ICCEPM 2022
The 9th International Conference on Construction Engineering and Project Management
Jun. 20-23, 2022, Las Vegas, NV, USA

Analysis of a Long Volumetric Module Lift Using Single and Multiple Cranes

Ali Khodabandelu[1]*, JeeWoong Park[2], Jin Ouk Choi[3], Mahsa Sanei[4]

[1]*Department of Civil and Environmental Engineering and Construction, University of Nevada, Las Vegas, 4505 S. Maryland Pkwy. Las Vegas, NV 89154, USA,* E-mail address: khodaban@unlv.nevada.edu
[2]*Department of Civil and Environmental Engineering and Construction, University of Nevada, Las Vegas, 4505 S. Maryland Pkwy. Las Vegas, NV 89154, USA,* E-mail address: jee.park@unlv.edu
[3]*Department of Civil and Environmental Engineering and Construction, University of Nevada, Las Vegas, 4505 S. Maryland Pkwy. Las Vegas, NV 89154, USA,* E-mail address: jinouk.choi@unlv.edu
[4]*School of Civil Engineering, College of Engineering, University of Tehran, 16th Azar St., P.O. Box: 14155-6619. Tehran, Iran,* E-mail address: mahsa.sanei@ut.ac.ir

Abstract: Industrialized and modular construction is a growing construction technique that can transfer a large portion of the construction process to off-site fabrication yards. This method of construction often involves the fabrication, pre-assembly, and transportation of massive and long volumetric modules. The module weight keeps increasing as the modules become more complete (with infill) to minimize the work at the site and, as higher productivity can be achieved at the fabrication shop. Thus, a volumetric module delivery gets more challenging and risky. Despite its importance, past research paid relatively insufficient attention to the problem related to the lifting of heavy modules. This can be a complex and time-consuming problem with multiple lifting for transportation-and-installation operations both in fabrication yard and jobsite, and require complex crane operations (sometimes, more than one crane) due to crane load capacity and load balance/stability. This study investigates this problem by focusing on the structural perspective of lifting such long volumetric modules through simulation studies. Various scenarios of lifting a weighty module from the top using four lifting cables attached to crane hooks (either a single crane or double crane) are simulated in SAP software. The simulations account for various factors pertaining to structural indices, e.g., bending stress and deflection, to identify a proper method of module lifting from a structural point of view. The method can identify differences in structural indices allowing identification of structural efficiency and safety levels during lifting, which further allows the selection of the number of cranes and location of lifting points.

Key words: crane, modularization, industrialized construction, lift, off-site construction

1. INTRODUCTION

As a relatively new construction method, modularization has recently experienced significant growth [1]. This construction method involves transferring some portion of on-site work to off-site fabrication shops [2]. The level of prefabrication can vary from small portions to significant amounts depending upon the project type, size, location, logistics, distance from fabrication shops, and many other factors [3]. Modularization has been recognized as a construction technique with a variety of benefits [4]. Raised accuracy in construction of building's elements, improved laborers' safety, accelerated construction process, and enhanced productivity are all among the benefits that modularization can bring [4].

Despite all the benefits, off-site construction deals with a number of barriers, most of which result from heavyweight and large dimensions of prefabricated volumetric modules [5]. Problems related to lifting, transportation, and installation of modules are among the main issues associated with the size and weight of modules [5]. Such problems include finding the optimum route from fabrication shops to a construction site [6], selecting appropriate pieces of equipment to carry modules [7], scheduling the delivery process [8], optimizing crane locations for the lifting process [9], and optimizing crane paths [10]. Although past research has found acceptable solutions for these problems, there is still a significant gap in research exploring the heavy volumetric modules' delivery process from a structural perspective.

From a structural point of view, modules undergo high-stress levels during the delivery task [6]. Such stresses are significantly higher than those applied to modules during the service and operation periods [6]. The stresses may reach their maximum limits during the lifting process [11]. Lifting is the most critical step throughout the entire module delivery task, in which modules are transferred from jobsite to transporting vehicles and from vehicles to a construction site. An improper handling method may result in structural damages to modules such as developed cracks and loosened connections, and further negatively affect the serviceability of modules after installation [6]. In addition, due to the high-stress levels, excessive geometrical deviations may occur in modules during the lifting process [12]. Geometrical deviations are one of the results of structural deflections that emerge in modules under high-stress levels [6]. Such deviations may lead to increased gaps or clashes between modules along with vertical and/or horizontal out-of-alignment effects on modules during or after installation [6].

Therefore, to avoid or mitigate the destructive structural impacts on volumetric modules, it is imperative to plan for their lift. Cranes are one of the most important pieces of equipment for any heavy lift, either on construction sites or fabrication yards [13], [14]. Sometimes due to the extremely large size of modules and sometimes due to unavailability of a proper heavy crane, instead of one heavy crane, multiple cranes of smaller sizes are deployed to implement the lift [15]. In either of the cases, the stresses and deflections imposed on modules are different and must be analyzed meticulously. In addition, the connection of cranes to modules through inclined cables, their position, along with the type of attachment, is another important factor in any heavy lift. Despite this importance, there is limited research that investigates the lifting process of long volumetric modules structurally.

To overcome the limitations of past research in the areas of industrialized and modular construction, the present research investigates the impacts of the lifting process on heavy volumetric modules in terms of critical structural indices. The present study is an extension of a recently published work by the same authors, in which the lifting process of heavy volumetric modules with unevenly-distributed weight was studied [11]. In the present study, the authors intend to compare the usage of one crane with multiple cranes in terms of the emerged forces and deflections and explore the optimum lifting strategy in either of the cases with respect to the position of lifting points.

2. RESEARCH OBJECTIVES

This research aims to investigate a safe and efficient strategy, from a structural standpoint, for lifting long volumetric modules. The optimum lift strategy is determined based on two critical structural indices, i.e., maximum bending stress and maximum deflection. The study generates and tests various lifting scenarios using SAP software and measures the mentioned indices to find the optimum lifting scenario with minimal structurally-destructive impacts on the lifted volumetric module. The core objectives of this study are to: 1) compare the usage of a single crane against double cranes in terms of lessening maximum stress and deflection on the under-lift module; and 2) explore the impact of the position of lifting points on the two mentioned structural indices.

3. METHODOLOGY

This study introduces a method to find the optimum lift strategy in the lifting process of long volumetric modules. The developed method in this research is generically applicable to almost every heavy lift task. The method consists of the following steps:

3.1. Modeling module

This step uses SAP software to structurally model any desired module. Throughout this paper, a long volumetric module, with the following features, is taken as a case study:

Length: 60' (18.28 m)

Width: 13' 8.25" (4.17 m)

Height: 11' 5" (3.48 m)

Weight: 23,712 pounds (11.86 tons)

The dimension and the weight are adopted from an actual modular project that was executed recently in Las Vegas, NV. It is assumed that the weight is distributed uniformly over the entire module. Figure 1 presents the case study module modeled in SAP.

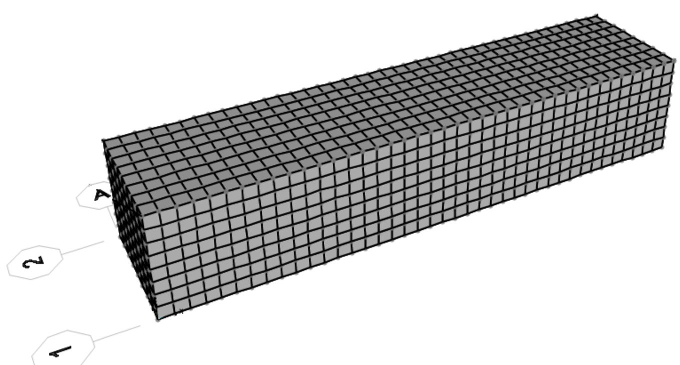
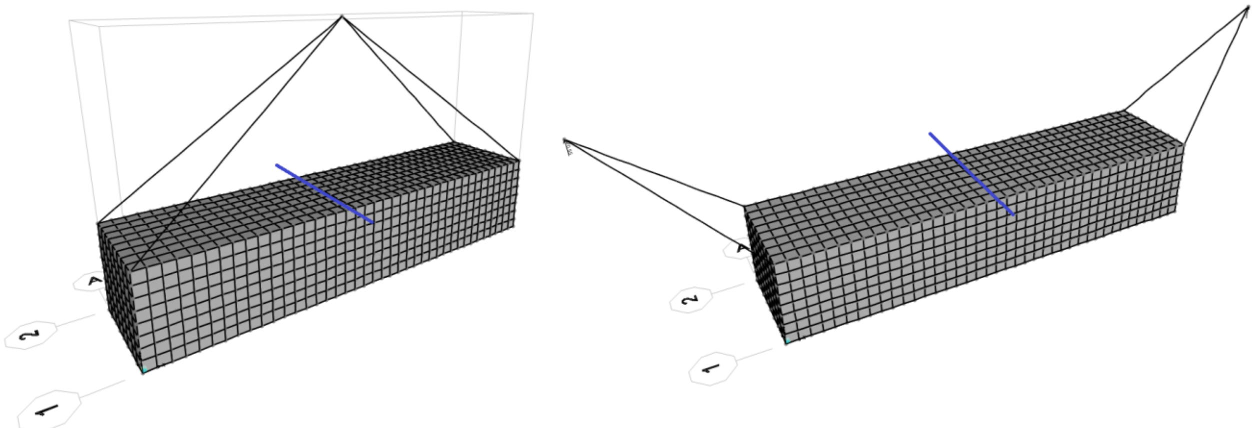


Figure 1. Case study module modeled in SAP

3.2. Simulating scenarios

This section presents the various module lift scenarios simulated in SAP. The lift of long volumetric modules can be conducted using one or multiple cranes. In an event of unavailable heavy cranes, the use of multiple smaller-sized cranes is the only feasible option for heavy lifting. In other situations of normal lifting, using a single heavy crane or a combination of smaller cranes is a matter of the management plan. Figure 2 represents the comparison between the deployment of a single heavy crane and two smaller cranes to lift the described module. Figure 2(a) depicts the module lift using a single crane, while Figure 2(b) shows the lift utilizing two cranes, both modeled in SAP.



(a) Module lift deploying one crane (b) Module lift deploying two cranes

Figure 2. Comparison of module lift deploying one crane against two cranes modeled in SAP

In addition to the number of cranes deployed for the implementation of a lifting task, the form of connection between the module and cranes through inclined cables is another matter of the lifting plan. The number of cables, type of attachment between the cables and the module, the position of cables with respect to the module, and the slopes of cables are among the parameters affecting the level of stresses and deflections that emerged in a module over the course of lift operation. Among all the parameters, this study examines the position of cables with respect to the module as one of the most critical factors affecting lift operation [6], [11]. For either of the cases shown in Figure 2, multiple scenarios are tested. In all scenarios, four lifting cables are positioned symmetrically with respect to the centroidal axis depicted with a blue color as shown in Figure 2.

In the first scenario, as represented in Figure 2a and 2b (representing one crane and double crane cases), the lifting cables are positioned at the four corners of the module. In the subsequent scenario, the four lifting cables move one foot inward (per each subsequent scenario) towards the centroidal axis along the two top edges of the module and so forth. The positioning of lifting cables with a one-foot inward increment pattern leads to the generation of 20 scenarios for each of the cases. Note that the following assumptions have also been made in all the simulations in this study:

1) The module is carried from its top via inclined cables.
2) The inclined cables are attached to the module via the hooks accommodated in the module's framework in advance. Note that no auxiliary beam, frame, or cage is used.
3) In each scenario, three different slopes (30, 45, and 60 degrees with respect to the horizontal axis) for inclined cables are tested to obtain the most critical structural outputs.

3.3. Analyzing structural indices

Structural simulations are executed for all scenarios. Figure 3 and Figure 4, associated respectively with single crane deployment and double crane deployment, present a few scenarios, as instances, after running simulations in SAP. In Figures 3 and 4, different colors represent different levels of stress that emerged on the module.

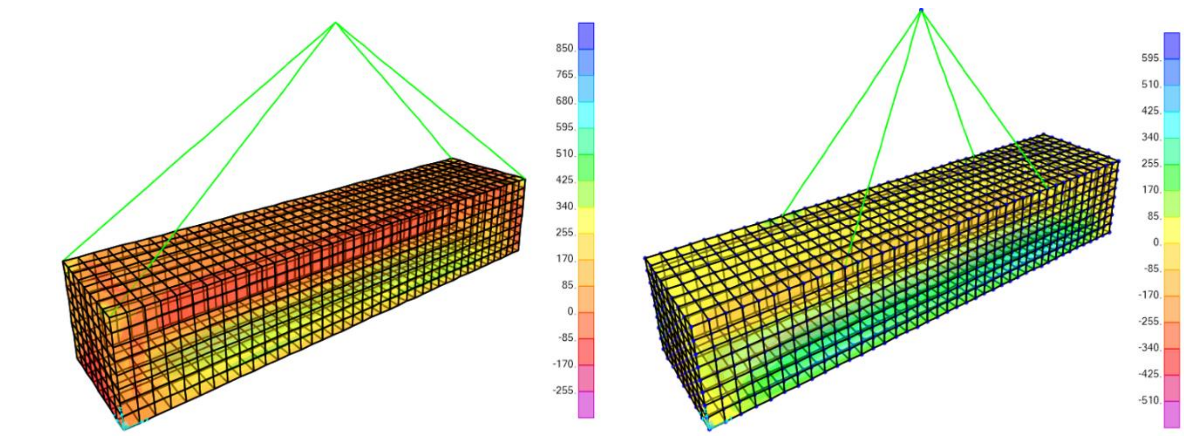


Figure 3. Examples of SAP visual output for one crane deployment

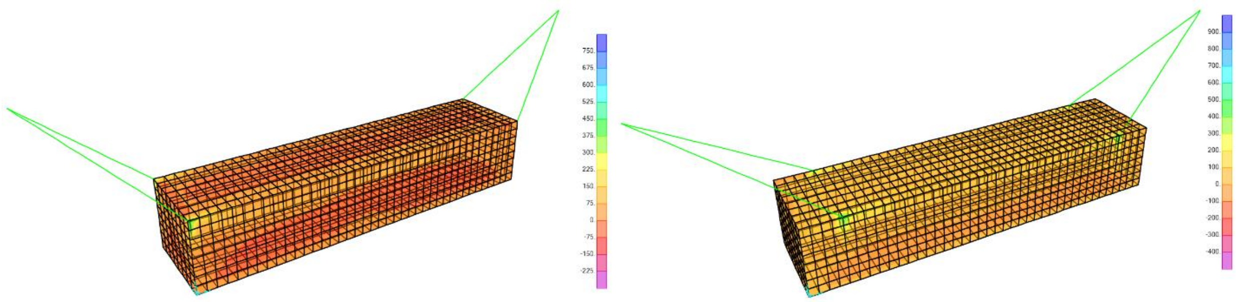


Figure 4. Examples of SAP visual output for double crane deployment

In addition, the software offers the desired numerical outputs, i.e., maximum bending stress and maximum deflection for each of the scenarios. Figure 5 depicts a diagram comparing single crane deployment against double crane deployment in terms of maximum bending stress emerged in the module in each of the 20 scenarios, while the diagram shown in Figure 6 demonstrates a similar comparison with regard to maximum deflection. The following section represents the interpretation of these diagrams.

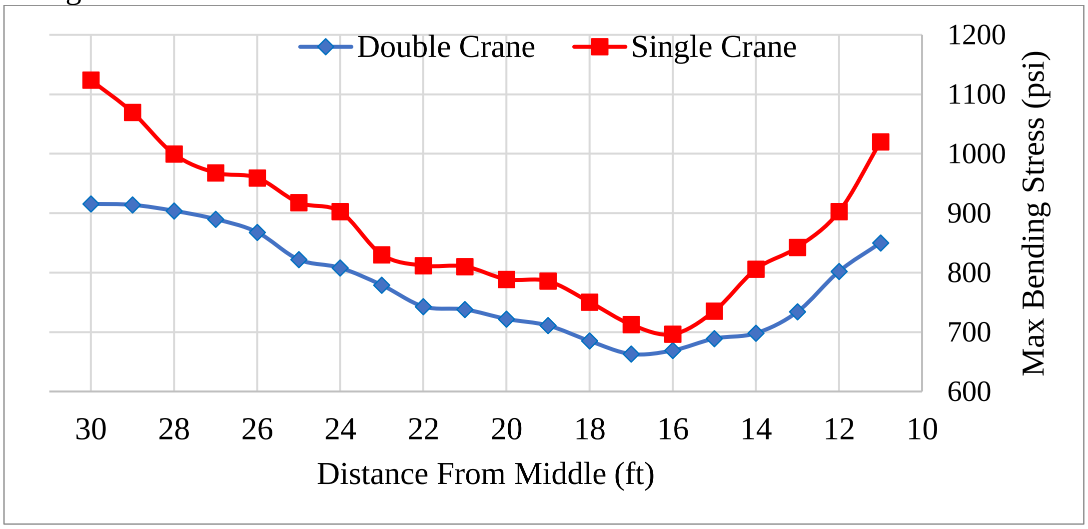


Figure 5. Comparing single crane and double crane by maximum bending stress

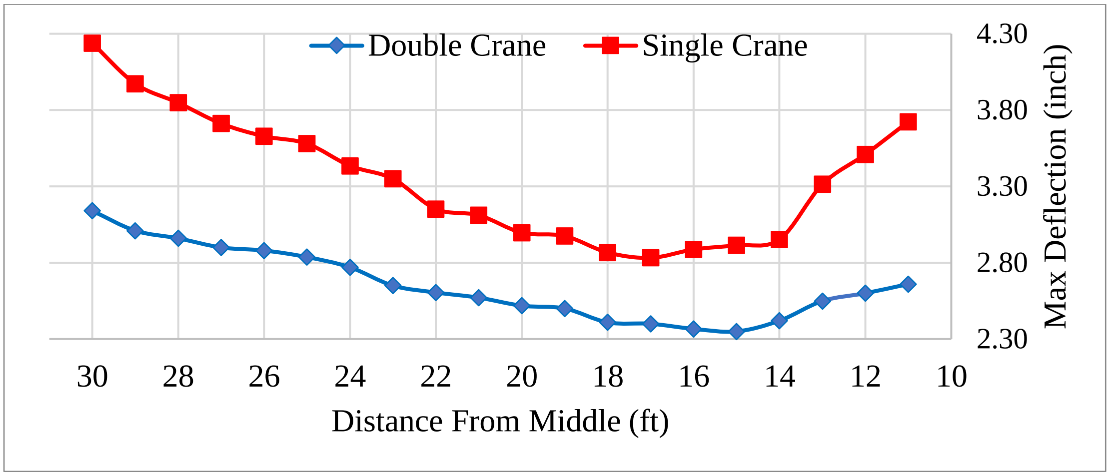


Figure 6. Comparing single crane and double crane by maximum deflection

4. DISCUSSION

The results of this study suggest a variety of interesting findings, the most striking of which are listed below:

1) The position of lifting points can considerably affect the level of stresses and deflections that emerge in long volumetric modules throughout the lifting process.
2) There is a comparatively strong correlation between maximum bending stress and maximum deflection, regardless of deploying a single crane or double crane.
3) The minimal maximum bending stress has occurred when lifting points are positioned somewhere in the middle of the centerline and corners of the module, regardless of deploying a single crane or double crane.
4) The minimal maximum deflection has also occurred when lifting points are positioned somewhere in the middle of the centerline and corners of the module, regardless of deploying a single crane or double crane.
5) Locating lifting points between the centerline and corners of the module can be an efficient solution to mitigate the level of stresses and deflections imposed on the module over the course of lift operation, regardless of whether a single crane or double crane is deployed.
6) The level of maximum bending stresses is relatively lower when two cranes are deployed for the lift implementation compared to when only one crane is used, given the identical position of the lifting points.
7) The level of deflections is significantly lower in the case of using two cranes compared to one crane, given the identical position of lifting points.
8) Deploying double cranes to implement the lift operation is more effective in lessening bending stresses and, more specifically, deflections than utilizing a single crane.

5. CONCLUSION

Lifting long volumetric modules is a delicate and risky process that demands an exact multi-dimensional plan. This study conducted a structural analysis on long volumetric modules throughout their lifting process using SAP software to account for the structural dimension of a lift plan. The study introduced a method for simulating the lift of heavy modules along with analyzing the most critical structural indices, i.e., maximum bending stresses and maximum deflections, over the course of lift operation. Various lifting scenarios were developed and tested to compare the usage of one crane against two cranes in the module lifting process from a structural perspective. Also, the optimum position of lifting points in either of the cases, i.e., using one crane or double crane, was sought with respect to the mentioned structural outputs. The findings of this study suggested that the deployment of two cranes can significantly mitigate maximum bending stress and maximum deflection imposed on a heavy and long volumetric module during its lift. Moreover, the position of lifting points can also considerably impact the two mentioned structural indices.

Although the study has considered multiple factors (e.g., simulating the deployment of one and two cranes, analyzing various positions for lifting points, considering two of the most critical structural indices), additional parameters can be considered in future studies. For instance, long volumetric modules can be lifted from their base or straps, while the current study only examined lifting from the top. Additionally, there are multiple approaches to attach cables to a module from its top, such as using supplemental lift frames or cages or auxiliary beams attached to cables (spreader bars), etc., while the current study only explored the simplest type of attachment. Furthermore, implementing the lifting process with more cables with various directions and slopes can be interesting for further studies. Also, this study made a critical assumption that the weight is distributed uniformly all over the entire module, which is very rare in real cases. More studies are needed with various weight distributions. Finally, even though the optimum lifting scenarios were determined based on two of the most critical structural outputs, the impact of other indices, such as shear and torsion stress, on the lifting process can be investigated in future research.

REFERENCES

[1] J. T. O. Connor, M. Asce, W. J. O. Brien, M. Asce, and J. O. Choi, "Industrial Project Execution Planning : Modularization versus Stick-Built," vol. 21, no. 1, pp. 1–11, 2016, doi: 10.1061/(ASCE)SC.1943-5576.0000270.

[2] A. Nekouvaght Tak, H. Taghaddos, A. Mousaei, and U. (Rick) Hermann, "Evaluating industrial modularization strategies: Local vs. overseas fabrication," *Automation in Construction*, vol. 114, no. February, p. 103175, 2020, doi: 10.1016/j.autcon.2020.103175.

[3] J. T. O. Connor, M. Asce, W. J. O. Brien, M. Asce, J. O. Choi, and S. M. Asce, "Critical Success Factors and Enablers for Optimum and Maximum Industrial Modularization," vol. 140, no. Cii 2002, pp. 1–11, 2014, doi: 10.1061/(ASCE)CO.1943-7862.0000842.

[4] J. O. Choi, X. Bin Chen, and T. W. Kim, "Opportunities and challenges of modular methods in dense urban environment," *International Journal of Construction Management*, vol. 0, no. 0, pp. 1–13, 2019, doi: 10.1080/15623599.2017.1382093.

[5] D. Naqvi, E. Wey, J. Morgan, M. Miller, and T. Nguyen, "Transportation Considerations in Module Design," pp. 1771–1781, 2014, doi: 10.1061/9780784413357.156.

[6] M. Lawson, R. Ogden, and C. Goodier, "Constructional issues in modular systems," *Design in Modular Construction*, vol. 302, pp. 211–224, 2014, doi: 10.1201/b16607-17.

[7] M. F. De La Colina and M. R. Cervera, "Handling Heavier Loads in Construction," *Procedia Engineering*, vol. 161, pp. 1127–1134, 2016, doi: 10.1016/j.proeng.2016.08.524.

[8] J. O. Choi, A. M. Asce, J. T. O. Connor, M. Asce, and T. W. Kim, "Recipes for Cost and Schedule Successes in Industrial Modular Projects : Qualitative Comparative Analysis," vol. 142, no. Ragin 2008, 2016, doi: 10.1061/(ASCE)CO.1943-7862.0001171.

[9] S. M. Bagheri, H. Taghaddos, A. Mousaei, F. Shahnavaz, and U. Hermann, "An A-Star algorithm for semi-optimization of crane location and configuration in modular construction," *Automation in Construction*, vol. 121, no. November 2019, p. 103447, 2021, doi: 10.1016/j.autcon.2020.103447.

[10] A. Mousaei, H. Taghaddos, A. Nekouvaght Tak, S. Behzadipour, and U. Hermann, "Optimized Mobile Crane Path Planning in Discretized Polar Space," *Journal of Construction Engineering and Management*, vol. 147, no. 5, pp. 1–14, 2021, doi: 10.1061/(ASCE)CO.1943-7862.0002033.

[11] A. Khodabandelu, J. O. Choi, J. Park, and M. Sanei, "Developing a Simulation Model for Lifting a Modular House," in *Construction Research Congress 2020: Computer Applications*, 2020, pp. 145–152. doi: doi.org/10.1061/9780784482865.016.

[12] S. Pooladvand, H. Taghaddos, A. Eslami, A. Nekouvaght Tak, and U. (Rick) Hermann, "Evaluating Mobile Crane Lift Operations Using an Interactive Virtual Reality System," *Journal of Construction Engineering and Management*, vol. 147, no. 11, p. 04021154, 2021, doi: 10.1061/(asce)co.1943-7862.0002177.

[13] A. Khodabandelu, J. W. Park, and C. Arteaga, "Crane operation planning in overlapping areas through dynamic supply selection," *Automation in Construction*, vol. 117, no. May, p. 103253, 2020, doi: 10.1016/j.autcon.2020.103253.

[14] A. N. Tak, H. Taghaddos, A. Mousaei, A. Bolourani, and U. Hermann, "BIM-based 4D mobile crane simulation and onsite operation management," *Automation in Construction*, vol. 128, no. May, p. 103766, 2021, doi: 10.1016/j.autcon.2021.103766.

[15] A. Mousaei, H. Taghaddos, S. Marzieh Bagheri, and U. Hermann, "Optimizing Heavy Lift Plans for Industrial Construction Sites Using Dijkstra's Algorithm," *Journal of Construction Engineering and Management*, vol. 147, no. 11, p. 04021160, 2021, doi: 10.1061/(asce)co.1943-7862.0002157.