An Automated Decision Support System for Pre-planning of Precast Bridge Installation using Heuristic-Based Simulation and Invariant Signatures

Meta Soy[1], Zirui Hong[2], Fan Yang[1], Jiansong Zhang, Ph.D.[1], and Hubo Cai, Ph.D.[2]

[1]Bowen School of Construction, Purdue University, USA
[2]Lyles School of Civil and Construction Engineering, Purdue University, USA
soym@purdue.edu, hong351@purdue.edu, yang2352@purdue.edu, zhan3062@purdue.edu, hubocai@purdue.edu

Abstract – Precast bridge construction accelerates the construction process and minimizes traffic disruptions. However, the onsite installation demands extensive planning efforts from experienced crane operators to ensure safe and efficient assembly operation. This study presents an integrated IFC-based simulation framework that combines automated BIM information extraction with heuristic crane planning algorithms to enhance pre-planning for precast bridge panel installation. The proposed methodology addresses critical interoperability gaps in current BIM-to-simulation workflows through an invariant signature-based approach that automatically extracts essential bridge component information (size, location, mass, etc.) from IFC models. A multi-stage heuristic planning algorithm evaluates crane operation feasibility by applying capacity-based filtering and geometric constraint analysis, considering boom-load collision prevention, rope length constraints, and boom-bridge collision avoidance. The framework was implemented in Unity3D with behavior-tree based crane control to provide realistic physical simulation & illustration and interactive constructability analysis capability. Validated using two IFC bridge models from two different software platforms across IFC versions, the newly developed method successfully demonstrated its capability in automated BIM component extraction and generation of collision-free operational plans with low computational cost. This approach enables crane operators to systematically evaluate multiple lifting scenarios during pre-planning, optimize crane positioning and model selection, and reduce onsite operational risks, contributing to improved safety and efficiency in precast bridge construction projects.

Keywords – Precast Bridge Construction; Crane Simulation; BIM Interoperability; Heuristic Planning; Unity3D; IFC

1 Introduction

Precast bridge projects have been widely adopted by the US Departments of Transportation (DOTs) to accelerate construction, minimize traffic disruptions, and enhance structural quality and durability [1,2]. However, the onsite installation of precast components remains a time-consuming, repetitive, and hazardous task [3]. The interplay of multiple factors, such as crane location, crane capacity, panel position, panel placement location, and obstacles, makes the installation complicated and demands extreme caution from experienced operators for safe operations. Pre-planning before the installation is routinely conducted to generate a safe lifting plan to guide field installation operations. Current pre-planning practice heavily relies on static 2D layout planning and manual calculation based on paper forms, which is tedious, inflexible, and of limited spatial accuracy. Simulation-based pre-planning is a promising solution which provides automated calculation and realistic visualization and therefore supports fast what-if analysis and accurate spatial assessment.

Building information modeling (BIM) plays an important role in gathering design and construction information for the planning and execution of construction simulation [4,5]. Although the IFC bridge standard is well developed to facilitate the communication and coordination of building information modeling (BIM)-based bridge construction [6], there is a lack of interoperable BIM to support construction installation simulation and its constructability analysis. This limitation restricts the achievement of BIM benefits throughout the lifecycle of a bridge project. In addition, to automate crane operational analysis, recent studies developed computational algorithms for lifting trajectory planning by focusing on 1) optimizing multiple performance objectives (e.g., minimum energy and time consumption, shortest path, smooth trajectories), and 2) improving computational efficiency of the algorithms [7,8]. However, there are few studies that integrated BIM as prior knowledge for automatic installation planning [9].

This study aims to develop technologies that enhance IFC-based BIM interoperability and facilitate automatic installation planning for large and complex precast bridge components (e.g., deck panels) through simulation-based installation pre-planning. Specifically, this is achieved by adopting an invariant signature-based approach for enhanced automated extraction of critical bridge component information from IFC data. Furthermore, heuristic and simulation-based planning are integrated to generate crane operational plans and provide a systematic assessment of the plans' constructability. The proposed methodology is investigated through applications that support BIM interoperability among precast bridge design, automatic installation simulation, and constructability analysis. The proposed framework is shown with the fully simulated testing of two IFC models (one exporting from OpenBridge and the other exporting from Autodesk Revit with different IFC versions). The simulation suggests that the proposed pipeline could help support pre-planning of the bridge precast installation effectively by providing the professional operator with more freedom in adjusting the possible lifting conditions and testing all possible lifting cases prior to the on-site process.

2 Related Work

The study focuses on developing a full system with enhanced IFC-based model information extraction through invariant signature concept to generate pre-planning simulation cases for the automatic mobile crane lifting simulation based on the proposed heuristic planning algorithm. Therefore, the review investigates how the invariant signature concept can support IFC information extraction and how heuristic algorithms were used for planning crane movement in previous studies.

2.1 IFC Information Extraction via Invariant Signature

While IFC file format is considered a key enabler of BIM interoperability following an open standard for information exchange, extracting information from IFC models with missing attributes still presents significant challenges. Mainly, the problem with IFC file conversion from various proprietary software results in incomplete data representation, with critical attributes missing or elements incorrectly classified as *IfcElementProxy* objects. Wu et al. introduced the concept invariant signature of architecture, engineering, and construction (AEC) objects, which considers a set of intrinsic properties of the IFC element which allows computational algorithms to differentiate those IFC elements based on the geometric signature, locational signature, and metadata signature [10]. Subsequent research on IFC information extraction based on the invariant signature concept shows promising results with high precision and recall [11, 12]. Therefore, in this paper, the proposed extracting process will integrate invariant signatures methodology with the help of IfcOpenShell Python library to gather extraction results effectively.

2.2 Heuristic Algorithms for Planning Crane Movement

Crane planning is a key process in lifting heavy objects in the manufacturing and construction industries. Crane movement and lifting actions were studied by many researchers in order to optimize: (1) the lifting path, (2) moving path with load, (3) safe lifting, (4) multi-crane collaboration, and (5) collision avoidance. Regarding crane path planning, which is one of the key challenges during the pre-planning stage, many researchers explore the use of heuristics, genetic A*, reinforcement learning, and hybrid algorithms to generate and optimize lifting paths [7-9,13-15]. For example, an improved A* algorithm based on energy and time consumption models for optimization of the lifting path was proposed by [7], where a method was provided for locating the lifting path and locating the obstacles' envelope in C-space which effectively avoids collision problems. [7] achieved the crane lifting path by not just minimizing the path but also considering the energy use. [9] proposed an exhaustive search method to identify optimal crane configurations in the digital twin environment based on a fixed unit grid system. Based on various crane lifting constraints, [9] derive mathematical formulas to maximize the total successful installable number of bridge decks based on the location of the crane and the crane capacity. The simulation suggests that the proposed system could locate optimal crane locations and lifting capacity. [13] chose different approaches by training reinforcement learning agents through virtual reality (VR) to produce an optimal path, emphasizing parameters such as lifting time, energy efficiency, and collision detection.

Despite effectively producing optimal paths, some approaches produce paths that are too complex or unsafe to operate [15], while others demand computing time. Therefore, in the pre-planning phase concerning bridge panel lifting operation, the traditional lifting method based on operator constraints could be employed. This could be achieved through the development of heuristic algorithms that consider the panel pickup location, crane location, and placement point on the bridge.

According to the literature review summarized above, and in the case of pre-planning simulations, the integration of invariant signature-based information extraction could provide accurate information for the input to the heuristic-based simulation. Since the crane lifting pre-planning simulation aims to support the lifting of panels to the bridge, in this paper, we use the key constraints such as collision avoidance to develop heuristic planning algorithms.

3 Methods

The study aims to develop preplanning simulations for crane lifting and installation of pre-cast concrete panels for bridge construction based on the IFC-based bridge design. The users/crane operators can preselect their crane and location of lifting and test out the possibilities of lifting prior to the construction installation. The proposed pipeline includes taking the IFC-based bridge design, extracting information based on invariant signatures, running the proposed heuristic planning algorithm for crane lifting, and generating lifting simulations. The simulation results showed that the integration of heuristic and simulation-based planning effectively: 1) assessed the feasibility of lifting operation using selected crane size and crane lifting location, 2) generated feasible plans given the chosen crane size and location with low computational cost, and 3) afforded plan validation via realistic physical simulations for constructability analysis.

3.1 IFC information extraction and Invariant Signature

The first step in establishing interoperable BIM for preplanning bridge components installation is the automated extraction of critical information from IFC models to serve as inputs to the installation planning. Figure 1 illustrates our pipeline for automated information extraction. Key information includes the size, location, and mass of bridge panels, as well as obstacle information such as the geometry of the bridge body. One major challenge in the extraction is the absence of explicit component-type attributes in the exported IFC data. For example, in early IFC versions, bridge components exported from OpenBridge were often labeled generically as *IfcBuildingElementProxy* rather than as specific IFC entities such as *IfcSlab* and *IfcBeam*. Additionally, the geometry of these components was typically represented as undifferentiated meshes, which makes it difficult for the computer to distinguish between critical components such as slabs, piers, and girders.

To address these challenges, we utilized invariant signatures to identify the target components. As demonstrated in previous research [10], different types of components have distinct ranges of geometric invariant signature values. Focusing on the installation of deck panels (slabs), we developed a classification algorithm that can automatically differentiate decks from other bridge components using invariant geometric signatures. Similarly, we applied the same approach to identify bridge body components (primarily Beams) to provide contextual information to assist downstream planning tasks.

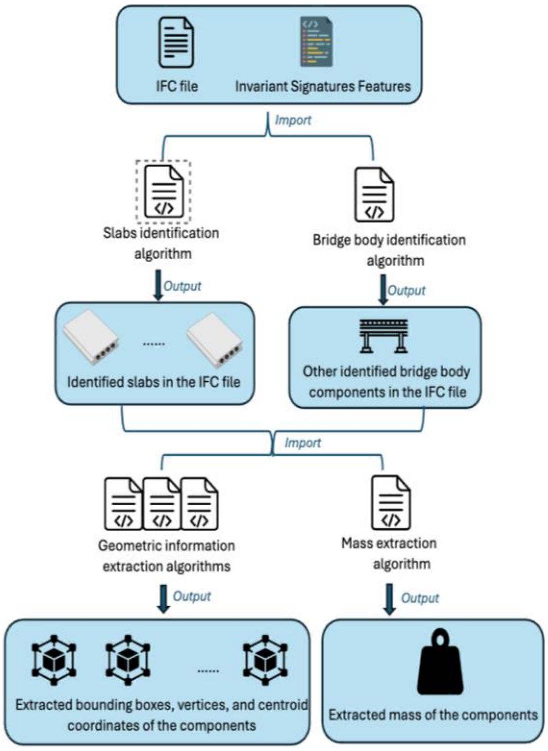

Figure 1. IFC-based information extraction pipeline

The second step involves extracting relevant information from identified components. Essential information includes ID, location, bounding box, mass of slabs, and other bridge body components. An extracted information sample is shown in Table 1, where three slabs in an IFC model were identified, and the coordinates of their bounding boxes' vertices and center points were extracted. The developed algorithms can adapt to different software platforms (e.g., OpenBridge and Revit) and IFC versions (IFC4, IFC4X3, IFC2X3).

Our developed algorithm successfully extracted the correct information from six different bridge model files, originating from two software (Revit and OpenBridge) and their exports into three IFC versions (IFC4, IFC2X3, and IFC4X3). This testing shows that the pipeline can successfully complete all the above extraction tasks correctly. The invariant signature-based pipeline is a robust and automated approach to IFC information extraction. The interoperability and automation levels in bridge automation construction are expected to be enhanced with this approach.

Table 1. Example of extracted IFC information

Slab_ID	Slab_001	Slab_002	Slab_003
Vertex_Min_X	4.32	7.368	10.416
Vertex_Min_Y	5.22	5.22	5.22
Vertex_Min_Z	5.724	5.724	5.724
Vertex_Max_X	7.368	10.416	13.464
Vertex_Max_Y	17.413	17.413	17.413
Vertex_Max_Z	6.096	6.096	6.096
CentroidX	5.844	8.892	11.940
CentroidY	11.316	11.316	11.316
Centroid Z	5.890	5.890	5.890

3.2 Heuristic Planning Algorithm

The presented algorithm is for analyzing the crane lifting conditions in a precast bridge construction project. The algorithm is based on the heuristic planning approach which evaluates crane operation feasibility, calculates optional boom configurations, and ensures safe lifting operation by avoiding physical collision. The heuristic planning approach is designed for locating the feasible crane location for lifting precast panels based on the crane lifting capacity configuration (in reference to the load chart). Engineering heuristics are applied to determine and identify the boom length and working radius based on the preferred crane location by users. With the feasible pairs of crane locations and boom length, under the physical movement constraint of the crane, the outputs of the heuristic planning algorithm serve as inputs to the crane simulation.

The proposed algorithm adopted a multi-stage planning strategy that mimics crane operators' engineering decisions under real-world crane operational constraints and three operation assumptions: (1) one action of the crane at a time (e.g., while rotating, the boom length cannot be extended or retracted), (2) the location of the crane and panel pick-up location can be provided by the user and adjusted in the simulation environment, (3) the distance from the pick-up location to the crane is closer than the distance from the crane to the placement location.

The heuristic planning algorithm contains two main filtering stages:

Stage 1: Capacity-based filtering: based on the load chart of a crane (see Figure 2), pairs of feasible radius and boom length, and the pairs valid for operation are obtained. For example, assuming the load is heavier than 10 tons, all the possible capacity in the box is satisfied, and the system will obtain corresponding pairs (radius and boom length).

The pairs are further filtered with the provided coordination of the crane which was obtained from the simulation environment. By using the coordination of the placement location and crane location, distance is calculated in the horizontal plane (XZ), based on which the number of valid pairs is further reduced. For example, assuming that the crane was parked at a distance of 9 m from the placement location, the valid capacity reduces to those values in the dashed line box shown in Figure 2.

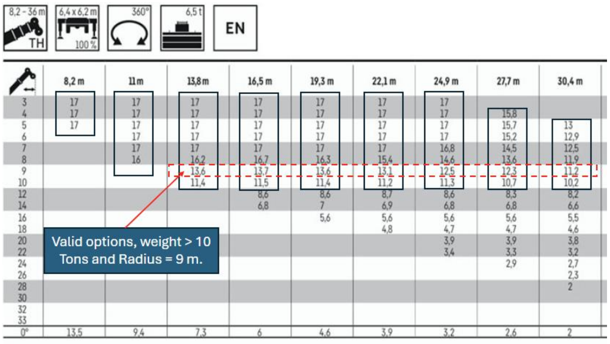

Figure 2. Partial load chart and example for valid pairs for load heavier than 10 tons [16]

Stage 2: Geometric constraint filtering: three geometric constraints are used for further filtering. Details based on the planning layout and lifting action diagram are as follows (Figure 3).

Constraint #1: Boom-Load Collision Prevention at Pickup location (see Figure 3b)

With the selected pairs, the length of the Boom (L) is known. Considering the radius of the panel, RL (assuming the panel can be rotated around its center) and the height of bridge (HB), the constraint #1 is obtained using Equations (1) to (3) below:

$$\frac{r_{min}}{R_L} = \frac{\sqrt{L^2-R_a^2}}{R_a} \quad (1)$$

$$\sqrt{L^2 - R_b^2} - r_{min} > H_B \quad (2)$$

$$\sqrt{L^2 - R_b^2} - \frac{\sqrt{L^2 - R_a^2}}{R_a} R_L > H_B \qquad (3)$$

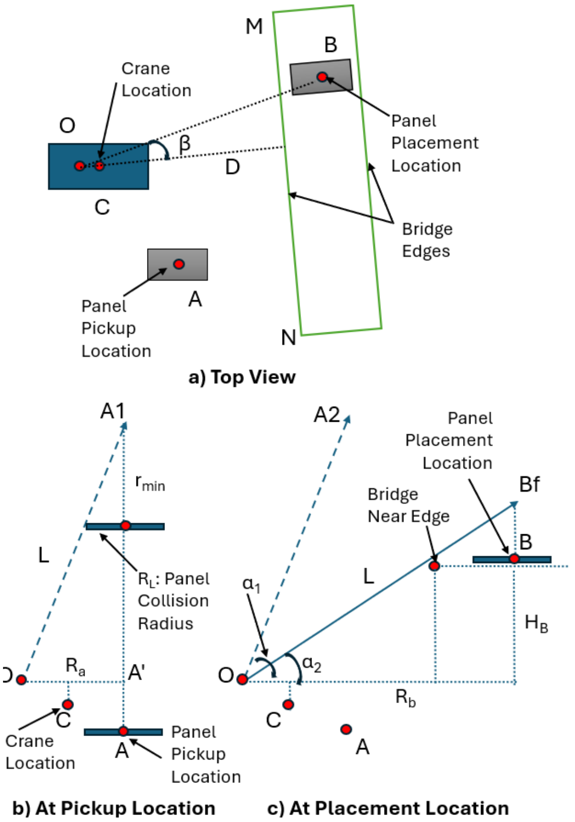

Figure 3. Crane, panel, and bridge layout and diagrams

Constraint #2: Load-Bridge Collision Prevention / Rope length constraints

By considering the length of the rope during the operation, from both the pickup location and placement location, we got the constraints of Equation (4) and Equation (5):

$$\frac{\sqrt{L^2 - R_a^2}}{R_a} R_L < r < \sqrt{L^2 - R_b^2} - H_B \qquad (4)$$

$$\frac{\sqrt{L^2 - R_a^2}}{R_a} R_L < \sqrt{L^2 - R_b^2} - H_B \qquad (5)$$

Also, the sling height (Hs) is user-provided and a part of the lifting cable length, presenting the constraints of Equations (6) to (8).

$$r_{min} > H_s \qquad (6)$$

$$r_{min} = \frac{\sqrt{L^2 - R_a^2}}{R_a} R_L \qquad (7)$$

$$\frac{\sqrt{L^2 - R_a^2}}{R_a} R_L > H_s \qquad (8)$$

Constraint #3: Boom-bridge collisions

While rotating the boom from the pickup location to the placement plane, the angle of pickup boom must be larger than the angle formed between the horizontal plane and the closest edge of the bridge boundary to the crane. Therefore, it ensures that there are no collisions while rotating. This is reflected in Equation (9), where d is the shortest distance from point O to the bridge's edge.

$$\frac{\sqrt{L^2 - R_a^2}}{R_a} > \frac{H_B}{d} \qquad (9)$$

During the placement of the panel onto the bridge, considering the placement plane in Figure 3c, the final angle of the boom (∠$α_2$) during placement must be larger than the angle between the edge of the bridge in place and the horizontal plane (∠B'OE). This ensures that when placed, the boom does not collide with the edge of the bridge. It is important to note that the bridge edge is governed by two points (i.e., point M and point N in Figure 3).

$$\frac{\sqrt{L^2 - R_b^2}}{R_b} > \frac{H_B}{d/\cos\beta} \qquad (10)$$

After applying the constraints [Equations (1)-(10)], only final feasible pairs of boom length remain and are used in setting up the simulation.

3.3 Unity3D based Simulation for Constructability Analysis

A simulation application was developed using Unity3D to support constructability analysis and plan refinement for automatic bridge panel installation. The development process comprises three primary components: virtual environment configuration, algorithm development, and simulation-based constructability analysis.

Virtual environment configuration aims at preparing 3D models (bridge and crane) and virtual scenes (terrain and layout of models) for simulation. To ensure model compatibility with Unity3D, IFC bridge models were preprocessed and converted into OBJ models using Blender. The preprocessing included merging components (e.g., columns, foundations, piles, and beams) into a single bridge body model while retaining individual deck panels as separate components. To facilitate accurate physical simulation, the pivot point of the bridge component, which defines the component's local coordinate system and controls its transformations (i.e., location, rotation, and scale), needs to be properly set up. In our case, the pivot of the bridge was set to the global origin, while deck panel pivots remained at their respective centroids. These models, along with a programmable crane, were then imported into Unity3D and augmented with colliders to enable realistic physical interactions. Figure 4 illustrates the workflow of model preprocessing and importing.

Algorithm development involves developing algorithms for heuristic planning and crane control. The heuristic planning algorithm calculates necessary parameters for crane installation actions. The crane control algorithm was developed based on behavior tree (BT) - a tree-like control architecture that sequences crane actions (Figure 5). BT decomposes a high-level installation goal into a set of primitive actions. Each action is responsible for a specific subtask/subgoal and consumes the generated parameters to execute the installation. As illustrated in Figure 5, the BT features a sequence node at the bottom for single-panel installation actions, and a repeater node at the top to loop through the process until all panels are installed. Figure 5 presents a screenshot of the BT execution interface, which enables intuitive monitoring of the whole installation process and status of individual nodes.

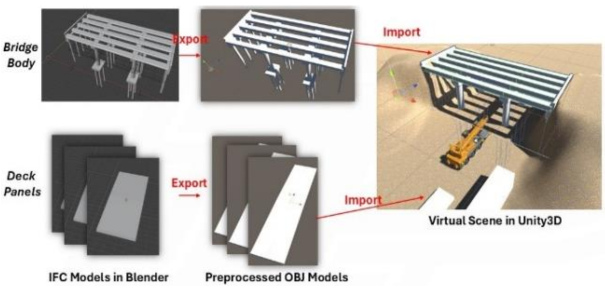

Figure 4. Preprocessing and importing IFC bridge models into Unity3D

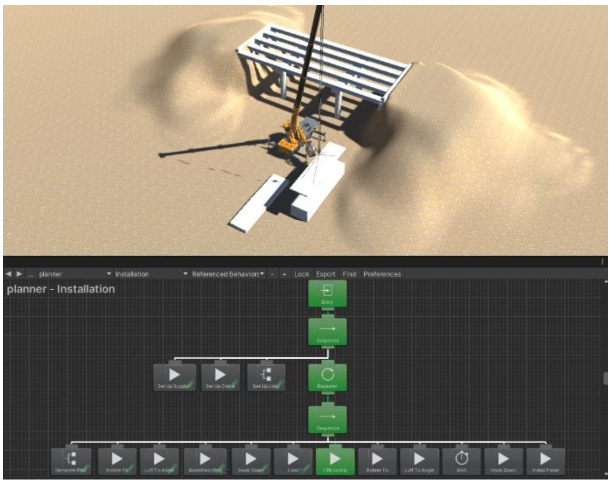

Figure 5. A screenshot of the execution of the developed behavior tree

Simulation-based constructability analysis evaluates and refines generated plans through iterative simulation. As illustrated in Figure 6, the process begins with crane selection and site layout setup, followed by heuristic planning. If the generated plan is valid, it is executed via physical simulation and visually evaluated by the human user. When planning or execution issues are identified, the user can adjust the layout or reselect a capable crane and repeat the process until a satisfactory plan is found.

This iterative process enables 1) feasibility assessment of the chosen crane size and site layout at the pre-execution planning phase, and 2) detailed validation of the generated plan by examining dynamics of the execution using Unity3D's physical engine.

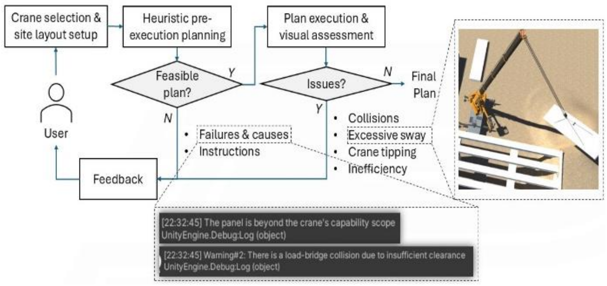

Figure 6. Workflow of simulation-based constructability analysis and feedback illustrations

4 Results and Discussion

We developed a full simulation of the crane based on two IFC bridge models (one was exported from OpenBridge and the other was exported from Autodesk Revit). With the selected crane and process as shown in Figure 6, the associated crane load chart was imported to Unity in the format of a .csv file. While the location of the imported bridge was defined based on the global coordinate specified in the IFC file, the locations of the crane and the pick-up panels were determined by users.

Case 1 – Non-installable panels (Out of reach, beyond loading capacity, or violating constraints): We place the crane at (x=-0.03, y=0.84) as shown in Figure 7a. The heuristic planning algorithm identifies Panel#1 and Panel#2 as non-installable panels and outputs related analysis information. Panel#1 cannot be installed because its placement location is out of reach, while Panel#2 has one valid pair which is determined as an infeasible pair since it will lead to load-bridge collisions. The feedback informs the operator to relocate the crane or panels to get feasible plans for installing Panel#1 and Panel#2.

Case 2 – Installable Panels: We set up another stack of panels at a different location, which contains eight panels with their IDs ranging from #3 to #10, as shown in Figure 7a. The algorithm recognizes all these panels as installable panels. Then the control parameters (i.e., swing angle, luffing angle, and rope length) are automatically calculated to generate the simulation of the installation process. Operators can visually assess the constructability of the generated plan and optimize it by adjusting the control parameters if needed (e.g., increasing luffing angle for a larger clearance between the boom and bridge to ensure safety).

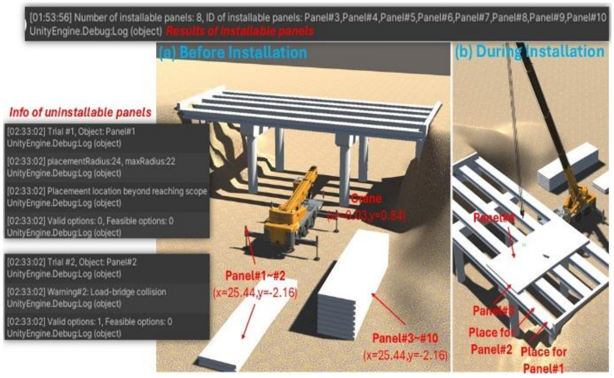

Figure 7. Illustration of planning results and execution of installation plan: (a) before-installation scene, and (b) during-installation scene

According to the workflow in Figure 6, our system can simulate all possible lifting cases and provide the operator with an early feasibility in their plan for lifting the bridge panel. By changing the locations of the crane and panel pickup point in different trials, the simulation could list all feasible installation options and infeasible options with associated reasons to support the users' decision-making during the pre-planning stage.

5 Conclusions

In the current practice, precast bridge installation relies heavily on the individual skills and experience of the operator. This practice faces challenges regarding the efficiency and safety of the operation. The use of simulation with IFC-based design models of precast bridge components (e.g., deck panels) in the installation process could allow crane operations to be smoother and more optimized during the preplanning phase. In this paper, we proposed a simulation pipeline that takes the IFC model of the designed precast bridge as input and produces 3D simulation with an analysis algorithm. The simulation allows users/operators to select the possible location of the drop-off panel, location of the crane, and number of possible placements based on collision scenarios. The simulation helps the operator to optimize the operation during pre-planning.

While the proposed simulation pipeline can be used to support pre-planning of the bridge desk installation, we acknowledge the following limitations to our approach. First, it requires the users/operators to have some knowledge/familiarity of the simulation engine. Besides, our approach assumes that there is no tall obstruction between the bridge and the crane, which is likely to be valid during most bridge installations, but exceptions could exist. For future work, further extensions to the heuristic algorithms for relaxing such constraints could be developed.

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