Constructing a Complex Precast Tilt-Up-Panel Structure Utilizing an Optimization Model, 3D CAD, and Animation

Juan D. Manrique[1]; Mohamed Al-Hussein[2]; Avi Telyas[3]; and Geoff Funston[4]

Abstract: This paper presents the concept used to construct a complex residential tilt-up-panel structure utilizing three-dimensional (3D) modeling and animations. The residence comprises of 108 precast concrete panels of varying rectangular shapes with "dog legs" and window and door "cutouts" that look like an assembled jigsaw puzzle. The erection and installation procedure called for a maximum panel-to-panel joint tolerance of 1.27 cm (0.5 in.), often in 90° joints between panels. 3D animations were used to experiment with the construction process on the computer screen prior to construction in order to avoid potential costly on-site errors. In addition, the 3D animations were also used as a training tool for the contractors. This paper focuses on describing the methodology used to integrate a crane selection algorithm and optimization model with 3D modeling and animation for the selection, utilization, and location of cranes on construction sites. Analytical optimization processes were used to decrease the traveling time and distance of the selected crane, to improve the crane lifting sequence and to minimize the use of panel casting slabs.

DOI: 10.1061/(ASCE)0733-9364(2007)133:3(199)

CE Database subject headings: Algorithms; Optimization; Three-dimensional analysis; Computer aided drafting (CAD); Computer models; Computer software; Cranes; Connections.

Introduction

Material handling is an important task in the delivery of construction projects, and cranes are the most crucial resource in achieving this task. Selection of the type, number, and location of cranes is essential in planning construction operations. Skilled judgment is critical in the crane selection process, which takes a number of technical and financial factors into account. Information utilized in this process may include required attachments, manufacturer performance specifications, and load-capacity charts. To aid practitioners in the selection and utilization of cranes, a number of computer applications have been developed. Some of these applications use integer programming and optimization techniques (Lin and Haas 1996) or 3D graphics and simulations (Hornaday et al. 1993; Dharwadkar et al. 1994). Other applications were developed for crane selection utilizing knowledge-based expert systems (Al-Hussein 1999; Zhang et al. 2005; Al-Hussein et al. 2001, 2005). They advanced crane utilization knowledge by assisting crane users with crane selection and location on construction sites utilizing the geometric cranes information stored in a comprehensive cranes database (Al-Hussein et al. 2000). CAD tools are being used to visualize construction operations by permitting the analysis of complicated on-site procedures to occur first in an office. Successful construction operations coordinate the complex interactions between multiple pieces of equipment, labor trades, and materials (Kamat and Martinez 2001).

Computer simulation and animations provide users with an innovative way to analyze a composition that contains different elements that all play a roll in a unique environment. For example, 3D modeling generates spaces that can be as accurate as real life. More and more users have become dependent on computational software because analyzing an operation in the office, as compared to improvising the same operation on-site, substantially reduces costs. With the advances in technology that have occurred during the past 10 years, computer applications have changed the industry. Simulation modeling and visualization substantially assist in the designing of operations and in making optimal decisions, whereas traditional methods prove ineffective or are unfeasible (Kamat and Martinez 2001). Any CAD software is based on input data (3D information) given by the user. The input data would behave more realistically if its graphic representations and user applications better reflected the customer's needs and could be applied without extensive effort. Research has been done in regards to automation and computer analyses based on 3D modeling and integrating systems: (Bjork 1989; Ammermann et al. 1994; Aouad 1994; Tracey et al. 1996; Zhong et al. 2004).

The combination of 3D modeling and optimization techniques can provide a wide range of possible solutions that would provide different perspectives when making managerial decisions. In order to do so, a combination of the CAD geometrical space and a syntax or optimization procedure must occur. There is a lack of

[1]MSc Student and Research Assistant, The Univ. of Alberta, Dept. of Civil and Environmental Engineering, Hole School of Construction, 1-080 Markin/CNRL Natural Resources Engineering Facility, Edmonton AB, Canada T6G 2W2. E-mail: jdm19@ualberta.ca

[2]Assistant Professor, The Dept. of Civil and Environmental Engineering, Hole School of Construction, 3-011 Markin/CNRL Natural Resources Engineering Facility. Edmonton AB, Canada T6G 2W2. E-mail: malhussein@ualberta.ca

[3]President, Seaview LLC Corp., General Builder and Contractor, Old Westbury, NY 11568. E-mail: avi@seaviewcorp.com

[4]Construction Manager, Seaview LLC Corp., Old Westbury, NY 11568. E-mail: geoff@seaviewcorp.com

Note. Discussion open until August 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on January 11, 2006; approved on May 15, 2006. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 133, No. 3, March 1, 2007. ©ASCE, ISSN 0733-9364/2007/3-199–207/$25.00.

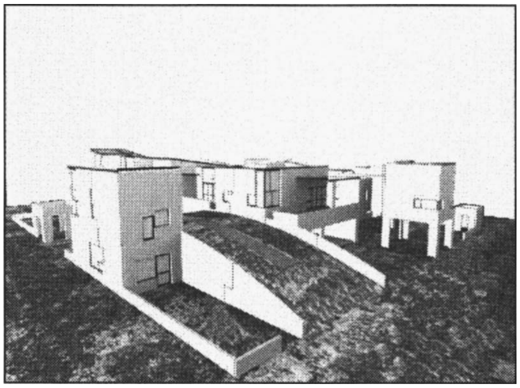


Fig. 1. Architectural model of the case study

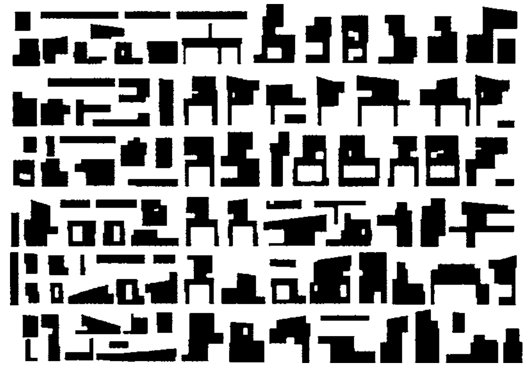


Fig. 2. 108 concrete panels used for the case study

connection between these two parts in many construction companies; the lack of consideration of spatial requirements for construction operations as a resource in their scheduling (Mallasi and Dawood 2002). This paper presents the challenges of the case study in regards to the unique construction method that was used with the set level of finishing quality tolerance and accuracy.

Case Study

The case study documented in this paper demands a high degree of accuracy in erecting the tilt-up concrete panels. Shape accuracy was extremely important for this complex architectural designs, which called for a maximum panel-to-panel joint tolerance of a total of 1.27 cm (0.5 in.) or 63.5 mm (0.25 in.) from each panel, often in 90° joints between panels. This required an extremely flat casting slab and precise formwork. In addition, since the exterior face received an acid stain treatment, the panels had to exhibit a smooth surface finish free of bug holes, voids or other surface irregularities including consistency in color and texture of the aggregate. One advantage of this singular method is that it reduces construction times and is less expensive (Meadow Burke 2002) and (TCA 2004). The case study presented in this paper involves the construction of a complex architectural design for a residence in New York, as shown in Fig. 1. The case study is a unique private residence, which had its main structure constructed during the summer of 2005. Designed by Steven Holl (Holl 2004), this facility uses a construction methodology called tilt-up panels, which is based on cast on-site reinforced concrete panels. The residence comprises of four pavilions and other facilities including a library, theater and a gallery. New York based firm Robert Silman Associates, P.C, engineered the structure of the facility.

This complex project includes 108 tilt-up panels (Fig. 2), extending up to 10 m (35 ft) in length and height with weights ranging from 1,500–30,000 kg (3,000–61,000 lb). Most of the panels have a thickness of 20 cm (8 in.), but some are as thick as 25.4 cm (10 in.), as determined by structural requirements. The construction covers more than 2,000 m^2 (22,000 ft^2) in gross area with two upper levels and an underground level. The unique structural complexity poses the challenge of optimizing the constructability process.

Precision and accuracy were important factors that played enormous roles during the assembly of the panels. The case study can be likened to the construction of a 3D jigsaw puzzle with 90° connections of puzzle pieces. A lifting sequence was required to put the panels together without increasing the risk of misfits or problems, based on space constraints and bracing needs, during the installation. There were many uncertainties to address; thus, a smaller model, hereafter referred to as the "mock-up model," was constructed to assist in the material selection and to learn more about the panels' erection procedure. The mock-up model is comprised of five concrete panels, similar to those in the actual structure, with window and door openings and rectangular and diagonal shapes as shown in Fig. 3. The dimensions of this mock-up model were one-third the size of the actual panels. The mock-up model gave invaluable insights regarding the process of erecting the concrete panels. Different constraints were tested and possible solutions or suggested changes needed for actual construction were obtained. Two of the tested constraints were the concrete mix and the casting slabs required to form the panels. The formwork could not be reused since each panel shape is different and since they also had to be poured within a short period of time for quality purposes and to ensure the same type of aggregate would be used.

Other challenges included the crane selection and location, in addition to the establishment of a casting panel layout, which was carried out using an optimization model described later in this paper. A novel feature of this construction is the introduction of 3D and 4D models to prevent problems that could arise unexpectedly during the erection of the structure. Knowing all the con-

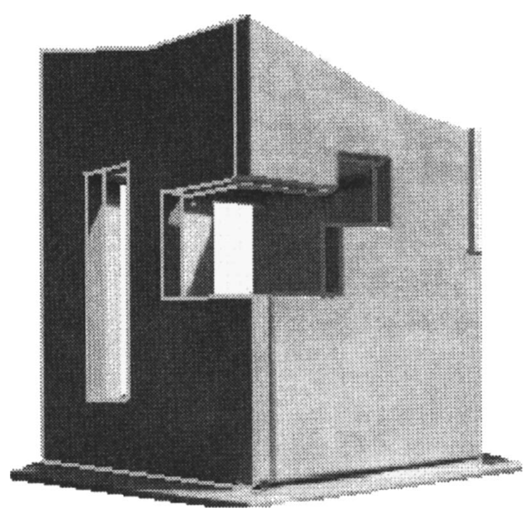


Fig. 3. Mock-up model

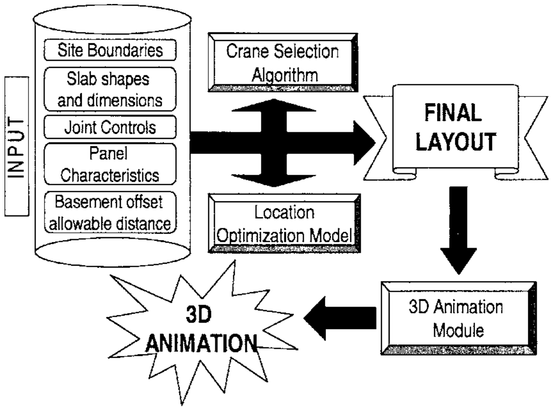


Fig. 4. Proposed methodology main process

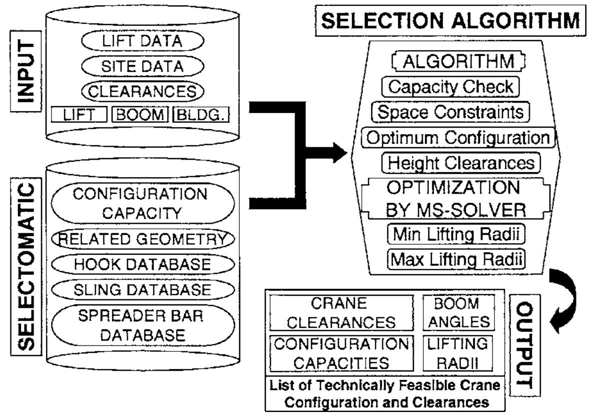


Fig. 5. Algorithm selectomatic

straints before tilting up each panel will not only reduce costs, time and labor, but the quality of the installation will also match the expected tolerances.

Proposed Methodology

The proposed methodology follows the concept illustrated in Fig. 4, which focuses on optimizing the layout for the casting slabs and lifting sequence while considering the following constraints: Site boundaries, casting slab joint-control connections, casting slab shapes and dimensions, panel characteristics, and maximum ground pressure exerted on the basement walls. In addition, the proposed methodology incorporated a crane selection process, which followed the algorithm described by (Al-Hussein et al. 2001, 2005), to maximize the crane utilization on-site, as well as analyzing different cranes in a variety of picking and placing point scenarios.

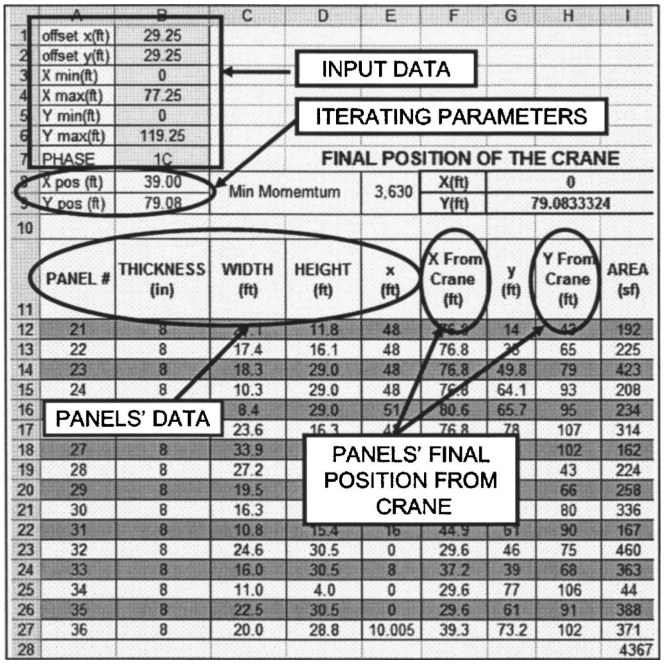
With this algorithm, more than 50 different types of cranes were tested in order to obtain the equipment with enough capacity to lift the 108 concrete panels, but at the same time, with the lowest rental cost. Space constraints and clearances between the lifted panel and the ongoing construction were verified with this algorithm. With the incorporation of a database and developing an optimization model, this research targeted to reduce the casting slab area by placing the concrete panels as close as possible from each other, and as close as possible to the crane in order to accomplish the following: Facilitate the lifting process on-site, maximize the crane capacity and obtain a cost reduction in concrete, workmanship, and equipment rental cost by minimizing the construction of casting slabs. Then, the construction site layout was designed using the output data from the crane selection algorithm, the optimization model and the construction characteristics. The main objective was to minimize the crane's travel by lifting as many panels as possible from the same location, minimizing as well the risk related hardware failure by dropping any panel during the travel. Due to the complexity of the shapes of the concrete panels, the lifting process was enhanced by developing 3D animations. The lifting and bracing crew benefited from this module since every morning before any installation took place, the lifting process was analyzed in detail, contemplating potential lifting movements and space constraints in regards to pivoting the panels on the casting slabs and bracing installation.

Development Process

The analysis was carried out in three steps. The analysis process used existing technology including software such as 3D STUDIO MAX, AUTOCAD, MS SOLVER, and algorithms as described in (Al-Hussein et al. 2001, 2005) (Step 1). An optimization model was developed in MS EXCEL in order to enhance the construction site layout and equipment utilization by making them more efficient (Step 2). For the crane, the goal was to optimize its use on-site by decreasing its mobilization and maximizing its lifting capacity (Step 3). For the construction site layout, the goal was to reduce its area and, at the same time, the incurred costs. The analysis process made use of the momentum equation; a vector (radii) multiplied by a force (panel weights) exerts a momentum on the crane. By locating the crane in specific locations around the facility, these momentums can have a small value, which at the same time, maximizes the crane capacity and the selection of cheaper equipment (Step 3).

Step 1—Crane Selection Process: During the crane selection step, the algorithms described (in Al-Hussein et al. 2001, 2005) were used to provide a list of technically feasible cranes for the tilt-up process; these algorithms processes are briefly described here to provide continuity. These algorithms have a friendly interface that allows users to specify location constraints such as barriers and obstacles surrounding the crane location. It also offers the user an opportunity to update the database with additional new cranes. The algorithms follow the process illustrated in Fig. 5 to assist in the selection of technically feasible crane-configurations. Therefore, based on the type of crane, the algorithm follows these two different streams: one for lattice boom cranes and the other for hydraulic cranes (a lattice boom crane was selected for the panel installation). The formulations for lifts performed only on the main boom are considered for this case study. The algorithm considers the detailed geometry of each crane in its calculation. To select a mobile crane, contractors need to know the following three main geometrical variables: Main boom length, main boom angle to ground and the crane's lifting radius. To determine the optimum boom length of a lattice boom crane, the geometry of the crane is expressed using the following: (1) the main boom length as a function of its angle to ground; (2) the main boom length as a function of the crane's lifting radius; and (3) the crane's lifting radius as a function of the main boom angle to ground.

The optimization module of the algorithm provides an easy-to-use environment for calculating the maximum and minimum



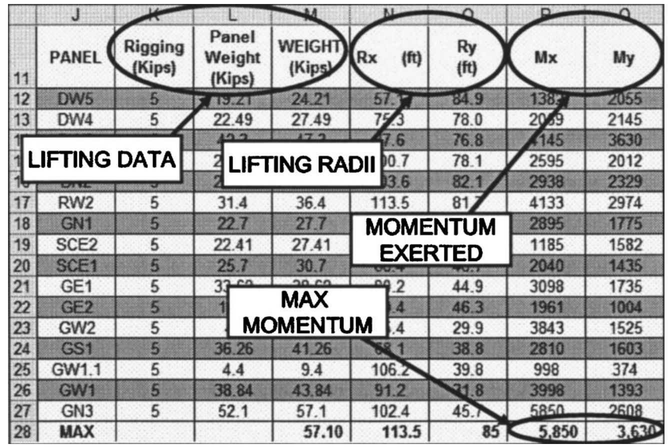
	A	B	C	D	E	F	G	H	I
1	offset x(ft)	29.25							
2	offset y(ft)	29.25							
3	X min(ft)	0							
4	X max(ft)	77.25							
5	Y min(ft)	0							
6	Y max(ft)	119.25							
7	PHASE	1C		FINAL POSITION OF THE CRANE					
8	X pos (ft)	39.00	Min Momemtum		3,630	X(ft)	0		
9	Y pos (ft)	79.08				Y(ft)	79.0833324		
10									
11	PANEL #	THICKNESS (in)	WIDTH (ft)	HEIGHT (ft)	x (ft)	X From Crane (ft)	y (ft)	Y From Crane (ft)	AREA (sf)
12	21	8	[illegible]	11.8	48	[illegible]	14	[illegible]	192
13	22	8	17.4	16.1	48	76.8	[illegible]	65	225
14	23	8	18.3	29.0	48	76.8	49.8	79	423
15	24	8	10.3	29.0	48	[illegible]	64.1	93	208
16	[illegible]	[illegible]	8.4	29.0	51	80.6	65.7	95	234
17	[illegible]	[illegible]	23.6	16.3	[illegible]	76.8	78	107	314
18	27	8	33.9	[illegible]	[illegible]	[illegible]	[illegible]	102	162
19	28	8	27.2	[illegible]	[illegible]	[illegible]	[illegible]	43	224
20	29	8	19.5	[illegible]	[illegible]	[illegible]	[illegible]	66	258
21	30	8	16.3	[illegible]	[illegible]	[illegible]	[illegible]	80	336
22	31	8	10.8	15.4	16	44.9	61	90	167
23	32	8	24.6	30.5	0	29.6	46	75	460
24	33	8	16.0	30.5	8	37.2	39	68	363
25	34	8	11.0	4.0	0	29.6	77	106	44
26	35	8	22.5	30.5	0	29.6	61	91	388
27	36	8	20.0	28.8	10.005	39.3	73.2	102	371
28									4367

Fig. 6. Optimization model, Part A

radii associated with the geometrical variables identified above. This module has been developed using MS SOLVER Optimizer, which is an add-on utility to MS EXCEL. It also provides a powerful tool for evaluating alternatives associated with the location of the selected crane (i.e., safe range in terms of lifting radius and boom angle to ground for the selected configurations). Information on crane configurations selected by the algorithm can be retrieved from the crane database (Al-Hussein 2000). However, their angles to the ground are subject to change when the lifting radius changes. The algorithm objective is to optimize the lifting radius (i.e., to determine the minimum and the maximum radii. Based on the results obtained from this interface, the next step was to choose the crane that is capable of performing the work, while minimizing mobility complications and considering operation costs, availability and accessibility parameters. A Manitowoc Crawler Mounted Crane 888 (230 t) was selected.

Step 2—Panels' Spreadsheet: To optimize the processes in the second phase of the analysis, an Excel model was developed to provide a range of possible solutions. Based on the location constraints of the construction site, the casting slabs and panels were placed in accordance with the crane's reach and capacity. Fig. 6 illustrates the characteristics of the panels included in each phase. As an example, the spreadsheet for Phase 1C is shown in Figs. 6 and 7. The offset distance from the footings/foundation walls to the center of rotation is taken into account as well as the quadrant dimensions. The input data for the model included the panels' tags, weights, and dimensions as well as a 3D model of the house with the final panel locations. The weight of the rigging system, including hooks, slings, spreader bar, and main block was 2,500 kg (5,000 lb, Fig. 7). The coordinate system started from the left bottom corner of the project (Quadrant C, Fig. 8). The final x and y locations in the house are relative to the center of gravity of each panel are shown in Fig. 6. For the calculations in Step 3, it was necessary to determine the distance of the crane to the final location in the house for each panel satisfying Eqs. (1) and (2)

$$x \text{ from crane} = \text{Offset } x + x \tag{1}$$



	J	K	L	M	N	O	P	Q
11	PANEL	Rigging (Kips)	Panel Weight (Kips)	WEIGHT (Kips)	Rx (ft)	Ry (ft)	Mx	My
12	DW5	5	19.21	24.21	[illegible]	84.9	[illegible]	2055
13	DW4	5	22.49	27.49	[illegible]	78.0	[illegible]	2145
14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	76.8	[illegible]	3630
15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	78.1	2595	2012
16	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	82.1	2938	2329
17	RW2	5	31.4	36.4	113.5	[illegible]	4133	2974
18	GN1	5	22.7	27.7	[illegible]	[illegible]	2895	1775
19	SCE2	5	22.41	27.41	[illegible]	[illegible]	1185	1582
20	SCE1	5	25.7	30.7	[illegible]	[illegible]	2040	1435
21	GE1	5	[illegible]	[illegible]	[illegible]	44.9	3098	1735
22	GE2	5	[illegible]	[illegible]	[illegible]	46.3	1961	1004
23	GW2	5	[illegible]	[illegible]	[illegible]	29.9	3843	1525
24	GS1	5	36.26	41.26	[illegible]	38.8	2810	1603
25	GW1.1	5	4.4	9.4	106.2	39.8	998	374
26	GW1	5	38.84	43.84	91.2	[illegible]	3998	1393
27	GN3	5	52.1	57.1	102.4	45.7	5850	2608
28	MAX			57.10	113.5	85	5,850	3,630

Fig. 7. Optimization model, Part B

$$y \text{ from crane} = \text{Offset } y + y \tag{2}$$

where Offset x, Offset y = offset distances between the house to the crane, measured from the edge of the footings to the center of rotation of the crane.

After calculating the distance from x and y of the crane with respect to the final location of the panel in the house, the following procedure was used to determine the lifting radius of the crane. Fig. 7 shows the calculations made in the optimization model, which are explained in detail in Step 3. Rx and Ry [Eqs. (3) and (4), respectively] represent the radii of the final location of the crane to the final location of the panel in the house (lifting radii), with the crane sitting on the x-axis or y-axis. The crane can be placed along the x-axis/y-axis and then, obtain a set o momentums exerted on the crane. $\mathbf{M}x$ and $\mathbf{M}y$ [Eqs. (5) and (6)] are mathematical functions based on the position the crane (radii from the x- or y-axis) and the lifting weights (concrete panels). In the same spreadsheet, the maximum values are shown at the bottom of each calculation

$$Rx = [(x \text{ pos} - x \text{ from crane})\,\hat{}\,2 + (y \text{ min} - y \text{ from crane})\,\hat{}\,2]\,\hat{}\,0.5 \tag{3}$$

$$Ry = [(y \text{ pos} - y \text{ from crane})\,\hat{}\,2 + (x \text{ min} - y \text{ from crane})\,\hat{}\,2]\,\hat{}\,0.5 \tag{4}$$

where x pos, y pos = iterated crane location along the x- or y-axis (Fig. 6); and x min, y min = coordinate values that indicate the start of the quadrant.

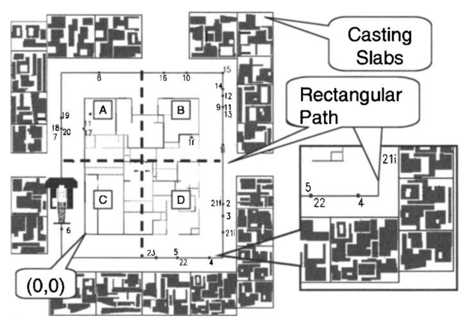
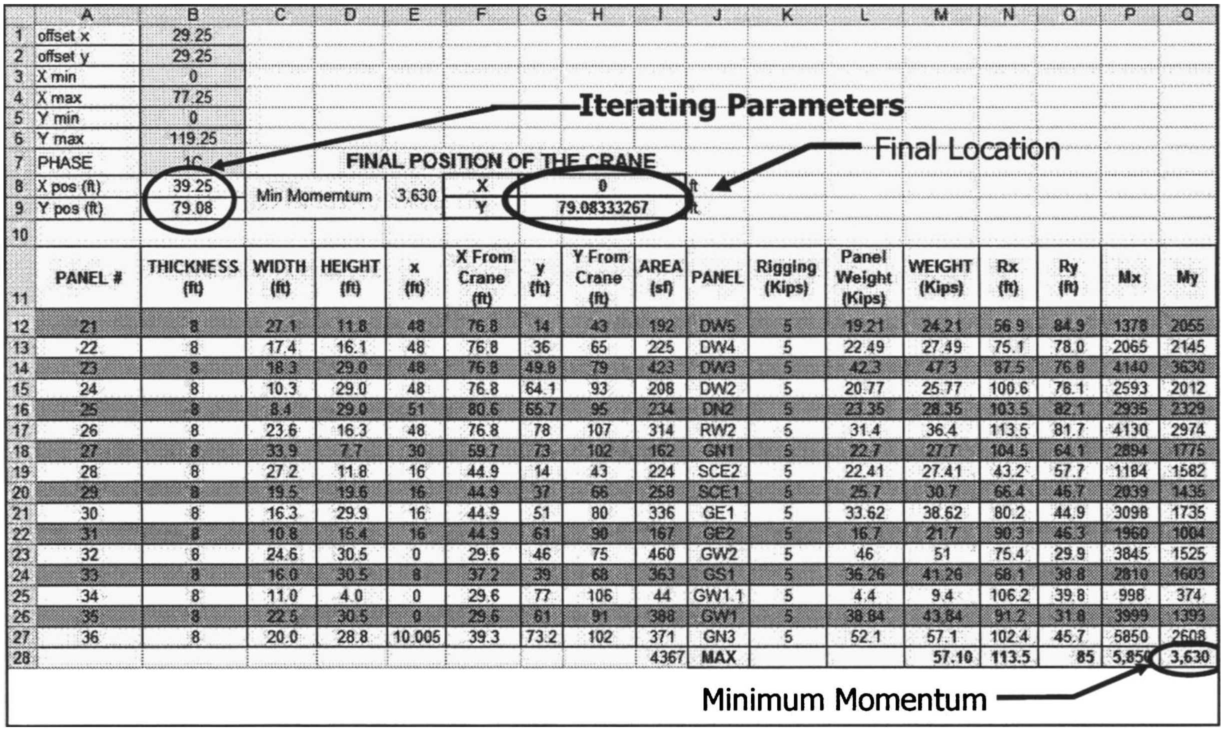


Fig. 8. Construction site layout



	A	B	C	D	E	F	G	H	I
1	offset x	29.25							
2	offset y	29.25							
3	X min	0							
4	X max	77.25							
5	Y min	0							
6	Y max	119.25							
7	PHASE	1C	FINAL POSITION OF THE CRANE						
8	X pos (ft)	39.25	Min Momemtum		3,630	X		0	ft
9	Y pos (ft)	79.08				Y		79.08333267	ft
10									

11	PANEL #	THICKNESS (ft)	WIDTH (ft)	HEIGHT (ft)	x (ft)	X From Crane (ft)	y (ft)	Y From Crane (ft)	AREA (sf)	PANEL	Rigging (Kips)	Panel Weight (Kips)	WEIGHT (Kips)	Rx (ft)	Ry (ft)	Mx	My
12	21	8	27.1	11.8	48	76.8	14	43	192	DW5	5	19.21	24.21	56.9	84.9	1378	2055
13	22	8	17.4	16.1	48	76.8	36	65	225	DW4	5	22.49	27.49	75.1	78.0	2065	2145
14	23	8	18.3	29.0	48	76.8	49.8	79	423	DW3	5	42.3	47.3	87.5	76.8	4140	3630
15	24	8	10.3	29.0	48	76.8	64.1	93	208	DW2	5	20.77	25.77	100.6	78.1	2593	2012
16	25	8	8.4	29.0	51	80.6	65.7	95	234	DN2	5	23.35	28.35	103.5	82.1	2935	2329
17	26	8	23.6	16.3	48	76.8	78	107	314	RW2	5	31.4	36.4	113.5	81.7	4130	2974
18	27	8	33.9	7.7	30	59.7	73	102	162	GN1	5	22.7	27.7	104.5	64.1	2894	1775
19	28	8	27.2	11.8	16	44.9	14	43	224	SCE2	5	22.41	27.41	43.2	57.7	1184	1582
20	29	8	19.5	19.6	16	44.9	37	66	258	SCE1	5	25.7	30.7	66.4	46.7	2039	1436
21	30	8	16.3	29.9	16	44.9	51	80	336	GE1	5	33.62	38.62	80.2	44.9	3098	1735
22	31	8	10.8	15.4	16	44.9	61	90	167	GE2	5	16.7	21.7	90.3	46.3	1960	1004
23	32	8	24.6	30.5	0	29.6	46	75	460	GW2	5	46	51	75.4	29.9	3845	1525
24	33	8	16.0	30.5	8	37.2	39	68	363	GS1	5	36.26	41.26	68.1	38.8	2810	1603
25	34	8	11.0	4.0	0	29.6	77	106	44	GW1.1	5	4.4	9.4	106.2	39.8	998	374
26	35	8	22.5	30.5	0	29.6	61	91	388	GW1	5	38.84	43.84	91.2	31.8	3999	1393
27	36	8	20.0	28.8	10.005	39.3	73.2	102	371	GN3	5	52.1	57.1	102.4	45.7	5850	2608
28									4367	MAX			57.10	113.5	85	5,850	3,630

Fig. 9. Final crane location

The variables x pos/y pos are used as the iterating parameters in regards to the crane location along the **x** axis or **y** axis in order to find the minimum momentum exerted on the crane by lifting a certain subset of panels. x min and y min are constants that indicate the starting position of the quadrant with respect to the coordinate system, previously defined. The structural design included a panel installation sequence, which could not be modified. The panel installation sequence was divided into two main phases. In the first phase, the building was divided into quadrants, each tagged with the letters A–D as shown in Fig. 8. This phase had a total of 63 panels, which partially composed the main structure of the house. The second phase did not require a specific lifting sequence; this phase had a total of 48 concrete panels, most of them to be installed on top of the panels from the first phase. Several layouts were made with different casting slab shapes. In the end, the constructability issue defined the casting slabs' layout.

The casting slabs were poured around the construction site to allow the crane to move between the construction and the cast panels. Panel sizes ranged from 12.80×12.80 m to 15.84×15.84 m (42×42 ft to 52×52 ft), covering a total area of 4316 m^2 or 46,459 sq ft (Fig. 8). With a preliminary casting slab area, the first task was to maximize the usage of the crane at its pick-up points. In other words, the objective was to lift as many panels as possible from each crane position. The second task was to maximize the efficiency of the casting slabs by reducing the wasted area between the cast concrete panels. The center of mass was retrieved from the 3D model (pair of x-, y-coordinates) using AUTOCAD Landscape. The pairs of coordinates were obtained by using the software's mass properties tool, and then, the data was exported to a spreadsheet. Subsets of panels were made within each main group according to the panels' final location. These subsets of panels contained consecutive panels in the structural sequence. An optimization model using MICROSOFT EXCEL SOLVER was then developed in order to find x-y locations for the crane that maximized lifting capacity and minimized crane displacement as shown in Fig. 9.

Step 3: Optimization Model and Panel Layout: The objective was to calculate the maximum momentum for each subset of panels while varying the crane location along the rectangular path around the house. The developed spreadsheet used a quadratic optimization model. The momentum theory was applied to the model, satisfying Eqs. (5) and (6)

$$\boldsymbol{M}x = \mathbf{F}\cdot Dx \quad (5)$$

$$\boldsymbol{M}y = \mathbf{F}\cdot Dy \quad (6)$$

where $\boldsymbol{M}$=momentum; $\mathbf{F}$=force vector (in this case, the panel weight); and Dx, Dy=shortest distance from the element's center of mass to the center of rotation of the crane (in this case, the crane radii distances Rx and Ry).

The model then selects the smallest value of the prospective maximum momentums as the most favorable location for the crane. From this quadratic model, MS SOLVER found locations which maximize the crane's capacity to lift most or all of the panels in the set without having to move to another position. To illustrate the effect, Fig. 10 shows the momentum results exerted on the crane by altering the crane's location along the path. The path that the crane can follow by varying its location in accordance with the installation sequence is shown in Fig. 8. One constraint included in the model was the ground pressure exerted on the existing basement walls. The geotechnical engineer calculated a minimum offset distance of 3.65 m (12 ft) from the edge face of the basement to the end of the crane crawlers. For each subset of panels, x-y coordinates were obtained by changing the crane location along the predefined path.

Solver and Solver Table were applied to obtain the result. As an example, Fig. 8 shows the crane's final location. Fig. 11 illustrates the quadratic model used in the investigation for targeting

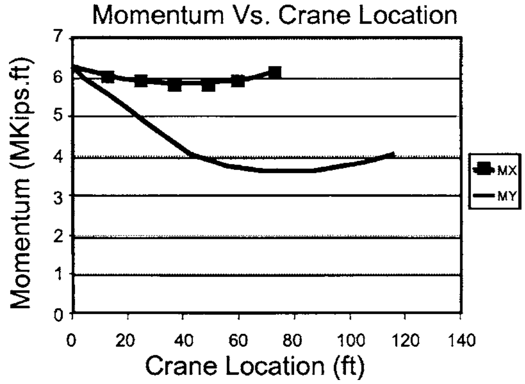


Fig. 10. Possible crane iterating locations

the minimum value (minimum momentum). The x-y coordinates were iterated by MS SOLVER to determine the min-max momentum. The variables included in MS SOLVER bounded the selection of the minimum momentum satisfying the objective function [Eq. (7)] and the set of constraints [Eq. (8)–(11)]

$$\mathrm{Min}(M_{xi}, M_{yi}) \tag{7}$$

$$x_i \geqslant x\ \mathrm{min} \tag{8}$$

$$x_i \leqslant x\ \mathrm{max} \tag{9}$$

$$y_i \geqslant y\ \mathrm{min} \tag{10}$$

$$y_i \leqslant y\ \mathrm{max} \tag{11}$$

where M_{xi}, M_{yi}=momentums along the rectangular path; x_i, y_i=iterating values along the rectangular path; and $x\ \mathrm{min}, y\ \mathrm{min}, x\ \mathrm{max}, y\ \mathrm{max}$=minimum and maximum path boundaries.

Sensitivity Analysis: The reduce gradient in Fig. 11 is the "rate of hurt in the objective function value as the variable is forced away from its zero value" (Moore and Weatheford 2001). For this case, the final location of the crane cannot be encountered in a better position since the encounter momentum is the minimum value, which is why the reduced gradient value is zero. The Lagrange multiplier in Fig. 11 is the rate at which the final value (minimum value in this case) would change when the constraints are increased. Since the optimization model is using a second degree equation, the minimum value obtained for each case is the value at the valley of the quadratic equation, where the slope (or rate of change) is zero.

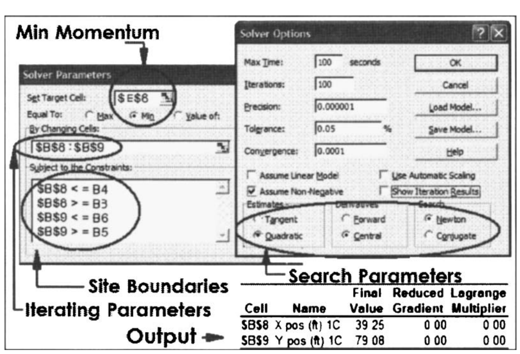


Fig. 11. Optimization model

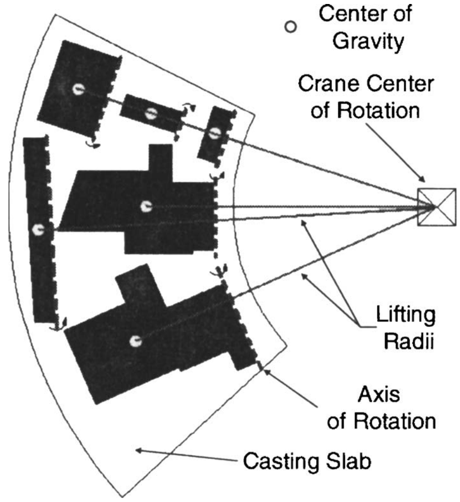


Fig. 12. Circular casting slab

Construction Site Layout

During the layout process, it was important to know the maximum radius at which each panel could be placed from the pick-up points previously defined. The joint control used to avoid fractures in the casting slab added to the panels' placement a new space constraint. In addition, the formwork of the panels could not be positioned across these joints. The minimum offset between the edge of the panels and the joints were held at 20 cm (8 in.), while the minimum separation between each panel was 25.4 cm (10 in.). With the use of a spreadsheet, the boom length was selected according to the capacity provided for the lifting process. The model also provided each boom length with the maximum radius for each panel. The best fit for the boom length was between 45.72 m (150 ft) and 54.86 m (180 ft); fulfilling with the maximum clearance requirement obtain by the algorithm in Step 1.

As the boom length decreases, the capacity is enhanced and at the same time, the picking radius is decreased. After checking all the maximum radii for all the panels, it was decided that the 45.72 m (150 ft) boom best suited the project. The 54.86 m (180 ft) boom length would cause more panels to be lifted near the crane's maximum capacity. Two different models of casting slab shapes were proposed in order to facilitate the lifting process. As shown in Fig. 12, the concrete panels were placed on the casting slab with their axis of rotation (pivot point), perpendicular to the boom of the crane (or lifting radius). The center of gravity was aligned with the center of the crane and the pivot point of the panel. As a result, when the panel was tilted from the casting slab, it would rotate without sliding (dragging movement) on the casting slab since its center of gravity will follow the path of the boom. This approach was proposed in order to minimize stresses on the concrete panels during the tilt-up. If the panels were going to be tilted from their axis of rotation, the center of gravity has to be always aligned with the main line of the crane (rigging system). Then, the tension force applied by the rigging system on the concrete panel will be in equilibrium with the center of gravity of the concrete panel (sum of forces in $\mathbf{Z}$=0). No momentums or dragging forces will be decomposed from the rigging system if it is kept plumb and aligned. Due to constructability issues, joint controls and the need for saving materials (casting slab area), this method was avoided. Although, it did have the two easiest lifting

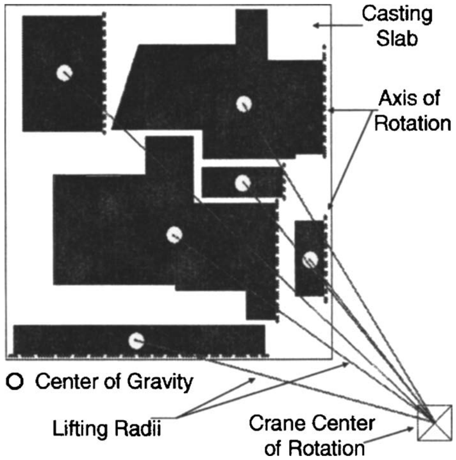


Fig. 13. Rectangular casting slab

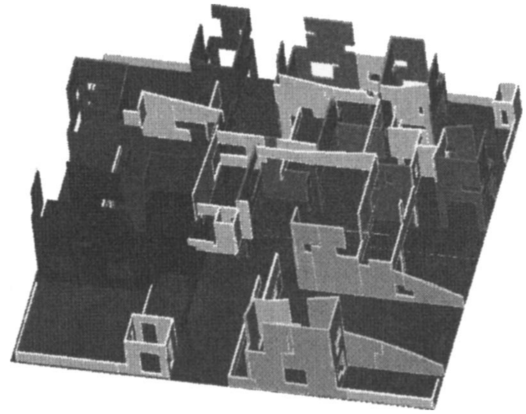


Fig. 15. 3D AUTOCAD model

movements for the crane operator (hoist up and boom up) and the minimum exerted stresses on the panel.

The next design for the casting slabs used rectangular shapes, allowing a better control of their construction and better material/area utilization. As a constructability issue, the casting slabs are made as square as possible to avoid fractures. If a fracture were to occur, the imperfection would appear on the exterior face of the panel, reducing its aesthetic quality. As shown in Fig. 13, the panels are closer to each other, which uses less space. Unfortunately, the axes of rotation of the panels were not perpendicular to the lifting radius; for tilting the panels, three movements were required from the crane operator: to hoist up, to boom up and to swing the boom (all of them at the same time). In order to provide a solution, 3D animations were made to help the lifting crew and the crane operator to understand the requirements involved with the tilting and installation process. For the type of crane selected, the minimum lifting radius is 7.31 m (24 ft), making it impossible to lift the panels by placing the crane in front of them in order to have their axis of rotation perpendicular to the lifting radius.

According to the lifting sequence and the subsets of panels defined with the optimization model, the panels were placed using the lifting points encounter in Step 3 and the maximum lifting radius for each panel (as explained before). Finally, the panels were placed within the maximum radii provided by the 45.72 m (150 ft) boom as shown in Fig. 14. The construction site layout was drawn in AUTOCAD (Fig. 8). Problems regarding space were encountered when placing the panels on the casting slabs due to the maximum lifting radii and the panel sizes. In total, 22 pick-up points were placed on the rectangular path around the facility. The crane had to travel with three panels due to the crane capacity, panel layout and placement positions. In addition, 10 panels were lifted within the range of 90–100% of the crane maximum capacity.

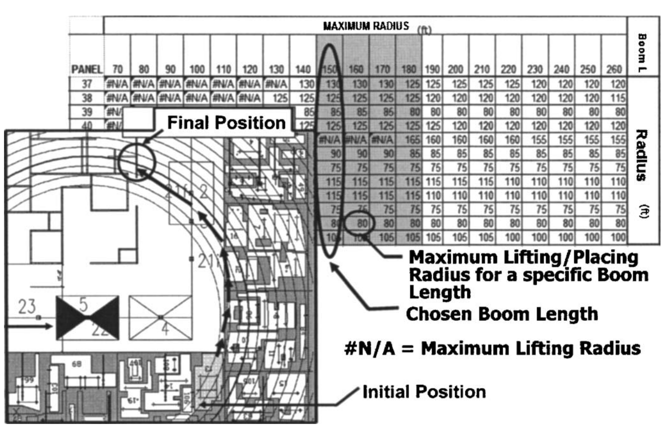


Fig. 14. Boom lengths and lifting radii

3D Animations

During the development of the 3D animation, potential problems were recognized and addressed accordingly. Based on the outputs of the optimization model, the crane selection algorithm and the construction site layout, the 3D animations were developed in 3D STUDIO MAX. Based on the need to visualize the lifting process, and in order to introduce the lifting crew to the complicated installation process, the development of the 3D model and the 3D animations were instrumental in the project by reducing constructability issues for panel lifting, bracing and final placement. Fig. 15, shows the complete 3D model of the facility made in AUTOCAD.

A special requirement, when constructing with tilt-up, is the need to pivot the panel from its base without dragging it. To keep the hook-block plumb, the crane operator has to maneuver the panel in the following three crane movements at the same time: Swinging the boom, booming up and hoisting up. The following two 3D models were made for the case study: the facility and the crane. The crane was designed according to the equipment specifications and dimensions. The pick-up locations found with the optimization model were used to place the 3D model of the crane around the facility using AUTOCAD, and then, the file was exported to 3D STUDIO MAX. A lack of integration between mathematical analyses and 3D visualization (Mallasi and Dawood 2002) is a common error in the present practice. Construction methods can be enhanced by computer modeling; small issues can be detected by repeating the construction process many times on a computer screen without taking the risk of failure at the construction site. Like the irregular concrete panels used in the case study, which depended on the location of the lift inserts, after tilting the panel from the casting slab, they could be hanging with or without a vertical inclination. If the lift inserts are cast on the exterior face of the concrete panel, the center of gravity will have to coincide with the main line of the crane (rigging system), making the panel incline during the lifting. During the panel installa-

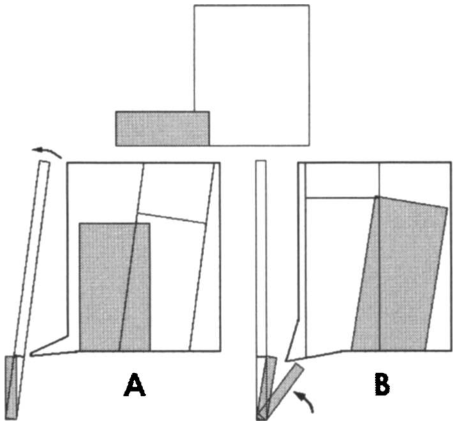


Fig. 16. Proper installation sequence

tion, if the inclined panel has to interlock with another that is already installed; special care has to be taken in order to fit the inclined panel to its final position without colliding the installed one.

As shown in Fig. 16, if the installation is made following case A, the panels will not collide to each other. If the installation is made according to case B, the panels will not fit. Due to this spatial issue, the lifting was changed and revised based on the output of the 3D animations. Another issue found was the coordination with the bracing system. For tilt-up constructions, a more efficient practice is to install the braces when the concrete panels are lying down on the casting slab. During the installation, braces have to be anchored to the slab on grade, foundation wall, footing or deadman (concrete block with dimensions of $1 \times 1 \times 1$ m) in order to provide support to the concrete panel after installation. For the case study, the concrete panels required two or three braces, ranging from 5.48 to 9.75 m (18–32 ft) in length. Due to space constraints, there were interferences between the braces. The 3D animations helped to determine where to install the end of the brace in order to avoid these interferences.

Two frame samples of one panel animation have been included in this paper (Fig. 17). Most of the panels are both pivoted and lifted from the face inserts with special lifting sequences. These lifting sequences were designated with letters A–C. In sequence A, the panel is pivoted to a vertical orientation using the face inserts. After it has been braced to the floor, the temporary legs need to be removed, at which point the panel can be elevated using the edge inserts. Sequence B is identical to A, only there are no temporary legs to remove from the panels. Sequence C panels are pivoted using both type of inserts (face and edge) and are lifted using the top inserts. Then, relevant information is incorporated into the animation to make the tilt-up process as real as possible. During the rotation of each panel, the animation includes the stretching of the slings and the movements of the crane. Although physics is not integrated into the model, the interface is a means to establish the rotation angles that the crane operator can use to lift the panel in accordance with the predefined specifications.

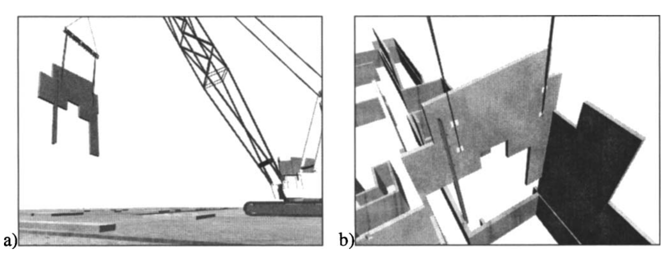


Fig. 17. 3D animation of lifting a panel

Conclusions

This paper presents a methodology used to construct a challenging project with a unique construction method with a high level of tolerance and accuracy. Therefore, the need for precise equipment utilization could not be ignored. Each of the 108 panels was animated using 3D STUDIO MAX in order to expose possible constraints, beginning with the tilt-up process for every panel and ending with their final placement. Errors can be avoided by analyzing the installation sequence with the 3D animations. Some of the panels, depending on their shape, structural configuration and architectural design, had to be tilt-up using four different lifting procedures, which were determined by the designing engineering firm. Most of the panels were both pivoted and lifted from the face inserts, but some had special lifting sequences. Although physics is not integrated into the model, the interface is a means to establish the rotation angles that the crane operator can utilize to lift the panel in accordance with the predefined specifications. It also allows for an opportunity to check if the panels fit depending on the installation sequence. The lifting operation also had to be as smooth as possible to avoid dragging movements.

Based on the optimization model, all the panels were cast in close proximity to minimize the construction of casting slabs and the traveling requirements of the crane. The optimization model helped to select the most technically and cost effective crane. Also, the lifting process was optimized by developing mathematical functions based on the max-min lifting moment that reduced the crane displacements along the construction layout. In addition, the use of the tools presented in this paper, helped to develop the construction layout and to reduce the amount of concrete used for the casting slabs by 14%, less than the originally expected. The 3D animations revealed which types of movements minimized errors in the tilt-up process. The development of computer animations reduced the uncertainty in the installation process and guided the construction crew. Based on this visualization tool, decisions were taken before any operation at the construction site was conducted. The 3D animations helped to understand the installation sequence and helped to modify it according to space constraints. Animating this procedure using 3D STUDIO MAX was useful. However, it was time consuming and improvements can be made to increase efficiency. 3D STUDIO MAX includes in its interface a programming tool called MAXSCRIPT that allows designers to repeat processes by declaring simple codes. This tool can be used in conjunction with inverse kinematics solutions (IK). IK calculates the positions and angles that are needed to target the displacement of objects from their initial to their final position (Madhavapeddy and Ferguson 1999). In this case, the initial position was the crane location with the boom and rigging at a certain instant in a coordinate system. The trajectory delineated the lifting maneuvers and the final position was the ultimately desired position of the panel. The success of this project paved the way to the adaptation of the concept of precast tilt-up panels to a residential, single-family, 5- to 6-story apartment building in Edmonton.

Notation

The following symbols are used in this paper:

Dx, Dy = shortest distance from the element's center of mass to the center of rotation of the crane (in this case, the crane radii distances Rx and Ry);

$\mathbf{F}$ = force vector (in this case, the panel weight);

$\boldsymbol{M}$ = momentum;

M_{xi}, M_{yi} = momentums along the rectangular path;

Offset x, Offset y = offset distances measured from the edge of the footings to the center of rotation;

Rx, Ry = crane lifting radii;

x_i, y_i = iterating values along the rectangular path;

$x\,\text{min}, y\,\text{min}, x\,\text{max}, y\,\text{max}$ = minimum and maximum path boundaries;

$x\,\text{pos}, y\,\text{pos}$ = iterated crane location along the x- or y-axis.

References

Al-Hussein, M. (1999). "An integrated system for crane selection and utilization." Ph.D. thesis. Dept. of Building Civil and Environmental Engineering, Concordia Univ., Montreal, Canada.

Al-Hussein, M., Alkass, S., and Moselhi, O. (2000). "D-CRANE: Database system for utilization of cranes." *Can. J. Civ. Eng.*, 27, 1130–1138.

Al-Hussein, M., Alkass, S., and Moselhi, O. (2001). "An algorithm for mobile crane selection and location on construction sites." *Constr. Innovation*, 1, 91–105.

Al-Hussein, M., Alkass, S., and Moselhi, O. (2005). "Optimization algorithm for selection and on site location of mobile cranes." *J. Constr. Eng. Manage.*, 131(5), 579–590.

Ammerman, E., Junge, R., Katranuschkov, P., and Scherer, R. J. (1994). "Concept of an object-oriented product model for building design." Technische Universitat, Dresden, Germany.

Aouad, G. (1997). "Integration from a modeling dream into an implementation reality." *Proc., of CIB W55*, International Support for Building Economics, Lake District, U.K., 7–29.

Bjork, B. C. (1989). "Basic structure of a proposed building product model." *CAD*, 21(2), 71–78.

Dharwadkar, P. V., Varghese, K., O'Connor, J. T., and Gatton, T. M. (1994). "Graphic visualization for planning heavy lifts." *Proc., Computing in Civil Engineering*. K. Khozeimeh, ed., ASCE, New York, 759–766.

Holl, S. (2004). Steven Holl Architects, ⟨http://www.stevenholl.com⟩ (January, 2006).

Hornaday, W. C., Haas, C. T., O'Connor, J. T., and Wen, J. (1993). "Computer-aided planning for heavy lifts." *J. Constr. Eng. Manage.*, 119(3), 498–3515.

Kamat, V., and Martinez, J. (2001). "Visualizing simulated construction operations in 3D." *J. Comput. Civ. Eng.*, 15(4), 329–337.

Lin, K. L., and Haas, C. T. (1996). "Multiple heavy lifts optimization." *J. Constr. Eng. Manage.*, 122(4), 354–362.

Mallasi, Z., and Dawood, N. (2002). "Registering space requirements of construction operations using site—PECASO model." International Council for Research and Innovation in Building and Construction CIB w78, Aarhus School of Architecture.

Madhavapeddy, N., and Ferguson, S. (1999). "Specialized constraints for an inverse kinematics animation system applied to articulated figures." School of Electrical Engineering and Computer Science, The Queen's University of Belfast, Northern Ireland.

Meadow Burk. (2002). *Meadow burke on tilt-up, the complete tilt-up system manual*, Meadow Burk Products, Tampa, Fla.

Moore, J., and Weatherford, L. (2001). *Decision modeling with Microsoft Excel*, 6th Ed., Prentice-Hall, Upper Saddle River, N.J.

Til-Up Concrete Association (TCA). (2004). "Tilt-up basics." ⟨www.tilt-up.org⟩ (Dec. 5, 2005).

Tracey, A., Child, T., Aouad, G., Brandon, P., and Rezgui, Y. (1996). "Developing integrated applications for construction: The OSCON approach." *1st Int. Conf. on Computing and Information Technology for Architecture, Engineering, and Construction*, Singapore, 361–368.

Zhang, C., Zayed, T., Hammad, A., and Wainer, G. (2005). "Representation and analysis of spatial resources in construction simulation." *Proc., 2005 Winter Simulation Conf.*, M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines, eds., 1541–1548.

Zhong, D., Li, J., Zhu, H., and Song, L. (2004). "Geographic information system-based visual simulation methodology and its application in concrete dam construction processes." *J. Constr. Eng. Manage.*, 130(5), 742–750.