4	v	v	v	M	8,000
F3	Office trailer (2)	11	3	-	v	v	M	4,000
F4	Fabrication Area	15	10	v	v	v	M	2,000
F5	Dump Area	15	15	v	v	v	M	0
F7	Labor Rest Area	5	5	v	v	v	M	500

* S = Stationary; M = Moveable

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In order 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 Figure 6; (2) the project stages and cumulative demand of each material over time, as shown in Figure 6; (3) the dimensions and relocation costs of each temporary facility as shown in Table 1; (4) the travel cost rates between site facilities (C_{ijt}) as shown in Table 2; (5) the purchase cost, delivery cost, and storage footprint data of each material, as shown in Table 2; (6) on-site materials handling quantities and cost data as shown in Table 2; (7) the layout constraints imposed on temporary facilities and material storage areas as shown in Table 2; (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-dependent 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 (DADm) of each material, which is estimated to be 0.7, 0.3, and 2 for the rebar, AAC blocks, and curtain walls, respectively.

Table –II: Travel Cost Rates (\$/m) among Facilities in all 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

The present CLP model was used to analyze the aforementioned input data to generate an integrated optimal material procurement and layout plan for the application example. Using a GA population size of 1500, the present model generated an optimal plan with a total cost of \$2,349,646 based on the identified optimal procurement decision variables shown in Table 2 and the optimal layout decision variables illustrated by the dynamic layout plan in Figure 6. 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 in order to calculate: (1) the order quantities of each material during every stage based on the generated FOP and the material's demand in that stage, as shown in Table 2; (2) the ordering costs based on the order quantities identified in step 1 and the suppliers purchase and delivery costs listed in Table 2; (3) the financing cost using Equation 3 based on the cumulative materials demand and the cumulative supply which is dependent on the generated FOP values; (4) the stock-out cost using Equation 5 and the aforementioned algorithm (see Figure 6) for calculating material-related project delay (MRPD); (5) the maximum inventory for each material m in every stage t based on the generated $FOP_{m,t}$ and material's demand; (6) the storage space needs and dimensions for each material in every stage (see Table 2) based on the planner-defined footprint schedules and the value of the FOP; and (7) the layout costs using Equations 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 (1) the criticality of construction activities consuming the material; and (2) 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 2. 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. Analyzing the generated optimal results reveals also that dynamic site layout decisions are affected by (1) procurement decisions and material storage space needs; and (2) site layout constraints. As shown in Figure 7, dynamic site layout decisions are affected by the procurement decisions their storage space needs, as shown in Table 2. Similarly, the dynamic site layout decisions are affected by the distance and zone constraints shown in Table 1 that are imposed to represent safety and/or operational issues, such as: (1) positioning the site office trailers (F2 and F3) and labor rest areas (F7) at least 5 meters away from building B1 and B2 and 15 meters away from the tower crane (F1) to mitigate the hazards of falling objects; (2) positioning the tower crane (F1) as shown in Figure 7 to comply with operational distance constraint of having buildings B1 and B2 within the crane jib reach (30 meters); and (3) positioning all temporary facilities and storage areas out of the gate exclusion zone to prevent blocking site access point.

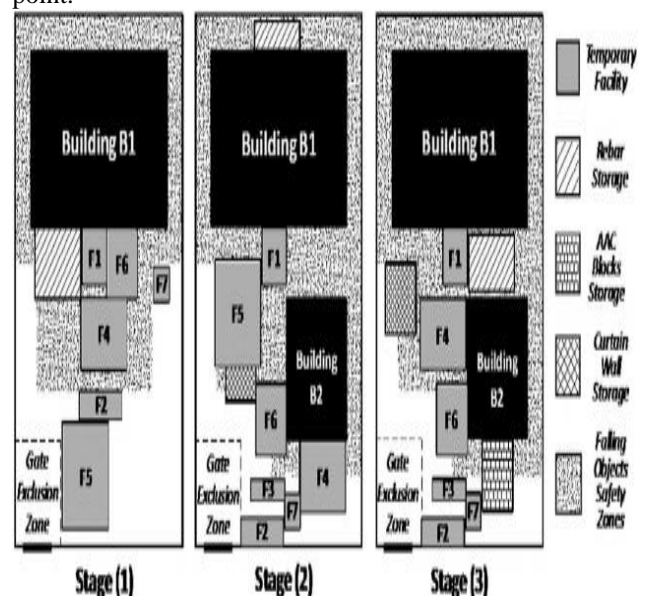


Fig.7. Generated Dynamic Layout Plan Considering Procurement Material Decisions.

VI. SUMMARY

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 in order to consider the changing demand rates of materials over the project duration. The dynamic layout decision variables are designed to identify the locations and orientations of material storage areas and other temporary facilities in each construction stage to dynamically consider the dynamic site space needs. The present model utilizes Genetic Algorithms to generate optimal material procurement and layout decisions in order 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, while the dynamic site layout decisions are affected by the material procurement decisions and material storage space needs as well as other site layout constraints.

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