Post simulation visualization model for effective scheduling of modular building construction

Mansooreh Moghadam, Mohamed Al-Hussein, Saad Al-Jibouri, and Avi Telyas

Abstract: The factory-based modular construction process has proven to increase the speed of construction, and improve quality and safety, while providing value to the customer and a rapid return on investment to the builder and owner. However, onsite module assembly creates new schedule demands, as activities are scheduled on a minute-by-minute basis; therefore simulation of the process becomes essential at early stages of a project. Although simulation proves to be an effective tool for project engineers to assess complex construction operations, it remains a symbolic base model with no visual link to the actual physical shape and look of the project’s activities. This paper presents the application of integrated simulation and post simulation visualization as a tool to assist the modular construction industry in scheduling onsite installation of prefabricated modules. The proposed methodology uses simulation model output as an ASCII file in a binary format and imports this ASCII file to 3D Studio Max to perform the animation. The output from the high level simulation model is transformed into frames/second in 3D Studio Max. The proposed methodology was tested on the planned construction of a 34-storey building in Brooklyn, New York, USA. Simulation visualization of the process proved to be effective in communicating the value and simplicity of a minute-by-minute schedule. Based on the output information, the most efficient solutions were generated. The use of post simulation visualization was effective in analyzing the construction methods of the case study which consisted of 950 structural steel modules. Issues related to construction activities’ productivity were synchronized to achieve onsite installation of the project in only 56 working days.

Key words: simulation, visualization, modular building, schedule.

Résumé : Il a été démontré que le procédé de construction modulaire en usine augmente la vitesse de construction et améliore la qualité et la sécurité tout en fournissant une valeur au client ainsi qu’un rapide retour sur l’investissement pour le constructeur et le propriétaire. Toutefois, l’assemblage des modules sur place engendre de nouvelles demandes sur l’échéancier puisque certaines activités sont programmées à la minute; la simulation d’un tel procédé devient donc essentielle aux premières étapes d’un projet. Bien que la simulation s’avère un outil efficace pour les ingénieurs de projet pour évaluer les opérations complexes de construction, elle demeure un modèle de base symbolique sans lien visuel avec la forme physique réelle et l’apparence des activités d’un projet. Le présent article montre l’application de la simulation intégrée et de la visualisation post-simulation comme outil pour aider l’industrie de la construction modulaire à programmer sur le site l’installation de modules préfabriqués. La méthodologie proposée utilise les résultats d’un modèle de simulation comme un dossier ASCII en format binaire et importe ce dossier ASCII dans 3D Studio Max pour réaliser l’animation. Les résultats de ce modèle de simulation avancé est transformé en images par seconde grâce à 3D Studio Max. La méthodologie proposée a été mise à l’œuvre sur la construction planifiée d’un bâtiment de 34 étages à Brooklyn, New York, É.-U. La visualisation de la simulation du procédé s’est avérée efficace pour communiquer la valeur et la simplicité d’un échéancier minute par minute. Les solutions les plus efficaces ont été générées en se basant sur l’information obtenue des résultats. L’utilisation de la visualisation post-simulation était efficace pour analyser les méthodes de construction de l’étude de cas, lequel comportait 950 modules structuraux en acier. Les enjeux liés à la productivité des activités de construction ont été synchronisés afin de compléter l’installation sur le site du projet en seulement 56 jours de travail.

Mots-clés : simulation, visualisation, bâtiment modulaire, échéancier.

[Traduit par la Rédaction]

1. Introduction

Modular buildings are built through a more efficient and cost-effective engineering method that can deliver market requirements for increased construction speed, improved quality, and rapid return of investment. Furthermore, there is a...
noticeable motivation for owners and developers to use modular building in affordable housing where speed of construction is related to the economy of production scale. Hence there is a significant need to evaluate the planning process from factory fabrication to construction and erection phases involving crane operation. There is a significant amount of research for optimizing mobile crane selection (Al-Hussein et al. 2005; Wu et al. 2011) and mobile crane operation that leads to modular building field operation optimization (Ole-arczyk et al. 2009; Hasan et al. 2010; Hermann et al. 2010). However, little research has been conducted in the area of tower crane utilization, which is required in complex construction projects to lift modules in high-rise modular buildings (Tam et al. 2001; Hasan and Al-Hussein 2010; Huang et al. 2011).

In general, once the construction stage of a modular building has started, changes to the design and construction plan are costly. Existing planning and scheduling tools are designed to support mainly the current practice of onsite stick-built construction, without considering modular building’s specific needs. The application of such practice for modular building could jeopardize a successful project outcome due to the lack of a detailed construction process evaluation system. For modular construction, it is essential to create a realistic simulation model to evaluate construction sequences during the planning phase and control the installation process onsite. Compared with typical construction projects, modular buildings are characterized by repetitive processes that require complex analysis. Additionally, the need to incorporate diverse information that is required to evaluate the design, cost, schedule, resources, quality, and safety complicates the procedure even further. This work proposes modeling using simulation to help analyse the process and reveal possible conflicts and errors for complicated processes.

Simulation is a computer-based tool that models, in scaled format, a real life system or process and facilitates the examination and evaluation of different scenarios to choose the best possible option. Before the introduction of CYCLONE (CYCLic Operation NEtworks) by Halpin in 1973, simulation was not common in construction (Huang and Halpin 1994). CYCLONE uses graphical representations to model various tasks in the construction process. The tool’s output typically consists of charts and diagrams. Simulation was limited to research applications before AbouRizk and Hajjar (1998) presented a framework that customized simulation for industry. They used Special Purpose Simulation (SPS) as a tool to build systems for specific purposes. Later they improved their approach and developed a construction simulation system called Simphony, which provides a set of predefined elements representing construction requirements (Hajjar and AbouRizk 2002). Specifically in the area of modular building, extensive research has been done to simulate construction operations. Mohsen et al. (2008) used Simphony to create a simulation model that analyses the construction process and predicts productivity and project duration. The model analysed scenarios and considered possible errors, which was effective in crane and crew utilization as well as preventing delays. Hasan et al. (2010) simulated the operation of a tower crane using an integrated dynamic modeling system and lean concepts. The result proved that the model provides schedule satisfaction, reduces required resources, and decreases the construction cost.

Although simulation tools are considered to be efficient in evaluating construction processes, the project management team often views them as a “black box” that can only be understood by a highly skilled manager. The gap between the specialist and management team leads to misunderstanding regarding simulation results and may result in incorrect interpretations (Al-Hussein et al. 2006). The project management team is unwilling to make decisions based on current simulation outputs, and statistically based charts and diagrams, because they do not provide adequate information related to construction process requirements (Kamat and Martinez 2000). Visualization is a more popular construction technique since it fosters better understanding of the construction process and performance. However, to be effective for decision making purposes, such a model is required to be linked to project information. As such, Kamat and Martinez (2001) developed a general purpose 3D text file driven visualization system named dynamic construction visualizer (DCV) that allows visualization of construction operations and enables construction planners to obtain more realistic feedback from simulation analysis. Huang et al. (2007) and Li et al. (2008) created a construction virtual prototyping (CVP) system that integrates visualization and simulation. The system can generate and modify 3D models of building components, construction equipment and labour, and temporary works. Although collecting input data for this VP system is a time consuming process, it allows project teams to check constructability through visualized 3D models of projects. Li et al. (2009) used VP to optimize construction planning schedules by analyzing resource allocation and planning with integrated construction models, resource models, construction planning schedules and site-layout plans. Staub-French et al. (2008) described a two-way relationship between 3D CAD software and software implementation of linear planning and described the consistency of product representation in CAD and scheduling models. They improved project scheduling by modifying construction sequences through a 4D CAD model and validated the project completeness by connecting the model to 3D objects and activities.

In a different manner, Golparvar-Fard and Peña-Mora (2007); Golparvar-Fard et al. (2009a, 2009b); and Kamat et al. (2011) developed visualization of construction sites via the four-dimensional (4D) geometric model. They developed an automated vision-based approach that monitors as-built progress and compares it to the as-planned construction progress. The system matches as-planned and as-built views with a selection of features where the as-built photographs are enhanced and augmented with the 4D as-planned model.

The objective of this paper is to introduce an integrated method referred to as a post simulation visualization (PSV) model for modular building construction with emphasis on schedule efficiency. The proposed PSV model is developed using the advantages of both simulation and visualization, where critical information such as the 3D model, time constraints, and resource demand are incorporated into the system. The proposed model has been tested on the modular construction of a 34-storey building that is planned to be constructed in Brooklyn, N.Y., USA.
2. Proposed PSV methodology

The proposed methodology follows the concept represented in Fig. 1. The purpose of the model is to integrate visualization with project information to create a simulation of project operations. Input data including project management requirements and specifications; activities’ logic and duration; and resource demands, which consist of equipment, material, and labour, are all collected in the first step. The main part of the system is focused on linking the information. The process performs satisfying the project criteria and limitations, including modules’ specifications such as weight and size; crane capacity for lifting purposes; trailer and transportation limits from storage area to lifting zone; deadlines and time constraints; structural constraints, such as the location of shear walls and stairs; law and regulations; and targeted cost.

The main process begins with the creation of a project information database. The activities are then put together in a defined sequence and duration to create the project schedule. Resources, such as material, equipment, and labour, required by individual activities are added to the database. The information gained from the above steps is used to create a simulation model in Simphony.Net 3.5© environment. The simulation output in the form of an ASCII file, a binary text file imported from Simphony, is then linked to 3D animation semi-automatically. Within the 3D animation environment (3D Studio Max) the high level simulation model is transformed to a micro level representation in frames/second. To develop the PSV model, 3D Studio Max’s scripting language, MaxScripts, is used. As inputs of the PSV model, two sources are required: the 3D model library of PSV and the simulation model output that stores the spatial configuration of the construction process along with performance time. The PSV model imports 3D models from the 3D library including models of the tower crane, modules, resources, and the 3D site, and assembles them in 3D Studio Max. Then the 3D animation engine uses the data from the simulation output file to create the key frames. The model’s output is a measurement of the productivity of labour and the main equipment such as crane, project schedule analysis, safety and quality control, and evaluation of potential scenarios for the construction operations.

3. Post simulation visualization (PSV) implementation

The proposed PSV model depicts the simulation of the construction process in detail, producing and displaying project information such as schedule and production rate simultaneously for evaluation purposes, whereas the proposed system has the capacity to be linked to all possible project information. The model needs to be flexible to deal with changes in project scope and to present a complex construction process in a simple way. The proposed PSV model has been tested on a construction plan for a challenging 34-storey modular project. The prospective project is to be constructed in Brooklyn, N.Y., USA and will be the highest modular building ever built. Visualization of the simulated process proved to be an effective tool in communicating the value and simplicity of the minute-by-minute schedule. The simulation result comparison between the initial model before applying PSV and the final version after running PSV several times, indicated significant improvements in the construction schedule, productivity, levelling of resources, and reductions in idle time. Furthermore, a comparison was conducted between various construction scenarios. Moreover, the project management team confirmed the considerable impact of the PSV model on decreasing the activities’ duration, eliminating errors and reworks, and identifying the best potential construction scenarios using visualization of the simulated project during the planning phase.

Figure 2 shows a snapshot from the model’s output for the case study that presents the module lifting process. The shuttle truck transports the modules from the storage area to the lifting zone and the crane lifts the modules to place them in their final locations. The schedule runs at the same window to display the most probable duration of each task. The schedule was produced using the critical path method (CPM) technique then a simulation model was created to evaluate the CPM and program evaluation and review technique (PERT) schedule based on predetermined optimistic, pessimistic, and most likely project durations. Clocks on the left hand side of the snapshot present the duration of critical equipment including trucks and the crane, and critical crews, including erection and welding. These clocks track working time, work flow, and idleness duration for each aforementioned instance separately and provide an evaluation for productivity analysis.

This research contributed to (1) assigning production tracking clocks to each critical resource (crane, truck, hooking crew, scaffolding crew, welders, alignment crew, and erection crew) as sampled in Fig. 2; and (2) changing the concept of construction planning to match the factory requirements. The work moves to the location where the station is assigned to each worker crew (for example, the erection crew stays on the platform waiting for the crane, while the crane operator waits for the truck which is transporting the module, then the crew hooks the module to the crane which lifts the module and moves it to the installation zone). Similarly, stations are assigned to the alignment crew, welding crew, and capping exterior finishing crew and work comes to their stations. Scheduling for the time, space, and movement of the workers is not possible without utilization of lean, simulation, and visualization.

4. Case study

Affordable housing has been a long sought after, yet seldom realized, goal. The very subsidy designed to assist moderate income renters accelerates housing inflation, and reduces affordability across every income range, and thus the elusive goal remains unmet. In an attempt to create affordable housing, in effect, to increase the supply of housing stock in one of the world’s costliest markets, the development team leading the Atlantic Yards Project of Forest City Ratner aimed to identify innovation which could affect the supply of affordable housing. The team realized that incremental improvement would not suffice and that a substantial re-arrangement of the status quo was necessary. Upon an intensive review of key cost drivers and a search for alternative construction methods, Kullman Buildings Corp. (KBC), a leader in industrialized construction, was selected to study the technical and...
**Fig. 1.** Proposed methodology of post simulation visualization model.

**Fig. 2.** Output of PSV model on the case study presenting module lifting operation.
economic feasibility of fabricating the building at its factory. Tall modular buildings have been built as high as 24-Storeys in Europe to great success, but few have been erected in North America, and certainly none at the proposed height. Kullman assembled a world-class team of designers, researchers and structural engineers, including a research team from the University of Alberta, to explore this mandate and prove its technical and economical viability. As noted, the stated mandate is quite ambitious in budget and scope. A 34-storey tower to be built entirely of prefabricated modules has never been accomplished anywhere in the world. Ultimately, a workable design solution to this challenge was selected that relied on a factory production line to produce 950 modules requiring very little field work other than assembly onsite. Adopting such a solution, the project would take less than a year to complete and save substantial cost. The 34-storey modular tower can be assembled, lifted into position, stacked and connected, and built in such a short duration only by tracking the time, resource, and equipment utilization in detail. The PSV model provides a visualized minute-by-minute schedule including a separate production clock for all the resources that are automated and can be updated for each simulation run.

This project faced a number of challenges due to its location in one of the busiest streets of Brooklyn, N.Y., USA, and its budget and time of construction which are cut to half. The trucks are expected to deliver the modules from the factory to the storage area near the construction site and from the storage area to the lifting area onsite where the tower crane is planned to lift two modules per hour. To succeed in this plan, a pull schedule was utilized which added to the challenges of resource utilization in the supply chain. Another challenge arose after adding the scaffolding activities to the project schedule which increased the duration of installing 950 modules to 83 working days from 56 working days. However, changes to the process eventually reduced the overall time required for the project completion. The sequence of activities, including module delivery by trucks and lifting by crane; lifting of modules, shear walls, and scaffolding intermittently; and arrangement of module sequence based on floor layout, created a dynamic schedule which was added to the long list of challenges in this project.

4.1. Building simulation model

To simulate the construction operation, a model was developed in the Simphony.Net 3.5 © environment as shown in Fig. 3. The main focus of creating the simulation model was crane activity, which is the most critical and schedule-driven task in modular building. In this model, crane activity was divided into proper work packages to create a non-stop work flow and efficient crane utilization. The simulation helped identify potential errors in the field operation and revealed possible conflicts. Also, the effect of different module installation sequence scenarios was analysed by the simulation model. The visualized model provided different scenarios, for which the simulation model calculated the corresponding impact on the total project duration through defining priority criteria. Once a module is chosen to be assembled, it captures the resources and obtains a higher priority. Therefore, the priority is defined as a function of the modules’ position in the specific scenario. The priority for the module in the queue and for the module in progress (the module that has already been captured by the crane) is calculated satisfying eq. [1] and eq. [2], respectively (Mohamed et al. 2007).

\[ P = F + \text{abs} \left( \min \left( F \right) \right) \]

\[ P = (\text{ES} - \text{TD}) + \max (P) \]

where \( P \) is the module priority; \( F \) is the free float for the module \( \text{PS} = \text{ES} - D \); \( \text{PS} \) is the planned ship date; \( \text{ES} \) is the early start date; \( D \) is the duration; and \( \text{TD} \) is today date.

The simulation model output was total project duration. Considering the probable duration distribution for each individual task enables the evaluation of project duration and level of confidence. The Simphony model output showed that the project could be finished in 26,616.57 working minutes (56 eight hour working days) with 95% confidence. The project duration result from the simulation model is shown in Table 1. The optimistic, pessimistic, and most likely duration for each task were estimated taking into account the resource operation (mainly crane working hours). Task durations were determined based on the crane manufacturer’s specifications to determine speed of operation and past similar operation experiences (please see Olearczyk 2010). The probability density function (PDF) and cumulative density function (CDF) charts for the model, as shown in Fig. 4, present the project duration distribution and level of confidence. The PDF chart describes the likelihood for the project duration, while the CDF presents the probability that the project duration at each point has that value or less. This result is used to evaluate and aid the decision maker in arriving at a near optimum solution with reference to an optimization model of the tower crane location (which is outside of this paper’s scope). The optimization model evaluated the technically feasible location of the tower crane and found the shortest total travel distance for all the modules from the picking and lifting location to the un-lifting point. Table 2 summarizes the total project duration statistics. This minimum travel distance was synchronized in 8-hour working days and onsite installation of the whole project was achieved in only 56 working days which is the minimum total project duration among all technically feasible solutions.

4.2. Schedule and resource allocation

Module onsite installation requires a detailed construction schedule. A breakdown of activities and required crews, as well as a complete lifting and assembly schedule for all modules was created. This analysis is based on the installation of 950 structural steel modules for a 34-storey building. The simulation model showed that, on average, 16 modules per day could be installed from floors 2 to 20, 15 modules per day from floors 21 to 29, and 14 modules per day for the remaining floors. This analysis showed that the bottleneck activity is the welding and bolting of modules at their final location. Outputs from the PSV model indicated that module erection is a function of crane capacity and utilization rate, and that typically 12 ft × 30 ft (3.6 m × 9 m) modules can be erected at a rate of 2 per hour or 16 modules per day. Setting crews would have 8 h per day to bolt the modules to each other. Mate-line connections include internally tying up...
each module electrically and mechanically to the building services as well as installing drywall in the mating areas. If a 4-person crew is assigned to finish a module per day, then completing 16 modules a day requires 16 crews, or 64 people working for approximately 3 months to finish the project as shown in Table 3. A typical schedule for onsite module installation is shown in Table 4.

The installation sequence per module was broken down into 16 tasks, making use of 8 construction crews. Based on the analysis of the model output, it was noticed that to keep the installation sequence flowing, a minimum of two trailers are required onsite (loaded with ready modules) and (in the staging area) the delivered modules must be moved to the lifting zone. Critical modules (modules next to shear walls,
where \( W \) is the module wrapping time; \( U \) is the module unwrapping time; and \( S_b \) is the spreader bars removal time.

To reduce the tower crane idle time, unwrapping and welding operations need to be considered satisfying eqs. [4] and [5]

\[
\begin{align*}
U &> SL + Uh + Sb \\
Wd &> H + Cr + U + Sb
\end{align*}
\]

where \( SL \) is the securing and lining time and \( Uh \) is the unhooking time.

Table 2. Summary statistics for project total duration.

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Minimum</th>
<th>Mean</th>
<th>Std Dev</th>
<th>Variance</th>
<th>Skewness</th>
<th>Kurtosis</th>
<th>Median</th>
<th>Left X</th>
<th>Left P</th>
<th>Left X</th>
<th>Right X</th>
<th>Right P</th>
<th>Diff X</th>
<th>Chi-Sq</th>
<th>Regr</th>
<th># Error</th>
<th>Run time</th>
<th>Simulation duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24925.1514</td>
<td>26064.1424</td>
<td>334.4575819</td>
<td>111861.8741</td>
<td>0.01127267</td>
<td>3.094436921</td>
<td>26063.79792</td>
<td>26102.30269</td>
<td>5%</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>25%</td>
<td>30%</td>
<td>35%</td>
<td>40%</td>
<td>45%</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>27189.018111</td>
<td>26064.1424</td>
<td>334.4575819</td>
<td>111861.8741</td>
<td>0.01127267</td>
<td>3.094436921</td>
<td>26063.79792</td>
<td>26102.30269</td>
<td>5%</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>25%</td>
<td>30%</td>
<td>35%</td>
<td>40%</td>
<td>45%</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>25511.75792</td>
<td>26064.1424</td>
<td>334.4575819</td>
<td>111861.8741</td>
<td>0.01127267</td>
<td>3.094436921</td>
<td>26063.79792</td>
<td>26102.30269</td>
<td>5%</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>25%</td>
<td>30%</td>
<td>35%</td>
<td>40%</td>
<td>45%</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>25511.75792</td>
<td>26064.1424</td>
<td>334.4575819</td>
<td>111861.8741</td>
<td>0.01127267</td>
<td>3.094436921</td>
<td>26063.79792</td>
<td>26102.30269</td>
<td>5%</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>25%</td>
<td>30%</td>
<td>35%</td>
<td>40%</td>
<td>45%</td>
<td>50%</td>
</tr>
</tbody>
</table>

Table 3. Mate-line crew specification.

<table>
<thead>
<tr>
<th>Crew size</th>
<th>4.0 Persons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crew capacity</td>
<td>1.0 modules/day</td>
</tr>
<tr>
<td>Crew needed</td>
<td>16.0 Crews</td>
</tr>
<tr>
<td>Persons needed</td>
<td>64.0 Persons</td>
</tr>
<tr>
<td>Weeks needed</td>
<td>11.8 Weeks</td>
</tr>
</tbody>
</table>

The developed PSV model is capable of producing a variety of outputs for analysis purposes. For instance, options for connecting modules in the lower floor with one in the upper floor were tested. Based on the evaluation of the PSV model, the best option was an oversized pop-rivet as shown in Fig. 5a. Its installation is expected to be smooth and fast with two workers making the connections. Essentially, the corners of four modules are brought together and a plate is installed with 8 rivets. The rivets can also be used for lifting purposes. To increase project productivity, the use of scaffolding was suggested to reduce total project duration and labour idle time. As shown in Fig. 5b, scaffolding is attached to the module to provide workers with access to the module’s façade. As the next module is lifted, the work on the prior module is finished and the scaffolding is carried by the crane to the next module. Safety was controlled through using the PSV model for the entire construction operation. For example, as shown in Fig. 5c, the use of a ladder was not safe enough for labourers to hook or un-hook modules. Therefore, a replacement system was suggested and tested. As shown through the model, the system also increased labour working speed.

Experts conducted scenario-based analysis through meetings with different trades to evaluate potential scenarios. For instance, for hooking and unhooking modules, several scenarios were proposed and investigated based on criteria such as equipment efficiency and activity duration. The experts, including the erection crew and management at Kullman, accepted the rivet (Fig. 5a) as the most effective option. Although this tool is made at an extra cost, it is still a more cost effective option compared to the other scenarios. The proposed result for the on-site construction process was reviewed and validated by the team involved in on-site work and the project management team. All changes to the construction

Published by NRC Research Press
process were incorporated into the developed model. As a result, the final analysis, including the proposed schedule, process evaluation, and resource allocation, was documented by Kullman’s team and formed the basis of the construction for the project. It is important to mention that this project is on-hold due to legal challenges between developers and other parties.

5. Conclusion

There is a noticeable motivation for owners and developers to use modular building in affordable housing, where speed of construction is related to economy of production scale. Hence there is a significant need to evaluate the planning process of modular construction from factory fabrication to
construction and erection phases. In this paper, modeling using simulation supported by visualization was proposed to analyze the process and reveal possible conflicts and errors. An integrated method, referred to here as a post-simulation visualization (PSV) model for modular building construction, was introduced. The proposed PSV model is developed as a technique using the advantages of both simulation and visualization. The model was tested on the construction of a prospective 34-storey modular building to be constructed in New York. Visualization of the simulated process proved to be an effective tool in communicating the value and simplicity of a minute-by-minute schedule. The focus of this project was improving the construction schedule and productivity, leveling resources, decreasing idleness time, and comparing various construction scenarios by applying the PSV model during the project planning phase. Issues related to productivity of construction activities were synchronized to achieve onsite installation of the whole project in only 56 working days.

Acknowledgements

The authors are sincerely grateful to Kullman Buildings Corporation for providing required data for this research. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of teams involved in the Atlantic Yards Project.

References


Published by NRC Research Press