Optimizing Site Layout Planning utilizing Building Information Modelling

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Abstract -

Site layout planning (SLP) is categorized as a non-deterministic polynomial time (NP) hard or complete class problem. Inefficient SLP can lead to congestion, safety conflicts and productivity reductions. Significant attention to the problem is evident in the field of construction management. A number of optimization routines and mathematical models are suggested in past research to reduce costs associated with improper layouts. However, such models are seldom adopted on real-life projects, where SLP is primarily carried out based on heuristics. The two significant inhibitors to the adoption of sophisticated approaches identified in this study are; lack of realism in the mathematical models and the significant effort involved in setting up the model for each construction site. These two inhibitors tend to reflect as reluctance on the part of the project teams to adopt SLP models. In the present study, the first inhibitor is addressed by incorporating realism into the mathematical model for SLP. The SLP is formulated as an optimization problem involving the reduction of transportation cost on construction site with associated constraints. Realism to the optimization model was brought through the modelled travel distances utilizing Building Information Modelling (BIM). Genetic Algorithm (GA) was used to optimize the objective function. The combined model thus incorporates all the site constraints in terms of travel paths as captured in the BIM model thus bringing in more realism into the SLP modelling. This work is preliminary work in developing a fully automated SLP process where the second inhibitor would also be addressed.

Keywords -

Site Layout Planning; Optimization; Building Information Modelling; Genetic Algorithm

1 Introduction

Research to address the problem of layout planning also exists in sectors like manufacturing, electronics, computer science and information technology and construction. The objectives to achieve and the constraints encountered are unique to the Architecture, Engineering and Construction (AEC) industry. The layout planning for a construction project starts at the initial phase of the project. The objectives during this phase are not limited to the identification of potential locations to accommodate temporary facilities (TFs) [1], finalizing the routes for vehicular movement [2] and selection of equipment [3]. Intertwined tasks brings more complexity to be handled while planning layouts for construction sites [4]. There exist literature where researchers have tried modelling SLP as a mathematical problem. Mathematical models too possessed the complexity and were referred to NP-Hard [5] and NP-Complete [6] class problems. Despite enormous research in the domain of layout planning, the AEC industry utilizes heuristics of the experienced stakeholders on the project for the purpose of SLP. Sometime the drawbacks of layout through experiential learning come to forth in the form of site congestion, restricted access, unnecessary vehicle movement, multiple handling of material etc. The mathematical approach existing in literature provides a segmental solution to the layout problem and lacks in capturing the realism of a construction site [7], [8]. Although the studies in the domain of layout planning have focused on developing a varied approach to tackle different objectives [7] and comparing the algorithms, adopted in the domain for the solution search [6]. This research in contrast presents an effort to understand the inhibitors to the adoption of existing mathematical models and approach. An evolution in the mathematical approach is also evident to make mathematical models closer to real site scenario; from discrete space layout planning problem to continuous space optimization [3] and from adopting rectilinear distances, to generating actual paths for planning layout [9]. This research effort is focused on the latter and is a distinguish approach as it involves modelling of paths rather generating it algorithmically.

The existing research presents the adoption of BIM and simulation-based methods to benefit the SLP process through optimization approach. The approach established in this research presents a simple and dissimilar method by utilizing BIM, to bring realism to the mathematical model for SLP. The actual paths modelled for SLP to represent the manoeuvring paths of vehicles and the site personnel replaces the Euclidean and the Manhattan distances considered in existing literature. A test case is also demonstrated with an objective to minimize the transportation cost of material on construction site. The domain of layout planning for construction site has shown significant advancement and the approach developed in this study conform to the recent advancements in the area.

2 Site Layout Planning

The task of allocating space to TFs, material, site personnel and equipment can be referred as 'Site layout planning'. During the task, ensuring optimal usage of the available space is among the prime objectives to the stakeholders involved [10]. The task is part of the front-end planning of a construction project and has close interaction with other processes like scheduling, equipment selection and supply management [3]. The existing research in the domain has attempted the problem in ways like static site layout [11], dynamic site layout [12] and phase based site layout [9]. There have been attempts to model the site space utilizing girds, discrete site spaces and continuous site space [13]. These approaches of representing site space present the peers' desire to model construction scenario close to reality. The methods presented in the existing research have utilized different ways to map the site distances. Some studies have considered the Euclidean and Manhattan distances to replicate the site movements of vehicles and site personnel [14]. The depiction of rectilinear distances on the site may help in mathematical modelling of the construction site but are of no good as the resulted output of these models also lead to sub-optimal solutions. Although there exist rich literary resources to plan site layout efficiently, the construction site layout planning is attempted by the responsible stakeholders utilizing heuristics and the experiential learning gained over the years. The employed approach to layout planning sometimes leads to sub-optimal layouts for the construction site resulting in congestion, multiple handling of material and a rise in safety concerns. The adoption of available optimization routines and mathematical models is still not profound in the AEC industry and the reason can be contributed to the lack of representing actuality in the approach [15]. BIM and computer simulation has marked applicability for SLP and offered help to the planners to plan close to reality. There have been advancements in the mathematical modelling for site layout planning and the adoption of fuzzy sets to incorporate uncertainty has also been employed. Some studies have highlighted the interaction of SLP with the other planning process in very recent years [16], [17].

2.1 Advancements in Research of SLP

Mathematical models for layout planning exist from a long period, formulated as a single objective to optimize [18] and sometime multi-objectives are transformed to a single objective by assigning appropriate weights to individual objectives [19]. The literature has an intensive focus towards optimizing the sum of weighted distance represented as $\sum w*d$ [20]. The primary focus of the existing studies has been on smooth interaction between the facilities on construction site [21]. It is also a shift observed from macro-level planning for the site to micro-level planning, leaving the problem of site utilization partially addressed. The concern towards other objectives has also captured the interest of the construction management researchers. The objectives of the layout problems are both qualitative and quantitative. The factors like safety are addressed in layout optimization in both ways [20]. To address the objectives in an efficient manner that were unaddressed due to the uncertainties involved were approached through the simulation technique integrated with optimization [22]. A few BIM based approaches for layout optimization of the construction site are also evident in the studies of recent past. The shape of a temporary facility is one parameter that can affect the site layout decisions. The area of site locations have a tendency of getting changed as the progress of construction moves forward. There exist research to generate a freeform geometry of the locations and its transformation [23]. Studies have presented a necessity to have 'shortest paths' [23] on construction site and a few have highlighted to have 'actual paths' in consideration [9]. The utilization of BIM for planning site layouts collaboratively is another application of BIM integrated with Augmented Reality (AR). The research presented the users' behavior when subjected to AR enabled platform for planning SLP [24]. The concepts of BIM help in providing the required level of realism to the virtual model by leveraging it with the information. There are few studies highlighting the requirement of BIM for rule based checking system for planning site layouts. The rule based checking is to identify conflicts with the design of the permanent facility [10]. Apart from adopting BIM, the four dimensional (4D) planning is also proposed in existing studies to replicate realistic site planning. These cases of 4D planning comprises of a three dimensional (3D) model integrated with the schedule of a construction project, and based on the generated 4D visualization of construction activities the SLP is carried out [8]. Moreover, to BIM, simulation and visualization aids; there exist efforts of researchers in the domain to generate paths on construction site for mobile cranes [25] and site personnel but sometime the computer generated paths may also be found infeasible to adopt.

The presented approach in this research combines the existing approach of SLP i.e. mathematical optimization and BIM. The BIM module of the study can be an add-on to the existing optimization models bringing them closer to the reality of the construction site.

3 BIM based Framework for SLP

The apparent utilization of BIM in the AEC industry has simplified the tasks of quantity take-off, detecting and resolving clashes, progress monitoring, asset management etc. This research highlights the potential of BIM for SLP. The BIM model of a hypothetical construction site has been developed and is detailed to a required level of detail (LOD). The LOD 300 model presented in Figure 3 is found apt for implementing the conceptual framework of this study. This detailed model acted as a supplement to the mathematical optimization module presented in section 3.1. The developed approach is depicted in Figure 1.

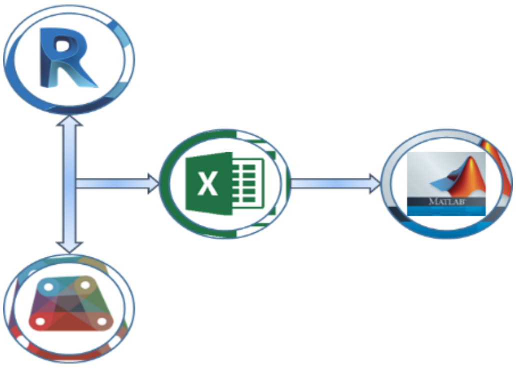


Figure 1. Interoperability Offered by BIM

The modelled site comprises of a reinforced concrete framed structure with isolated footings and a site area of 12385.42 square meters (sq.m.). The main structure has been divided into four quadrants marked in Figure 2.

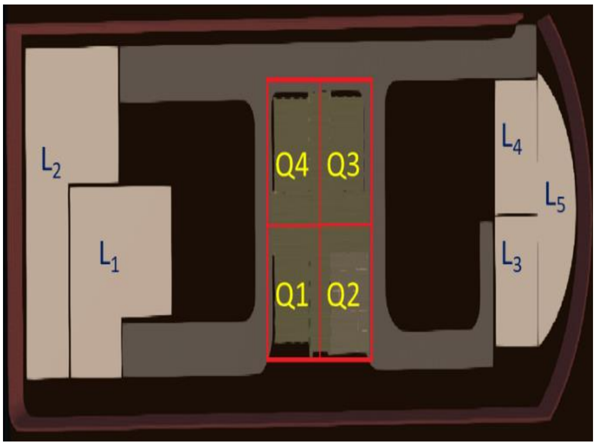


Figure 2. Top View of the Modelled Site

The locations to accommodate TFs, marked as L_1...L_5 in Figure 2 are identified and this represents a case of discrete SLP. It is assumed that the route planning for the construction site is in place and the movement of the vehicles for supporting construction is restricted to the planned paths. During the preparation of the 3D model for the main structure, the paths are modelled to the desired precision. The LOD 300 provided flexibility to takeoff the quantity with high accuracy through Dynamo 2.0, an add-in to Autodesk Revit.

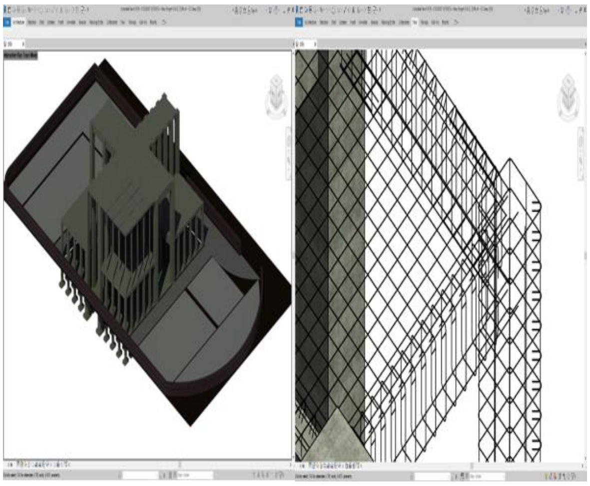


Figure 3. Construction Site Model (LOD 300)

The whole construction site elements are mapped utilizing the visual programming interface of the Dynamo. Figure 4 shows the mapped routes on the construction site joining the locations for temporary facilities and the quadrants of the main structure.

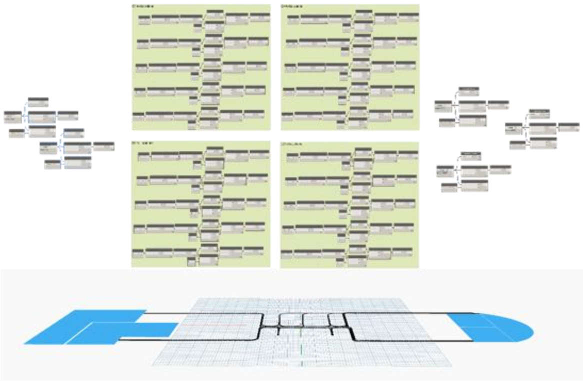


Figure 4. Dynamo Workspace and Preview

The length of the planned routes is extracted from the model and stored in location-distance (LD) matrix as shown in Table 1. The LD matrix is one input for the mathematical optimization module presented in this research.

The quantity takeoff for the required material (M) has been extracted for each quadrant (Q) utilizing Dynamo. The materials required for the modelled framed structure and its respective quantity is tabulated in Table 2. The muck quantity is taken as an approximate of 1.5 times the quantity of concrete required for the isolated footings. The quantities generated by Dynamo are in different SI units and are brought to a common measurement unit by required arithmetic operations.

Table 1. Location to Quadrant Distance

Quadrant Location	Q1	Q2	Q3	Q4
	Distance in Meters			
L_1	175.8	215.6	220.5	176.7
L_2	186.7	228.1	227.3	166.4
L_3	204.0	164.2	163.1	206.6
L_4	243.5	199.5	195.2	239.2
L_5	242.2	201.0	153.1	210.7

The materials for which the quantity takeoff has been executed are Reinforcement Steel (M_1), Concrete (M_2), Pre-Engineered Steel Sections (M_3), Excavated Muck (M_4) and Shuttering Formwork (M_5). Data from five construction sites of similar area and are at an initial project phase have been acquired to identify the equipment requirement and the cost of operating the equipment. Table 3 highlights the equipment running cost and the maximum carrying capacity per trip.

Table 2. Quantity Takeoff from BIM Model

Q M		Q1	Q2	Q3	Q4
M_1	m^3	3.1	3.1	3.1	3.1
M_2	m^3	405.5	405.5	405.5	405.5
M_3	m^3	0.0	91.2	0.0	0.0
M_4	m^3	1459.8	1458.7	1458.2	1459.8
M_5	m^2	1900.2	1897.3	1894.1	1900.2

The trips are calculated utilizing the derived quantities and converting into an appropriate unit. The conversion has been done for M_1, M_2, M_3 and M_4 using the density of material as 7850 kg/m^3 [26], 2400 kg/m^3 [27], 7700 kg/m^3 [28] and 2000 kg/m^3 [29] respectively. The quantity of M_5 is transformed by adopting a value from the industry of 11.3 kg/m^2. The trips required for transporting the entire material to the construction site is shown in Table 4, and is calculated adopting the operable capacity of the appropriate equipment.

Table 3. Data from Field

Equipment	Rated Capacity	Operable Capacity	Cost Unit per Trip of Unit Meter
Transit Mixer	6 m^3	5 m^3	100
Mobile Crane	16 T	16 T	100
Dumping Truck	35 T	32 T	100

Table 4. Required Number of Trips

Material	Q1 Trips	Q2 Trips	Q3 Trips	Q4 Trips
M_1	2.0	2.0	2.0	2.0
M_2	82.0	82.0	82.0	82.0
M_3	0.0	44.0	0.0	0.0
M_4	92.0	92.0	92.0	92.0
M_5	2.0	2.0	2.0	2.0

The transit mixer is found suitable for material M_2 and likewise M_1, M_3 and M_5 are expected to be hauled by a mobile crane. The material M_4 is required to be transported from the execution site to a location for storage by a dumping truck. The excavated soil is stored for backfilling once the planned footings are installed.

Table 5. Transportation Cost Matrix

Q / M	Q1	Q2	Q3	Q4
M_1	200.0	200.0	200.0	200.0
M_2	8200.0	8200.0	8200.0	8200.0
M_3	0.0	4400.0	0.0	0.0
M_4	9200.0	9200.0	9200.0	9200.0
M_5	200.0	200.0	200.0	200.0

The trip matrix and the cost unit matrix provided the transportation cost unit for materials (TCM) which is another input to the optimization module of this study. The TCM matrix is presented in Table 5. The TCM matrix is the product of cost unit per trip of equipment and the number of trips required to transport the material to the quadrants.

Once the inputs for the mathematical module are acquired, the SLP optimization approach is formulated. The approach adopted is developed to identify the position for storing the materials before transporting to the quadrants along with an objective of minimizing the transportation cost of the materials.

3.1 GA based Optimization for SLP

The adoption of GA for layout optimization is evident in the existing literature. The algorithm follows the criteria 'survival of the fittest' of natural evolution. This study adopts the algorithm to optimize the cost function formulated in equation 1.

$$\text{Min} \sum_{L=1}^{5}\sum_{M=1}^{5}\sum_{Q=1}^{4} \mathbf{C}_{\mathbf{MQ}}\mathbf{D}_{\mathbf{LQ}}\mathbf{X}_{\mathbf{ML}} \qquad (1)$$

The objective function represents the transportation cost of materials from locations to the quadrants of the proposed main facility. The term C_{MQ} is the cost of transporting material (M) to quadrant (Q), D_{LQ} is the distance between the location (L) and the quadrant (Q) and X_{ML} represents the decision variable depicting the location of material 'M' at location 'L'. The decision variable is chosen as a Boolean variable, limiting its value to 0 or 1.

This research presents a case of constrained optimization where the above-mentioned cost function is minimized subjected to the constraints presented in equation 2 and 3.

$$\sum_{L=1}^{5} \mathbf{X}_{\mathbf{ML}} = 1 \qquad \text{Where, } \{M=1,2,\ldots 5\} \qquad (2)$$

$$\sum_{M=1}^{5} \mathbf{X}_{ML} = 1 \qquad \text{Where, } \{L=1,2,\ldots 5\} \qquad (3)$$

The formulated constraints represent a case of an equal area site layout problem [30]. Here the locations are assumed to accommodate any temporary facility for storing material, irrespective of the area requirement. The constraint in equation 2 limits the allocation of one material to only one location and in equation 3 the restriction is upon the location to accommodate only one material.

This case of constrained optimization is dealt utilizing GA, and MATLAB® is used for running the algorithm. GA requires encoding of the desired parameter, and in this research, the binary encoding is employed. The working of GA starts with initializing a population, followed by performing operations and once the stopping criteria are met, GA provides the optimal value of the fitness function.

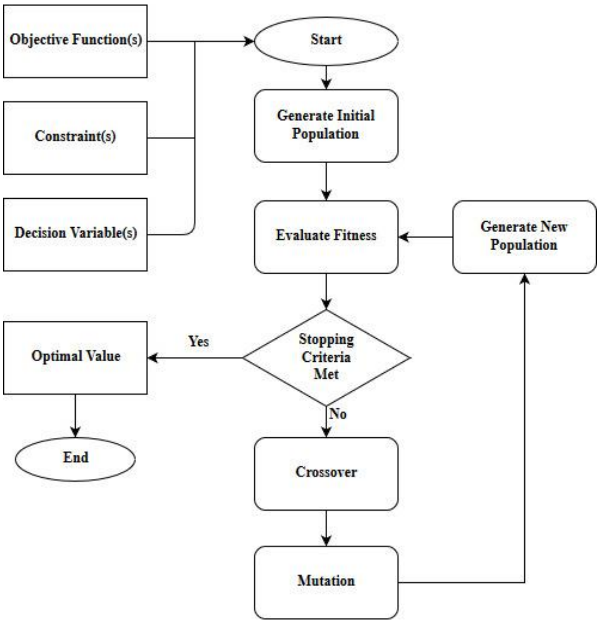


Figure 5. Adopted GA Flow Process

The results from GA are obtained at the parameter values [14] presented in Table 6. A minimum of ten trials are executed for every combination. The optimal results obtained from each combination are presented in Figure 6, Figure 7 and Figure 8.

Table 6. GA Parameters

Item	**Minimum**	**Intermediate**	**Maximum**
Initial Population	100	100	100
Crossover Rate	0.3	0.5	0.8
Mutation Rate	0.01	0.1	0.3

This study has not focused upon tuning up the GA parameters for achieving the optimal or the near-optimal results.

4 Results and Discussion

With the growing demand of BIM for AEC and being mandated on a number of construction projects, it could be anticipated that BIM models would exist for the projects in the near future. The present framework will mandate the creation of material flow paths in BIM models. The depiction of paths on the site model provided a clear view of the vehicular movement anticipated to happen on the modelled site. Whereas manoeuvring on the planned path is expected for safe site conditions, this exercise is expected to enhance safety on construction sites. The adoption of BIM has penetrated in the AEC industry for all phases of construction, but a few studies have highlighted its adoption for SLP. The present study details out the task of integrating BIM into the SLP process. The optimization model supplemented with realistic data of the site could result in better and realistic solutions.

The adoption of GA in this research is an outcome of the existing literature focused on evolutionary algorithm based SLP. The comparative analysis of GA with other evolutionary algorithms and some deterministic algorithms showed the suitability of GA for SLP. The results obtained from all three combinations of parameter set are presented in Figure 6, Figure 7 and Figure 8. The results show the variation in the convergence due to the parameter variation and in this study the ten trials with each parameter set provided an opportunity to understand the concept of near optimality.

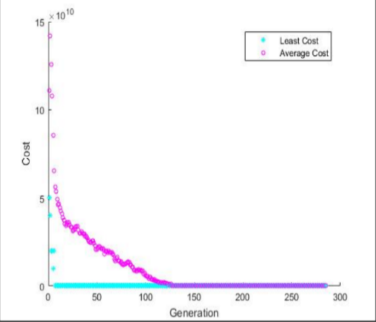
Parameter Value	**Convergence Plot**	**Achieved Optimal Value**
Initial Population = 100 Crossover Rate = 0.3 Mutation Rate = 0.01		**1,44,59,221**

Figure 6. Convergence Plot at Crossover=0.3 and Mutation=0.01

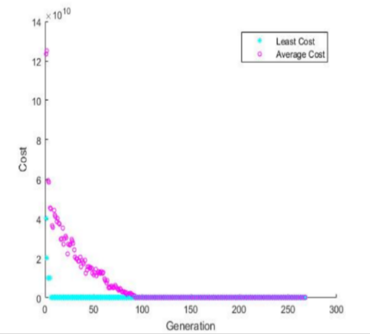
Parameter Value	**Convergence Plot**	**Achieved Optimal Value**
Initial Population = 100 Crossover Rate = 0.5 Mutation Rate = 0.1		**1,44,59,221**

Figure 7. Convergence Plot at Crossover=0.5 and Mutation=0.1

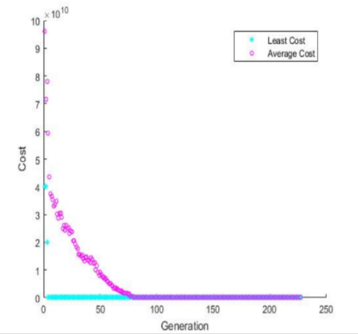
Parameter Value	**Convergence Plot**	**Achieved Optimal Value**
Initial Population = 100 Crossover Rate = 0.8 Mutation Rate = 0.3		**1,44,59,221**

Figure 8. Convergence Plot at Crossover=0.8 and Mutation=0.3

The observation of the convergence plot revealed the effect of the tuned GA parameters and the difference in the plots is easily identifiable. The crossover rate and the mutation rate in Figure 6 reveal the delayed convergence in comparison to other plots in Figure 7 and Figure 8. Whereas the plot in Figure 7 depicts the early convergence due to a high mutation and crossover in comparison to the mutation rate of 0.01 and crossover of 0.3, adopted as the minimum rate in this study. The convergence plot in Figure 8 also justifies the parameter values of GA by representing a mixed convergence i.e. uneven and early due to high crossover and mutation.

Ten trials with each combination allowed the researchers to verify no premature convergence of GA. The optimal value of cost resulted out to be 1,44,59,221 cost unit. The interpretation of the resulted GA output is presented in Table 7.

Table 7. GA Result Interpretation

Optimal Position	Interpretation	Achieved Optimal Cost Unit
$\begin{bmatrix} \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} \end{bmatrix}$	M_2 at L_1 M_1 at L_2 M_4 at L_3 M_3 at L_4 M_5 at L_5	1,44,59,221

5 Limitation and Future Scope

The study is focused to bring the realism of the construction site to the mathematical approach for SLP. Close integration of BIM with mathematical optimization for the purpose of layout planning has been presented. The study is still under process and is supposed to bring more complexities to the formulation by including multi-objectives and constraints to be solved. The case of discrete layout can also be made continuous. A comparative study of Euclidean distances and the actual travel paths will also add to the understanding and will bring up the necessity of the presented approach. The parameter value optimization presented here is in brief, and further study may include adaptive parameters for GA. Simulation integrated optimization based studies are also expected to help the planners for SLP in an efficient way.

6 Conclusion

There have been attempts to make the process of SLP efficient. The past research optimization routines have received limited adoption in the AEC industry and this research highlights some of the inhibitors to the adoption. This study is an attempt to supplement the existing models with the realism of the construction site. It has been found that the technological advancements like BIM have the potential to promote the existing models by bringing actuality of the site to the mathematical models. In an attempt to do so, the researchers here have modelled a mathematical optimization problem and have presented a framework to integrate it with the available BIM tools. The interaction of the tools resulted in an optimal solution to the formulated problem of transportation on a construction site. The study presented the applicability of GA with this new approach of capturing site realism and thus have strengthened the existing literature of SLP on the other hand.

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