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ENHANCING SAFETY AND EFFICIENCY IN CRANE OPERATIONS: ADDRESSING COMMUNICATION CHALLENGES AND BLIND LIFTS

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ABSTRACT

This study presents a methodology to improve safety and efficiency in crane operations, particularly addressing challenges in modular construction and complex lifts. It focuses on enhancing communication between crane operators and signalmen, especially in congested environments. Through a literature review, it highlights the need for innovative solutions in signalman location planning and communication methods. The proposed methodology involves preplanning and optimizing signalman visibility using a grid system to determine suitable standing locations. By assessing visibility in relation to lifting module corners, the study aims to ensure clear lines of sight for safe lifting. Validated through two case studies, the methodology demonstrates effectiveness in planning signalman locations for various lifting scenarios. This research offers a systematic approach to tackle crane operation challenges, improving safety, efficiency, and precision in construction projects. Further development and implementation of such methodologies are vital for the success of modular construction and heavy industrial projects.

1 INTRODUCTION

In recent years, modular construction has gained significant popularity in the construction industry; this type of construction requires projects to be manufactured offsite and transported to the construction site using cranes. The vital need for cranes in modern construction sites made cranes the cornerstone of any construction project, specifically those of a modular or heavy industrial nature (Boutouhami et al. 2023). However, within the planning of crane operations lies a challenge of interaction between crane operators and signalmen. This presents a major issue for crane operations lift planning from both an efficiency and safety perspective. To ensure a safe lift, maintaining effective communication between the signalman and the crane operator is essential. Improper communication between them is a major cause of these accidents (Mansoor et al. 2020).

Additionally, within crane operations, challenges often arise in navigating complex lifts, where operators must execute maneuvers without clear visibility of the payload pick-up or set locations. "Blind lifts on congested environments are inherently dangerous because of the substantial presence of spatial conflicts in the crane workspace and the operator's limited visibility to the load" (Fang, Chen, et al. 2018). These scenarios pose considerable risks and demand meticulous planning and innovative solutions to mitigate potential hazards.

The main aim of this work is to address the challenges faced during crane operations and ensure their safety and efficiency, even in demanding conditions, by developing a methodology for planning the location of signalmen in crane operations that goes beyond conventional practices. Our specific goals include 1) developing a systematic methodology for planning the location of signalmen in crane operations, 2) improving communication between signalmen and crane operators to facilitate smoother coordination and workflow, reducing the occurrence of blind spots within lifting scenarios 3) addressing complex lifts that may require operators to conduct maneuvers without proper visibility of payload pick-up or set locations 4) Validate the developed methodology through the use of a case study. The significance of this endeavor is crucial in the construction industry, where safety, efficiency, and precision are the foundation of successful projects.

2 LITERATURE REVIEW

The signalman location problem is a critical aspect of crane operations in construction projects, particularly in environments characterized by modular construction and complex lifts. This problem revolves around determining optimal positions for signal persons who communicate visually with crane operators during lifting operations. Effective signalman placement is essential for maintaining safety and efficiency, as it ensures clear communication and visibility of critical points on the lifted module. Early research aimed to understand the problem better, while more recent studies have focused on finding solutions. For example, initial research examined the challenges of locating signallers during crane operations. One study, referenced as (Cheng and Teizer 2014), identified the risks associated with limited visibility on the ground and the need to measure spatial visibility for tower crane operators accurately. Another study, (Fang, Cho, et al. 2018)**,** stressed the importance of situational awareness for crane operators to ensure safety and efficiency. Finally, (Fang and Yong K Cho 2017) proposed a technical framework to enhance the situational awareness of tower crane operators.

The initial works on improving communication between crane operators and signalmen are (Mansoor et al. 2020) and (Mansoor et al. 2022), which introduced conceptual frameworks and methodological solutions. (Mansoor et al. 2020) suggested using helmet-mounted cameras and mathematical algorithms to interpret hand signals, while (Mansoor et al. 2022) presented a deep learning-based approach for classifying them. In contrast, (Fang and Yong Kwon Cho 2017) introduced a crane lift assistance system to enhance operator awareness and lift performance. Lastly, (Cheng and Teizer 2011) proposed a method to improve situational awareness for tower crane operators by enhancing their understanding of the construction layout and visibility.

Further research has delved into various methods to address the problem of locating signalmen. For instance, (Zhang, Wong, and Pan 2023) and (Mansoor et al. 2023)have introduced Virtual Reality (VR) and advanced deep learning frameworks to improve multi-role collaboration and dynamic hand signal classification. Similarly, (Fang, Chen, et al. 2018) has tackled the issue of blind lifts by utilizing computer vision for real-time crane state sensing and visualization. Additionally, (Sutjaritvorakul et al. 2020) has proposed a simulation platform for crane visibility safety assistance that leverages deep learning techniques for person detection to enhance crane operators' situational awareness.

After conducting a comprehensive literature review, several critical gaps were identified in the field of signalman location planning for crane operations within construction projects. These gaps underscore the pressing need for innovative solutions that can adapt to the dynamic environments typical of construction sites. Moreover, there is a notable opportunity to leverage Building Information Modeling (BIM) to revolutionize crane operations planning, enhancing coordination and efficiency across project lifecycles. The identified gaps highlight the overarching necessity for further research and development of advanced methodologies and algorithms. These advancements are crucial for optimizing signalman locations and lift paths, thereby significantly improving both the safety and operational efficiency of crane operations in complex construction environments.

3 METHOD

The methodology outlined in this study, depicted in Figure 1, seeks to enhance the safety of mobile crane operations in crowded construction sites by emphasizing preplanning and optimizing the visibility of the lifting crew towards the lifting module. The study suggests that ensuring a clear line of sight for the lifting crew (comprising the crane operator and signal persons) from all four corners of a rectangular module can enhance the safety of lifting operations. Through various stages, the study examines if the crew can see the corners of the lifting module as it transitions from the pick-up point to its designated location. The proposed methodology relies on several inputs to enhance mobile crane operation safety. These inputs include: (1) the lifting module, (2) information about installed objects detailing their dimensions and locations, (3) the crane's location within the construction site, and (4) project requirements. These requirements involve verifying clearances between objects and signal persons, as well as determining the maximum distance at which a signal person can effectively observe an object.

The process section initiates by establishing a (5) grid system, defining the feasible points where a signal person can stand. Subsequently, (6) the grids are adjusted by removing those intersected by installed objects, ensuring accuracy. Following this, subsection (7) entails determining the path of the lifting module, outlining its sequential movements towards the destination. Subsection (8) involves assessing the crane operator's visibility and editing the grids for the lifting module at each designated step. This includes modifying grids for module clearance, verifying signal persons' visibility from available grids, and categorizing grids based on the number of visible corners. The resulting outputs consist of (9) identifiable crane-visible corners, (10) signal persons' locations and the corresponding visible corner count, and (11) the necessary number of signal persons required for a given lift operation.

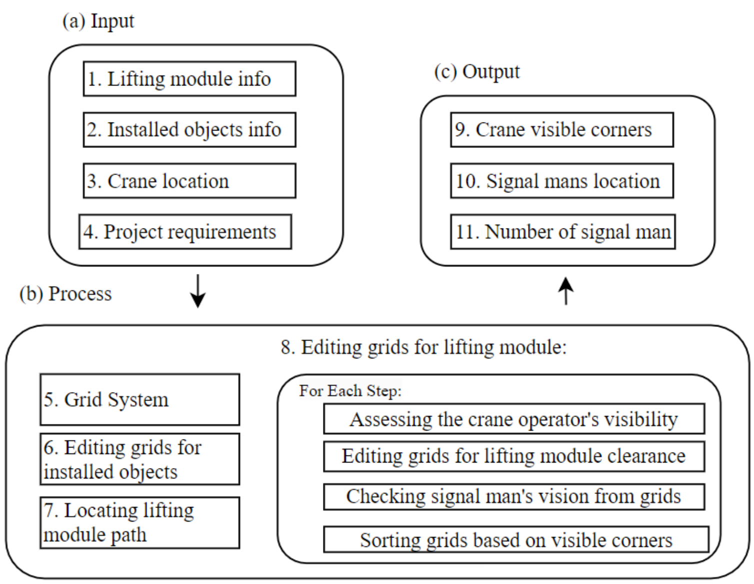


Figure 1. The outline of the proposed methodology

3.1 Inputs

To represent the signal man problem in a computerized environment, we adopt a modeling approach where each object is defined as a rectangle. For every object, its characteristics include its dimensions, the 2D coordinates of its southwest corner, and its orientation. Orientation is described as an angle measured between the minimum side of the object and the x-axis of the coordinate system. The subsequent inputs encompass the 2D coordinates of the crane operator and project requirements. These project requirements outline the minimum and maximum clearances necessary for signals to the sides of the lifting object, denoted as LOMin and LOMax respectively in this article. They also specify the minimum clearance required for each signal person to the sides of installed objects, referred to as IOC. Additionally, they set a maximum distance within which the crew can effectively observe an object, termed Crew Vision Limit or CVL. Lastly, the final input is the distance between two adjacent locations in the grid system where a signal person can stand, referred to as Grid Step or GS.

3.2 Process

The process phase begins by creating a (5) grid system, which represents potential standing locations for a signal person. Each grid is identified by its 2D coordinates, indicating its precise position. The distance between these grids (GS) is fixed at 2 feet, reflecting the minimum movement required for a signal person to transition between adjacent locations. Following the establishment of the grid system, (6) Editing grids for installed objects is executed, removing grids that fall within the boundaries of installed objects, considering a 2-foot IOC. To accomplish this adjustment, each side of an installed object is expanded by 2 feet to create a larger rectangle. Subsequently, any grids contained within this expanded rectangle are eliminated. The grid system remains consistent for each step of the lifting module along its path, with modifications made according to the location of the lifting object in that specific step.

The process advances with subsection (7), locating the lifting module path, outlining a polar path for the lifting operation. Within this path, the mobile crane undergoes distinct operation phases: (a) lifting the object from the pick location and aligning it perpendicular to the crane boom, (b) rotating the boom and object to the set location, (c) adjusting the object's rotation based on the orientation of the set location, and (d) positioning the object in its designated location. This article explores crew vision towards the lifting module at both the pick and set locations, as well as during a minimum of three steps within phase (b) of the mobile crane operation. Each position of the lifting object along its path is referred to as a step in the remainder of this article. Assuming a minimum of three steps in phase (b), they are as follows: Step 1 occurs when the lifting object is located in the pick area, Step 2 refers to the object's location at the beginning of phase (b) of the mobile crane operation, Step 3 refers to the object's location midway through phase (b), Step 4 refers to the object's location towards the end of phase (b), and Step 5 marks when the object is positioned in the set location. Figure 2 serves as an illustrative example depicting the layout of installed objects, represented in blue. The red and green rectangles denote the pick (step 1) and set (step 5) locations of the lifting module, respectively. Additionally, the orange rectangles illustrate steps 2 to 4, arranged from left to right, during phase (b) of the mobile crane operation.

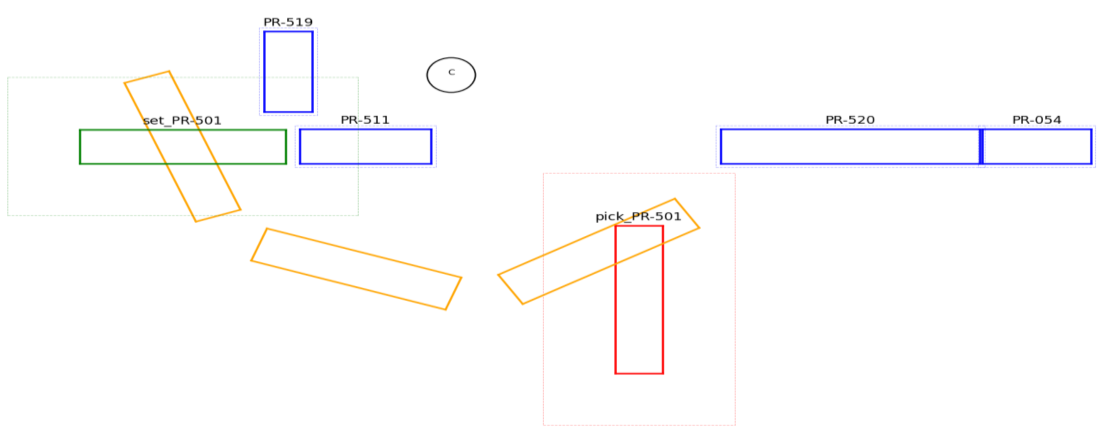


Figure 2. Layout of the construction site

Subsection 8 of the process focuses on examining the visibility of the crane operator and signal person in relation to the corners of the lifting object. This article operates under the assumption that if all four corners of an object are visible to the crew, then the object can be safely lifted at the site. Accordingly, the process of assessing vision entails determining the availability of line-of-sight between two points. One of these points represents the standing position of the crew member (either the signal person or the crane operator), while the other point corresponds to one of the corners of the object. In this subsection, each step of the lifting object's path (from pick to set) undergoes four strides (a to d):

(a) Assessing the crane operator's visibility: this stride involves developing a Python function to assess the availability of line-of-sight between two points: the crew point and one corner of the lifting object. The flowchart outlining this function is presented in Figure 3. The function takes as input two points, the installed objects, and the lifting module step. It then generates a vision line segment using the mentioned two points. If the length of this line segment is less than the Crew Vision Limit (CVL), assumed to be 130 feet in this study, the process proceeds to the next level; otherwise, the corner is considered not visible. Subsequently, each side of the installed objects and the lifting module (in its step location) are represented as line segments, collectively forming a group of line segments. Finally, the function checks for intersections between the vision line segment and all members of this group. If no intersections are found, indicating a clear line-of-sight between the two points, the corner is deemed visible to the crew; otherwise, it is not. After completing this stride, the corners that are visible to the crane operator will be identified. Subsequently, the next task is to locate signal persons for the remaining corners that are not visible to the crane operator.

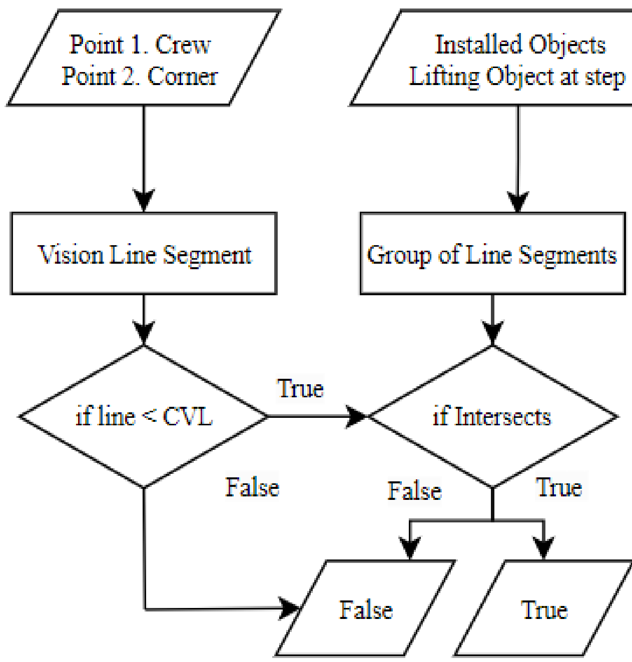


Figure 3. Line-of-sight function flowchart

(b) Editing grids for lifting module clearance: In this stride, a grid area is defined around the lifting module at each step of its path. This area is bounded by two expanded rectangles. The smaller rectangle represents an expanded lifting module, with each of its sides extended based on the lifting module's minimum clearance (LOMin), which is set at 30 feet. The larger rectangle is expanded based on the lifting module's maximum clearance (LOMax), assumed to be 65 feet. Once this area is generated, the signal persons' locations should be within this area to ensure visibility of the remaining corners that are not visible to the crane operator.

(c) Checking signal man's vision from grids: Each grid located within the area generated in stride b must undergo the line-of-sight function to verify if there is a clear view towards the remaining corners. Subsequently, the number of corners visible to each grid will be determined.

(d) Sorting grids based on visible corners: For each grid point generated in stride b, a signal person can observe a maximum of 3 corners and a minimum of 0 corners. Grids that have 0 visible corners will be removed from the grid system. Grids with 1, 2, or 3 visible corners will be colored black, blue, and green, respectively. Figure 4 illustrates the outcome of this process for step 1 (pick location) of the illustrative example depicted in Figure 2. As depicted in the figure, two corners of the lifting module at the pick location are visible to the operator, while 2 other corners require observation by a signal person. The blue grids indicate visibility of the remaining 2 corners, indicating the need for a signal person to be positioned in that area to monitor the corners not visible to the crane operator.

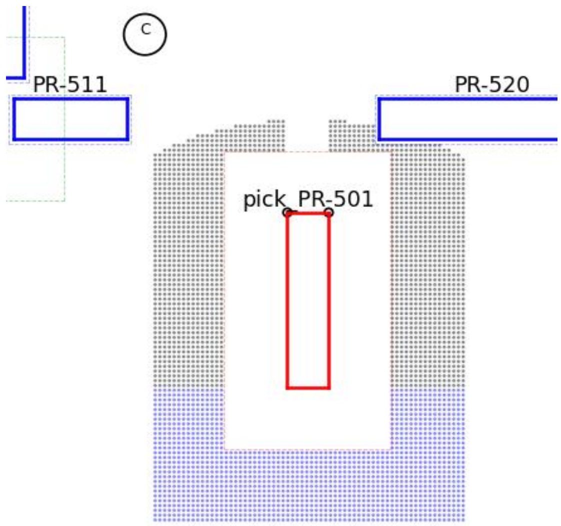


Figure 4. The grid status for the lifting module in step 1 (pick location)

4 CASE STUDIES

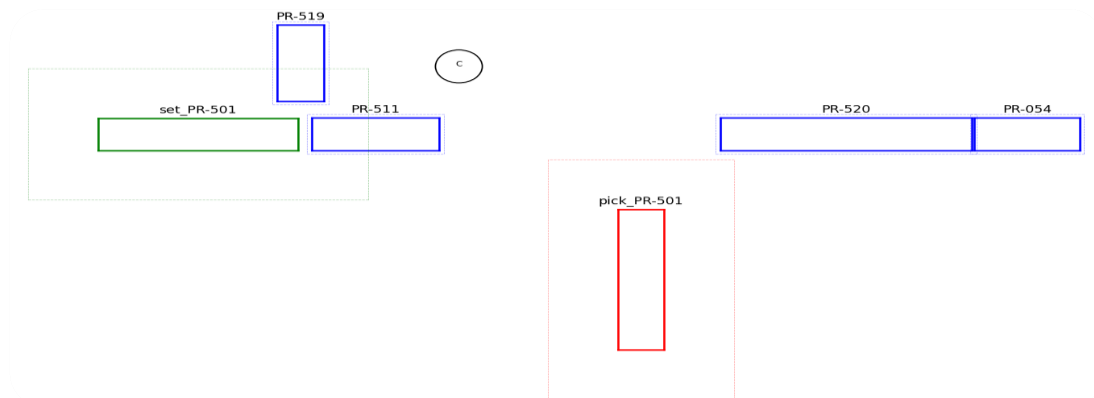
The proposed methodology in this study is evaluated through two case studies to demonstrate its effectiveness and outcomes. It is acknowledged that the current study, which simplifies lifting tasks to concentrate on specific components, does not fully encompass the complexities of real-world construction activities. Construction site lifting tasks inherently involve a dynamic and multifaceted environment with numerous workers, various construction elements, and a diversity of materials, all contributing to operational complexity and uncertainty.

Analogously, consider lifting operations within an industrial plant. In these settings, the affected area of the lift operation is typically restricted through the use of fences and signage, prohibiting entry to maintain a controlled and safe environment for workers. Similarly, construction components and materials can be represented as bounding boxes and integrated into the grid system as installed objects, allowing the grid system to incorporate them into the workflow. By adding IoT sensors into our proposed method, construction sites can more effectively adapt to the dynamic nature of real-world job sites. Just as IoT sensors alert the crew when an individual enters a restricted lifting zone, they can monitor and signal the presence of unauthorized personnel in hazardous areas, thereby enhancing safety and ensuring timely responses to dynamic changes.

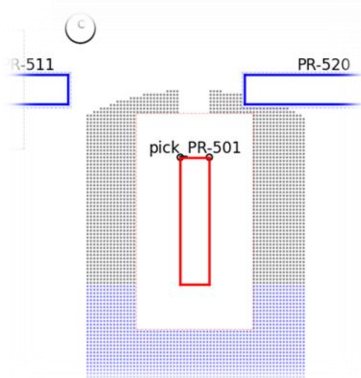
4.1 Case 1

The site layout for this case study was briefly introduced earlier in Figure 1, while Figure 6 illustrates the signal planning for this layout. The objective of the mobile crane is to lift module PR-501 from its pick location (red rectangle) to its set location (green rectangle), with the position of the mobile crane indicated by the label "C". In step 1 (see Figure 6.b), the operator can observe 2 corners highlighted with black circles, while the blue grid indicates the location where the signal person can observe the remaining 2 corners. Step

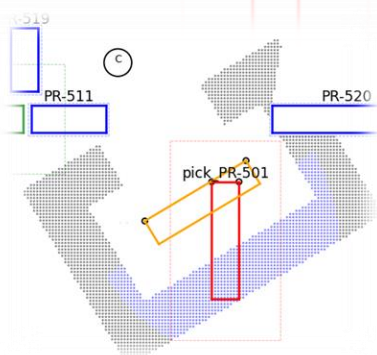
2 (see Figure 6.c) also reveals 2 visible corners for the operator, with the remaining corners visible to the signal person from the blue grids. In step 3 (see Figure 6.d), only one corner is visible for the operator, necessitating the signal person to locate in the green grids to observe the remaining corners. As no corners are visible for the crane operator in step 4 (see Figure 6.e), two signal persons are required to position themselves in two of the green grid zones. Finally, in step 5 (see Figure 6.f), one corner is visible to the operator, and one signal person should locate in the green grid zone to observe the remaining corner.



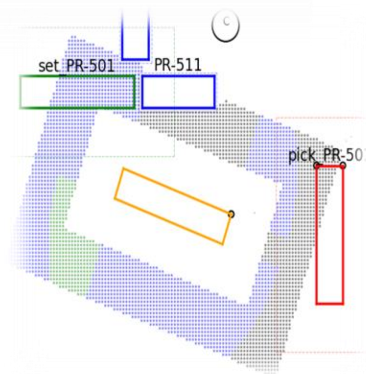
(a) Site layout of case study 1



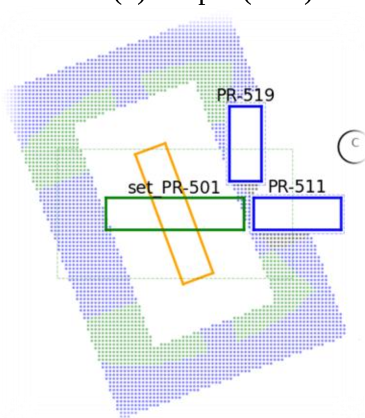
(b) Step 1 (Pick)



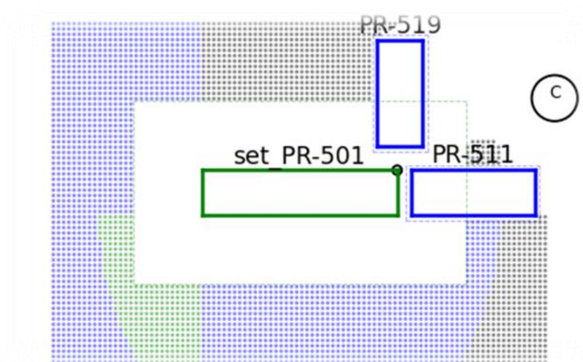
(c) Step 2



(d) Step 3



(e) Step 4

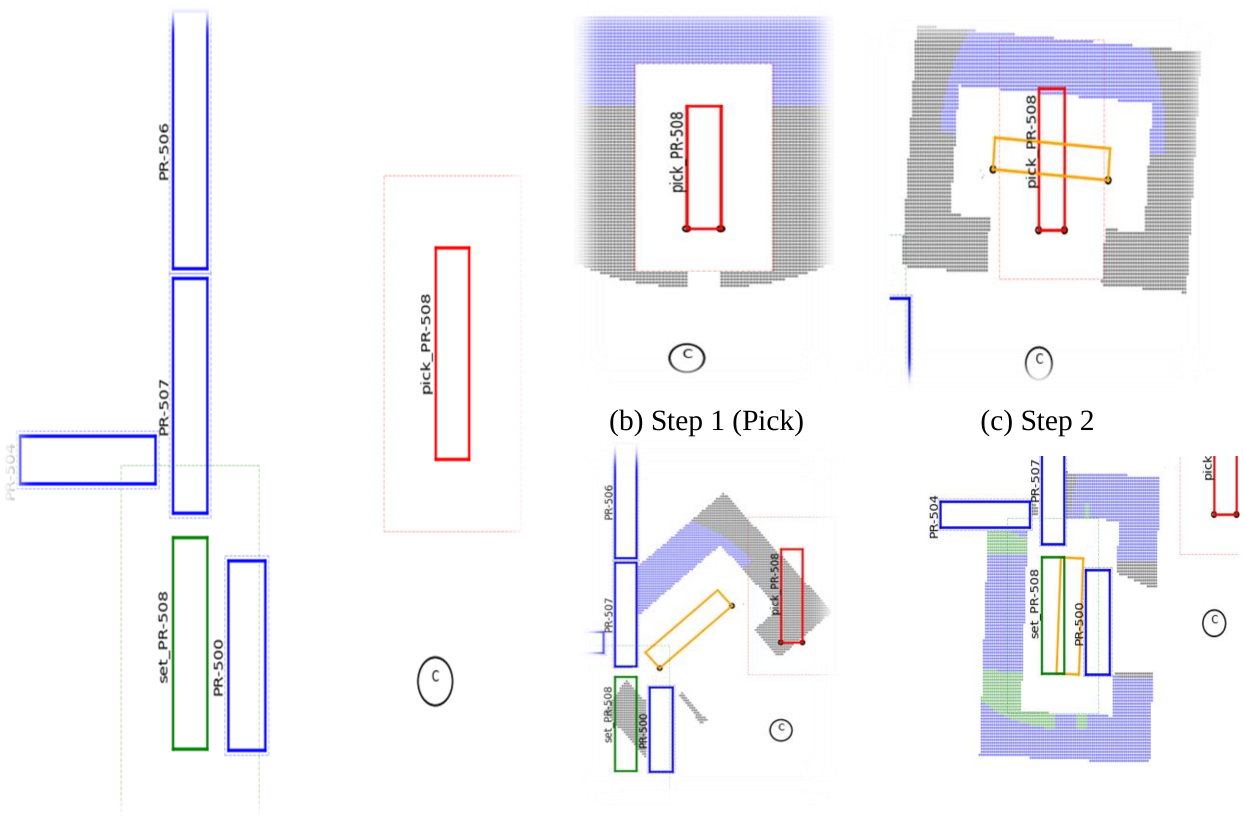


(f) Step 5 (set)

Figure 6. Signal man planning for case study 1

4.2 Case 2

This case study focuses on signal man planning for lifting module PR-508, highlighted with red and green rectangles in the pick and set locations, respectively. In the pick location (see Figure 7.b), two corners are visible for the operator, while the remaining corners are observable for a signal person from the blue grid zone. In the subsequent step (see Figure 7.c), when the boom is perpendicular to the lifting module, two corners are still visible, and the signal person should be positioned in the blue grid zone. Similarly, in step 3 (see Figure 7.d), two corners remain visible for the crane operator, and the signal person should remain in the blue grids to observe the remaining corners. Moving to step 4 (see Figure 7.e), no corners are visible for the crane operator, requiring the two signal persons to relocate to two different green grid zones to observe all corners. Finally, in the set step (see Figure 7.f), no corners are visible for the operator, necessitating the two signal persons to position themselves in two different green grid zones to ensure complete observation of all corners.



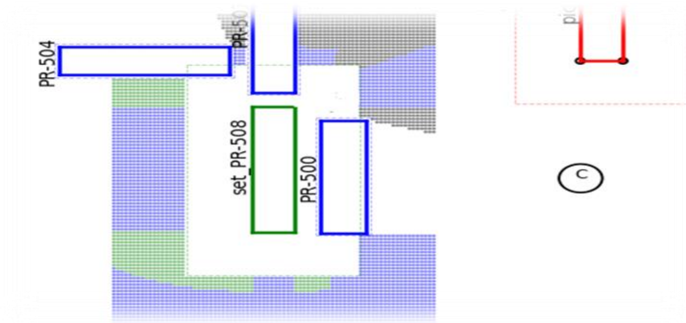
(b) Step 1 (Pick)

(c) Step 2

(a) Site layout of case study 1

(d) Step 3

(e) Step 4



(f) Step 5 (set)

Figure 7. Signal man planning for case study 2

5 CONCLUSION

This study presents a comprehensive methodology aimed at enhancing the safety and efficiency of crane operations in construction projects, with a particular focus on the challenges associated with modular construction and complex lifts. By addressing issues such as communication between crane operators and signalmen, as well as blind lifts in congested environments, this research underscores the critical importance of meticulous planning and innovative solutions in ensuring the success of construction projects. Through a thorough literature review, the study identifies the need for novel approaches to improve signalman location planning and communication methods. The proposed methodology, which involves preplanning and optimizing the visibility of the lifting crew towards the lifting module, offers a systematic framework for addressing these challenges. By utilizing a grid system to determine feasible standing locations for signal persons and assessing the visibility of crane operators in relation to the corners of the lifting object, the study aims to ensure a clear line of sight for safe lifting operations.

The methodology's efficacy is evidenced by the validation of two case studies, which emphasize its practical relevance in determining optimal signalman placements for diverse lifting situations. This research contributes significantly to the construction industry's continual endeavor to improve safety, productivity, and accuracy in crane operations, emphasizing the necessity for ongoing refinement and adoption of such methodologies. This study's 2D modeling approach suggests future investigations into a more immersive 3D environment, enhancing the realism and applicability of findings by analyzing spatial relationships comprehensively. Currently, the study evaluates box shapes, simplifying real-world geometries. Future research should address this limitation by developing methods to handle diverse shapes and sizes, broadening the grid system's scope. Ultimately, the incorporation of these innovative strategies is imperative for ensuring the long-term success of modular construction and other large-scale industrial endeavors.

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