Intelligent Crane Management Algorithm for Construction Operation (iCrane)

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ABSTRACT

Heavy industrial construction project requires the installation of hundreds of large heavy modules. Effective utilization of lifting equipment is critical to ensuring economical project start-up. Capturing and evaluating global crane relocation, movement, and decommissioning, as well as object lift study and digital visualization, is essential in order to reduce costs and time. This paper presents a unique methodology that combines crane selection, optimum lift sequencing, and project global and individual lift visualizations in a single-sequenced algorithm. The state-of-the-art methodology incorporates all site constraints needed to ensure safe, economical crane lifts and proper reactions responsive to site condition changes.

The algorithm is divided into several modules and sub-modules which focus on different aspects of the crane management process. The algorithm build-up structure is designed to employ specific volumes or even stage sections independently which allows the user to run either the entire program or just a specific portion. In this paper the authors also discuss modules of site preparation stages of the algorithm and the mechanism for lift object path development. The visualization algorithm presented in this paper is based on specific case studies, and synopsis for such case is provided for further evaluation. A student dormitory at Muhlenberg College in Allentown, Pennsylvania, is presented as a case study demonstrating efficient construction based on advanced equipment planning. 3D visualization-based motion planning is presented to develop motions of mobile crane operation based on various design changes. In the case study, real time construction schedule updating in the weather changes allows the construction site manager to accurately modify crane lift sequence to ensure timely project delivery.

Keywords - mobile crane lifts, lift logistic, site layout, mathematical algorithm, visualisation,

1 Introduction

Driven by demand for oil and gas in the global market, the province of Alberta, Canada has been a leading crude oil supplier due to its abundant oil sands reserves. The exploitation of these reserves leads to the expansion of current industrial plants and frequent maintenance of the infrastructure, in which mobile cranes play an important role, being readily utilized to lift heavy modules that have been prefabricated offsite and shipped to site for installation. While the large scale of these projects necessitates frequent utilization of mobile cranes, the complexity of these projects makes heavy lifting difficult. Improper management of these mobile cranes can cause significant budget overruns, although the losses resulting from delays, declined productivity, and safety hazards resulting from misuse of mobile cranes can be difficult to quantify. In recent decades, researchers have been developing algorithms and methodologies to assist with planning of heavy lifts performed by cranes. Some of these crane-related research topics have included crane type selection [1; 2; 3; 4); crane location and supplying location optimization [5; 6; 7]; lift sequence simulation [8; 9; 10]; crane lift path planning [11, 12, 13, 14, 15; 16; 17], 3D visualization of crane operations to detect potential conflicts [18, 19, 20] and rigging analysis [21]. However, the above listed methods-technologies are not available in the market, either having been developed for research purposes or for internal use by companies. Also, these programs have been built individually and thus cannot be used as part of an integrated system by clients. Meanwhile, there are several commercial programs for heavy lift studies which are available in the current market. One example of a commercially available lift study application is the 3D Lift Plan [22]. Nevertheless, these programs are usually developed for single-lift studies and overlook the importance of multi-lifts on the site. For example, for multi-lifts the lifting sequence may have an impact on the feasibility of module lifts, which necessitates that the site obstructions be considered as time-dependent in the analysis. In addition, each of these programs only focuses on one side of the heavy lift planning (e.g., crane type/location selection or crane operation visualization), and communication among these programs is difficult to achieve. Therefore, the proposed Intelligent Crane Automation, Planning and Simulation (iCrane) fills the gap by integrating all heavy lift planning components together and delivers the clients a complete approach to heavy lift studies. In the current market, there is no such program that can facilitate comprehensive heavy lift studies and automate the planning process for industrial projects. This program has the potential to be used by large oil companies and contractors for complex refinery plant construction for heavy lift studies and management. In addition, this tool can be applicable to any industrial project that involves off-site modular installation by mobile cranes.

2 iCrane Methodology

This paper presents advancements in the development of mathematical algorithms for crane selection, crane position determination, the lifted object pick-point optimization, and lifted object trajectory and analysis. The methodology is divided into smaller manageable phases to control the process. Each step of the lifted object movement is algebraically-digitally tracked, starting at the lifted object pick-point through an optimum path development to the object's final position or set-point. The methodology, as illustrated in Figure 1 comprises nine modules.

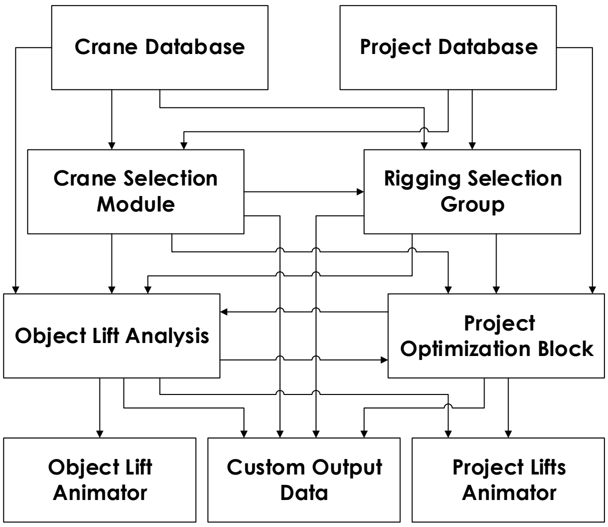

Figure 1. iCrane methodology

Two components—the Crane Database and Project Database—are collections of information with respect to which an algorithm initiates specific analyses. The Crane Database deposits all necessary parameters for cranes, such as main body, boom, superlift and /or counterweight, which can be prepared prior to any program initiation. The Crane Database is updated continually depending on the type of crane usage. Each crane includes all possible configuration types, which expand the database size such that it must be managed by mean of reliable program. The Crane Database schema and layout are thus critical aspects of the iCrane program.

The Project Database contains data related to individual projects and must be altered for algorithm calculation. Such alterations are carried out by a qualified professional directly involved in the program and are carefully planned. In addition to dimensions, weights and CofG position, lifted object data must include position, orientation, and proper sized of lifted lug for the object lift. This particular check task option is embedded in the iCrane algorithm in order to validate the lifted object lug data input. The job site layout with defined services, lifted object setup and obstruction areas must be identified prior to entering information to the appropriate database section.

2.1 Crane Selection Module

The Crane Selection Module algorithm performs crane selection analysis based on project object data and client crane availability. This algorithm, which is the first to be applied, selects only cranes that can meet criteria related to lifted object weight, site condition requirements and client availability. The Crane Selection module is an important section of the iCrane program due to the fact that the selected crane "drives" all downstream algorithm tasks. Figure 2 shows the Crane Selection methodology schema.

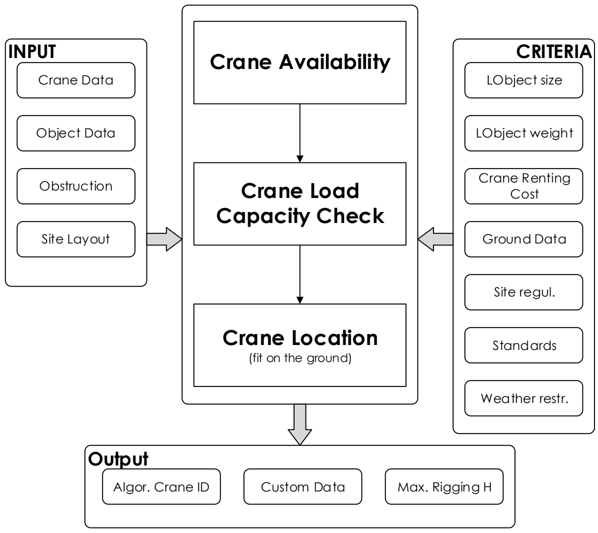

Figure 2. Crane selection module methodology

Any change to the selected "driver" must be initiated from the Crane Selection Module. This module utilizes some methods and research previously described [3, 21] but is remodelled to accommodate the iCrane concept layout. The Crane Selection Module is a passive source to the Crane Database and Project Database but active to the Rigging Selection Group, Object Lift Analysis, Project Optimization Block, and Custom Data Output.

2.2 Rigging Selection Group

The Rigging Selection Group is a unique section which includes the rigging database and particular object lift rigging calculation components with simple optimization engine. Rigging selection includes calculation formulas starting from the lifted lug (lug validation submodule implemented), then transfer of load to lifted lines, which may include special slings ends, turnbuckles, links, shackles and hooks, specially designed connecting components, and crane hooks. Figure 3 shows the lift frame rigging lines with specially designed adjuster component, turnbuckle, link, and shackle.

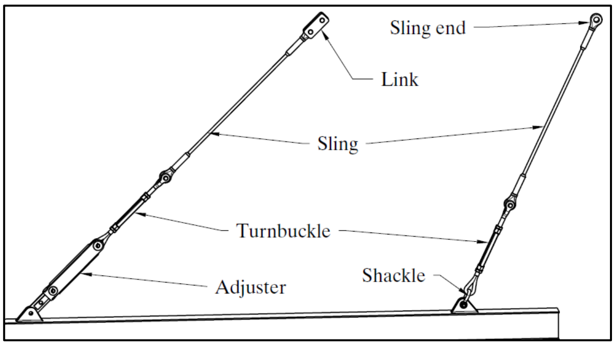

Figure 3. Rigging lines

This combination of rigging components must be carefully analyzed in order to calculate the line forces with proper safety factors in mind. The designed algorithm in this module validates the strength of components against the actual line force loading. In some industrial projects, it should be noted, heavy module lift require 8, 10, 12, 14, or even 16 pick-point rigging assembly. A traditional rigging assembly requires several spreader bars, slings, and shackles. In this traditional configuration there are: seven 6 metre (20 ft) width spreader bars, two 12 metre (40 ft) length first-level transfer spreader bars, and one 24 metre (80 ft) main bar, which contain lift ear end supported by heavy wall pipe, 36 slings with varying diameters and lengths, 54 shackles ranging in size from 25-150 tonnes. It also noted that for one lift there can be over 150 pieces in one rigging three equipment inventory that must be managed Figure 4 shows a traditional 14 pick-point rigging assembly.

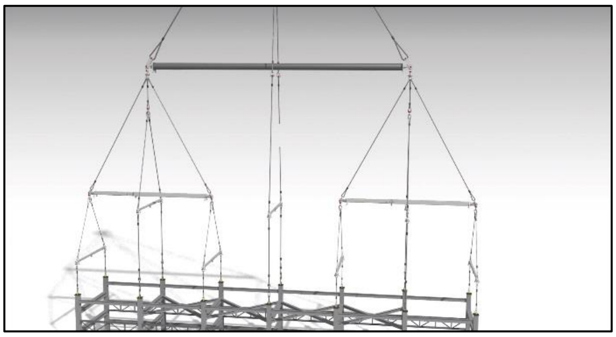
Figure 4. Traditional 14 pick-point rigging

Furthermore, large shackles or long slings must be handled by a forklift since they are too heavy to be lifted manually. Rigging simplification and software such as the proposed iCrane can facilitate accurate selection of the proper rigging configuration. Figure 5 illustrate the Rigging Selection Group methodology.

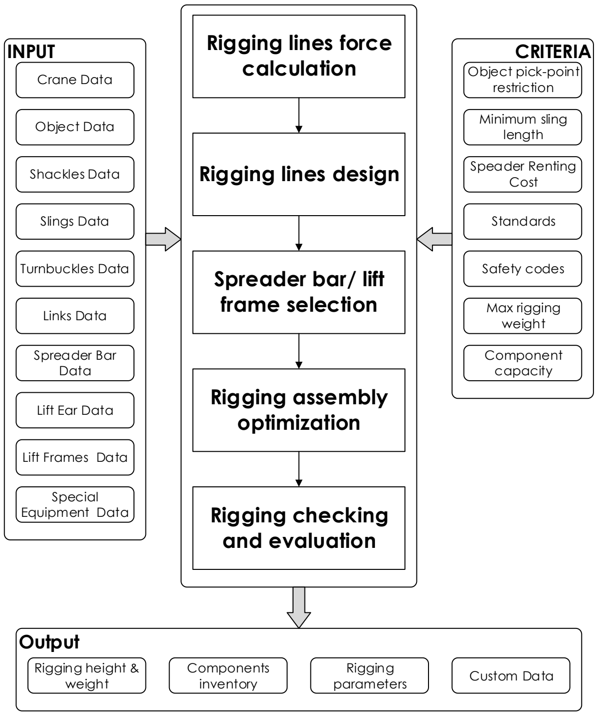

Figure 5. Rigging selection group methodology

The Rigging Selection Group is a passive source to the Crane Database, Project Database and Crane Selection Module but active to the Object Lift Analysis, Project Optimization Block, and the Custom Data Output.

2.3 Object Lift Analysis

The Object Lift Analysis module comprises several algorithms which evaluate and optimize crane location position based on restrictions (obstructions), lift radius reach, and other issues related to a given lifts. The Object Lift Analysis module mainly focuses on implementing a robotic motion planning method to check/plan lift paths at selected crane locations from the Crane Selection Module set. The lift path checking/planning process considers the boom clearance and rigging limits, lifting capacity, and tail-swing/superlift equipment constraints. For mobile crane operation the boom clearance and rigging limits under given lift radius and elevations must be satisfied, as well as the minimum lifting capacity; furthermore, the mobile crane's body and tail-swing/superlift equipment must be collision-free during crane operations. Ultimately, the robotic motion planning method creates the configuration space based on the existing onsite obstructions under the given lifting sequence. Based on this, the detailed lift path can be generated in the configuration space. It is essential that, if the mobile crane fails to perform the lift at the given crane locations, the crane walking is taken into account; accordingly, the Object Lift Analysis embeds crane walking by checking the crane's walking path in the context of the surrounding environment. Figure 6 shows the Object Lift Analysis methodology.

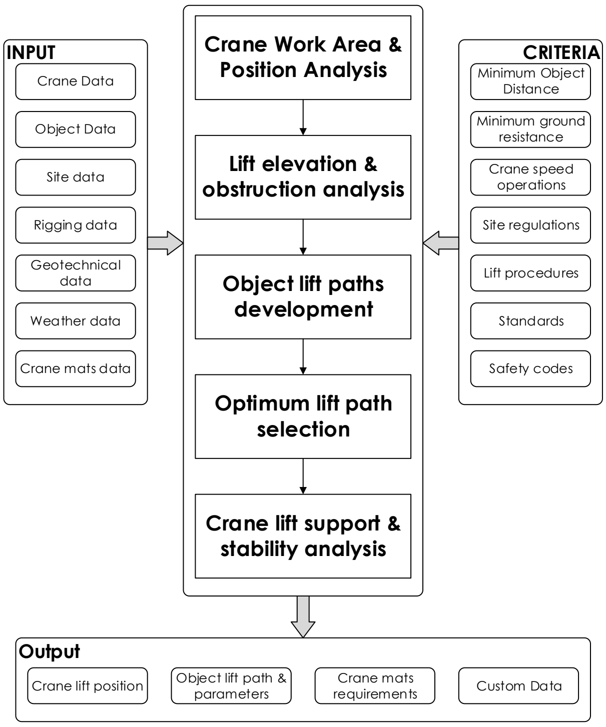

Figure 6. Object lift analysis methodology

The expected outputs of the Object Lift Analysis section are:
(1) feasibility of crane lift for every individual crane location;
(2) detailed crane lift path/walking path; and
(3) detected problems (failed crane locations).

The results are utilized to improve the current lifting sequence and consequently select the best crane location combinations. Output from this module maybe utilized in global optimization lift sequences (Project Optimization Block) as well as in the creation of individual lift studies (Custom Output Data) for professional acceptance and/or confirmation of Object Lift Animator visualization results. Figure 7 represent a web sample drawing of all possible lift paths of a given lift.

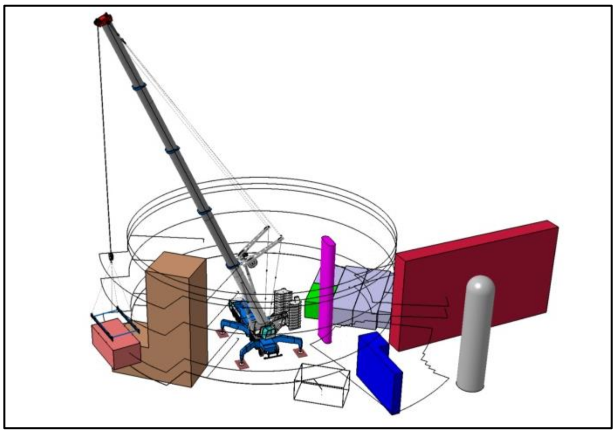
Figure 7. Lift paths of selected object.

The Optimum Lift Path Selection algorithm sub-model selects the optimum path based on the defined criteria.

2.4 Project Optimization Block

The Project Optimization Block module includes algorithms that can optimize the desired selection of collected data during the calculation process, such as logic sequences based on Object Lift Analysis output and predefined client lifts schedule.

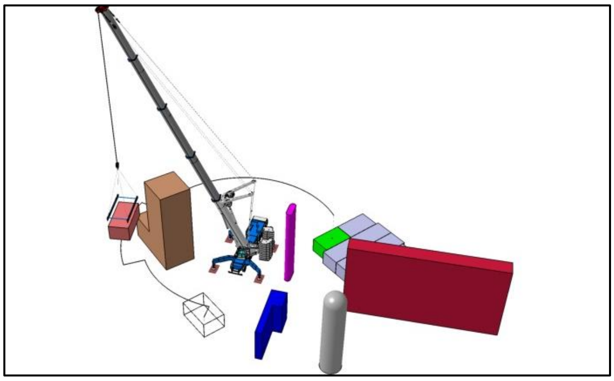
Figure 8. Optimized object lift path.

This module can be designed to provide real-time results either to feed to the next module, the Project Lift Animator, for global project progress evaluation or to retract the modified optimization lift sequence output based on the altered delivery object schedule. In the case of lift sequence modification the Object Optimization Block module "requests" the Object Lift Analysis to check the affected modules to be analyzed because of a new "floated obstruction" (where modules placed prior the lift act as floating obstructions) (see Figure 8). The Project Optimization Block improves (i.e., shortens) the walking path of the crane with load from the object pick point to the object set point if the lift cannot be performed by the crane from a stationary position. A unique algorithm code defines the object pick points from the available pick area based on entered input, such as shortest crane boom radius, minimum crane boom angle rotation, or available area centroid calculation. These are only a few options that are implemented in the Project Optimization Block. Figure 9 shows the Project Optimization Block methodology.

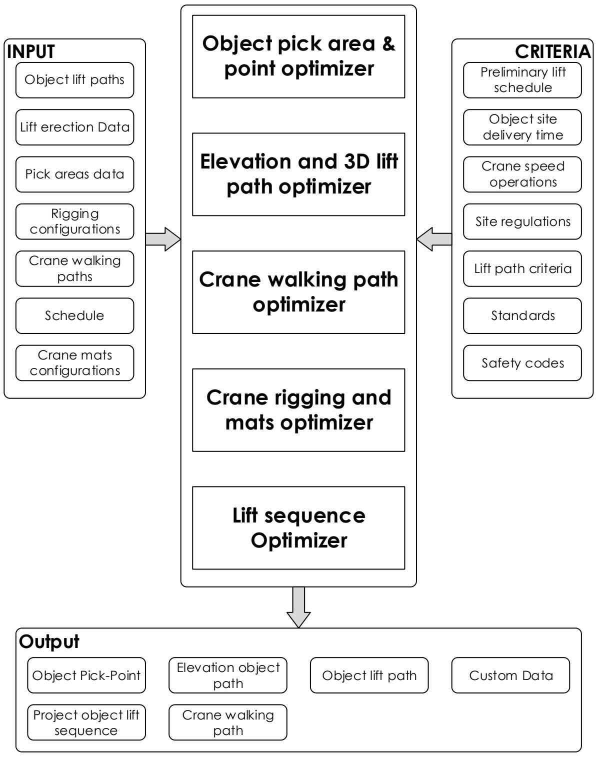

Figure 9. Project optimization block methodology

This module optimizes repetitive tasks of any segment of the algorithm according to client-specified or default requirements. The provided flowchart represents only a few of the inputs and criteria for the sub-module algorithm. Sub-modules are designed to solve specific tasks and provide optimum solutions. The solution from this sub-module either is utilized to repeat lift analysis on the modified scenario or is passed to the Project Lift Animator for the purpose of customer visualization. Some information can be extracted individually for evaluation and comparison purpose in order to test multiple possible project lift scenarios.

2.5 Object Lift Animator

The Object Lift Animator module is capable of "building" digitally and in detail the entire interested area in a CAD program. The crane, lifted object, and affected obstructions are presented for in-clash detection as well as for the purpose of visualization. Based on Object Lift Analysis outputs such as crane location and pick and set position of lifted objects, the Object Lift Animator module builds all 3D models, including lifting objects, 3D crane model, and site layout. These models are built in CAD programs such as AutoCAD, CATIA, and 3D Studio Max, and the module describes detailed modes in order to design automatically collision-free motions of crane operation for each lifted objects. The Object Lift Animator module computes the required angles of crane body parts from current positions to the desired ones and collision-free material paths by detecting feasible collision errors (clearances) between crane parts and existing obstacles on site during animation time. Figure 10 illustrates the Object Lift Animator methodology.

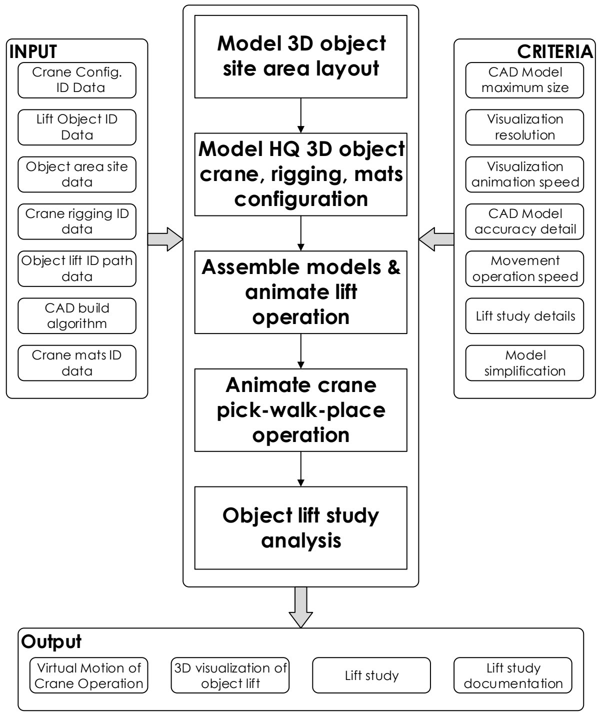

Figure 10. Object lift animator methodology

This module provides lifting analysis in order to evaluate the crane performance in terms of crane capacity, time and speed when cranes have different motions designed in the Object Lift Animator module.

This lifting analysis also supports and validates lifting schedules determining the best option of crane operation for a lifted object that may have more than one crane location. The Object Lift Animator module employs a simulation engine such as Simphony (developed by University of Alberta) in order to analyze expected crane operation cycle time on each crane location for lifted objects. The expected outputs of the Object Lift Animator module are as follows:
(1) provide collision-free crane operations for each lifted object;
(2) support and optimal crane operation based on outputs of lift analysis and simulation; and
(3) improve decision making with respect to critical issues in lifting planning
Figure 11 shows an example of the Object Lift Animator output data.

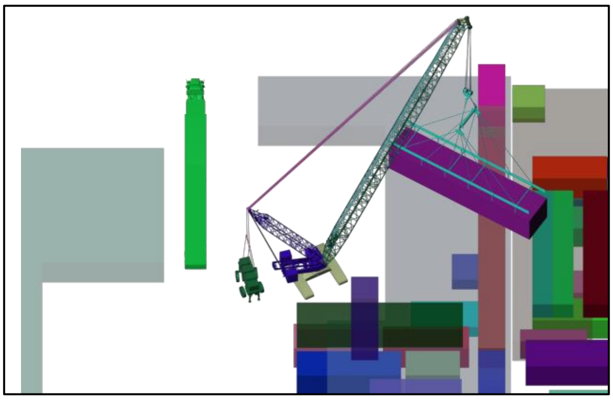

Figure 11. Snapshot of crane object placement (AVI file)

2.6 Custom Output Data

The Custom Output Data module selects specific information defined by the customer or user. At the time of project preparation or execution decision makers requires accurate and readily available information about different aspects of the project assembly details, e.g., rigging inventory, crane mattings amount, object lift study details, and weather interruption schedule schema. Such information can be retrieved in real-time during project operation by means of the algorithm employed in the Custom Output Data module. The authors intend to devise a list of common algorithmic answers for pre-project module setup but to also include an option for the user to create Client Defined Real Data (CDRD) algorithm output. The iCrane algorithm modular design permits the retrieval of any information at any stage on of the running of the program. The CDRD option as part of the Custom Output Data module is unique in construction operation and position iCrane at the leading edge of equipment utilization planning and execution.

2.7 Project Lift Animator

The Project Lift Animator module shows simplified solid models of the entire project site with an embedded timeframe aspect. The current crane positions are taken directly from the Project Optimization Block; however, simulation of individual lifts is not performed. Acceleration of the schedule gives a visual and global perspective of crane placement schema (related to possible demobilization and mobilization), critical areas crane occupancy timeframe, transportation and delivery accessibility. Based on individual crane operations analyzed from the Object Lift Animator module, the Project Lift Animator module illustrates entire crane operations and animation in order to provide a perspective view of crane operation to project participants for error detection and path validation, which are critical elements in lift planning, especially when a large number of lifts need to be performed in congested sites. Figure 12 shows the methodology for the Project Lift Animator, which is similar to the Object Lift Animator. The Project Lift Animator provides a general view of the entire project and visualizes daily crane utilization output.

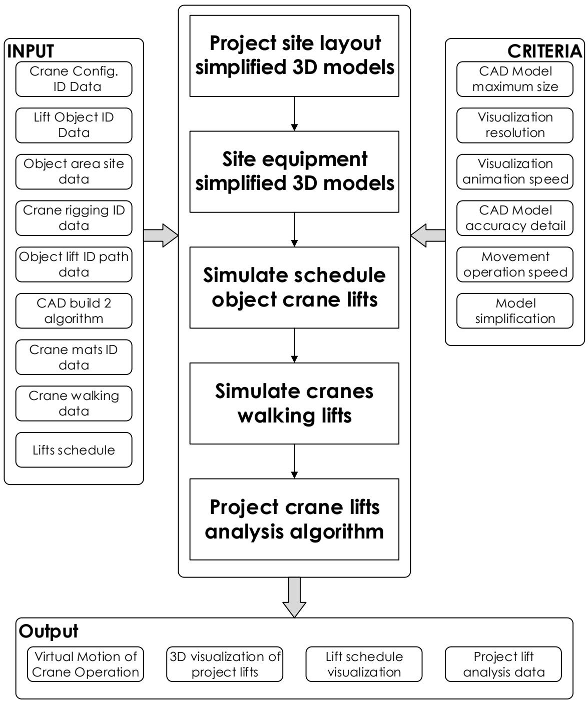

Figure 12. Project lift animator methodology

The Project Lift Animator module computes and then visualizes clearances between cranes on sites, which is especially important for multiple crane operation in congested sites, in order to identify feasible crane conflicts. Since this module is a comprehensive validation tool, the Project Lift Animator module provides lifting schedules during crane operation concurrently so that the lifting schedule can be compared and potential errors detected. It may use a simulation engine such as Simphony in order to analyze expected cycle time of crane operation (productivity). The expected outputs of the Project Lift Animator module are follows:

(1) provide collision-free single- or multiple- crane operations;

(2) validate lifting schedules with productivity analysis when a project has a large number of lifted objects; and

(3) improve communication and collaboration among all participants in a project.

3 Case study

The case study involves the assembly of a student dormitory constructed at Muhlenberg College in Allentown, Pennsylvania using a modular construction method. The project is composed of five three-storey dormitory buildings built to replace out dated single-level dorm units. A key challenge of the project is that the new buildings must accommodate the surrounding buildings from an aesthetic and architectural perspective while maintaining the structural integrity needed for a large building comprising 18 modular units (see Figure 13).

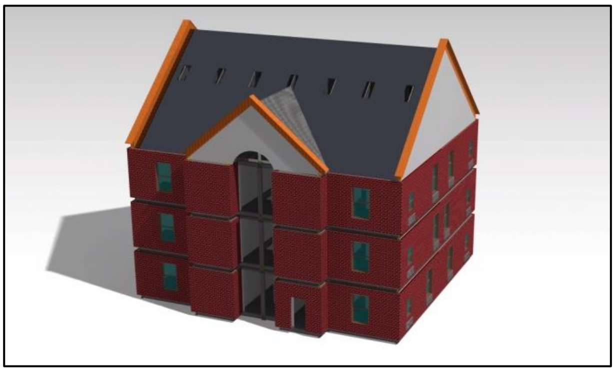

Figure 13. Muhlenberg College dorm building

A total of 90 inhabitable modules are manufactured in Lebanon, NJ by Kullman Building Corporation and delivered to the job site in Allentown. Five roofs and walking bridges (man access to each building is through the second floor) are constructed on site. The construction assembly challenge is to optimize lift time schedule, and applying novel planning methods the number of lift days is reduced from 21 to just 10.

4 Conclusion

The proposed Intelligent Crane Algorithm for Construction Operation (iCrane) program combines all aspects of crane lift planning for on-site assembly on heavy industrial projects—including automation, planning, and simulation—into a single software application. Currently, project execution teams rely on separate applications or methods to select project cranes, optimize on-site crane placement for lifts, prepare critical lift studies, control project schedules and budgets, and assign project resources. iCrane will function as an independent unit where outputs can be extracted at desired algorithm processing steps and converted into numerical values for specific task process durations, and can generate individual lift visualization movies or automated critical lift study drawings. Outputs of the iCrane algorithm can be client-defined at different levels of the processing sequences and may reflect project/contract requirements. A customized user interface can reflect client preferences and the importance of input/output information, and can integrate owners' unique preferences. Historically-proven best practices will be used to enhance the iCrane algorithm in order to implement it for analysis of future projects. The iCrane algorithm can be customized for specific industry implementation, although it will be designed (as a default) for automation and planning of onsite crane operations

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