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A BIM-based automated site layout planning framework for congested construction sites

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ABSTRACT

Site layout planning is often performed on construction sites to find the best arrangement of temporary facilities so that transportation distances of on-site personnel and equipment are minimized. It could be achieved by creating dynamic layout models, which capture the changing requirements of construction sites. However, formulating such models is extremely tedious because it requires much manual data input and changes to design and construction plans are manually updated by layout planners. This study presents an automated framework of creating dynamic site layout models by utilizing information from BIM. The A* algorithm is used in conjunction with genetic algorithms to develop an optimization framework that considers the actual travel paths of on-site personnel and equipment. To address the space limitation on site, our model optimizes the dimensions of facilities and also considers interior storage within buildings under construction. A case example is demonstrated to validate this framework and shows a 13.5% reduction in total travel distance compared with conventional methods.

1. Introduction

Construction site layout planning (CSLP) is a crucial step in construction planning that has been proven to reduce material handling costs while improving safety and productivity of a project [1–3]. Construction projects require a large number of temporary facilities such as material storage areas, fabrication shops, etc. in order to support various construction activities. Traditionally these facilities are set up on unoccupied areas, within the boundaries of the construction site. In such situations the goal of CSLP is to determine the best arrangement of temporary facilities such that the travel distances of construction personnel is minimized [4,5]. An obvious solution could be to set up temporary facilities on the free areas surrounding the building under construction. However, this is possible only on construction sites which have adequate amounts of free area to facilitate such an arrangement. In most urban construction projects, site space is limited and must be used judiciously in order to avoid problems with accessibility, safety and congestion. Comprehensive site layout planning can ensure a smooth flow of materials, equipment, and labour, thereby improving the safety and efficiency of on-site operations.

Site layout models fall into two categories – (1) static layout models, which assume that all of the facilities are assembled at the start and exist for the entire duration of construction [1,4–10], and (2) dynamic layout models, which consider the actual duration for which facilities are required [11–18]. Dynamic layout models are far superior to static models in generating optimum layout plans because they allow layout planners to cater to the changing site requirements and facilitate site space to be reused. Currently dynamic models are created specific to a project, based on the following information – (1) the number and types of facilities required, (2) the dimensions of each facility, and (3) the specific time interval for which each facility would be required on the construction site [19]. In most CSLP tools, such information has to be determined by the layout planner and manually entered into the software program. However manually determining this information could be quite laborious, especially for projects with complex schedules spanning several days. Changes to the design or construction plans would have to be continuously updated into the site layout models, resulting in an inefficient workflow that is very time consuming. This severely limits the practicality of current CSLP tools and is one of the reasons for their failure to achieve widespread adoption by the construction industry. There is a need for a practical and generic tool, which not only reduces unnecessary work by the layout planner but can also be easily adapted for use on different projects. Several research studies have attempted to improve the ease of use of dynamic CSLP tools. Tommelein et al. [2] developed a dynamic layout tool called MovePlan with a graphical user interface, which took activity relationships as input and generated optimized site layouts. Xing et al. [20] developed a GIS- based construction site material layout evaluation tool which took the resource loaded schedule as input to calculate the material accessibility grade on a construction site. Said and El-Rayes [21] developed a construction logistics optimization system, which automated the retrieval of spatial and temporal data from BIM models and construction schedules. In this study, we further improve on the practicality

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of current tools, by presenting a BIM based framework that automates the creation of mathematical models for dynamic CSLP. BIM models are rich sources of information and have been used to facilitate site layout planning [21–26]. The focus of this paper is to leverage information from BIM models and construction schedules, to estimate the size, dimensions and number of temporary facilities required during different stages of construction. Since this methodology is pivoted on BIM, design and construction changes can be automatically integrated into the mathematical models, significantly reducing redundant work by layout planners.

In almost all of the studies on site layout planning, the optimization goal is to determine temporary facility layouts that would minimize on-site transportation costs, without compromising the safety or accessibility of the site. [1–9,11–20,24,27–34]. A common formula used to achieve this is

$$\mathrm{Min}\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} d_{ij} f_{ij} \tag{1}$$

where d_{ij} and f_{ij} represent the distance and frequency of trips between two facilities *i and j*, respectively, while n represents the total number of facilities. For the sake of simplicity, most early studies on CSLP approximated d_{ij} by using linear distances such as the Euclidean (straight line) or Manhattan (rectangular) distance. However, due to the presence of obstacles it is nearly impossible to always follow straight line paths, due to which the Euclidean and Manhattan distances would be significantly different from the actual travel distances of site personnel. Yahya and Saka [18] introduced the concept of obstruction distance, which was added to the computed Euclidean path in order to approximate the actual travel distances. Park et al. [30] demonstrated the benefits of using actual travel distances instead of linear distances in solving the floor-level material layout problem for an indoor environment. In our study, we use the A* algorithm to accurately compute the actual travel distances between facilities on a construction site, and use them as a basis for site layout optimization. Our method also considers variations in path widths between construction personnel and machines, thereby resulting in a more accurate representation of on-site transportation activities. Another drawback among all of the previous studies on CSLP is that the dimensions of facilities are taken as input parameters, prior to performing the optimization. As a result, only the position and orientation of each facility are considered as the decision variables for optimization. As will be demonstrated in this paper, the previous approach severely limits the range of possible solutions. In this study, we consider the position, orientation and dimensions of each facility as decision variables, which are then optimized using Genetic Algorithms (GA). As a result, our CSLP tool determines the optimal dimensions of each facility, significantly improving the efficiency of generated layouts. To facilitate the use of GA, a modified crossover and mutation operator has been developed in this study.

A characteristic of urban construction projects is the lack of on-site storage space. To make up for this shortage of space, layout planners may assign storage facilities to be set up inside the buildings under construction [31]. Such an approach increases the total area for setting up of facilities and consequently reduces on-site congestion. However, the interior regions of a building are active workspaces for a number of floor-level construction activities [35]. This imposes a limitation on the amount of space that can be used for interior storage. As a result, interior storage plans must be planned and coordinated carefully, to ensure maximum utilization of the available space. Park et al. [30] developed a system framework to optimize the interior storage locations of construction materials on every floor of the building under construction. However, their study was limited to optimizing storage locations in interior spaces only and did not address the storage needs in exterior regions of the construction site. Elbeltagi et al. [13] developed a dynamic CSLP tool, which used the constructed space of a building to store temporary facilities, with a view to reduce congestion. Said and El-Rayes [15] proposed a congested construction logistics planning (C2LP) model that generates optimal material logistics and site layout plans. The C2LP model requires input parameters such as the site exterior and interior spatial data, dimensions of temporary facilities, their relationship with activities on the construction schedule and material assignment to activities, based on which it optimizes the storage locations in exterior and interior building spaces. In a following study, Said and El-Rayes [21] developed an automated multi-objective construction logistics optimization system (AMCLOS), which uses information in BIM models and schedules to optimize the utilization of interior storage spaces in a building. The AMCLOS system uses IFC (Industry Foundation Classes) files to extract the geometry of interior and exterior site regions, thereby automating the computation of available storage space. However, the permissible periods of interior storage areas of the materials and dimensions of each temporary facility have to be manually specified in the AMCLOS system. In our study, we leverage information from BIM models to develop an automated method for interior and exterior storage optimization. At any particular instant of time, the amount of interior storage space is dependent upon the number of completed floors, the geometry of the building and the presence of floor-level construction activities. By linking material and spatial data from BIM models to activity data from the schedule, we are able to automate the computation of available interior storage space during different stages of the project. Our framework also automates the computation of required storage amounts for each material, and optimally assigns them to different storage locations. Therefore, this study presents an automated framework for CSLP, which addresses the requirements of congested construction sites by utilizing interior building spaces to store materials. Our framework, which relies on BIM, enables us to develop a CSLP model that is generic enough to be useful in a variety of cases. The number of inputs from layout planners is minimized since most of the computations are performed on information available from the BIM model and construction schedule.

Our framework for automated CSLP using BIM consists of three modules (see Fig. 1). In the first module, BIM based facility size estimation is used to accurately compute the required size and dimensions for each facility. In the second module, we present a methodology framework to automate the creation of dynamic layout models. The third module deals with formulating the objective function and using an actual travel path driven optimization to generate facility layouts. A demonstrative example is considered to highlight the benefits of this new approach.

2. BIM-based facility size estimation

The CSLP problem consists of optimizing the locations for temporary facilities, which may be approximated as one or more rectangles, on the unoccupied areas of a construction site. Most CSLP tools require the user to specify what the dimensions of each facility are, prior to performing the layout optimization. However, this approach has a significant drawback, which leads to an under-utilization of site space. Facilities are used for storing materials and equipment, or to provide a working area for humans. It is thus essential that the facilities be large enough to satisfy these requirements. For example, it could be specified by the layout planner, that a site office with 10 engineers should provide a floor area of 100 m^2. However, its exact dimensions can only be decided after taking into consideration the dimensions of the available space which it is to be set up on. The facility in this case can take the form of a variety of rectangles with different values of length and width. The only constraints imposed are that the facility should provide the necessary floor area while being of reasonable dimensions. Hence, specifying a fixed dimension for a facility prior to assigning its location on the site severely restricts the range of possible solutions. On construction sites with limited spaces, it is thus essential to optimize the dimensions of each facility according to the dimensions of the available site locations. In this study, we consider their dimensions as variables, which are optimized using Genetic Algorithms.

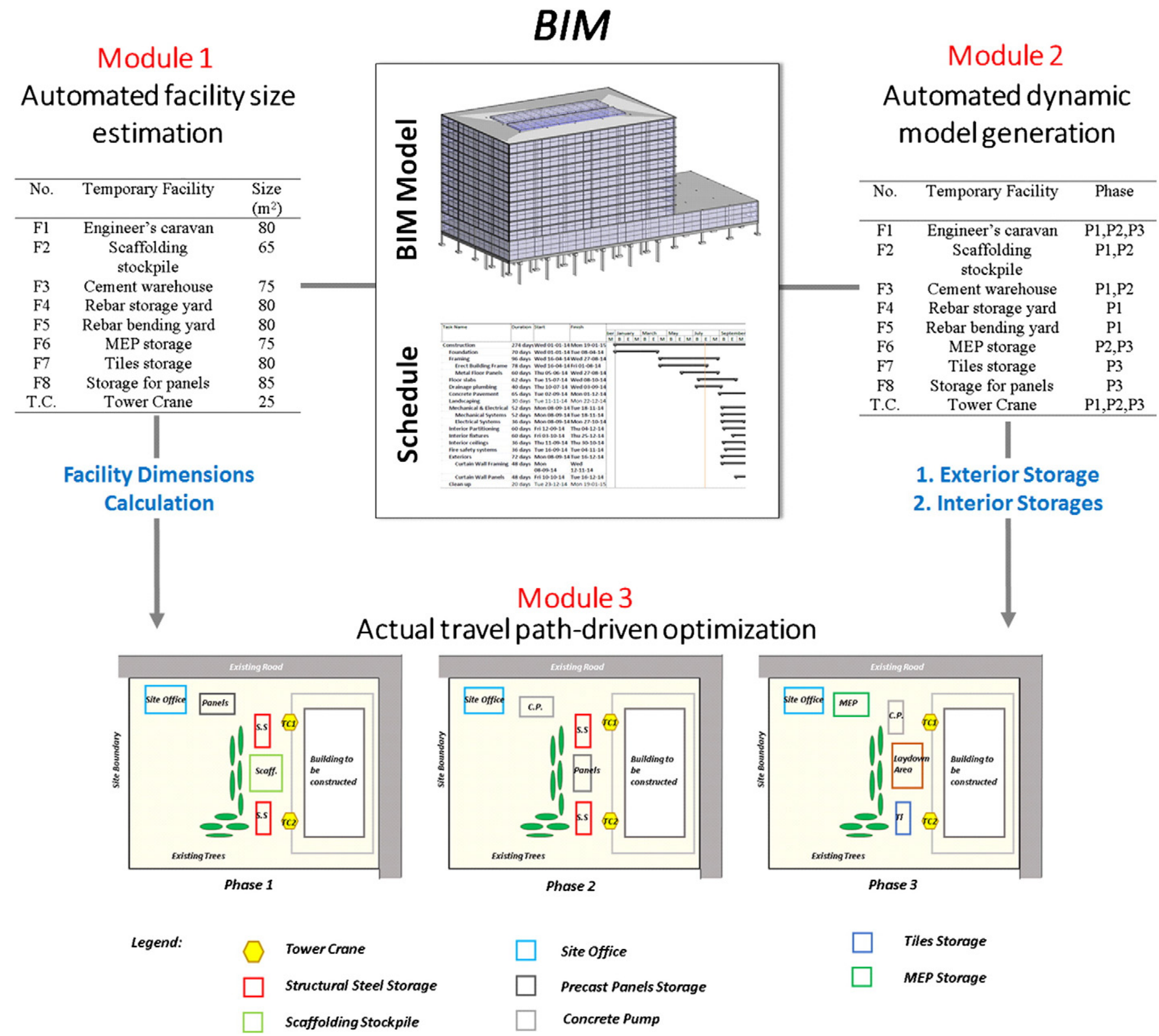

Fig. 1. The proposed BIM-based construction site layout planning framework.

Another obvious drawback of having user defined facility sizes is that it makes the process extremely tedious, since the user has to calculate the required size for several facilities. Changes to the design or construction schedules may require a majority of these calculations to be revised, resulting in increased work for the layout planner. To simplify and improve the practicality of this process, we propose a methodology which uses information from BIM to determine facility sizes, as shown in Fig. 2. In the first step, we use the BIM based facility size estimation module to determine the area required by each facility. The areas are then used as a basis to decide their optimized dimensions.

2.1. Facility area estimation

The primary role of temporary facilities is to support construction operations. These facilities can be classified into three categories, (1) storage facilities, (2) processing facilities, and (3) residence facilities. Storage facilities are used to temporarily store materials that will be used for construction. Examples of these are steel storage yards, precast panel storage yards, cement warehouses, etc. Storage facilities should provide adequate storage area for materials while protecting them from damage due to sun, wind or rain. Processing facilities are used to process the raw materials on a construction site. Examples of these are fabrication shops, rebar cutting shops, steel bending yards, etc. Since processing facilities usually house humans and machines, it is essential that they provide enough space to perform the required activities in a safe and efficient manner. Residence facilities provide shelter and cater to the requirements of personnel involved in the construction project. Common examples of residence facilities include site offices, pantries, toilets, etc. Residence facilities should provide adequate space for humans to work efficiently. Thus, the size of a storage facility is governed by the quantity of material to be stored in it, whereas the size of processing and residence facilities depends on the number of machines and humans, respectively.

Assuming a fixed order quantity inventory cycle, the maximum inventory level is related to the rate of consumption of that material and the time between successive deliveries as given by

$$Q = R \times T \tag{2}$$

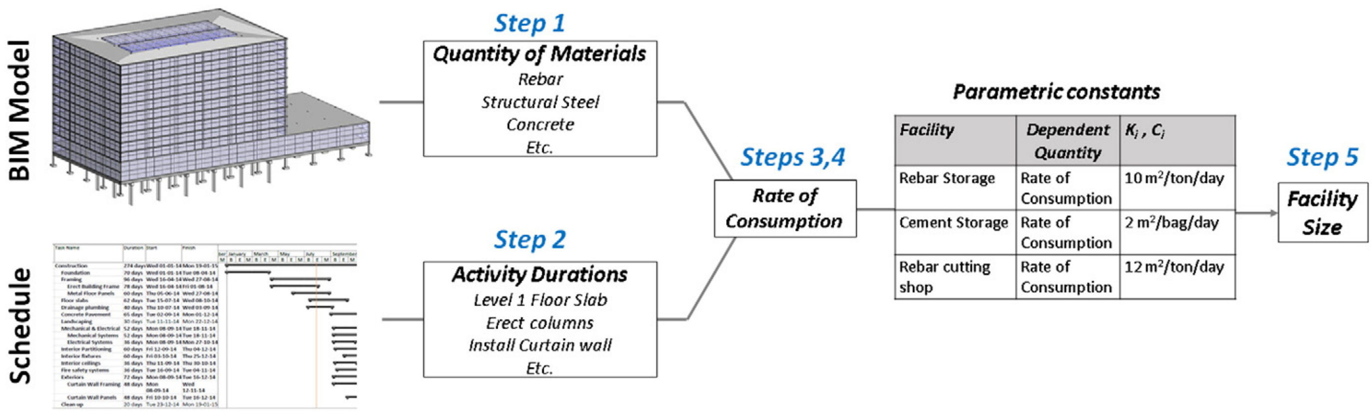

Fig. 2. The proposed facility size estimation module.

where Q is the maximum inventory level, R refers to the peak material demand or rate of consumption of that resource, and T is the time between successive deliveries. Thus, we can calculate the required size of a storage facility if we know the rate of consumption and time between successive deliveries, using the equation:

$$A_s = C \times R \times T \tag{3}$$

where, A_s refers to the area of a storage facility, C is a constant which is an indicator of the amount of space needed to store a unit quantity of that material, R refers to the peak rate of consumption of the material stored in that facility, and T refers to the time between deliveries.

In the case of processing facilities, the number of machines used is dependent on the quantity of material that needs to be processed each day. Considering the case of a rebar bending shop, the number of machines housed in it will be determined by the quantity of rebar that needs to be processed each day and the capacity of each machine. Hence the size of a processing facility can be determined from the rate of consumption of the processed material, given by:

$$A_p = K \times R \tag{4}$$

where A_p refers to the size of a processing facility, K is a constant which depends on the material being processed, and R refers to the rate of consumption of the dependent resource.

Since BIM models do not usually contain information about the number of site personnel, the size of residence facilities has to be manually inputted by the user. Based on this logic, the required size of a facility could be computed using the following five steps, as shown in Fig. 2. A drawback of the proposed facility size estimation framework is the assumption that materials will be delivered to the construction site at fixed intervals.

Step 1: Material quantities extraction module. The quantities of various materials used in different components of the building are calculated, from the BIM model. For example, in the component "Column 001" the quantities to be determined would be (1) volume of concrete and (2) amount of rebar. This was performed by extracting the material quantities of individual components from the BIM model. Autodesk Revit, which provides an Application Programming Interface (API), was used as the modelling software. Using the Revit API, we developed a program in Microsoft C# to extract and tabulate the necessary quantities. This framework also allows us to compute derived quantities such as the amount of formwork, scaffolding, etc. which may be missing from in BIM model.

Step 2: Activity duration computation module. In this module, the durations of different activities are determined from the planned construction schedule. For example, the scheduled duration of an activity "Level 1: Columns 001 – 005" is read from the planned schedule and it would provide us the approximate time needed to complete that activity. To facilitate this, the schedule was exported as a csv file, which could be read by our program.

Step 3: BIM-Schedule linkage. In this step, the activities on the schedule are linked with their corresponding components in the BIM model. For example the activity "Level 1: Columns 001: Pour Concrete" is linked to the quantity of concrete used in "column 001", resulting in a 4D BIM model. In our study, we use a program to parse each activity name on the schedule and link it with the corresponding element in the BIM model. Each activity in the schedule should therefore follow a naming convention, so that the activity can be correctly identified by the parser program. It is also crucial that the granularity of the schedule matches with the level of development (LOD) in the BIM model. For our study, the architectural, structural and MEP elements are modelled at LOD 300.

Step 4: Rate of consumption calculation. By dividing the quantity of materials consumed by the duration of consumption, we thus obtain the rate of consumption of different materials during the different stages of construction. A limitation of this approach is that it assumes a linear rate of consumption in order to simplify the calculations.

Step 5: Facility size estimation. Using the relationships defined previously, the size of each facility is thus determined. This information is then parsed to the facility dimensions computation module. The only input from the user is the time interval between successive deliveries.

2.2. Permissible facility dimensions

Once we have the floor area requirement of a facility, we must determine its dimensions. The dimensions should be selected such that it can accommodate even the largest object to be stored in it. For example, if the standard length of rebar is 8m, the rebar storage yard must have either a length or width greater than 8m. Thus, the dimensions of a facility should be selected keeping in mind the nature of objects to be stored in it as well as the floor area requirement. Based on this logic, we developed a set of mathematical relationships which represent the possible dimensions of a facility.

Consider a rectangular facility with an area A, length L and width W. Let L_{min} and W_{min} represent its minimum allowable length and width, respectively. L_{min} and W_{min} are determined from the size of the objects that will be contained in the facility.

$$L = \alpha + L_{\min}, \text{ where } \alpha \geq 0; \tag{5}$$

$$W = \beta + W_{\min}, \text{ where } \beta \geq 0; \tag{6}$$

$$(L_{\min} + \alpha) \times (W_{\min} + \beta) = A; \tag{7}$$

Rearrange the terms to get,

$$\beta = \frac{A - L_{min} W_{min} - \alpha W_{min}}{L_{min} + \alpha} \tag{8}$$

For each value of α we obtain a corresponding value of β. This gives us a range of permissible values for length and width of each facility. Unlike previous studies which specify fixed dimensions for facilities, we represent them as a range of permissible values, and based on the characteristics of the available site space, determine what their optimized dimensions should be. As will be demonstrated in Section 5, the permissible range of values are used as the basis for determining the optimized dimensions of each facility

3. Dynamic layout planning

A construction project commences in various construction stages or phases. Foundation, framing, MEP and finishing works are common examples of different phases. As a result, the requirement of facilities will also differ between phases. Facilities required in one phase may not be required in the next phase. In such cases, unnecessary facilities may be dismantled after use and the space previously occupied by them could be used to set up other facilities. In certain cases the use of a facility may be altered to avoid de-mobilization and mobilization costs. On construction sites with limited space availability, multiple facilities may occupy the same location on the site at different stages of construction. To model these changing facility requirements, dynamic layout models should be created. Dynamic layouts refer to a sequence of site layouts that are spread over distinct time intervals and when taken together represent the entire construction project [11]. In most approaches, the construction project is split into discrete phases and partial layouts for each phase are determined [12]. Since some facilities may be required in multiple phases, the partial layouts will be interdependent.

In this study, we developed an automated method of creating a dynamic site layout model from the construction schedule of the project. Activities from the construction schedule were mapped to the corresponding facilities that they would require. For example, the activity "Floor Slab level 1" is linked with the rebar storage and processing yards, which are facilities required to store materials used in the slabs. First, a set of relations is created to determine the facilities that would be required to complete each activity. Next, a corresponding facility requirement schedule is generated from the construction schedule by using the previously defined relationships. The underlying logic of this mapping is that facilities will be required as long as activities requiring them are underway. Generally construction materials are delivered to the site a couple of days prior to their requirement, to account for delivery delays. This information must be accounted for while generating the facility requirement schedule. Thus, each bar on the facility requirement schedule indicates the total duration for which a facility will occupy space on the site. Since most commercial scheduling software allow the schedule to be exported as a csv file, we were able to write a program to determine the facility requirement schedule from the activity schedule (see Fig. 3).

The next step of dynamic layout planning is to identify the space availability on the site. The available spaces on a site can be separated into – (1) interior and (2) exterior storage areas. In most construction projects, the exterior storage area remains fixed throughout the construction project and can hence be treated as a constant. Interior spaces, however, are dynamic in nature and vary as the construction progresses. In the following section, we describe in detail our methodology for automatically computing the available interior storage area in a building.

3.1. Interior storage processing module

The interior storage processing module is designed to compute the interior space availability for material storage. This is performed in three main steps.

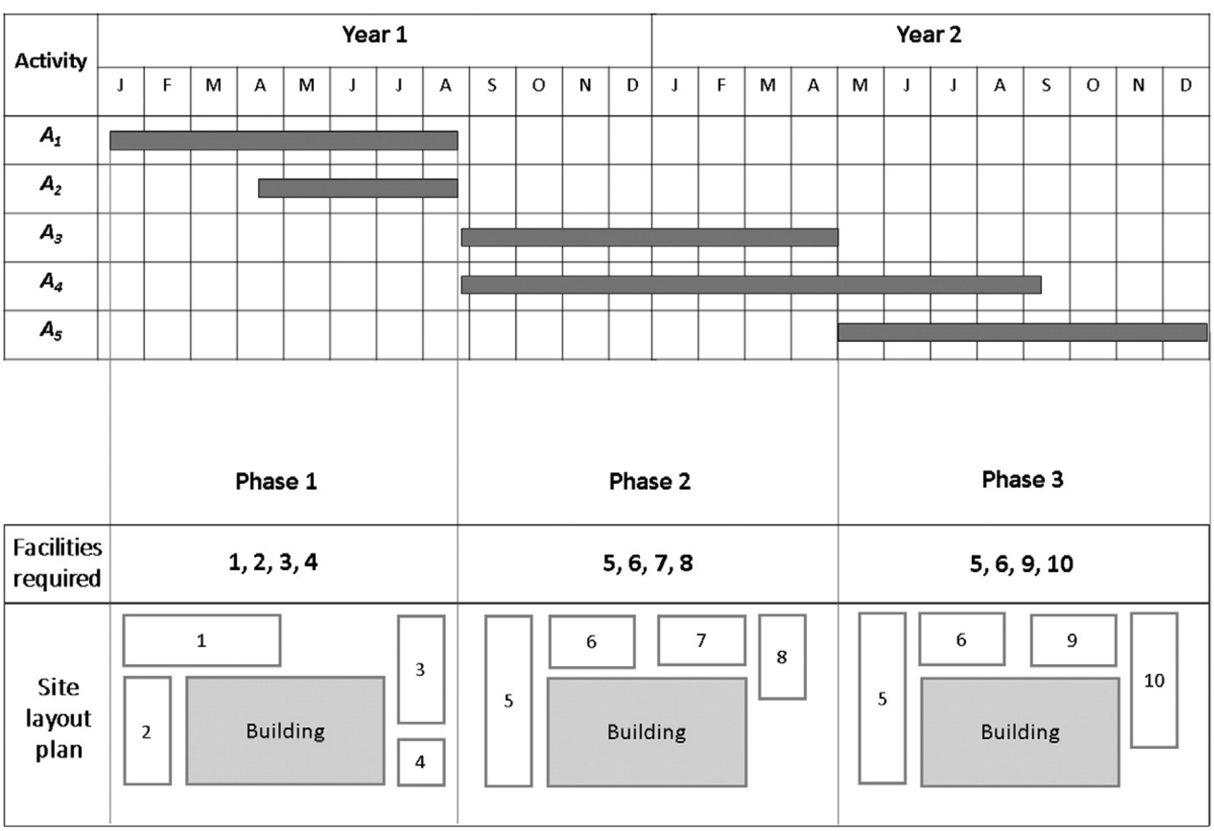

Fig. 3. Dynamic CSLP model based on the construction schedule.

Step 1: Calculation of feasible dates for interior storage. In order to utilize the interior building spaces for material storage, it is important to identify the beginning date when any given floor becomes suitable for storing materials. In most building construction projects, this is given by the date of slab completion. Thus, we assign the start date of interior storage on a given floor as the date of slab completion.

Step 2: Computation of available storage space. In the United States of America, Occupational Safety and Health Administration (OSHA) [36] rules specify that materials stored inside buildings under construction shall not be placed within 6 feet of any hoist-way or inside floor openings, nor within 10 feet of an exterior wall which does not extend above the top of the material stored. The gross permissible storage area for every floor can thus be determined from the floor plan.

However, owing to the presence of floor level activities, only a fraction of this space can be used for material storage. It is also necessary to provide sufficient amount of free space on every floor to facilitate the unrestricted movement of materials and personnel. Finally, a reduction in the total available space due to floor partitioning must also be considered. The net available area for material storage on a floor at any given point in time is thus computed by deducting the clear space and workspaces of indoor activities from the gross storage area. A further reduction in available space is made after the completion of floor partitioning. Mathematically, this is represented as:

$$A_{i,t} = G_{i,t} - C_{i,t} - \sum FO_{i,t} - FP_{i,t} \tag{9}$$

where, $A_{i,t}$ is the net space available, $G_{i,t}$ is the gross floor area, C_{it} is the clear area required, $FO_{i,t}$ is the floor space occupied by an activity and FP_{it} is the reduction in floor space after floor partitioning for the floor i, at time t. Said and El. Rayes [21] proposed a method of extracting the gross floor area from BIM models represented in the IFC format. In our study, we use classes provided by the Revit API to calculate the gross floor area, whereas the clear area and the floor space occupied by activities are determined based on prior experience and interviews with practitioners. There is scope for further improvement in the calculation of these values.

The construction schedule which lists all the activities, their start dates and duration is exported as a csv file in order to be parsed by our program. The start and end dates of each activity are identified and using Eq. (9), we calculate the net available storage area for each floor.

Step 3: Interior storage assignment. Since each activity occurring on a floor will require a corresponding material storage area, it is more efficient to store the required materials on the same floor as opposed to on another floor. For example, it is advisable to store wallboards and metal studs, both of which are needed for interior partitioning, on a floor for the duration of the interior partitioning activity on that same floor. The facility requirement schedule defined in Section 3 allows us to compute the amount of space required for facilities during different construction stages. Based on this, we seek to optimally allocate storage facilities to interior regions of the building. To optimize the usage of interior storage, we define a term called floor space utilization efficiency (FUE) as follows:

$$FUE_{i,t} = \frac{Space\ \ assigned\ \ to\ \ facilities}{A_{i,t}} \tag{10}$$

where $A_{i,t}$ is the net space available on the floor i at time t. The floor space utilization efficiency is an indicator of how efficiently the net available interior space is used for storage. A value of 1 indicates that the space is utilized to its maximum efficiency, whereas a lower value signifies under-utilization. The problem now is that of selecting materials to be stored inside, such that the FUE is maximized. Material assignment should, however, comply with the constraints that each material should be stored on the same floor as its activity workspace. This is mathematically represented as:

$$Maximize \sum_{i=1}^{N} \sum_{t=0}^{T} FUE_{i,t} \tag{11}$$

where N is the number of floors and T is the number of time steps. Due to the presence of floor-level activities and safety regulations, only a limited amount of interior floor space is available for storage and should hence be used judiciously. The optimization of interior storage matches the availability of storage space with the storage requirements of materials. Hence, the optimization has a single objective function subject to multiple constraints. It is important to note that because of the similarities between each floor, most building schedules are planned in floor construction cycles. That is to say, the scheduling of labour, resources and time is very similar between different storeys and hence the construction of a multi-storey building can be regarded as the repetitive construction of a single storey. As a consequence, the interior storage schedules will follow the same repetitive process. The complexity of the optimization problem therefore becomes 2^N where N is the number of storage facilities.

3.2. Exterior storage processing module

The remaining facilities are assigned to the exterior regions of the site. In order to facilitate the creation of a dynamic layout model, the remaining activities are grouped into discrete phases. Andayesh and Sadeghpour [11] argued that dynamic layout models, which split the project into fewer phases, suffer from under-utilization of available space. However, splitting the construction operation into too many different phases would result in the generation of several partial layout plans, which could be difficult to implement in practice. Keeping both these conflicting factors in mind, we chose a system that splits the project into three discrete phases. However, the number of phases can be changed according to the project complexity.

This splitting of the project into phases was done to promote reutilization of space. Facilities which are no longer needed should give way to new facilities. Hence, we use the logic that a significant change in the facility space demand should indicate the beginning of a new phase. Fig. 3 shows the relationship between the construction schedule and the start and end date of each phase.

4. Formulation of the optimization problem

4.1. Objective function formulation

After determining the facility requirements and space availability, we formulate the CSLP problem into an optimization problem. On a construction site, personnel travel from one facility to another either to perform certain activities or to transfer materials. Each such trip is assumed to incur a cost, which is directly proportional to the distance travelled and also depends on the mode of transportation. The frequency of these movements is stored in a trip frequency matrix, whereas the cost of transportation per unit length is stored in the cost matrix. The cost per unit length, which represents the ease of transportation, depends on the mode of transport and the nature of the materials being transported. The total transportation cost (TTC) is mathematically represented as:

$$TTC = \sum\nolimits_{p=1}^{N} \sum\nolimits_{i=1}^{n-1} \sum\nolimits_{j=i+1}^{n} d_{ijp} E_{ijp} f_{ijp} \tag{12}$$

where N refers to the number of construction phases, n refers to the total number of facilities, and d_{ijp}, E_{ijp} and f_{ijp} refer to the actual travel distance, cost per unit length and frequency of transportation between facilities i and j during phase p, respectively. The value of d_{ijp} is dependent upon the position of each facility and the presence of obstacles on the construction site (See Section 4.2). E_{ijp} and f_{ijp} depend on the mode of transportation and number of trips that have to make, respectively.

Facilities that are not required on the construction site anymore are either dismantled, relocated or re-used for storing other materials. As a result, each facility has an associated assembling, dismantling and relocation cost, which would depend on the labour and equipment required.

$$FC = \sum_{p=1}^{N} \sum_{i=1}^{n} \left(Ac_{ip} + Dc_{ip} + Rc_{ip}\right) \tag{13}$$

where FC refers to the total cost incurred in assembling, dismantling or moving facilities. Ac_{ip}, Dc_{ip} and Rc_{ip} are the costs associated with assembling, dismantling and relocating facility i in phase p, respectively.

The total cost incurred due to on-site material storage and transportation (TC) can thus be represented as

$$TC = TTC + FC \tag{14}$$

In another words, the optimization objective is to minimize TC, subject to various constraints (see Section 4.3). Layouts corresponding to the lowest value of the objective function represent optimal solutions to the site layout problem.

4.2. Computation of actual travel paths

A drawback of most studies is that they used linear distances to model the travel paths of site personnel. In reality however, due to the presence of obstacles, it is nearly impossible to always follow linear paths. In this study, we use the actual travel paths that would be followed instead, as a basis for site layout optimization. It is human nature to take the path of least effort while travelling from one place to another. On a construction site, this is manifested in site personnel following the shortest possible path between two facilities. The actual travel path is therefore assumed to be the shortest path from one facility to another, considering the presence of site obstacles [37–39].

To calculate the actual travel paths, the site is converted into a grid with a spacing of one metre in the X and Y directions. Obstacles such as trees, boundaries, temporary and permanent facilities are marked on this grid. A number of heuristics could be used to calculate the shortest paths between two points on such a grid. Soltani et al. [39] compared the accuracy and time complexity of Dijkstra's algorithm, A* algorithm and Genetic Algorithms in finding the shortest route on construction sites. Andayesh and Sadeghpour [37] conducted a study to compare direct, grid based and visibility graph approaches in finding the actual distance between objects on a construction site. Lin et al. [40] proposed an IFC-based method of finding the shortest path between two points in a 3D indoor space. In our study, we use the A* algorithm to determine the shortest possible path between two locations, and use it as a basis for site layout optimization (see Fig. 4). Although the accuracy of computed paths can be improved by selecting a smaller grid spacing, the time taken to calculate the path would significantly increase [30,38,39]. To ensure that accessibility has not been compromised, it is important to consider the mode of transportation used on site. Light materials may be carried by hand or wheelbarrow whereas heavier materials may need a forklift. The clear width of the path needed by a forklift will differ from that required by a wheelbarrow or a human being. As a result, the shortest path available on site might differ for each mode of transportation. Accordingly we specify a clear width of 1m for labourers, 3m for small hauling machines, and 5m for larger hauling machines. This approach ensures that the generated site layouts cater to the use machines in on-site transportation and do not restrict their accessibility.

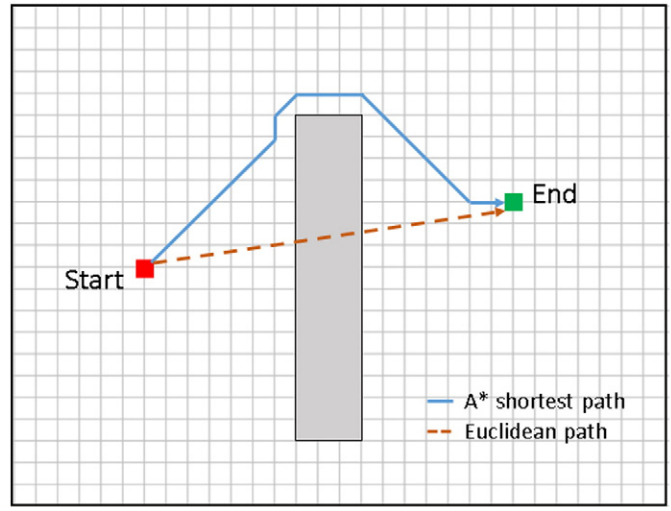

Fig. 4. Actual travel path using the A* algorithm.

4.3. Constraints of the facility layout optimization problem

4.3.1. Available site space

Osman et al. [10] proposed a method of extracting the spatial information of a construction site from CAD files. BIM encompasses all of the functionalities of CAD, hence by extracting the site layout plans of the construction project, we were able to automatically generate the site spatial data. This was done by extracting data contained in the layout plans into an excel database and formulating them into a set of mathematical inequalities. The closed area bounded by these inequalities represented the total site area available for construction. The fixed facilities (buildings) were then identified in a similar manner and subtracted from the total area encompassed by the site. The remaining area represents the total space allocated for setting up of temporary facilities.

Gene encoding

No.	Facility	Position (x,y)	Dimensions (l,w)
1	Steel storage	(3,3)	(10,4)
2	Site office	(3,10)	(7,9)
3	Precast panels	(15,2)	(7,7)

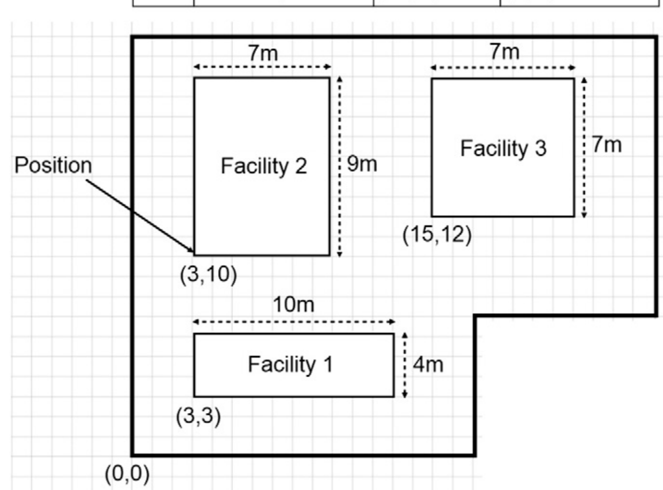

Fig. 5. Encoding the position of a facility as well as its dimension into a gene.

Facility	Permissible Dimensions			
1	L_{11}, W_{11}	L_{12}, W_{12}	…	L_{1m}, W_{1m}
2	L_{21}, W_{21}	L_{22}, W_{22}	…	L_{2m}, W_{2m}
…				
n	L_{n1}, W_{n1}	L_{n2}, W_{n2}	…	L_{nm}, W_{nm}

Fig. 6. The set of permissible dimensions for each facility (set D).

4.3.2. Safety constraint

In our study, we represent the safety constraint with the following inequality:

$$e_{ij} \geq s_{ij} \tag{15}$$

$$e_{ij} = \sqrt{(x_i - x_j)^2 + \left(y_i - y_j\right)^2} \tag{16}$$

where, e_{ij} refers to the Euclidean distance between two facilities and s_{ij} is the minimum safe distance between facilities i and j, with centroids at coordinates (x_i, y_i) and (x_j, y_j) respectively. A large value of s_{ij} implies a safety concern in positioning facilities i and j within close proximity of one another.

4.3.3. Overlapping constraint

We use a mathematical inequality to ensure that facilities do not overlap with one another or with the building to be constructed. A facility is represented by two parameters, (1) the coordinates of one corner point, and (2) its length and width. The constraint to avoid overlapping between facilities thus becomes:

$$\max\left[(x_j - x_i - l_i)(x_j - x_i + l_j),\ \left(y_j - y_i - w_i\right)\left(y_j - y_i + w_i\right)\right] \geq 0 \tag{17}$$

where (x, y) represent the coordinates of the top left corner, l represents the length and w represents the width of the facility.

4.3.4. Tower crane reachability constraint

Certain material storage yards need to be located within the reachable radius of the tower crane. This is mathematically represented as:

$$(x_t - x_f)^2 + \left(y_t - y_f\right)^2 \leq T_R \tag{18}$$

where (x_t, y_t) represents the axis of rotation of the tower crane, (x_f, y_f) represents the corner of the facility which is farthest away from the tower crane and T_R represents the tower crane's pickup radius. The tower crane's pickup radius is inversely related to the weight of object being lifted. This entails that heavier objects must be located within closer proximity to the tower crane than lighter materials. In our system, the radius of tower crane pertaining to different lifted materials can be specified by the user. In the demonstrative example, we ensured that structural steel storage yards and metal panel storage yards were within the reachable radius of the tower crane. Currently our system assumes a predefined location for setting up a tower crane. The system will be extended later to consider different crane types, locations and operations so as to address this limitation.

4.3.5. Site accessibility constraints

In this study, we defined a fixed path for material delivery trucks to ensure easy access to the construction site. In order to facilitate smooth site operations, it is important that facilities should not obstruct these paths. For the safety of the site personnel, it is also necessary to ensure that work areas are not too close to these paths. In our study, we ensured that all facilities had a minimum clearance of 1m from this path. This ensured that the paths were never obstructed by facilities while minimizing the safety hazard.

4.3.6. Miscellaneous constraints

Based on the layout engineer's discretion or environmental concerns, a range of project specific constraints could be added to the paper. For example, in some cases the construction site may share one or more boundaries with schools, hospitals or other environmentally sensitive zones. In such situations, it must be ensured that the sound generated due to on site activities are within acceptable limits. Thus, facilities that create a lot of noise would have to be placed at a sufficient distance from these zones. In certain situations from prior experience, the layout engineer might require a certain relationship in the locations of two facilities. Such conditions can be formulated into mathematical relationships and incorporated into the optimization model.

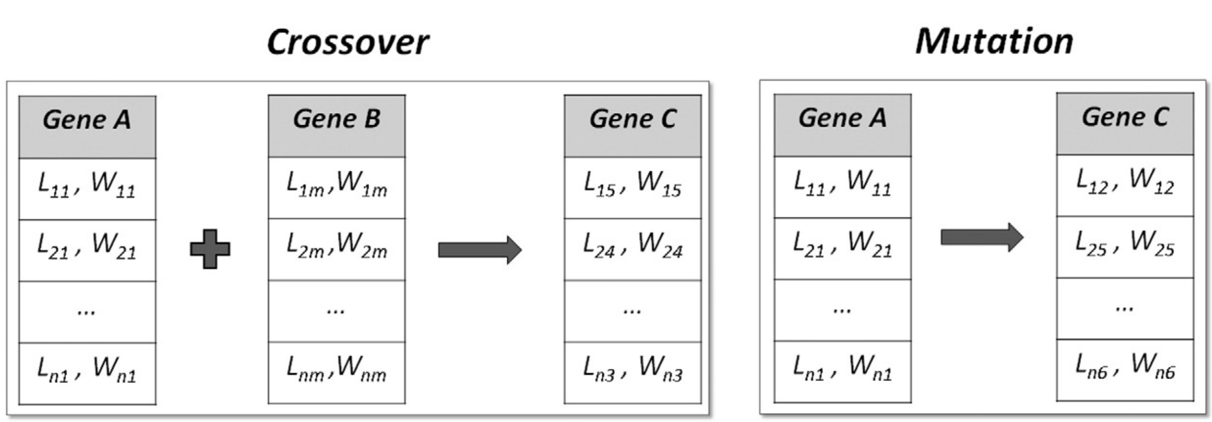

Fig. 7. Crossover and mutation operators.

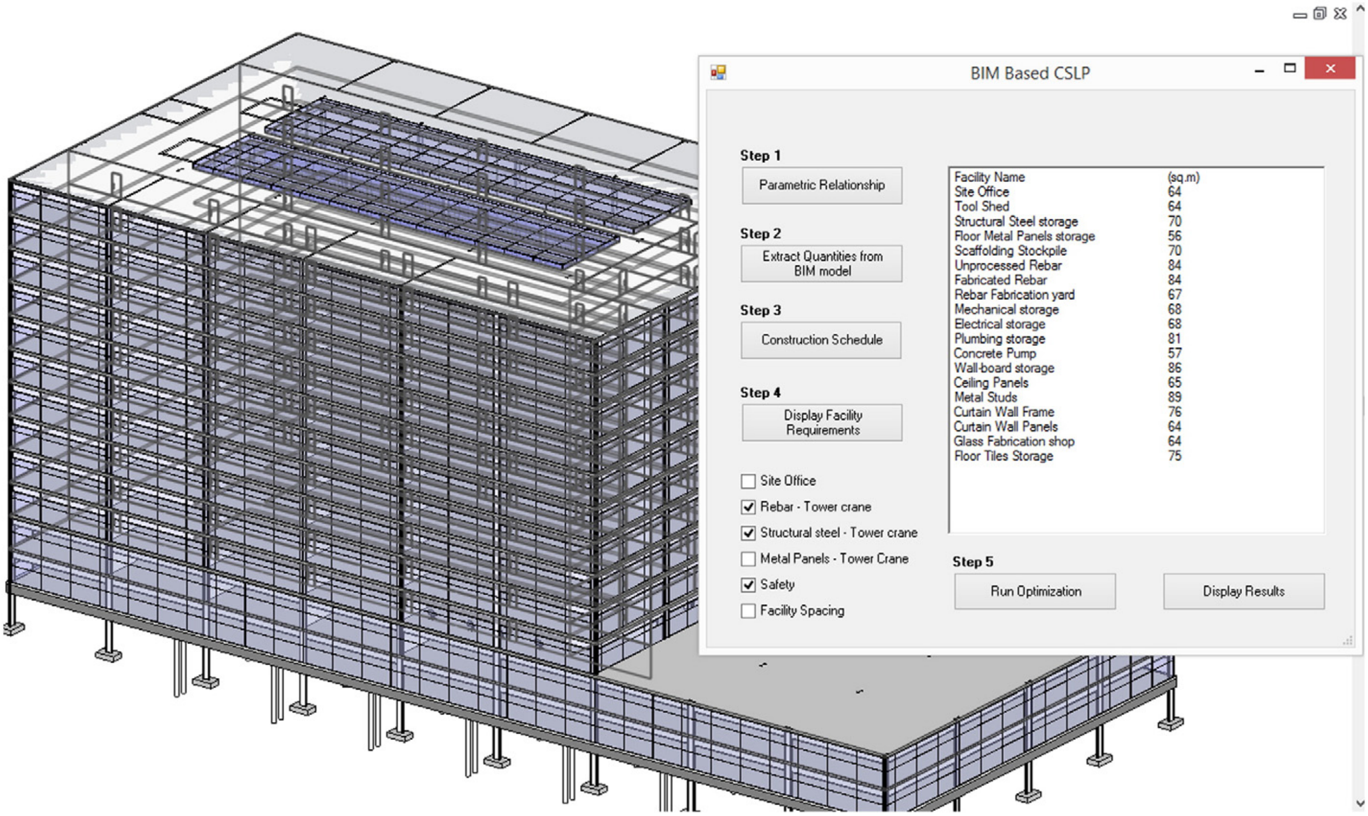

Fig. 8. Revit model of the 12-storey office building in the demonstrative example and the developed Revit Plugin.

5. Optimization using genetic algorithms

The CSLP problem is considered to be 'NP-hard' and several research studies have attempted to arrive at solutions using heuristics [13,14,17,32,34] or mathematical optimization techniques [28]. Genetic algorithms (GA), due to its ease of implementation, is one of the most common methods of solving the site layout problem. The essence of GA lies in combining elements from two solutions of the same generation (parents) or mutating individual solutions to produce a third solution which is then evaluated based on the objective function [8]. If the third solution is better than its parents, it is kept; otherwise, it is discarded. This process is repeated until there is no significant difference in the fitness of resulting chromosomes, which represents convergence on an optimal solution. To prevent the algorithm from getting stuck on a local minima, crossover and mutation operations are developed.

5.1. Gene encoding

In GA, the variables to be optimized are represented as genes. Traditional CSLP approaches optimize only the locations of facilities on the construction site. Hence, in traditional practice only the positional information of each facility is encoded into a gene. In our study, we seek to optimize the dimensions of each facility in addition to its positions. As a result, the dimensions of each facility are also encoded into a gene along with their positions (see Fig. 5). Subsequently modified crossover and mutation operators need to be developed in order to generate variations in facility dimensions as well.

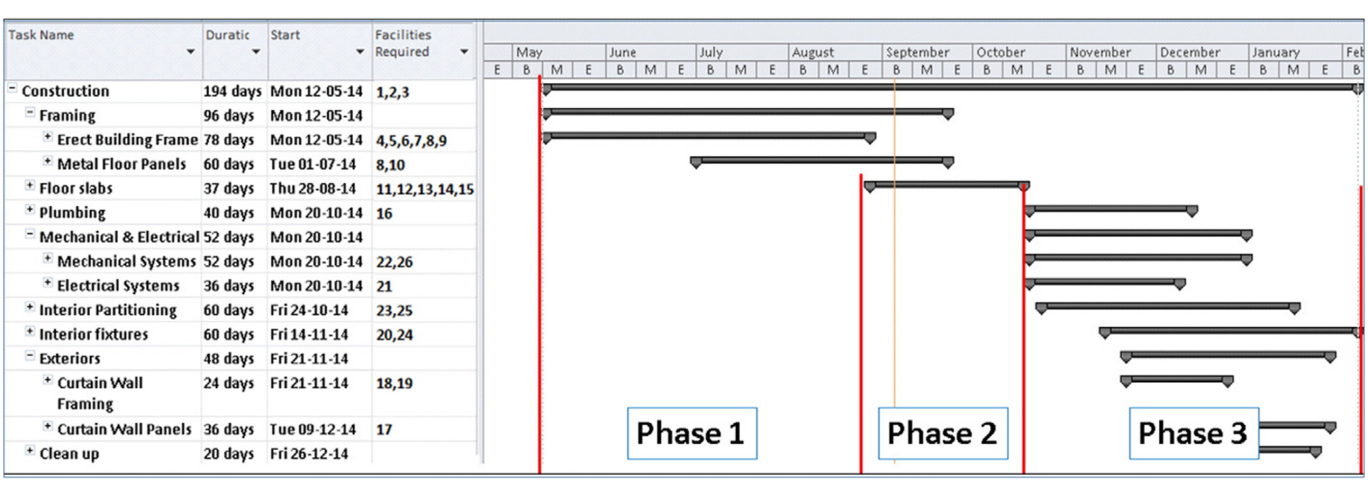

Fig. 9. Construction schedule and corresponding phases in the demonstrative example.

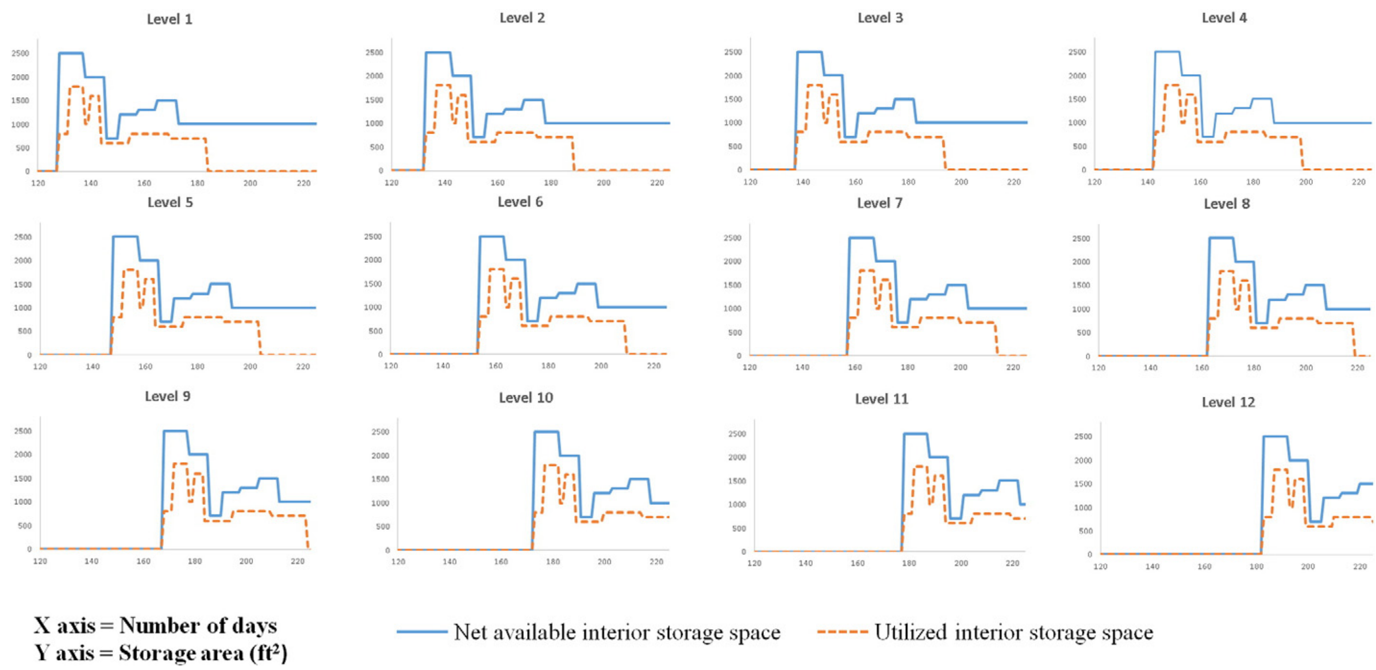

Fig. 10. Utilization of interior storage areas in the demonstrative example.

5.2. Modified crossover and mutation operators

The crossover operator combines the genes of two parents to create an offspring. In all of the previous studies which used GA to optimize site layouts, the crossover operator combined only the positional information of facilities. In our study, we develop a modified crossover operator which combines facility dimension information as well. The crossover operation for a facility's positional information has been explained numerous times in previous studies and hence we skip the explanation. However, a crossover for facility dimensions has not been attempted before. This is explained with the help of the following example.

Consider the trivial case in which we just have one temporary facility of area A_i on a construction site. The range of permissible values for length and width for this facility are calculated using Eq. (8), and represented by *set* $D = \{(l_1, w_1), (l_2, w_2) \ldots (l_n, w_n)\}$, (see Fig. 6). Consider two parent genes, *Gene A* and *Gene B* which represent two possible facility layouts for this problem. The positional information of each gene, represented by the corner points of the facility are (x_A, y_A) and (x_B, y_B), respectively. In addition to positional information, *Gene A* and *Gene B* also contain information about the facility's length and width (l_A, w_A) and (l_B, w_B), respectively. By definition, (l_A, w_A) and (l_B, w_B) belong to set *D*, which is the range of permissible facility dimensions. The two parent genes are to be crossed and would result in an offspring, represented by *Gene C*. We generate *Gene C* in such a way that it contains information from both *Gene A* and *Gene B*. As a result, the dimensions of the facility stored in *Gene C* lie somewhere in between those of *Gene A* and *Gene B* and by definition also belong to set *D*. Fig. 7 shows the modified crossover and mutation operators for a construction site comprising of *n* facilities. This ensures that genes in the offspring *Gene C*, are a combination of its parents. A random function is used to decide how much genetic material is inherited from each parent. The positional information

Table 1
Facilities assigned to the exterior site regions.

Facility number	Name	Type	Area (m^2)	Phase required	Size calculation
1	Tool shed	Storage	55	1,2,3	User defined
2	Site office	Residence	70	1,2,3	User defined
3	Restrooms	Residence	35	1,2,3	User defined
4	Structural steel primary beams	Storage	40	1	BIM and Schedule
5	Structural steel secondary beams	Storage	65	1	BIM and Schedule
6	Structural steel columns	Storage	80	1	BIM and Schedule
7	Structural steel assembly yard	Processing	75	1,2	BIM and Schedule
8	Scaffolding pile	Storage	40	1	BIM and Schedule
9	Fire proofing materials	Storage	50	1	BIM and Schedule
10	Floor metal panels	Storage	85	1,2	BIM and Schedule
11	Rebar storage	Storage	70	2	BIM and Schedule
12	Formwork storage	Processing	50	2	BIM and Schedule
13	Aggregate warehouse	Storage	60	2	BIM and Schedule
14	Cement warehouse	Storage	35	2	BIM and Schedule
15	Concrete mixer	Processing	65	2	BIM and Schedule
16	Plumbing storage	Storage	50	3	BIM and Schedule
17	Curtain wall glass	Storage	90	3	BIM and Schedule
18	Curtain wall framing storage	Storage	70	3	BIM and Schedule
19	Curtain wall assembly yard	Processing	75	3	BIM and Schedule
20	Floor tiles storage	Storage	65	3	BIM and Schedule
21	Electrical systems storage	Storage	75	3	BIM and Schedule

Table 2
Facilities stored inside the building.

Facility number	Name	Type	Area (m^2)	Size calculation
22	Mechanical storage	Storage	80	BIM and Schedule
23	Interior wallboard and metal studs	Storage	100	BIM and Schedule
24	Fixtures storage	Storage	90	BIM and Schedule
25	False ceiling panels storage	Storage	80	BIM and Schedule
26	Fire safety systems storage	Storage	65	BIM and Schedule

in *Gene C*, is obtained using a simple crossover operator, which combines the positional information of the two parent genes, with a random function determining the amount of genetic information inherited from each parent.

The modified mutation operator works similar to the crossover operator. In this function, genes are randomly picked and their facility dimensions are given a random change such that the new dimensions would also belong to *set D*. The crossover and mutation operations try

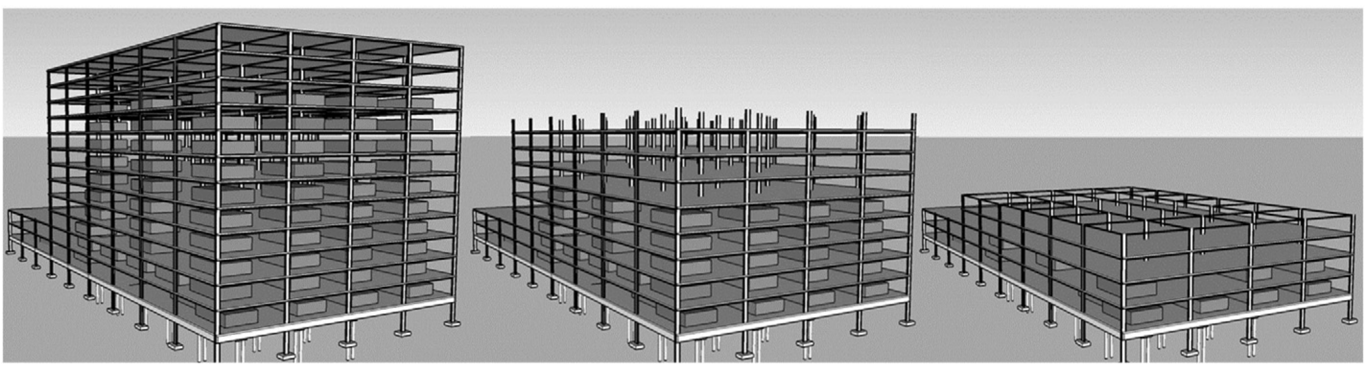

Fig. 11. 4D visualization of the interior storage space.

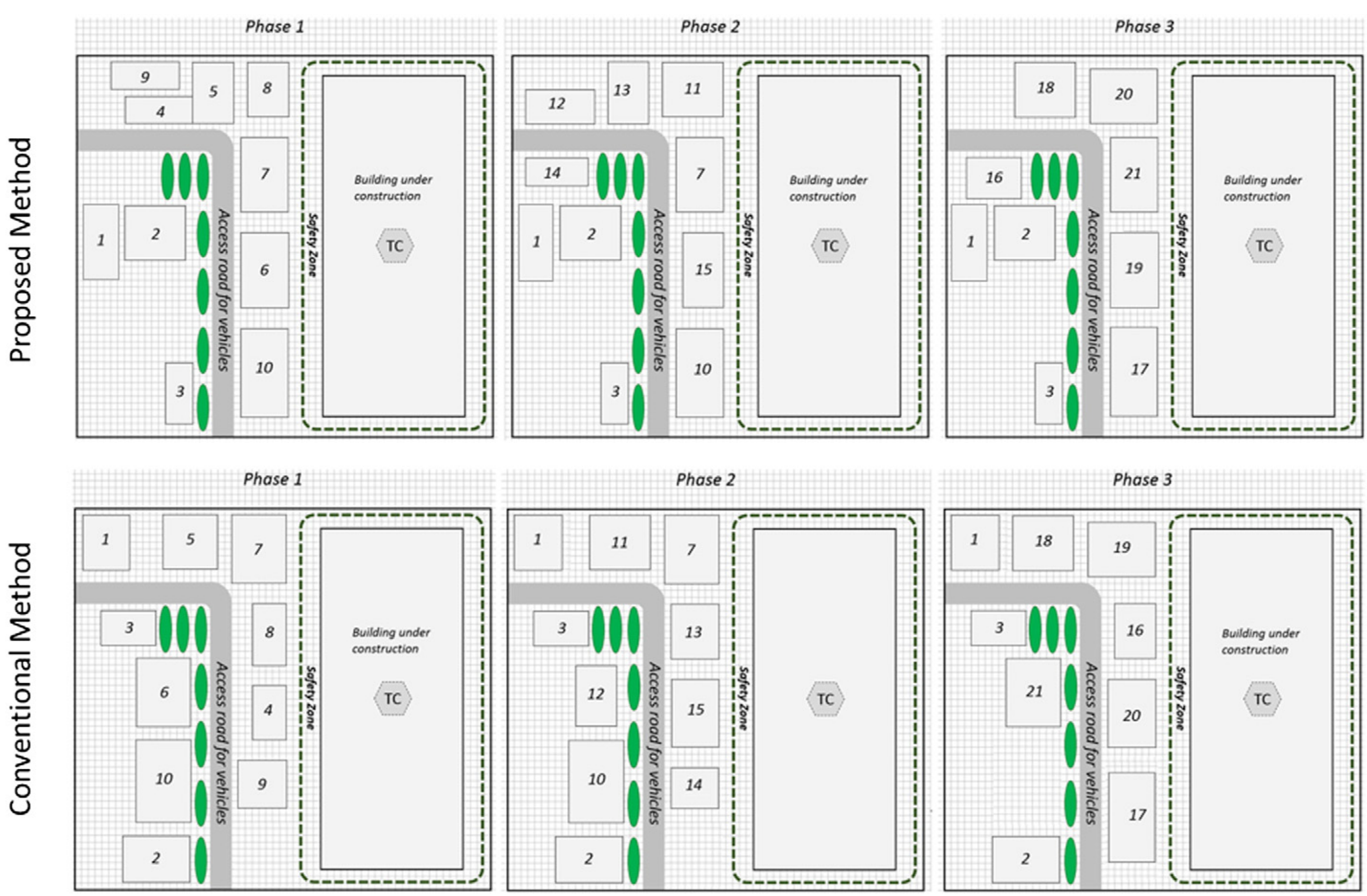

Fig. 12. Comparison of layouts obtained from the two cases.

Table 3
Comparison of the dimensions of facilities.

Facility number	Name	Area (m^2)	Facility dimensions (L,W)(rounded to the nearest metre)	
			Conventional method (user defined dimensions)	Proposed method (optimized dimensions)
1	Tool shed	55	7,8	5,11
2	Site office	70	10,7	9,8
3	Restrooms	35	9,4	4,9
4	Structural steel primary beams	40	5,8	10,4
5	Structural steel secondary beams	55	8,7	6,9
6	Structural steel columns	80	8,10	7,11
7	Structural steel assembly yard	75	8,9	7,11
8	Scaffolding pile	40	5,8	6,7
9	Fire proofing materials	50	7,7	10,5
10	Floor metal panels	85	8,11	7,12
11	Rebar storage	70	9,8	9,8
12	Formwork storage	50	6,8	10,5
13	Aggregate warehouse	60	7,8	6,10
14	Cement warehouse	35	7,5	9,4
15	Concrete mixer	65	7,9	6,11
16	Plumbing storage	50	6,9	9,6
17	Curtain wall glass	90	7,13	7,13
18	Curtain wall framing storage	70	9,8	9,8
19	Curtain wall assembly yard	80	10,8	7,11
20	Floor tiles storage	75	7,11	10,8
21	Electrical systems storage	75	8,10	7,11

to account for the variations in genetic information between successive generations of offspring.

6. Demonstrative example

We tested the BIM based CSLP framework on an illustrative example of a building construction project. The project involves construction of a 12-story steel building with concrete floor slabs on a site area with some existing trees and an access road. Autodesk Revit was used to create the BIM model, which contained the material information of the building (see Fig. 8). A schedule for the construction activities was created using Microsoft Project (see Fig. 9).

The construction site was converted into a square grid of side 80 units, where 1 unit represented 1 m on the site. The building to be constructed, existing trees, existing access road and the site boundary were marked on this grid. To facilitate the export of material quantities, we created a plugin named “BIM based CSLP”, using the Revit API and Microsoft C# (Fig. 8). The schedule was exported from Microsoft Project as a csv file, which could be taken as input by the Revit plugin. Using the previously defined methodology, we were then able to determine the area requirement of each temporary facility. The size of the site office was decided to be 100 m^2 based on the assumption that 13 engineers would be needed for the project. The size of the tool shed and toilet, based on similar assumptions, were defined to be 55 m^2 and 35 m^2, respectively. The frequency of trips made by workers between facilities was defined with logical assumptions, based on the quantity of work each day. For the sake of simplicity we assumed that each path started and ended on the centroid of a rectangular facility.

Using the schedule file and the information about floor plans, we developed an indoor storage utilization schedule (Fig. 10). The schedule tells us how much indoor storage space is available during different stages of construction. Based on this information the facilities that would be assigned to exterior storage locations (Table 1) and interior storage locations (Table 2) were determined. Since the number of facilities to be considered for interior storage was 13, an optimized solution could be found using an exhaustive search. Setting up the MEP, tiles, ceiling and wall board storage inside the built environment was found to represent the most optimal allocation of interior space.

Once the dynamic model of the site was created, we move over to optimizing the layouts of facilities on the exterior regions of the site. The optimization was performed using genetic algorithms with a population size of 1500.

6.1. Results and discussions

In order to demonstrate the benefit of our framework, two cases were considered: (1) Euclidean distance based optimization with fixed facility dimensions (conventional method) and (2) actual travel distance driven optimization with variable facility dimensions (the proposed method) (see Fig. 12). Table 3 compares the dimensions of facilities in the two cases. Tables 4 and 5 compare the Euclidean and actual travel distances corresponding to the two cases. In order to compare the two layouts, we calculated what the total distance travelled in each case would be. The conventional method, which assumes Euclidean or centre-to-centre distances, yielded a total Euclidean distance of 2390 km for the entire project. However, the actual travel distance for this case was computed as 3520 km. This suggests that the presence of site obstacles lead to a significant under-estimation of travel distances while using a linear distance driven optimization. Our proposed method of using actual travel distances and variable facility dimensions yielded a total travel distance of 3050 km, a reduction of approximately 13.5 % in the actual travel distance. This large difference can be attributed to two causes. Firstly, the conventional algorithm of using centre-to-centre distances in the optimization is not intelligent enough

Table 4
Comparison of the Euclidean distance in layouts obtained using Euclidean and actual travel path driven optimization.

Layout obtained taking d_{ij} as	Euclidean distance (km)			
	Phase 1	Phase 2	Phase 3	Total
Euclidean	900	670	820	2390
Actual path	990	740	980	2710

Table 5
Comparison of the actual travel distance in layouts obtained using Euclidean and actual travel path driven optimization.

Layout obtained taking d_{ij} as	Actual distance travelled (km)			
	Phase 1	Phase 2	Phase 3	Total
Euclidean	1330	960	1230	3520
Actual path	1100	810	1140	3050

Table 6
Comparison of the total transportation cost in the conventional and proposed methods.

	Total Transportation Cost ($)			
	Phase 1	Phase 2	Phase 3	Total
Conventional method	15,960	11,520	14,740	42,240
Proposed method	13,200	9720	13,680	36,600

to identify the presence of obstructions to the travel paths. As a result, they fail to accurately represent the on-site transportation activities. The A* algorithm on the other hand identifies obstacles on the site and is better equipped to model the actual travel patterns. Modelling the path widths of personnel and machines further improves the accuracy of the computed travel paths. The second reason attributable to the significant difference in travel distances is the optimization of facility dimensions. The conventional method specified fixed dimensions for each facility prior to the optimization and as a result, the range of solutions was severely restricted. The proposed approach optimizes facility dimensions based on the dimensions of the available site spaces. By varying the length and breadth of a facility, they could even be allocated to constricted spaces. These findings strongly suggest using actual travel distance driven optimization in favour of linear distances. They also suggest that a method that optimizes facility dimensions should be used in favour of the conventional method. Tables 6 and 7 compare the total transportation cost and total cost (including facility setup, dismantling and relocation cost).

As can be seen in Fig. 10, the net available storage area undergoes a significant variation with time. The interior storage optimization module recommended using interior storage for MEP, tiles, ceiling panels and wallboards and to store the pipes required for the safety sprinklers. The average of the floor space utilization efficiency (FUE) achieved by this combination was equal to 0.65, indicating that on average, 65% of the net available interior space was utilized for storage. Such a low value is attributable to the lack of coordination between material procurement and interior storage feasibility. Planning material logistics based on the feasibility of interior storage could improve the FUE. The optimized site layout and interior storage assignments can be used as a basis to generate 4D BIM models of the project (see Fig. 11). Such models can then further be used for a variety of analyses, such as clash detection and construction sequence coordination.

7. Conclusions and future work

This paper presents a BIM based framework that enables automating the construction site layout planning (CSLP) process. Based on this, we developed a tool to optimize the dynamic layouts of temporary facilities on a construction site. Our framework allows quick and easy facility sizing and does not require users to manually input project specific information. Since all the calculations are based on information from BIM, changes to the design and schedule could be updated at the click of a button, enabling them to be reflected in the final calculations. This achieves a significant reduction in effort when coping with frequent changes. Our model could be easily incorporated into existing CSLP tools to improve their practicality. The effort spent by layout planners in performing unnecessary calculations would thus be significantly reduced, allowing them to focus on decision making instead. This paper also develops a more realistic representation of site-level activities, by computing the actual travel paths followed on a construction site. Furthermore, this paper presents a method to determine optimized dimensions for each facility, thus allowing for an increase in the efficiency of layouts. By giving consideration to interior storage within the building under construction, our model becomes suitable to deal with CSLP on congested urban building projects as well. In the demonstrative example, our optimization method lead to layouts which reduced the overall travel distance by 13.5 percent over conventional methods. Our CSLP engine can be integrated with graphical visualization tools to facilitate 3D interactive site layout planning. This model has the potential to be extended to address supply chain planning as well. Future efforts will focus on developing a system that incorporates real time construction schedules in order to track inventories and manage material logistics.

Table 7
Comparison of the total cost (including facility setup, dismantling and relocation) in the conventional and proposed methods.

	Total Cost ($)			
	Phase 1	Phase 2	Phase 3	Total
Conventional method	25,960	22.520	27,740	76,240
Proposed method	23,200	20,720	26,680	70,600

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