# Dynamic Site Layout Planning Using Approximate Dynamic Programming

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# Dynamic Site Layout Planning Using Approximate Dynamic Programming

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**Abstract:** Dynamic site layout planning requires identifying and updating the positions of all temporary construction facilities such as offices, storage areas, and workshops over the entire project duration. Existing models do not guarantee global optimal solutions because they focus on optimizing the planning and layout of successive construction stages in a chronological order, without considering the future implications of layout decisions made in early stages. This paper presents the development of an approximate dynamic programming model that is capable of searching for and identifying global optimal dynamic site layout plans. The model applies the concepts of approximate dynamic programming to estimate the future effects of layout decisions in early stages on future decisions in later stages. The model is developed in three main phases: (1) formulating the decision variables, geometric constraints, and objective function of the dynamic site layout planning problem; (2) modeling the problem using approximate dynamic programming; and (3) implementing and evaluating the performance of the model. An evaluation example is analyzed to illustrate the use of the model and demonstrate its capabilities in generating global optimal solution for dynamic site layout planning of construction projects.

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## Introduction

Planning the site layout of construction projects is a crucial task that has a significant impact on construction cost, productivity, and safety. It involves the positioning of temporary facilities that are needed to support various construction activities on site such as offices, storage areas, workshops, and parking areas. Due to the complexity of the site layout planning problem, construction managers often perform this task using previous experience, ad hoc rules, and first-come-first-serve basis which leads to ambiguity and even to inefficiency (Mawdesley et al. 2002). A number of site layout planning models have been developed over the past 3 decades to support this important planning task. Existing construction site layout planning models can be classified into two main categories: static and dynamic plannings.

Static site layout models adopt various methodologies and tools such as goal programming (Osman and Georgy 2005); computer simulation (Retik and Shapira 1999; Dawood and Marasini 2002); knowledge-based systems (Tam et al. 2002; Chau and Anson 2002; Sadeghpour et al. 2006); hybrid systems (Zhang et al. 2002); and genetic algorithms (Hegazy and Elbeltagi 1999; Mawdesley et al. 2002; Zouein et al. 2002; Cheung et al. 2002; Tam et al. 2001; Osman et al. 2003b; Khalafallah and El-Rayes 2005, 2006). These static site layout planning models produce a single site layout that identifies static locations for all temporary facilities in the project. These static locations of facilities are not allowed to change over the project duration and accordingly existing static models do not consider the dynamic changes in the space availability and needs on construction sites.

Dynamic site layout planning models provide the capability of considering possible reuse of space, relocation of temporary facilities, and the changing space needs. Existing dynamic site layout planning models subdivide the project duration into successive stages and identify the locations of temporary facilities in each of these stages. They generate an optimal site layout for each stage in a chronological order starting from the first stage. Zouein and Tommelein (1999) developed a hybrid model that utilizes constraint satisfaction and linear programming (LP) to optimize the positions of temporary facilities in order to minimize transportation and relocation costs. Temporary facilities are ordered first based on a set of heuristic rules and then positioned one at a time considering geometric constraints among them. Elbeltagi et al. (2004) utilized genetic algorithms (GAs) to search for optimal layouts in successive construction stages in order to minimize the travel distance among selected temporary facilities while maximizing safety which was represented by user-defined weights. Osman et al. (2003a) proposed an optimization model to search for the optimal dynamic site layout by developing trials of successive site layouts and selecting the best trial that provides the minimum site layout cost. Other research efforts focused on developing four-dimensional (4D) site management models that link 3D computer aided design (CAD) building models and scheduling software to provide 4D graphical visualization of construction site layout planning (Wang et al. 2004, Ma et al. 2005).

Despite the contributions of the aforementioned dynamic site layout planning models, they all adopt a chronological procedure to identify a local optimal solution for each of the identified stages of the project duration. Such early-commitment strategy means that layout efficiency of later stages is greatly affected by

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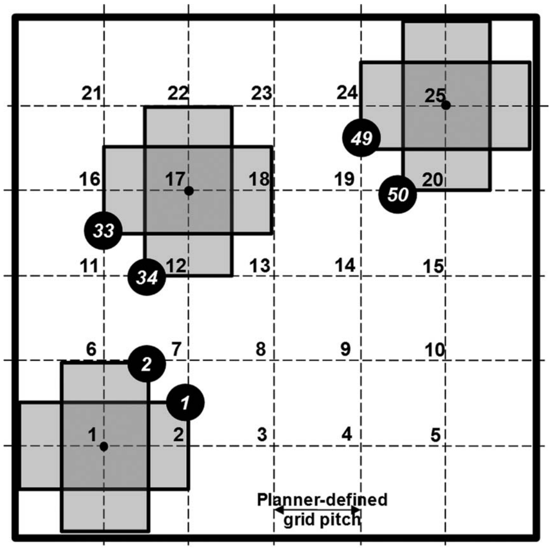


Possible Positioning Options

| Option | 1 | 2 | --------- | 33 | 34 | --------- | 49 | 50 |
|---|---|---|---|---|---|---|---|---|
| Location | 1 | 1 | --------- | 17 | 17 | --------- | 25 | 25 |
| Orientation | 0° | 90° | --------- | 0° | 90° | --------- | 0° | 90° |

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**Fig. 1.** Representation of site space and decision options

decisions taken in early layouts, which does not guarantee a global optimal solution. Moreover, these approaches may provide infeasible solutions where early located facilities may cause insufficient space for future facilities, especially in congested construction sites.

## Objective

The objective of this paper is to present the development of a robust optimization model for dynamic site layout planning of construction projects. The model utilizes approximate dynamic programming (ADP) and provides the capability of: (1) searching for the global optimal site layout plan in order to minimize the total site layout costs over the entire project duration; and (2) modeling different geometric constraints that exist between temporary facilities to reflect operational, organizational, and/or safety requirements. The model is developed in three stages that are designed to: (1) formulate a dynamic construction site layout planning model; (2) implement the model using approximate dynamic programming; and (3) evaluate the performance of the model. The following sections of the paper describe these three development stages.

## Model Formulation

A dynamic site layout planning model is formulated to identify the optimal location of all construction facilities within the available space on the construction site. As shown in Fig. 1, the construction site is represented in the present model by a two-dimensional rectangle that contains all construction facilities that occupy space such as buildings, access roads, storage areas, and site offices. Each construction facility is also represented by a two-dimensional rectangle with a fixed size that does not change during its existence on site. Construction facilities are classified, in this model, into three main categories: fixed, moveable, and stationary facilities.

1. *Fixed facilities* are those with predetermined fixed positions on site such as the constructed building and site access. Planners do not need to select the locations of these facilities as their positions and dimensions are predetermined and can be extracted from the construction drawings;
2. *Stationary facilities* are temporary facilities that planners need to determine their positions only once such as tower cranes and batch plants. These facilities are not allowed to be repositioned on site in later project stages due to the significant time, cost, and/or effort required to relocate them; and
3. *Moveable facilities* are temporary construction facilities that can be relocated at the start of any of the identified project stages. Examples of moveable facilities include site offices, testing laboratories, storage areas, fabrication areas, and rest areas. A moveable facility can be relocated in cases where there is newly freed space that is better than its currently occupied spot, or if other new facilities have a greater need for its current location. The ability to modify the locations of moveable facilities in various project stages can improve the [illegible]ency of the overall site layout; however this repositio[illegible] [illegible]equires an additional relocation cost.

The following three sections in the model formulation focus on: (1) the decision variables used to model this site layout planning problem; (2) the geometric constraints that are typically encountered in construction site layouts including boundary, overlap, distance, and zone constraints; and (3) the objective function adopted in the present model to minimize the total site layout cost over the entire project duration.

### *Decision Variables*

Site layout planning requires making decisions on the positioning of each temporary facility on site. As such, the main decision variables in the present model are the location and orientation (either 0 or 90°) of each temporary facility in each construction stage. The decision space for each planning stage depends on the selected grid to represent the possible locations for the center of each facility (see Fig. 1). For example, the decision space in Fig. 1 includes 50 possible positioning options for the facility shown (i.e., 25 possible locations $\times$ 2 possible orientations). In the present model, the decision space depends on the planner-specified grid pitch, as shown in Fig. 1. Decreasing the grid pitch improves the planning precision and quality of the optimal site layout solution as it decreases the possibility of skipping optimal facility locations. This decrease in the grid pitch however increases the decision space as well as the computational time and cost. Accordingly, the planner needs to consider this tradeoff between planning quality and computational cost during the selection of the grid pitch.

The number of decision variables in the model is affected by the number of planner-defined construction stages. For each of these stages, the model is designed to represent the positioning of each temporary facility with two decision variables (i.e., location and orientation). Accordingly, the total number of decision variables in the model is equal to the summation of the number of decision variables in all the planner-specified stages. The quality of site layout planning can be enhanced by increasing the number of these stages as it provides more frequent updates of the site layout needs. This increase in the number of stages, however, creates a larger number of decision variables which requires more computational time and cost. This tradeoff between the quality of the site layout solution and the computational costs also needs to be considered by planners when they specify the number of stages. Planners can specify the start of these stages to coincide with schedule milestones, which represent the finish and start of major tasks and accordingly the release of and demand for significant site space.

### Geometric Constraints

The positioning of any temporary facility on site should consider a set of geometric constraints, including boundary, overlap, distance, and zone constraints.

1. *Boundary constraints* are imposed to ensure that all positioned moveable and stationary facilities are located within the site boundaries;
2. *Overlap constraints* are imposed to prevent any physical overlap between the positions of any pair of facilities $(i, j)$ in the same construction stage;
3. *Min/Max distance constraints* are imposed on the face distances between construction facilities to satisfy operational, safety, and/or security requirements on site. For example, it may be required to provide safety buffer distances around constructed buildings to minimize the hazards of falling objects. To represent this safety requirement, a set of *minimum distance* constraints can be imposed on the distance between the constructed building and all temporary facilities that are affected by these falling objects. On the other hand, the distance between the tower crane and its supply points should not exceed the reach of the crane jib, which can be represented by a *maximum distance* constraint for this operational requirement; and
4. *Exclusion/Inclusion-zone constraints* are imposed to limit the presence of a construction facility outside or inside a specified zone on site. For example, an exclusion zone can be placed around the access gate to restrict the positioning of any construction facility that may block this access area. Exclusion zones can also be used to represent construction activity zones such as building exterior works that cannot be used to position any temporary facilities. On the other hand, the *inclusion-zone constraint* is used to restrict the positioning of a facility within a specified inclusion zone.

### Objective Function

The objective function in the present model is formulated to minimize the total site layout cost incurred by the contractor over the entire project duration. As shown in Eq. (1), the objective function minimizes the summation of three cost components that occur in each construction stage ($t$): travel cost ($\mathrm{TC}_t$), relocation cost ($\mathrm{RC}_t$), and constraint-violation cost ($\mathrm{CVC}_t$). First, the travel cost ($\mathrm{TC}_t$) is calculated between all construction facilities that exist in stage $t$ based on the Euclidian distances and the travel cost rates between them in the corresponding stage. Second, the relocation cost ($\mathrm{RC}_t$) is calculated for each moveable facility in construction stage $t$ if any one of the following two cases is encountered: (1) the orientation of the facility is changed while maintaining its location in the previous stage; or (2) moving the facility from its previous location to a different one regardless of its new orientation. The relocation cost in the former case can be represented by a fixed cost while the same cost in the latter case is represented by a fixed cost and a variable cost that depends on the relocation distance. Third, the constraint-violation cost ($\mathrm{CVC}_t$) for all temporary facilities in stage $t$ is calculated based on the number of constraint violations committed during positioning each one of these facilities. The calculation of these three components of site layout costs depends on the type of facility and is described in more detail in the "Contribution Function" section of this paper

$$\text{Minimize total site layout cost} = \text{minimize} \left[ \sum_{t=1}^{T} \mathrm{TC}_t + \sum_{t=2}^{T} \mathrm{RC}_t + \sum_{t=1}^{T} \mathrm{CVC}_t \right] \tag{1}$$

where $T$=number of construction stages; $\mathrm{TC}_t$=travel costs between all facilities in stage $t$; $\mathrm{RC}_t$=relocation cost of moveable facilities in stage $t$; and $\mathrm{CVC}_t$=constraint-violation cost for all facilities in stage $t$.

## Approximate Dynamic Programming Modeling

ADP offers a powerful methodology to analyze complex and multidimensional dynamic problems that are computationally hard to solve using traditional dynamic programming (Powell et al. 2005). This powerful ADP methodology is used to model the present complex and multidimensional site layout planning problem that requires the optimization of site layout decisions for multiple facilities in successive stages. The following sections describe the six main components of the developed ADP model: decision epochs, state vector, transition function, contribution function, optimality equation, and ADP algorithm.

### Decision Epochs

Modeling a complex problem using dynamic programming requires breaking it down into a set of simpler and easier subproblems (decision epochs) that are solved sequentially to generate the optimal solution for the larger problem (Zayed 2002). As shown in Fig. 2, the decision epochs are used in the present model to represent the positioning decisions of every *positionable* (i.e., *moveable* or new *stationary* facility) in every construction stage. For example, the present model identifies facilities F2 and F3 (see Fig. 2) as *positionable* facilities in the first stage because F2 is a new stationary facility that was not positioned before, while F3 is a moveable facility. Similarly in the second and third stages, facilities F3 and F4 are identified as positionable facilities because both are moveable facilities. In each decision epoch $d$, an action ($X_d$) is taken to determine the values of the two decision variables (the location and orientation) of the corresponding facility in the current stage. As shown in Fig. 2, a chain of decision epochs can be constructed for the dynamic site layout planning problem, where each decision epoch refers to the positioning decision of a specific positionable facility in each construction stage. Accordingly, the number of decision epochs in the present model is calculated as shown in Eq. (2). For the example shown in Fig. 2, the site layout planning model is composed of six decision epochs that represent two decision epochs for the two positionable facilities in each of the three construction stages

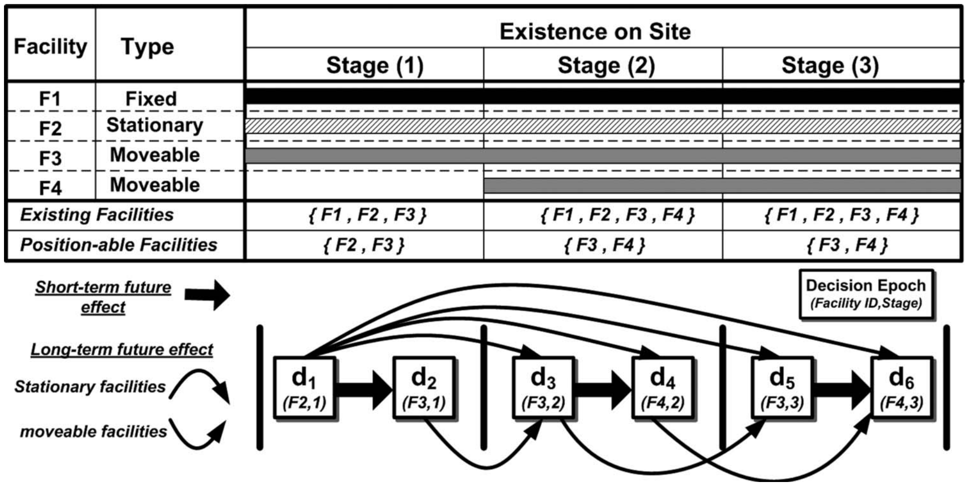


**Fig. 2.** Decision epochs in dynamic site layout planning model

$$D = \sum_{t=1}^{T} \text{NPF}_t \tag{2}$$

where $D$=number of decision epochs; $T$=number of construction stages; and $\text{NPF}_t$=number of positionable facilities in construction stage $t$.

The present dynamic site layout planning problem can be classified as a nonserial dynamic programming (Bertelé and Brioschi 1972), because each decision epoch can have a short-term and/or long-term effect on future decisions epochs, as shown in Fig. 2. The "short-term effect" is used to describe the impact of positioning a facility on the subsequent decisions in the same stage, such as the effect of decision epoch $d_3$ on $d_4$ in Fig. 2. The "long-term effect" is used to represent the impact of positioning either a stationary or moveable facility in the current stage on the subsequent positioning decisions in future stages. As shown in Fig. 2, the positioning of stationary facilities (e.g., $d_1$) affects the positioning decisions of all other facilities in future stages ($d_3$, $d_4$, $d_5$, and $d_6$). Similarly, the positioning of moveable facilities (e.g., $d_3$) has a long-term effect on positioning the same facility in future stages (e.g., $d_5$) as shown in Fig. 2. The present model keeps track of all preceding epochs that have either a short or long-term effects on epoch $d$, and represents this information using a vector called preceding decision epochs ($\text{PDE}_d$). For example, decision epoch $d_6$ (i.e., positioning facility F4 in the third stage) is affected both in the short and long terms by preceding epochs $d_1$, $d_4$, and $d_5$, and accordingly its $\text{PDE}_6$ includes these three epochs as shown in Fig. 3.

### State Vector

State vector ($S_d$) is the minimal description of system history at decision epoch $d$ that is crucial to compute the possible reward or cost of the current decision (Denardo 2003). In the present model, the description of system history at decision epoch $d$ is needed to keep track of the free and occupied spaces on site and to compute the travel and relocation costs. State vector ($S_d$) is represented by a vector of binary values that captures the decisions made (i.e., locations and orientations) in each of the preceding decision epochs ($\text{PDE}_d$). The size ($I_d$) of the state vector ($S_d$) is calculated by multiplying the number of preceding decision epochs by the number of possible positioning decisions. For example, state vector $S_6$ is a vector of 150 binary values that are used to refer to the 50 possible actions (25 locations with 2 possible orientations) of each of the three PDEs ($d_1$, $d_4$, and $d_5$). Each element of the state vector $S_6$ is assigned a binary value of either 1 if the corresponding action was chosen or 0 otherwise. It should be noted that there are only three elements in the 150 binary elements in $S_6$ that will have a binary value of 1 (i.e., $S_{6,39}$, $S_{6,64}$, and $S_{6,129}$) because only one action can be selected for each of the three PDEs.

### Transition Function

The transition function in the present model represents the dynamics in the system and how the states of the future decision epochs are affected as a result of the actions taken in early epochs (Powell 2007). For each decision epoch ($d$), the transition function ($S_{d'}(X_d)$) is used to update the state vectors of the affected future epochs ($d'$) based on the taken action ($X_d$) as shown in Eq. (3). For the example shown in Fig. 3, taking an action in decision epoch $d_1$ requires updating the state vectors of subsequent decision epochs $d_2$, $d_3$, $d_4$, $d_5$, and $d_6$ because $d_1$ exists in their PDEs. The state vector of each of these decision epochs is updated by making the value of the corresponding state vector element equal to 1

$$S_{d'}(X_d) = S_{d'} + \ell_{d'X_d}, \quad \forall\, d' \quad \text{where } d \in \text{PDE}_{d'} \tag{3}$$

where $d'$=any future decision epoch that is affected by decision epoch $d$, where $d \in \text{PDE}_{d'}$; $S_{d'}$=state vector of future decision epoch $d'$; and $\ell_{d'X_d}$=vector with the same size as $S_{d'}$ that consists of zero values except for the element that refers to the decision value of $X_d$ for epoch $d$.

### Contribution Function

The contribution function ($C_d(S_d, X_d)$) is used in the present model as a "local" measure of the optimization objective at each decision epoch $d$ (Denardo 2003) by returning the current site layout costs incurred as a result of taking action $X_d$ based on the current state $S_d$, as shown in Eqs. (4)–(6). The cost of positioning a temporary facility depends on whether it is a moveable or stationary facility. The positioning cost of each moveable facility ($C_d(S_d, X_d)_{\text{moveable}}$) includes the travel cost ($\text{TC}_d$), relocation cost ($\text{RC}_d$), and constraint-violation cost ($\text{CVC}_d$), as shown in Eq. (4). The travel cost is calculated for all resources that are required to travel between the positioned moveable facility and: (1) all tem-

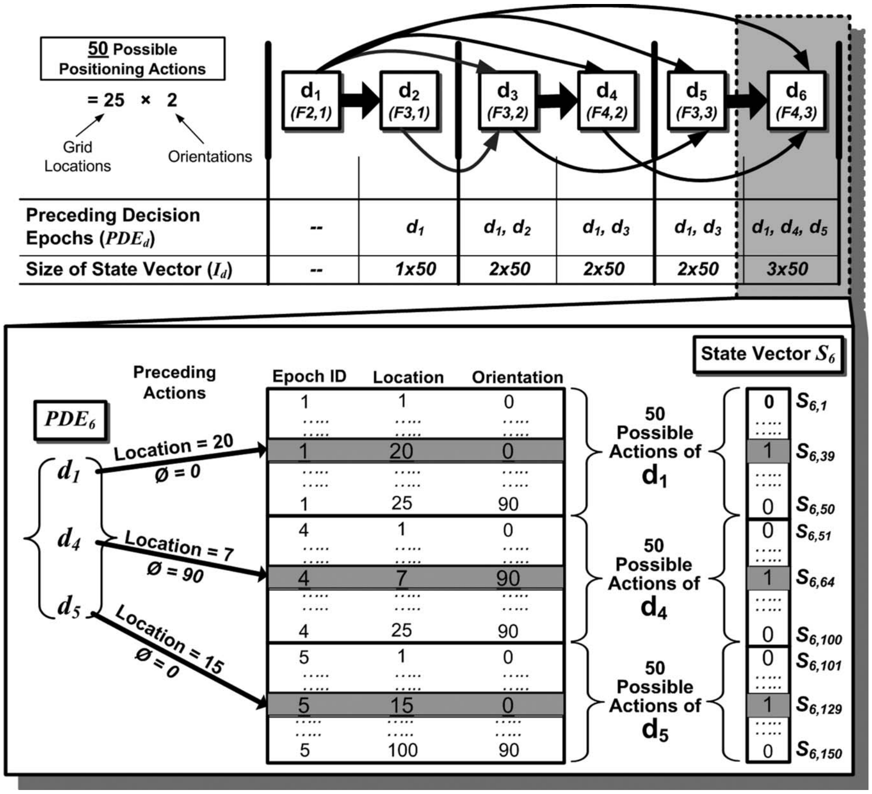


**Fig. 3.** State vector representation

porary facilities that have already been positioned in the current stage; (2) all fixed facilities that exist in the current stage; and (3) all stationary facilities continuing from previous stages. On the other hand, the positioning cost of each stationary facility ($C_d(S_d,X_d)_{\text{stationary}}$) includes only the travel cost ($\text{TC}_d$) and constraint-violation cost ($\text{CVC}_d$), as shown in Eq. (6). It should be noted that the travel cost of positioning a stationary facility comprise its travel cost with every fixed and continuing stationary facility in current and future stages where this facility exists (i.e., stages $t_1-t_2$)

$$C_d(S_d,X_d)_{\text{moveable}} = \text{TC}_d + \text{RC}_d + \text{CVC}_d = \left(\sum_{i=1}^{P_d} \text{TCR}_{di}^{t} D_{di}^{t} + \sum_{j=1}^{\text{NFF}_t} \text{TCR}_{dj}^{t} D_{dj}^{t} + \sum_{k=1}^{\text{NCF}_t} \text{TCR}_{dk}^{t} D_{dk}^{t}\right) + \text{RC}_d + (\text{NCV}_d^{t} P) \quad (4)$$

$$\text{RC}_d = E_d \times \begin{cases} 0 & \varphi_{\bar{d}} = \varphi_d \quad \text{AND } D_{d\bar{d}} = 0 \\ (\text{FRC}_d + \text{VRC}_d D_{d\bar{d}}) & \text{otherwise} \end{cases} \quad (5)$$

$$C_d(S_d,X_d)_{\text{stationary}} = \text{TC}_d + \text{CVC}_d = \left(\sum_{i=1}^{P_d} \text{TCR}_{di}^{t} D_{di}^{t} + \sum_{y=t_1}^{y=t_2}\left(\sum_{j=1}^{\text{NFF}_y} \text{TCR}_{dj}^{y} D_{dj}^{y} + \sum_{k=1}^{\text{NCF}_y} \text{TCR}_{dk}^{y} D_{dk}^{y}\right)\right) + \left(\sum_{y=t_1}^{y=t_2} (\text{NCV}_d^{y} P)\right) \quad (6)$$

where $t$=construction stage where the decision epoch $d$ is taken; $\text{TC}_d$=travel cost of resources traveling to and from the temporary facility positioned by epoch $d$; $\text{RC}_d$=relocation cost of moveable facility positioned by epoch $d$ after it was positioned in the previous stage; $\text{CVC}_d$=constraint violation cost of the facility positioned by epoch $d$; $P_d$=number of already positioned facilities before decision epoch $d$ in stage $t$; $\text{TCR}_{di}^{t}$=travel cost rate (\$/m) between the facility positioned by action $X_d$ and already positioned facility $i$ in the same stage $t$; $D_{di}^{t}$=travel distance between facility positioned by action $X_d$ and facility $i$ in the same stage $t$; $E_d$=existence coefficient equals to 1 if the moveable facility positioned at epoch $d$ exists in previous stage $t-1$, and 0 otherwise; $\phi_d$=orientation angle of moveable facility positioned by action $X_d$; $\text{FRC}_d$=fixed relocation cost (\$) of moveable facility positioned at epoch $d$; $\text{VRC}_d$=variable relocation cost (\$/m) of moveable facility positioned at epoch $d$; $\text{NFF}_t$=number of fixed facilities at stage $t$; $\text{NCF}_t$=number of continuing stationary facilities in stage $t$ positioned at previous stages;$\bar{d}$ decision epoch that refers to the same moveable facility positioned by $d$ but in previous stage $t-1$; $D_{d\bar{d}}$ relocation distance of facility positioned by decision epoch $d$ after it was positioned in previous stage by epoch $\bar{d}$;$t_1$ and $t_2$ first and last construction stages of the existence of stationary facility positioned by decision epoch $d$; $\text{NCV}_d^{t}$ number of constraint violations in stage $t$ caused by taking action $X_d$; and$P$ constraint-violation penalty factor.

### Optimality Equation

The optimality equation is a recursive function that is designed to minimize the current cost $C_d(S_d,X_d)$ of taking action $X_d$ in decision epoch $d$ as well as its future cost $V_{d'}(S_{d'}(X_d))$ in all the affected subsequent epochs ($d'$), as shown in Eq. (7). For example, the model selects the optimal action at decision epoch $d_3$ (see Fig. 3) that minimizes: (1) the current cost calculated by the contribution function $C_d(S_d, X_d)$ based on the actions taken in $d_1$ and $d_2$ which are stored in state vector $S_3$; and (2) the future costs $V_{d'}(S_{d'}(X_d))$ in epochs $d_4$ and $d_5$. Because future costs cannot be calculated exactly with the available information, they are approximated using vectors of linear regression factors analogous to state vectors (Bertsimas and Demir 2002). Accordingly, the future layout cost in the exact optimality equation [Eq. (7)] is approximated as shown in Eq. (8). This approximation is accomplished by multiplying the updated state vector ($S_{d'}(X_d)$) by its regression factors vector ($\bar{\theta}_{d'}$) for each of the affected future epochs ($d'$), as shown in Eq. (8). It should be noted that the accuracy of this approximation in ADP improves iteratively by updating the values of these regression factors vector ($\bar{\theta}_{d'}$) over a number of specified iterations ($N$). This iterative procedure for improving the approximation is described in more details in the following ADP algorithm section.

Exact optimality equation

$$V_d(S_d) = \min_{X_d}\left\{ C_d(S_d, X_d) + \sum_{d'} V_{d'}(S_{d'}(X_d)) \right\} \tag{7}$$

Approximated optimality equation

$$\hat{v}_d = \min_{X_d}\left\{ C_d(S_d, X_d) + \sum_{d'} (S_{d'}(X_d) \cdot \bar{\theta}_{d'}) \right\} \tag{8}$$

where $V_d(S_d)$=minimum layout cost of being in state $S_d$ at decision epoch $d$; $C_d(S_d, X_d)$=current layout cost (contribution function) of taking action $X_d$ at decision epoch $d$ based on state $S_d$ [see Eq. (4)]; $d'$=any decision epoch that is affected by the current decision (i.e., $d \in \mathrm{PDE}_{d'}$); $S_{d'}(X_d)$=updated state of $d'$ as a result of taking action $X_d$ [see Eq. (3)]; $V_{d'}(S_{d'}(X_d))$=future layout cost at decision epoch $d'$ with the updated state $S_{d'}(X_d)$; $\hat{v}_d$=approximated minimum layout cost of being in state $S_d$ at decision epoch $d$; and $\bar{\theta}_{d'}$=vector of linear-regression factors, of size $I_{d'}$, used to calculate the approximate future layout cost at decision epoch $d'$.

### ADP Algorithm

The ADP in the present model is an iterative forward path algorithm that depends on approximating the optimality equation and updating this approximation iteratively. ADP algorithm steps forward through the chain of decision epochs, where decisions are made successively starting from the first epoch (Si et al. 2004). The detailed procedure of the present ADP algorithm is explained in the following sections and shown in Fig. 4.

1. *Initialization*. The algorithm starts by initializing the values of regression factors and the initial state of the construction site layout. First, regression factors are initialized with zero values. Second, the initial state of the construction site layout is provided by identifying the layout of all temporary facilities positioned before running the model. This enables the model to be used at any time during the construction phase to dynamically plan the site layout of the remaining construction work based on the current layout at the analysis time;
2. *Taking optimal action at decision epoch d*. At decision epoch $d$, the model applies the approximated optimality equation [Eq. (8)] to search for the optimal action ($X_d$) to position the corresponding facility using the updated regression factors ($\bar{\theta}_d$). The model then records the optimal action $X_d^n$ and its resulting approximate layout cost $\hat{v}_d^n$;
3. *Updating regression factors vector* ($\bar{\theta}_d$). The calculated approximate layout cost $\hat{v}_d^n$ resulting from action ($X_d^n$) at decision epoch $d$ is then used to update the previous estimate of the regression factors vector ($\bar{\theta}_d$) using the concept of gradient stochastic smoothing (Powell 2007);
4. *Updating the states of future decision epochs*. The model utilizes the transition function [Eq. (3)] to update the state vectors of all future decision epochs that are affected by taking action ($X_d^n$) at decision epoch $d$. Steps 2–4 are repeated for each decision epoch ($d=1-D$) in a forward path algorithm, as shown in the internal loop in Fig. 4. This forward path algorithm is repeated over $N$ iterations (see the external loop in Fig. 4) to improve the approximation accuracy of the algorithm by updating the values of the regression factors ($\bar{\theta}_d$). After completion of the external loop, the algorithm extracts the global optimal actions $(X_d^*)_{d=1}^D$ that produce the minimum total site layout cost.

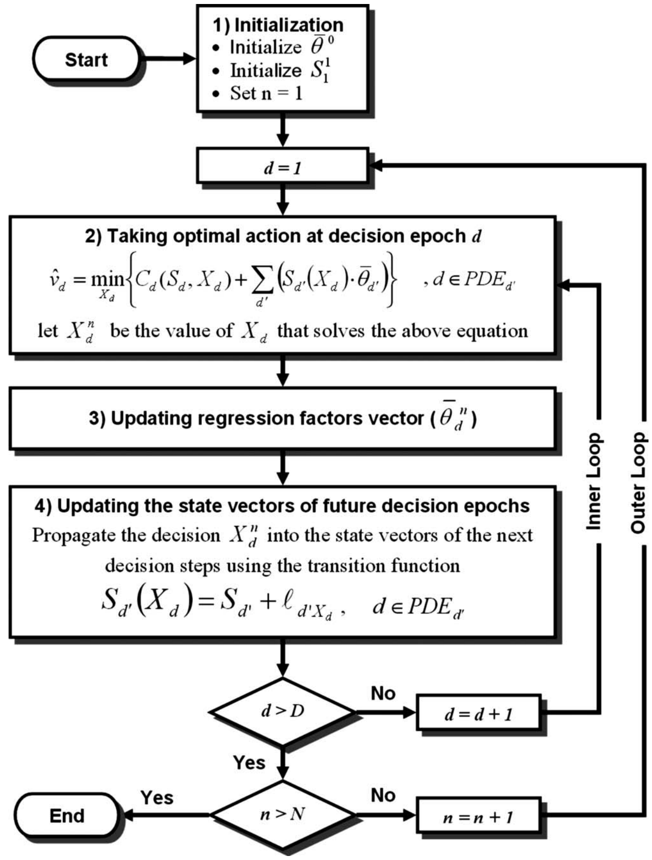


**Fig. 4.** ADP algorithm for dynamic site layout planning

## Performance Evaluation

An application example is used to evaluate the performance of the present model and demonstrate its capabilities in optimizing the dynamic planning of construction site layouts. The application example was originally introduced by Zouein and Tommelein (1999) to analyze the dynamic site layout planning for a 4-day hypothetical project with a $20 \times 10$ site. The project duration of

**Table 1.** Construction Facilities

| Facility | Dimension $Lx \times Ly$ | Time on site Stage 1 | Time on site Stage 2 | Relocation cost | Fixed positions ($x$, $y$, orient) |
|---|---|---|---|---|---|
| F1[a] | $8 \times 8$ | √ | √ | 75 | — |
| F2 | $2 \times 1$ | √ | — | 0 | (16, 8.5, 0) |
| F3[a] | $2.8 \times 2.8$ | — | √ | 50 | — |
| F4 | $4 \times 2$ | √ | √ | 75 | — |
| F5 | $4 \times 2$ | √ | — | 0 | (11, 6, 90) |
| F6 | $4 \times 3$ | — | √ | 75 | — |
| F7 | $4 \times 2$ | — | √ | 50 | — |

[a]There is a minimum distance constraint in the $X$ direction of eight units between facilities F3 and F1.

**Table 2.** Travel Cost Rates

| Stage (1) | | | | | Stage (2) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Facilities | | | | | Facilities | | | | |
| Facilities | F1 | F2 | F4 | F5 | Facilities | F1 | F3 | F4 | F6 | F7 |
| F1 | 0 | 50 | 0 | 25 | F1 | 0 | 100 | 75 | 0 | 0 |
| F2 | — | 0 | 100 | 0 | F3 | — | 0 | 100 | 0 | 0 |
| F4 | — | — | 0 | 75 | F4 | — | — | 0 | 0 | 0 |
| F5 | — | — | — | 0 | F6 | — | — | — | 0 | 0 |
| | | | | | F7 | — | — | — | — | 0 |

this application example is divided into two equal stages or primary time frames (PTFs): PTF-0-2 and PTF-2-4. This example was selected in this analysis due to its complete data and clear description of its modeling assumptions. To enable a comparison between the results generated by the present model and those provided by Zouein and Tommelein (1999), the same data and modeling assumptions of the original example are used in this application example. First, the analyzed data in this example include: (1) construction facilities data, as shown in Table 1; and (2) travel cost rates data, as shown in Table 2 (Zouein and Tommelein 1999). Second, the modeling assumptions in this example include: (1) the distances between site facilities are calculated using the rectilinear/Manhattan distances approach; (2) the travel cost rates (TCRs) are represented by \$/m/day, as shown in Table 2; and (3) there are no relocation costs if a moveable facility is only rotated without being moved (Zouein and Tommelein 1999).

The present model was used to analyze the application example in order to identify an optimal location for all positionable facilities, which include two in the first stage (F1 and F4), and five in the second stage (F1, F3, F4, F6, and F7). The positioning decision of these facilities is represented in the present model by seven decision epochs, where each consists of two decision variables (i.e., location and orientation). To provide the dynamic site layout plan of the evaluation example, a set of run parameters were identified, including: (1) the site grid pitch equals 0.5; (2) 500 ADP iterations; and (3) the constraint-violation factor ($P$) equal to $10^5$. On the one hand, the site grid pitch and the number of iterations in this example were specified to establish a reasonable tradeoff between the solution accuracy and computational time. On the other hand, the constraint-violation factor is set to a very high value to penalize unfeasible solutions that violate any imposed layout constraints.

In this site layout planning problem, the sequence of positioning facilities in each stage has a direct impact on the generated results. For example, one possible sequence of decision epochs for this example can be represented by [(F1, F4),(F1, F3, F4, F6, F7)]. This example sequence produces a site layout planning solution that is different from other possible sequences such as the one represented by [(F4, F1),(F7, F6, F4, F3, F1)]. Enumerating and analyzing all possible sequences of decision epochs in this site layout planning problem is impractical and can be computationally prohibitive. Alternatively, a set of ordering heuristics can be utilized to produce promising sequences of decision epochs similar to those presented by Zouein and Tommelein (1999). Ordering heuristics are often based on rules-of-thumb and human reasoning to prioritize decision epochs, such as placing first facilities with the largest area, or relocation cost. Table 3 summarizes the five decision sequences analyzed in this example. The optimization analysis was performed using a server with Dual Core Intel Xeon 1.8 GHz processors, 4 MB of cache memory, and a total of 4 GB of SDRAM. The computational time of this analysis was approximately 2 min for each of the five sequences of decision epochs considered.

The optimization results generated by the present (ADP) model are compared to those produced by Zouein and Tommelein (1999), as shown in Table 3. The results illustrate that the present model was capable of generating optimal site layout plans that outperformed those presented by Zouein and Tommelein (1999) for each of the five sequences of decision epochs analyzed. This improvement in the optimization results can be attributed to the

**Table 3.** Optimization Results

| | | Site layout cost of optimal solution | | | | | |
|---|---|---|---|---|---|---|---|
| | | Present model | | | Zouein and Tommelein (1999) | | |
| Number | Sequence of decision epochs | 1st stage | 2nd stage | Total | 1st stage | 2nd stage | Total |
| 1 | (F1,F4), (F1,F3,F4,F6,F7) | 2,900 | 4,850 | **7,750** | 2,250 | 5,635 | **7,885** |
| 2 | (F1,F4), (F4,F3,F1,F6,F7) | 2,975 | 5,037.5 | **8,012.5** | 2,250 | 7,010 | **9,260** |
| 3 | (F1,F4), (F3,F4,F1,F7,F6) | 2,275 | 6,987.5 | **9,262.5** | 2,250 | 7,206.3 | **9,456.3** |
| 4 | (F1,F4), (F6,F4,F3,F1,F7) | 2,350 | 6,475 | **8,825** | No feasible solution found | | |
| 5 | (F1,F4), (F1,F3,F4,F7,F1) | 2,900 | 4,850 | **7,750** | 2,250 | 5,635 | **7,885** |

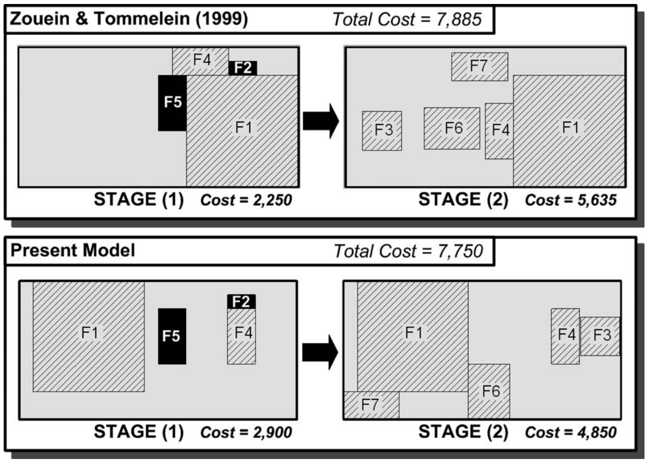


**Fig. 5.** Generated optimal layouts for first analyzed decisions sequence

new capabilities of the present model that estimate and optimize the future effects of facility positioning in early stages on positioning decisions in future stages. This enables the model to provide global rather than local optimization results for construction site layouts. For example, the model generated a globally optimal dynamic site layout plan for the first sequence of decisions (see Fig. 5) that provides further reduction in the total layout cost from 7,885 to 7,750 as shown in Table 3. This globally optimal solution was based on a site layout that is not necessarily the local optimal solution for the first stage, as shown in Table 3. The selection of this locally nonoptimal plan in the first stage enabled the model to find the optimal plan in the second stage, which led to the global optimal layout plan for the entire project.

## Summary and Conclusion

A dynamic site layout planning model was developed to enable contractors to minimize total site layout costs in construction projects. The model is designed to identify a global optimal location and orientation for each temporary construction facility on site. The model is also capable of considering and complying with practical site layout constraints, including operational, organizational, and/or safety constraints. The model is implemented using approximate dynamic programming and utilizes a chain of decision epochs to represent the positioning decisions of all facilities in each construction stage. The model is capable of generating global optimal dynamic site layout plans by estimating and optimizing the future costs of layout decisions made in early stages. Optimal actions are taken at each decision epoch by applying the optimality equation that minimizes both the current and future layout costs of possible actions. Current costs are calculated using the contribution function based on the previous decisions stored in the state vector, while future costs are estimated using a vector of regression factors that are updated through the ADP iterations. An application example is analyzed to evaluate the performance of the present model. The results of the analysis illustrate the new capabilities of the model developed in outperforming existing models and in generating global optimal solutions. These new and unique capabilities should prove useful to construction planners and are expected to produce much needed savings in the total site layout costs of construction projects. Despite these capabilities, the current limitations of the present model include modeling site space using two-dimensional rectangles, approximating resource travel paths as the shortest direct distance between site facilities, and assuming that site storage requirements are predetermined and static. To address these limitations, the present model can be expanded in future research to support 3D modeling of site layouts, detailed planning of resource travel paths, and considering the dynamic impact of material procurement decisions on site storage and layout planning.

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## Notation

*The following symbols are used in this paper:*

$C_d(S_d,X_d)_{\text{moveable}}$ = contribution function of positioning stationary facility at decision epoch $d$;
$C_d(S_d,X_d)_{\text{stationary}}$ = contribution function of positioning moveable facility at decision epoch $d$;
$\mathrm{CVC}_d$ = constraint-violation cost of facility positioned by epoch $d$;
$\mathrm{CVC}_t$ = constraint-violation cost for all facilities in stage $t$;
$D$ = number of decision epochs;
$D_{d\bar{d}}$ = relocation distance of facility positioned by decision epoch $d$ after it was positioned in previous stage by epoch $\bar{d}$;
$D_{di}^t$ = travel distance between facility positioned by action $X_d$ and facility $i$ in same stage $t$;
$\bar{d}$ = decision epoch that refers to same moveable facility positioned by $d$ but in previous stage $t-1$;
$E_d$ = existence coefficient equals to 1 if moveable facility positioned at epoch $d$ exists in previous stage $t-1$, and 0 otherwise;
$\mathrm{FRC}_d$ = fixed relocation cost (\$) of moveable facility positioned at epoch $d$;
$I_d$ = size of state vector $S_d$ of decision epoch $d$;
$\ell_{d,X_d}$ = vector with same size as $S_d$, that consists of zero values except for element that refers to decision value of $X_d$ for epoch $d$;
$\mathrm{NCF}_t$ = number of continuing stationary facilities in stage $t$ positioned at previous stages;
$\mathrm{NCV}_d^t$ = number of constraint-violations in stage $t$ caused by taking action $X_d$;
$\mathrm{NFF}_t$ = number of fixed facilities at stage $t$;
$\mathrm{NPF}_t$ = number of positionable facilities in construction stage $t$;
$P$ = constraint-violation penalty factor;
$P_d$ = number of already positioned facilities before decision epoch $d$ in stage $t$;
$\mathrm{PDE}_d$ = preceding decision epoch that affects current epoch $d$;

$\mathrm{RC}_d$ = relocation cost of moveable facility positioned by epoch $d$ after it was positioned in previous stage;

$\mathrm{RC}_t$ = relocation cost of moveable facilities in stage $t$;

$S_d$ = state vector of decision epoch $d$;

$S_{d'}(X_d)$ = transition function ($S_{d'}(X_d)$) is used to update state vectors of affected future epochs based on taken action ($X_d$);

$T$ = number of construction stages;

$\mathrm{TC}_d$ = travel cost of resources traveling to and from temporary facility positioned by epoch $d$;

$\mathrm{TC}_t$ = travel costs between all facilities in stage $t$;

$\mathrm{TCR}_{di}^t$ = travel cost rate (\$/m) between facility positioned by action $X_d$ and already positioned facility $i$ in same stage $t$;

$t_1$ and $t_2$ = first and last construction stages of existence of stationary facility positioned by decision epoch $d$;

$V_d(S_d)$ = minimum layout cost of being in state $S_d$ at decision epoch $d$;

$\mathrm{VRC}_d$ = variable relocation cost (\$/m) of moveable facility positioned at epoch $d$;

$\hat{v}_d$ = approximated minimum layout cost of being in state $S_d$ at decision epoch $d$;

$X_d$ = action taken at decision epoch $d$;

$\bar{\theta}_{d'}$ = vector of linear-regression factors, of size $I_{d'}$, used to calculate approximate future layout cost at decision epoch $d'$; and

$\phi_d$ = orientation angle of moveable facility positioned by action $X_d$.

### Subscripts and Superscripts

$d$ = decision epoch counter (from $d=1$ to $D$);

$i$ = counter of already positioned temporary facilities (from $i=1$ to $P_d$);

$j$ = counter of fixed facilities in stage $t$ (from $j=1$ to $\mathrm{NFF}_t$);

$k$ = counter of continuing stationary facilities in stage $t$ positioned at previous stages (from $j=1$ to $\mathrm{NCF}_t$); and

$t$ = construction stage counter (from $t=1$ to $T$).

## References


Bertelé, U., and Brioschi, F. (1972). *Nonserial dynamic programming*, Academic, New York.

Bertsimas, D., and Demir, R. (2002). "An approximate dynamic programming approach to multidimensional knapsack problems." *Manage. Sci.*, 48(4), 550–565.

Chau, K. W., and Anson, M. (2002). "A knowledge-based system for construction site level facilities layout." *Lect. Notes in Artif. Intell.*, 2358, 393–402.

Cheung, S., Tong, T. K., and Tam, C. (2002). "Site pre-cast yard layout arrangement through genetic algorithms." *Autom. Constr.*, 11, 35–46.

Dawood, N., and Marasini, R. (2002). "Visualization of a stockyard layout simulator "SimStock:" A case study in precast concrete products industry." *Autom. Constr.*, 12, 113–122.

Denardo, E. V. (2003). *Dynamic programming: Models and applications*, Prentice-Hall, Inc., Englewood Cliffs, N.J.

Elbeltagi, E., Hegazy, T., and Eldosouky, A. (2004). "Dynamic layout of construction temporary facilities considering safety." *J. Constr. Eng. Manage.*, 130(4), 534–541.

Hegazy, T., and Elbeltagi, E. (1999). "EvoSite: Evolutionary-based model for site layout planning." *J. Comput. Civ. Eng.*, 13(3), 198–206.

Khalafallah, A., and El-Rayes, K. (2005). "Trade-off between safety and cost in planning construction site layouts." *J. Constr. Eng. Manage.*, 131(11), 1186–1195.

Khalafallah, A., and El-Rayes, K. (2006). "Minimizing construction-related hazards in airport expansion projects." *J. Constr. Eng. Manage.*, 132(6), 562–572.

Ma, Z., Shen, Q., and Zhang, J. (2005). "Application of 4D for dynamic site layout and management of construction projects." *Autom. Constr.*, 14, 369–381.

Mawdesley, M. J., Al-jibouri, S. H., and Yang, H. (2002). "Genetic algorithms for construction site layout in project planning." *J. Constr. Eng. Manage.*, 128(5), 418–426.

Osman, H., Georgy, M., E., and Ibrahim, M. E. (2003a). "An automated system for dynamic construction site layout planning." *Proc., 10th Int. Colloquium on Structural and Geotechnical Engineering*, Ain Shams University, Cairo, Egypt.

Osman, H., Georgy, M. E., and Ibrahim, M. E. (2003b), "A hybrid CAD-based construction site layout planning system using genetic algorithms." *Autom. Constr.*, 12, 749–764.

Osman, H. M., and Georgy, M. E. (2005). "Layout planning of construction sites considering multiple objectives: A goal-programming approach." *Proc., Construction Research Congress*, ASCE, San Diego, 1–10.

Powell, W. B. (2007). *Approximate dynamic programming: Solving the curses of dimensionality*, Wiley, New York.

Powell, W. B., George, A., Bouzaiene-Ayari, B., and Simao, H. (2005). "Approximate dynamic programming for high dimensional resource allocation problems." *Proc., Int. Joint Conference on Neural Networks (IJCNN)*, International Neural Network Society (INNS), Montreal, Quebec, Canada.

Retik, A., and Shapira, A. (1999). "VR-based planning of construction site activities." *Autom. Constr.*, 8, 671–680.

Sadeghpour, F., Moslehi, O., and Alkass, S. T. (2006). "Computer-aided sit layout planning." *J. Constr. Eng. Manage.*, 132(2), 143–151.

Si, J., Barto, A. G., Powell, W. B., and Wunsch, D. (2004). *Handbook of learning and approximate dynamic programming*, IEEE Press Series on Computational Intelligence, Wiley-IEEE, New York.

Tam, C. M., Tong, T. K., and Chan, W. K. W. (2001). "Genetic algorithms for optimizing supply locations around tower crane." *J. Constr. Eng. Manage.*, 127(4), 315–321.

Tam, C. M., Tong, T. K., Leung, A. W., and Chiu, G. W. (2002). "Site layout planning using nonstructural fuzzy decision support system." *J. Constr. Eng. Manage.*, 128(3), 220–231.

Wang, H. J., Zhang, J. P., Chau, K. W., and Anson, M. (2004). "4D dynamic management for construction planning and resource utilization." *Autom. Constr.*, 13(5), 575–589.

Zayed, T. (2002). "Budget allocation for steel bridge paint maintenance." *J. Perform. Constr. Facil.*, 18(1), 36–46.

Zhang, J. P., Liu, L. H., and Coble, R. J. (2002). "Hybrid intelligence utilization for construction site layout." *Autom. Constr.*, 11, 551–519.

Zouein, P. P., Harmanani, H., and Hajar, A. (2002). "Genetic algorithms for solving site layout problem with unequal-size and constrained facilities." *J. Comput. Civ. Eng.*, 16(2), 143–151.

Zouein, P. P., and Tommelein, I. D. (1999). "Dynamic layout planning using a hybrid incremental solution method." *J. Constr. Eng. Manage.*, 125(6), 400–408.

# Dynamic Site Layout Planning Using Approximate Dynamic Programming

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