UNIVERSITY OF ALBERTA

3D and 4D Modeling for Planning and On-Site Utilization of Tilt-Up Panel Constructions

By

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ABSTRACT

The simplicity of tilt-up concrete panels' construction allows contractors for building facilities in a short period of time. This thesis provides a comprehensive analytical approach to the construction of a complex residential tilt-up-panel structure. The residence is comprised of 108 concrete panels of varying rectangular shapes with "dog legs" windows 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-degree joints, between panels. Due to the inherent complexities of the project, the owner, designer and construction team decided to utilize 3D/4D modeling and animations to experiment with the construction process on the computer screen prior to construction in order to avoid potential, costly on-site errors. To ensure that the final result met expectations, a mock-up model was built using different types of materials and site constraints.

ACKNOWLEDGEMENTS

To those who in many ways supported me through the years of hard work in my Masters program, I want to thank you all for your selfless help. I want to give special thanks to Dr. Mohamed Al-Hussein, a person who never let me down and encouraged me to always give my best. I want to dedicate my work to the three most important people in my life who have made me the man I am today: my parents Consuelo and Guillermo, for their moral support and constant belief in me, and mostly, to Lindsay, for sharing her life and much happiness with me on my journey.

The information gathered and presented in this document is derived from the good practice of engineering and a commitment to improve and enhance a process that satisfied the owner's desire for excellent results. As stated by Isaac Newton, "If I have seen further it is by standing on the shoulders of Giants;" it would not have been possible to relay this construction process without the help of the Seaview LLC team. Special thanks to the general contractor and the project manager for providing the opportunity to participate and for their patience, help and unconditional support.

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NOMENCLATURE

The symbols listed below are used in this thesis.

α	Main boom angle to ground
C1	Boom clearance
C2, C3, C4	Sheave offset
CLR, CLS, CLF	Clearance constraints
D	Shortest distance from the panel's center of mass to a point of rotation
E1, E2	Maximum path boundaries
F	Force vector (panel weight)
F_F	Floor flatness
F_L	Floor levelness
G_C	Gross capacity
H	Building height
h	Crane lift height
HW	Hook block weight
LW	Lift or object weight
M	Momentum
Mxi, Myi	Momentums along the rectangular path
OTw	Outriggers width
P2G	Boom pin to ground
P2P	Boom pin to rotation centre
R	Boom pin to lifted load

R2C	Distance between the Boom pin and the operator's cabin
Rh	Rigging height
Rw	Rigging weight
r_q	Number of measurements.
SLW	Slings weight
SPW	Spreader beam weight
S_S	Distance between the crane's center of rotation and the building
TBw	Distance between the panel's final location and the edge of the building
TLS, OTL	Distance between the carrier and the crane weights
Tw	Total lifting weight
Wh	Lift height
Xi, Yi	Iterating values along the rectangular path

Chapter 1: Introduction

1.1 Motivation

More than 60 million m^2 (650 million square feet) of structures are constructed every year using Tilt-Up technology. This fast procedure allows contractors to erect facilities in a short period of time, due in part to the simplicity of the method. Nowadays, most construction companies have the tendency to construct prefabricated structural elements that would reduce material cost, installation time and increase quality; it also allows constructors to build facilities even during extreme weather conditions. Tilt-up, since is prefabricated in a controlled environment, provides many advantages, including: loads transferred to the ground are uniform requiring less expensive support; due to the variety of wall thicknesses and insulation materials that can be inserted in the precast concrete panels, a lower operating cost will be obtained for any facility that requires heating and air conditioning systems. Many square meters can be installed quickly, with less skilled labor and allowing trades to start sooner. Safety is also increased by constructing with Tilt-up because the process avoids scaffolding and the lifting is performed by a few people, allowing more control during the operation. Fire resistance is also enhanced; Tilt-up exposes better fire resistance compared to steel and wood facilities and finally, the architectural aesthetic is enhanced using this method due to the smooth finish obtained by casting the concrete panels on casting slabs [Tilt-up Concrete Association, TCA, 2004].

There are some disadvantages of the method such as lifting equipment (crane) accessibility and space constraints at the construction site; also, depending on the chosen equipment, rental expenses can be high.

The method requires good planning; Tilt-up is based on casting areas, heavy equipment and lifting sequences. The method requires analysis in regards to space constraints, construction layout, material and equipment utilization, and structural temporary support.

1.2 Research Objectives

The following are the main objectives of this research:

1. Utilize 3D CAD Modeling software applications to provide a tool to ensure efficacy, efficiency and precision in order to assist the decision making process;
2. Analyze the construction activities with 4D Models through the integration of the project schedule and the 3D CAD objects;
3. Optimizing the crane selection and operation processes with the use of mathematical algorithms;
4. Minimizing the crane displacements trough the development of mathematical functions that optimize the lifting process;
5. Optimizing the casting slab layout in order to minimize the material use and facilitate efficient crane operation during panel erections;
6. Developing a systematic methodology and guidelines to ensuring optimal floor flatness and levelness of casting slabs;
7. Design computer animations to reduce uncertainty in the installation process and to guide the construction crew;

8. Make use of spatial analyses to optimize the bracing process in terms of time, materials and function.

1.3 Report Organization

Chapter 2 describes the state of the art of the literature in the construction industry in the fields of computer modeling, crane selection, material handling, construction management and concrete floor flatness and levelness. Chapter 3 introduces a generic methodology used to manage the construction project, starting from a global view of the problem and continuing with specific approaches for the crane selection, site layout optimization, computer animations, concrete handling and spatial analyses. Chapter 4 describes in detail the results from the research that is related to the case study and the proposed methodology. Conclusions and suggestions for further work are described in Chapter 5.

Chapter 2: Literature Review

Since the case study demanded the utilization of different modules, the following sections were used as a reference for the development of the case study described in this thesis.

2.1 Tilt-Up Constructions

Many materials and methods have been implemented to decrease construction costs and accelerate the building process. Tilt-up is a construction method that takes advantages of the construction site by casting concrete panels over casting slabs, and then, with the use of lifting equipment (cranes), the panels are lifted, swung and set on to their final location. A casting slab a prepared concrete floor that has to be flattened and leveled with a laser screed machine in order to transfer these characteristics to the cast elements on top of it and in order to maximize their smoothness, flatness and levelness. Some parameters for this procedure have to be taken into account, including: the construction of flatten and leveled casting slabs in order to transfer their quality finishing to the concrete panels; a bracing system that would temporary support the concrete panels during the installation procedure; a well organized lifting sequence that would save time and money and, increase the safety at the construction site; the construction of precise formwork that would provide to the concrete panels the ability to fit with each other; and the selection of construction materials that would improve the structural and architectural design. Over 10,000 Tilt-up panel structures are constructed each year in North America allowing constructors to build facilities in shorts periods of time [Tilt-up Concrete Association, 2004]. The construction and installation of Tilt-up concrete panels require a full interaction between the structural engineer, the architect and the installation manager to proceed efficiently [Remmetter and Baty, 2006].

These concrete panels are heavy weight structures that require a special treatment in regards to the lifting and bracing system; the lifting procedure is the most critical operation during the construction of the structure, requiring safety guidelines for workers and special hardware to lift the concrete panels [Palmer, 2005]. There are many parameters that can reduce the cost of the construction of tilt-up concrete panels, such as: the use of the slab on grade of the building to cast the concrete panels, and later on, to use the slab on grade to brace the concrete panels to avoid the use of deadmen; a predefine lifting sequence; the re-use of formwork, liners and casting slabs and others. The use of storage for tilt-up concrete panels can reduce the waste of casting slabs [Harrison, 2005]. According to the cited reference, the lifting sequence can be optimized due to the reduction of crane mobilization; several panels can be stored in the same place, stacking them in a stand position. Tilt-up can be used for small facilities and projects that require a small structure area. Based on the materials selected for the structure (concrete or masonry), and the final finishing required to suit the architect's view, the construction of a small facility can be cost-effective due to the fast installation and small installation crew [Olson and Smith, 2005].

The most common use of Tilt-up is in the construction of warehouses, malls, schools, and buildings in general. Interesting projects can be erected, but a misconception of the method is that tilt-up works mainly for medium height buildings due to the difficulty to brace tall concrete panels, and for the need of space required to cast them. The structure can be composed of tall concrete panels or can be constructed by stacking multiple concrete panels [Sauter, 2004]. Tilt-up is gaining a strong influence in residential constructions; such is the case exposed as case study in this thesis. Moreover, Tilt-up is being used to erect multi-residential facilities due to its fast installation. Residential facilities do not have to have a squared looking, and rock can be used among other construction materials in order to construct the tilt-up panels [McMichael, 2004].

2.2 Prefabricates and Concrete Finishing

Constructing buildings with prefabricates in a mass production, helps to minimize overhead and material costs [Hanna and Zenon, 2003]. Some of the advantages of constructing a facility with such elements are related to the use of less expensive lifting equipment (depending on the sizes of the prefabricated modules) and fewer installation personnel. This advantage can be exploited by constructors who develop similar facilities in repetition, or those whose focus is on offering a competitive selling cost [N. Chitharanjan, 1998]. Furthermore, prefabricated concrete elements provide a higher resistance to load solicitations and weather conditions than conventional systems; depending on the mold and the procedure used to precast concrete, the architectural appearance is better than cast in place elements [Canadian Precast Prestressed Concrete Institute, 2003], [West, et al 2002]. One defect that can be found when casting concrete elements is the way concrete shrinks. Shrinkage depends on many factors: the concrete mix, water content, ambient temperature, curing method, formwork and so on. During the curing and drying process, tensile stresses are created due to hydration or loss of moisture, causing the concrete to shrink. When this happens, the concrete reduces in volume and cracks can arise [Mehta, 1993]. In recent years, due to the need for high dimension accuracy, in order to avoid deformation of concrete elements, laser cutters have been implemented in the precast method [Weimann, 2004].

Another procedure followed by constructors is to build prefabricates in concrete, cast on-site. Precise formwork, flattened and leveled casting slabs are required in order to obtain structural members with accurate dimensions. Many factors are involved in the development of the construction of casting slabs on-site, including: the nature, extent, and location of cracks; the type of soils underlying the casting slab, and issues related to the dips and bumps from level, among others [Walsh et al. 2001] and [Walsh and Miguel, 2003]. An advantage for constructing cast on-site concrete elements is that the characteristics of the casting slabs regarding the surface quality are transferred to the cast elements. Settlements for the casting slabs are not expected due to the short period of use and relative low pressure over the ground (the load of a concrete cast element transferred to the casting slab/ground is a uniform load).

Another field that uses flattened and leveled concrete slabs is in the construction of highways, exposing a high concrete finishing. White topping is a construction method utilized to construct concrete slabs with special parameters for the transportation system. With the use of a slipform paver (laser screed machine), concrete is placed and leveled according to the highway design requirements. In order to provide friction between the tires and the concrete slab, these slipform pavers have the ability to texture the exposed surface, or it can be done manually with a burlap or turf drag [The Transtect Group, 1995]. Laser screed machines ensure the flatness and levelness of the slab with the use of an automatic laser control system and electro-hydraulic controls. Two laser receivers, each mounted at the end of the screed head, receive multiple signals from a transmitter, providing automatic control on the work that is being done [Somero, 2004]

2.3 Construction Site Layout

During the life cycle of a construction project, materials, labor and equipment will be interacting all together to accomplish different tasks and duties. Construction companies are trying to make a better use of their limited construction space by designing a construction site layout more suitable and easy to access. Simulation processes for material handling and storage are been investigated in order to minimize labor mobilization and maximize efficiency. This efficiency depends on the objectives of the facility layout study, the stochastic nature of the problem and the complexity of the systems' interactions [Kuhl et al, 2005]. Algorithms and simulation processes based on the construction characteristics are the most common approaches by engineers in order to plan construction layouts. As described by [Norman and Smith, 1999], considerations for multiple study periods and stochastic parameters have to be taken in account due to the efficiency that a block layout has on multiple (certain or uncertain) scenarios. These block layouts can be defined as small facilities inside the construction site where material can be allocated. The amount of facilities designated for material storage should be moved to strategic places during the construction in order to warranty an uncomplicated and fast material handling [Samdani et al. 2005]. New approaches are linking 3D modeling with generic algorithms (GA's) to facilitate the location analysis of the construction site layouts. Layout arrangements are easy to compare due to its visualization, minimizing spatial constraints and helping in the decision making process [Tam and Leung, 2002]. When construction sites experience space limitations, GA's help to maximize the space utilization by allocating resources where and when they are requested. In order to maximize the use of space, it is required to identify the shape and size of the facilities to be laid out, to identify constraints between them, and to determine their relative positions, in order to make them work efficiently [Harmanani et al, 2002]. As expressed by [El-Rayes and Khalafallah, 2005] and [Anumba and Bishop, 1997] many models are designed to minimize travel cost of resources on-site and improve the efficiency for material handling, but none of them include a model to address the construction safety. When using lifting equipment (tower cranes), the construction site layout should include in its design: "1) proper positioning of temporary facilities to improve the safety to crane operations and minimize accidents caused by falling objects; 2) control of hazardous material and equipment on site; and 3) reducing intersections between heavily traveled routes of construction resources" [El-Rayes and Khalafallah, 2005].

2.4 3D and 4D Modeling in Construction

Currently, implementation techniques in construction procedures have been a central focus of the industry. One of these great tools is Computed Aided Design (CAD). Computers are enabling Project Managers to improve productivity by allowing them to simultaneously optimize their use of materials and equipment and save time on installation procedures. CAD tools are being used to visualize construction operations by permitting the analysis of complicated on-site procedures to take place 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 a new way to analyze a composition of the different elements playing 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 to computational software owing to the fact that analyzing an operation in the office, as compared to improvising the same operation on-site, substantially reduces costs. Planning construction projects during the 90's did not involve complete reliance on simulation methods [Tucker et al. 1998]. However, 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. 3D and 4D models must then work like an automated system that integrates as many disciplines as possible to provide a broad view of the situation. Some researchers in the mid 90's believed that these systems had created "islands of automation" and are far from achieving an acceptable level of integration across the design and construction processes [Kartam, 1994]. This insufficiency has been improved in recent years by linking all disciplines involved in the construction field. An extensive body of research has been done regarding automation and computer analyses based on 3D modeling and integrating systems [Bjork, 1989]; [Ammermann et al, 1994]; [Aouad et al, 1994]; [Tracey et al, 1996]; [Wix, 1997], [Ekholm and Fridqvist 2000], and [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 has to take place. There is a lack of connection between these two parts in many construction companies; the problem with current project planning techniques is the lack of spatial requirements of construction operations as a resource in their scheduling [Mallasi and Dawood, 2002].

In order to help visualize space constraints during installation procedures, 4D models allow contractors and the parties involved to analyze, in detail, any possible change before performing the operation on-site. 4D modeling is a new technique that allows the connection between 3D models with the construction activities of the project. By analyzing a construction process with this modeling system, constructors can determine constraints during the installation sequence without having to construct on-site the facility. This technique is called 4D due to the integration of time in a static model (3D), showing step by step how a construction is being erected.

Most of the software currently available on the market generates benefits by integrating schedules and 3D models and rehearsing different 'what-if' scenarios for coordinating site operations and communicating the project plan in 4D [Mallasi and Dawood, 2003]; [Akinci, et al 2003]; and [Zhang, 2005]. The aim of future research has to be the integration of all components required to construct any facility in 3D and 4D spaces by allowing for changes if needed. It has to behave as a virtual building laboratory for the concurrent simulation of all components [Zimmermann, 2003].

For complicated construction projects where many multi-activity tasks take place in a predefine area, 3D and 4D models help to minimize inconveniences with regards to space constraints. Current industry practice lacks a formalized approach or a tool to help project managers analyze spatial conflicts between activities prior to construction [Akinci, et al 2002]. Unfortunately, at this point in time, many construction companies do not integrate computational models with construction schedules and cost controls. Conventional models govern the way constructors build facilities; planning procedures are not based on 3D or 4D models, precluding the chance to reduce problems on-site.

2.5 Heavy Equipment and Cranes in Construction

In any construction project, especially those that demand an elevated level of accuracy such as mega projects, a planned sequence must be followed to minimize costs and time, while producing satisfactory quality. Such was the case for the construction of the Petronas Towers [Terranova, 2003] and the 37.5 km underground Channel Tunnel that connects England and France. A unique construction process was developed to accomplish this engineering feat. It was necessary to coordinate the work of 13,000 people to construct two main tunnels (rail lines) and a service tunnel designed for maintenance and evacuation. The construction crew was divided into two teams who started digging with Tunnel Boring Machines (TBM) from both shores and met at a central location under the sea [Harris, 2005].

On the other hand, equipment utilization plays an important role for any construction development. For mega projects, the most common equipment used for handling and delivering materials are cranes. To aid practitioners in the selection and utilization of cranes, a certain number of computer applications have been developed in order to achieve efficiency, efficacy and mostly, to carry out the project needs. Some of these applications use integer programming and optimization techniques [Lin and Haas, et. al 1996] or 3D graphics and simulations [Hornaday, et. al 1993] and [Dharwadkar, et. al 1994]. Other applications were developed for crane selection utilizing knowledge-based expert systems [Al-Hussein, et. al 1999] , [Zhang, et. al 1999], and [Al-Hussein et. al 2001, and 2005], advanced crane utilization knowledge by developing an optimization algorithm that assists crane users with selecting and locating cranes on construction sites, utilizing the geometric cranes' information stored in a comprehensive crane database [Al-Hussein, et. al 2000].

New approaches are linking lifting equipment and material handling with automated kinematics. Nowadays, computers are interacting directly with the operator to smoothen the lifting, making it more precise. Micro controllers can modify on real time the crane movements with use of sensors and strain gauges [Munzer, 2002]. Planned paths for the lifting operation can reduce equipment utilization. Inverse Kinematics (IK) and computer simulation can predict the fastest and safest path a crane should take in order to move the material from its starting point to its point of delivery. Many parameters can be analyzed, such as: velocity, clearance, maximum lifting weight, lifting radius, among others [ShihChung and Miranda, 2004].

Chapter 3: Proposed Methodology

The case study described in this thesis was approached in three modules as illustrated in Figures 1 and 2. The main process used the information from project characteristics plus the construction parameters indicated as Criteria from Figure 2. Most of the fundamental information about the tilt-up process was gathered from the Mockup Model, which is crucial for the development of the construction project. The core consideration for this facility was to reach the customer's needs regarding the installation precision and the finishing quality for the tilt-up structure. By addressing both needs, input and criteria, the research process occurs and focuses in the following three main areas:

- Panel Layout and Crane Optimization Analysis
- Concrete Finishing Analysis
- Bracing Spatial Analysis.

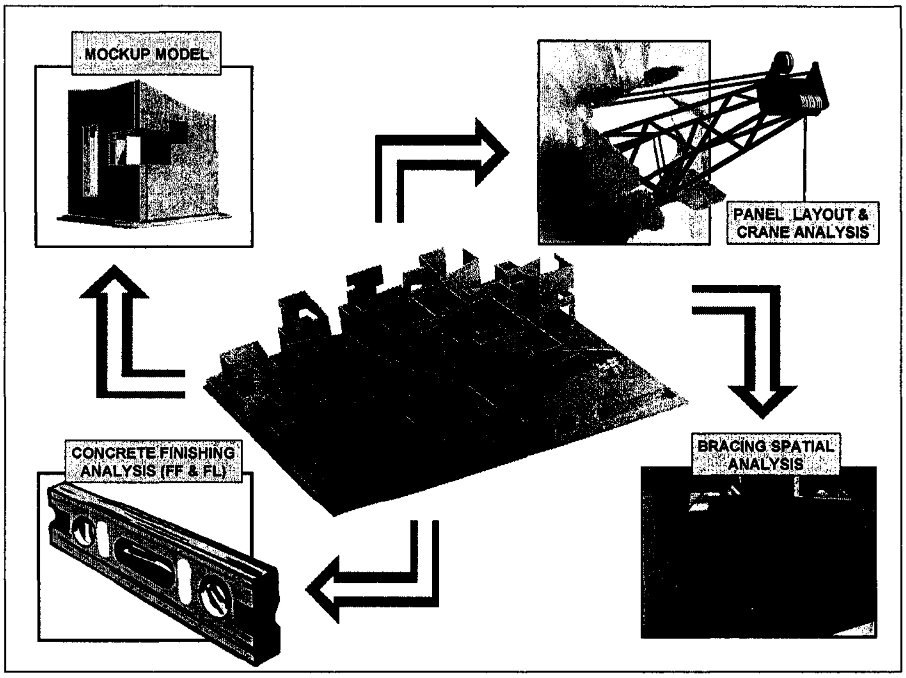

Figure 1: Proposed Main Process Components

The Panel Layout and Crane Optimization Analysis module targeted the crane selection, location and mobilization around the facility, the optimization of the panel layout in concordance with the tilt-up requirements and with the goal of minimizing the use of concrete for the casting slabs. It also targeted computer animations that guided the installation crew (See Figure 2).

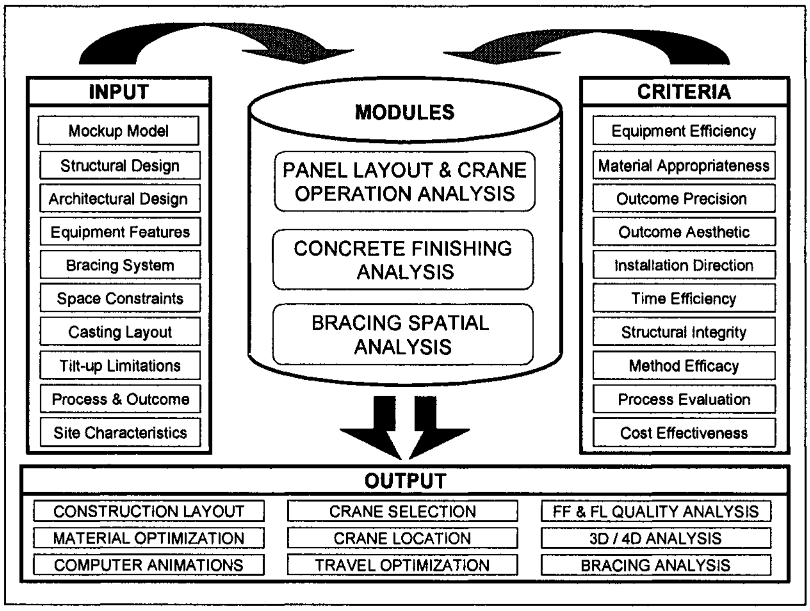

Figure 2: Proposed System Architecture

The second module involved the concrete finishing process developed by the Project Manager and the contractors. Aesthetics is one of the most important considerations in this project. The stated architectural design calls for flat concrete surfaces due to the 90-degree connections between panels that require a precise joint separation of 1.27 cm (half an inch). Recommendations for future work related to floor flatness and floor levelness are described at the end of this thesis.

The third module describes the process followed by the installation and bracing contractors. Both 3D and 4D modeling helped to reduce errors on-site, facilitated decision making and allowed the parties involved (Project Manager and contractors) to ensure workplace safety.

Chapter 4: Research Implementation

4.1 Case Study

The facility used for the case study is a unique, private facility in the United States that has been in construction since June 2004. Designed by Steven Holl [Web-3], this facility uses a construction methodology based on tilt-up panels, which uses reinforced concrete panels that are cast and cured on-site and then lifted with a crane. With more than 22,000 square feet in footprint area, this facility comprises four pavilions and includes a library, garden house, gallery, sport and entertainment facilities. Robert Silman Associates and DSI Engineering developed the structural design for the facility (Figure 3).

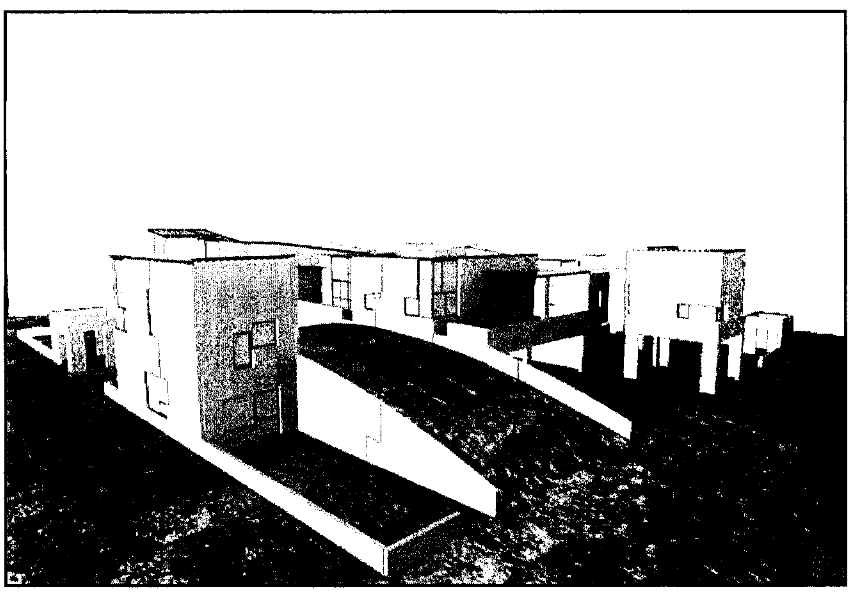

Figure 3: Architectural model, case study

The panels had maximum dimensions of 10 x 10 m (35 x 35 ft) and weighed from 1,356 kg (3,000 lb) to 27,572 kg (61,000 lb). Most of the panels have a thickness of 20 cm (8 in), but some are as thick as 27.94 cm (11 in). Erecting tilt-up panels is not a widely used technique for residential construction, especially for buildings with panels that have irregular shapes, such as the case presented in this thesis. As shown in Figure 4, no two panels are alike, presenting challenges to interlocking them as one unit.

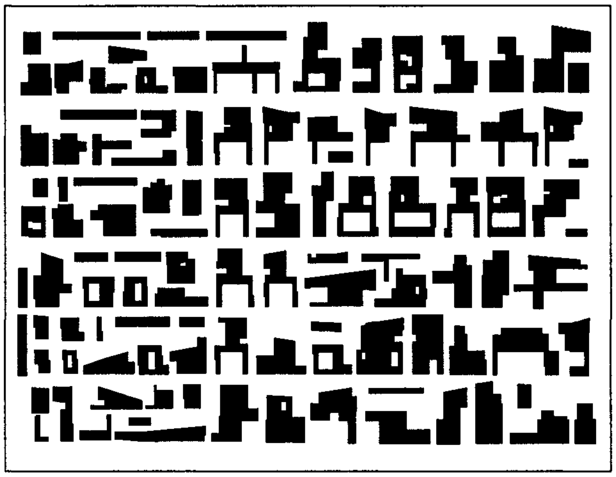

Figure 4: 108 concrete panels used for the case study

Shape accuracy is extremely important for complex architectural designs; such was the case for the structure presented in this document that called for a maximum panel-to-panel joint tolerance of 1.27 cm (0.5 in), which was often found in ninety-degree joints between panels. This required an extremely flat casting slab and precise formwork (Figure 5).

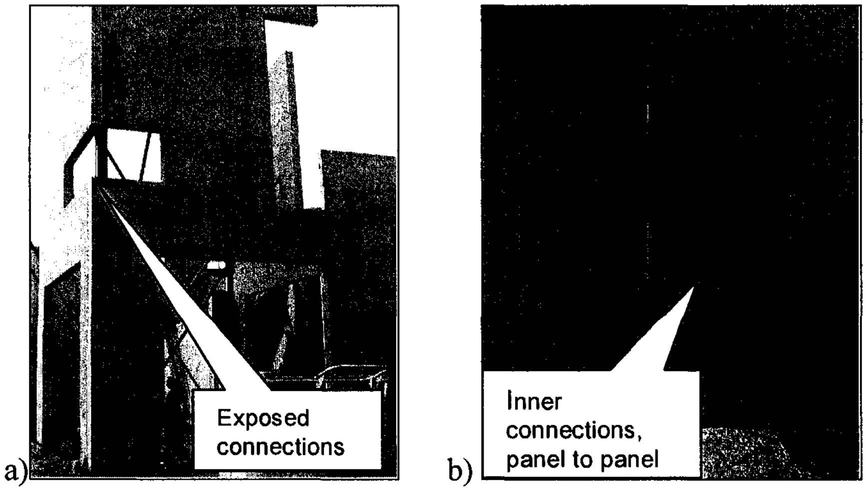

Figure 5: Panel connections

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 colour and texture of the aggregate. Since the panels are exposed to the outdoors and will be stained with an amber colour, the smoothness of the surface plays an important role in the development of this construction.

Due to space constraints, short time for the erection process and high equipment costs (crane rental costs), the construction layout needed to be as simple as possible to minimize the constraints for the lifting process. 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. The construction process required a high-capacity crane for panel installation, with the lowest rental cost possible, but with the capacity to lift and place all the panels in their final locations. A crawler crane was selected for this purpose (Manitowoc 888 [230 tonnes]). This lifting process required an optimization model to minimize crane displacements on-site and to ensure better use of the concrete required for the casting slabs [Manrique, et al 2005]. The final layout of the concrete panels' locations on the casting slab, was the key in enhancing the installation process (Figure 6). The numbers on Figure 6 describe the crane picking/lifting points for the different subsets of panels. There were many uncertainties and risk factors that needed to be addressed in order to prevent the failure of the project. Thus, a smaller model was constructed to manage the risk of material selection and to learn more about the panels' erection procedure. A mock-up model was constructed and gave invaluable insights regarding the process of erecting the concrete panels.

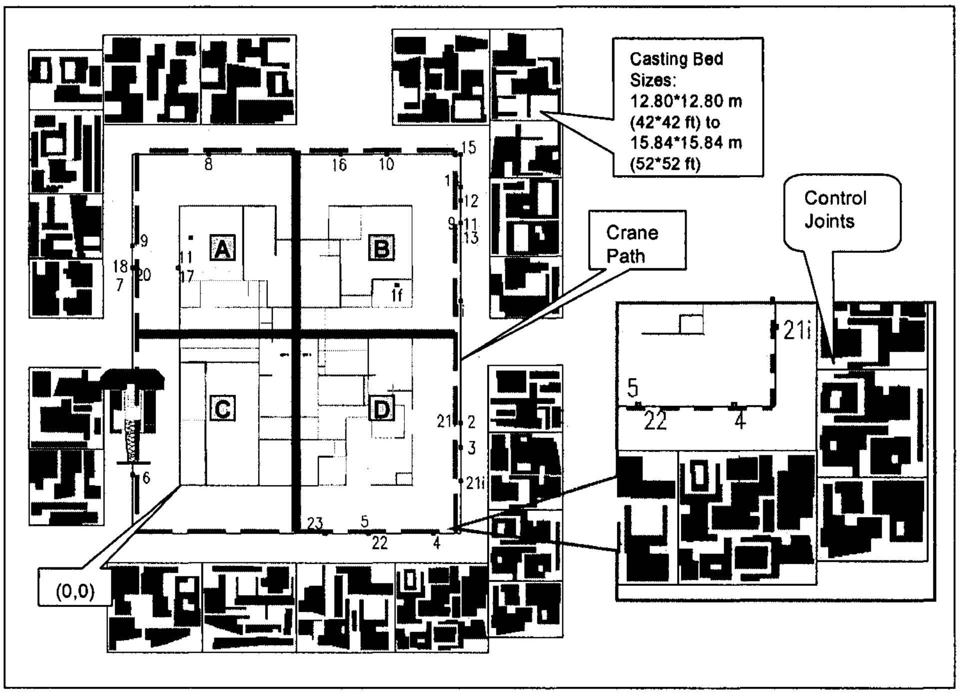

Figure 6: Construction Site layout

Different constraints were tested and possible solutions or suggested changes needed for actual construction were obtained as described in Table 1. Two of the tested constraints were the concrete mix and the casting slabs required to form the panels. Four different concrete mixes were tested in order to identify the mix that would produce the fewer amounts of bug holes and honey combs. Different casting slabs were considered in order to minimize the errors during the lifting process as explained in 4.2.4. The formwork could not be reused for the following two reasons: each panel shape is different and each panel had to be poured within a short period of time for quality purposes and to ensure use of the same type of aggregate. This inconvenient represented the use of more material. It is of interest here to mention that the construction and the detail analysis of the Mock-Up model was carried out by a third party consultant firm.

4.1.1 Mock-Up Model

A mock-up model was designed and built to minimize imperfections during construction. Many characteristics were explained during the conceptual planning and feasibility analysis phase.

The model comprised of five concrete panels, comparable to those in the actual structure, with window and door openings and rectangular and diagonal shapes as shown in Figure 7. The dimensions of this mock-up model were one-third the size of an actual panel.

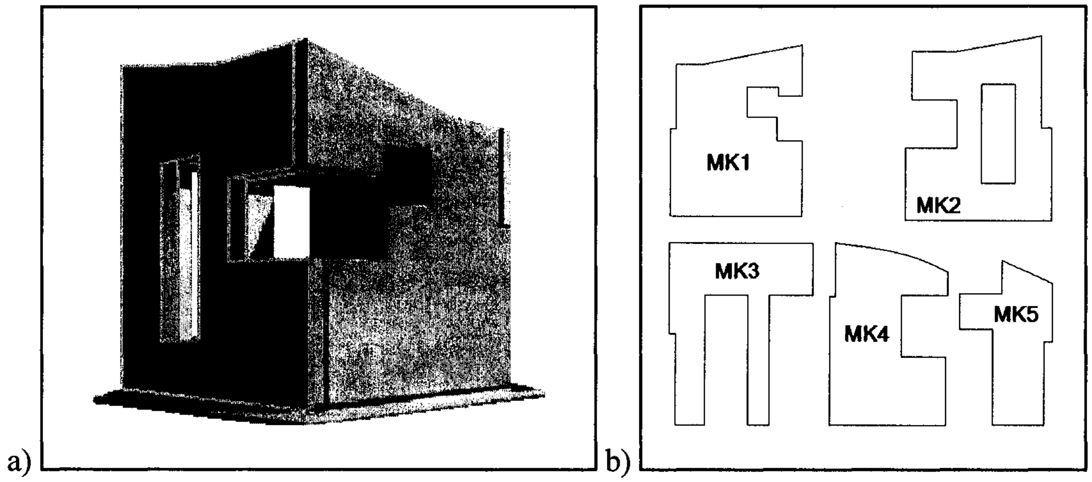

Figure 7: Mock-up model configuration

Lessons were learned from the process of erecting the structure. Table 1 [Web-1] details the elements tested, the variables for each and the possible solutions or suggested changes obtained.

4.1.2 Mock-Up Model Findings

An analysis of the mock-up model demonstrated that the finishing quality, and production and installation of the panels, would be among the biggest challenges of the construction of this project. Experiments were made using plastic chairs. These plastic objects held up the panels' steel reinforcing, avoiding any contact with the bottom surface. During the construction of the concrete panels for the mock-up model, four different types of chairs were used to test whether or not their legs (contact points with the casting slab) would telegraph the surface of the concrete panels. The four types of chairs included a 1.5 inch GTI Composite Chair, a 3.5 inch Aztec Chair, an Aztec PTC 600 Tower Chair and a 1.5 inch Aztec EZ Lock Slab Bolster Chair. Examples of the test are shown in Figure 8. All four types of chairs showed marks on the external panels' surfaces, demanding for a better construction technique for the actual panels [Web-2].

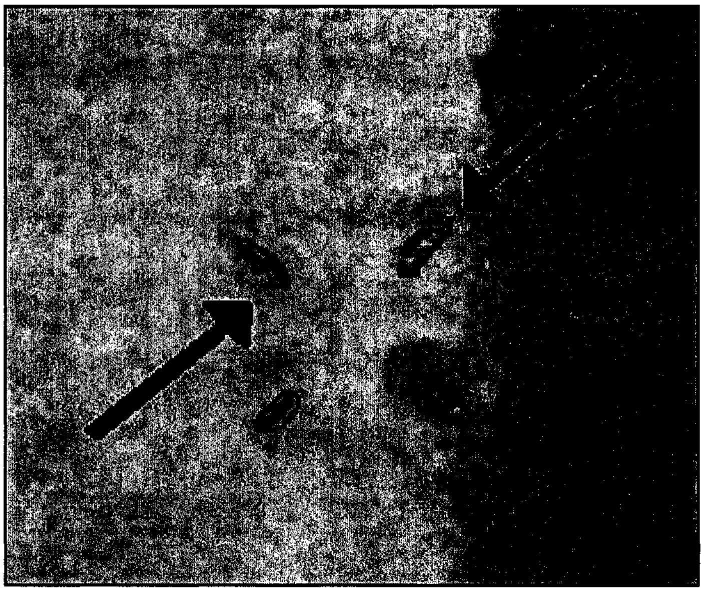

Figure 8: Indentation marks produced by plastic chairs, mock-up model

In addition, the general contractor is faced with the challenge of delivering a flat and smooth concrete surface for acid staining later in the process. "Bug Holes," "Honey combs" and voids have to be eliminated to meet the owner's expectations in both quality and architectural aesthetics.

Table 1 Mock-Up Model Results [Web-1]

ELEMENT	VARIABLE TESTED	LESSONS LEARNED
SLAB	Mix design, finishing techniques, curing compound, thickness	Use laser screed. Specify formal flatness and levelness and method of measuring same. Establish specifications for acceptable surface finish. Increase thickness. Use the slump test on-site.
CURING COMPOUND	Used only Expired Silcoseal 2000F as curing compound	Curing compound must be used. Explore other cure/hardener/seal products. Test epoxy coating of slab.
FORM LAYOUT	Chalk line method only	Must increase precision of layout and formwork. Ensure stability of formwork during and after pour with positive method.
FORM MATERIAL	Standard 5.08 x 20.32 cm (2 x 8 in) wood planks, MDO, 19 plywood and coated high density Finnform. All cut by hand on site	Must seal form to prevent hemicellulose-induced retardation. Must use dimensionally stable lumber (TJI LSL Board).
FORM LINER	Victory Bear radius and drip edges, caulking	Use full height 20.32 cm (8 in) by 0.675 cm (0.25 in) tapered radius edge form. Use caulking if necessary in mitered joints of edge such as in corners. Caution with air trapped under radius insert at top edges of forms on panels that will be exposed on both sides.
REBAR	Site cut as well as factory pre-cut rebar were used	Contractors disliked pre-cut, bundled and delivered rebar, preferring to measure and cut on-site. Abrasive cutting saw contaminated forms with grinding dust.
CHAIRS	Plastic chairs of various heights and configurations, some tied to rebar, some not	Some chairs more visible than others. Chairs in SCC panel showed up most. Explore colored chairs, suspending rebar. Explore possibility of eliminating chairs. Investigate whether increasing cover of slab runners and not tying chairs to rebar would help.
LIFTING HARDWARE	Meadow Burke Super Lift III lifting insert, M/B B-75 bracing inserts	Worked well, not visible on panel face. Used oval opening on lifts. Are circular openings better in cases where crane cables need to move while placing panel?
BOND BREAKER	Silcoseal 2000F. Spray and brush applied. Nozzle used had 0.062 diameter hole with fan-shaped slot, resulting in circular spray pattern	Clearly misapplied. 90% of all panels dusted and showed signs of retardation. Spray two coats at right angles to each other, with manufacturer's recommended sprayer. Allow proper curing time and do not re-spray once cured. Explore possibility of using solvent-based bond breaker.
CONCRETE MIX	350 Kg/cm^2 (5,000 psi) Plasticizer. 350 Kg/cm^2 (5,000 psi) SCC and a 350 Kg/cm^2 (5,000 psi) Super P	SCC had the best finish, fewest bug holes and voids. Preferred mix if applied properly. Establish proper slump test procedure, explore having mixes certified at concrete plant.
VIBRATION	Mechanical vibrator was placed in the plasticizer mix, a palm sander was used on the forms only for the SCC and Super P	Again, SCC had least amount of voids. Establish whether SCC should be vibrated at all and whether allowing vibrator to contact rebar cage contributes to visibility of rebar pattern.

The mock-up model was successful in providing the following insights, among many others, for the final construction:

- Accuracy can be improved by leveling and flattening the casting slabs with screed machines. A Dipstick ® (Accuracy of 127/10,000 of a millimeter) was used to check the F-Numbers on one of the casting slabs used in the mock-up model and produced a FL of 10.83. With this unsatisfactory level of accuracy, the concrete panels barely fit together. F-Numbers of 60 and 50 (for FF and FL respectively) were suggested as standards for the actual construction. Casting over joint controls was also denied because they left visible marks on the panel surfaces [ACI 117].
- Shape precision for the concrete panels can be improved by cutting the formwork on-site. A tolerance table was determined to achieve better results (Table 2) [Web-1].
- A concrete mix of 350 Kg/cm^2 (5,000 psi) with plasticizer can reduce bug holes.
- A curing compound is necessary to enhance the finishing quality. A double-silicon seal coat should be applied to separate the casting slabs from the panels.

After obtaining enough hardness in the concrete panels, water was applied on the concrete surface and then covered with tarp in order to minimize the shrinkage and the dehydration process.

Table 2 Tolerances for Tilt-Up Panels [Web-1]

FEATURE	MIN	MAX
Height and width up to 30 ft	-1/8 in (-0.317 cm)	+0
Each additional 10 ft increment over 30 ft	-1/16 in (-0.158 cm)	+0
Thickness of panels	-1/8 in (-0.371 cm)	+0
Squareness of panels as measured on two diagonals	-1/4 in (-0.635 cm)	+0
Size and location of openings cast into panels	-1/16 in (-0.158 cm)	+1/16 in (+0.158 cm)
Location of embedded connection	-1/8 in (-0.317 cm)	+1/8 in (+0.317 cm)
Reinforcing steel cover	-1/4 in (-0.635 cm)	+1/4 in (+0.635 cm)
Seam width between panels	-1/16 in (-0.158 cm)	+0
Offset at face of adjoining panels	-1/16 in (-0.158 cm)	+1/16 in (+0.158 cm)

4.2 Panel Layout and Crane Operational Analysis

4.2.1 Objective

Due to the inherent complexities of the project, the owner, designer and construction team decided to utilize 3D modeling and animations to experiment with the construction process on the computer screen prior to construction in order to avoid the potential of costly on-site errors. In addition, the 3D animation was also used as a training tool for the contractors. The objective of this module is to describe the methodology used to integrate a crane selection algorithm with 3D modeling and animation for the selection and optimized utilization 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 cost of the panel casting slabs.

This module presents the challenges of the case study, regarding the lifting of the concrete panels, due to the unique construction method that was used with the set level of tolerance and accuracy. Since there are no baring walls, the panels will hold each other. Therefore, the need for precise equipment utilization can not be ignored. 3D animation becomes a valuable tool to simulate and experiment with the construction process on the computer screen to identify future potential problems and to avoid costly on-site errors.

4.2.2 Proposed Methodology

The proposed methodology follows the concept illustrated in Figure 9, 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 [Al-Hussein et al. 2001 and 2005], to maximize the crane utilization on-site, as well as analyzing different cranes in a variety of picking and placing point scenarios.

This algorithm selects from a database, the cranes that can perform the lifting sorted by price. It takes in consideration site constraints such as buildings and obstacles; it considers the geometry of the crane such as the boom clearances, rigging system, crawler dimensions, points of rotation etc., and it also uses the information required to perform the lifting such as load weights and dimensions. The algorithm optimizes the process by reducing the time utilized for the crane selection by providing the most feasible option.

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 reach capacity of the crane selected with the 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 in shape of the concrete panels, the lifting process was enhanced by developing 3D animations. Spatial constraints were analyzed by visualizing in the computer screen the lift before it took place at the construction site; the tilting of the panels had to be introduced to the crane operator in order to dragging movements and to avoid collisions with other panels.

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.

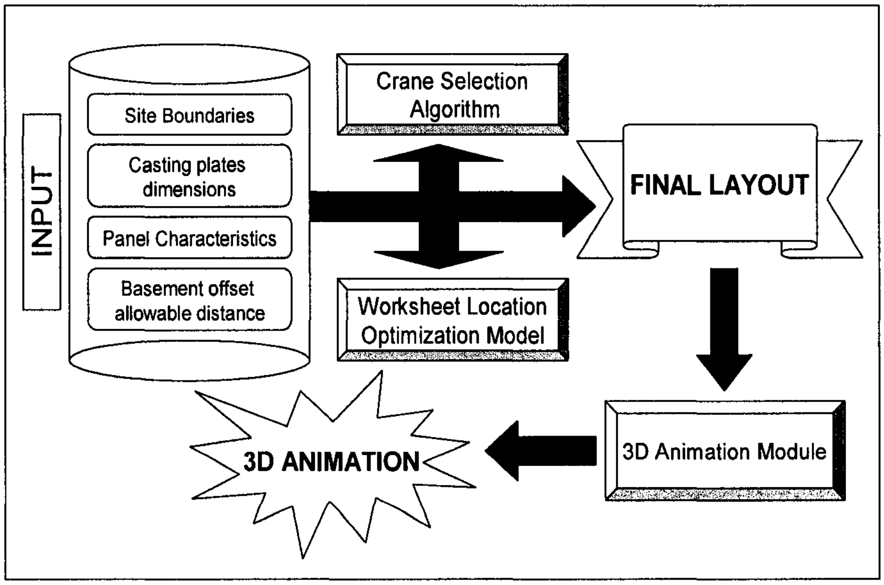

Figure 9: Proposed methodology, crane selection, panel layout and 3D animations

4.2.3 Optimization Model

The analysis was carried out in three stages. The process used existing technology including software such as 3D Studio Max, AutoCAD, MS Solver and algorithms as described in (Al-Hussein et. al, 2001 and 2005). An optimization model was developed in MS Excel in order to enhance the construction site layout and equipment utilization by making them more efficient. For the crane, the goal was to optimize its use on-site by decreasing its mobilization and maximizing its lifting capacity. For the construction site layout, the goal was to reduce its area and, at the same time, the incurred costs.

Step 1 - ***Crane Selection Process:*** During the crane selection step, the algorithms [Al-Hussein et. al 2001 and 2005] were used to provide a list of technically feasible cranes for the tilt-up process. 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 Figure 10 to assist in the selection of technically feasible crane-configurations. Therefore, based on the type of crane, the algorithms follow these two different streams: one for lattice boom cranes and the other for hydraulic cranes (this module will focus on lattice boom cranes). For lattice boom cranes, the lifting radii are optimized. The algorithm makes use of the output of Phase 1 (lift capacity check, satisfying Equation 1) and 2 (crane fit on construction sites, satisfying Equations 2 to 10). Figure 11 shows some of the dialog boxes of the Algorithm. The variables used in the analysis are of these two categories: crane-specific geometry and user-defined clearances. These variables are illustrated in Figures 12 and 13.

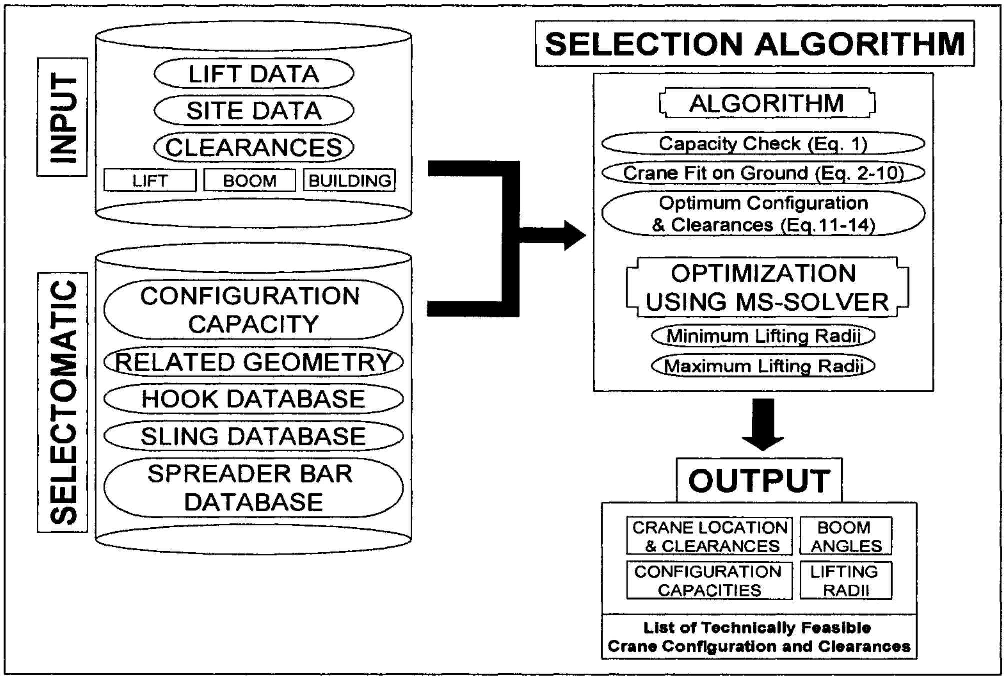

Figure 10: Algorithm Selectomatic, main process components

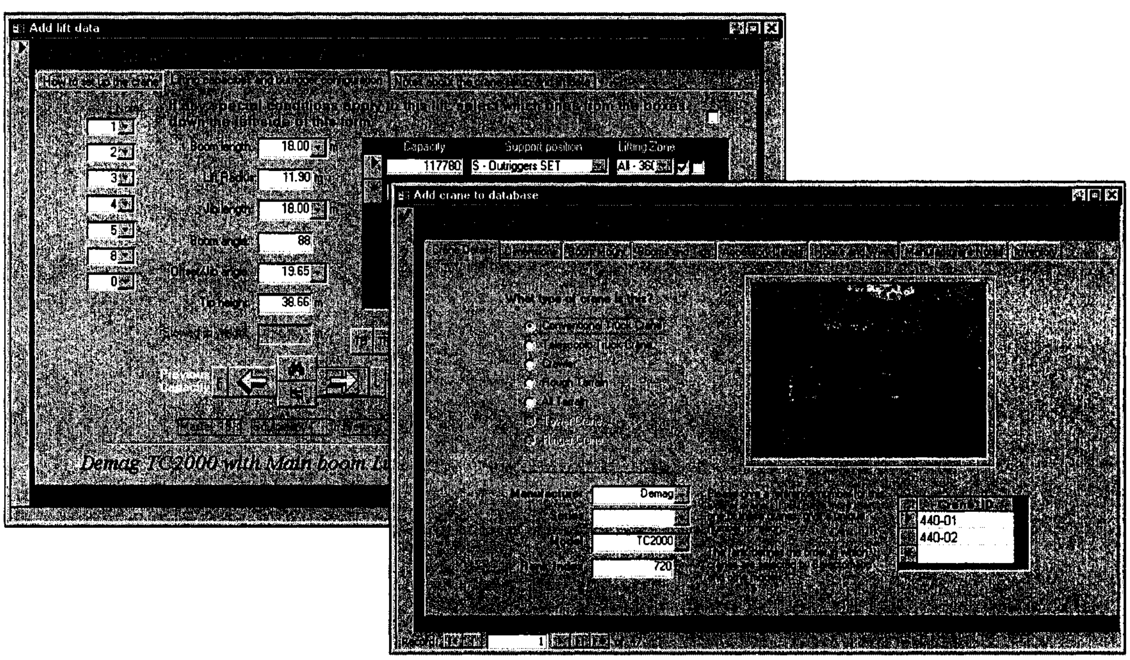

Figure 11: Crane Algorithm, dialog boxes

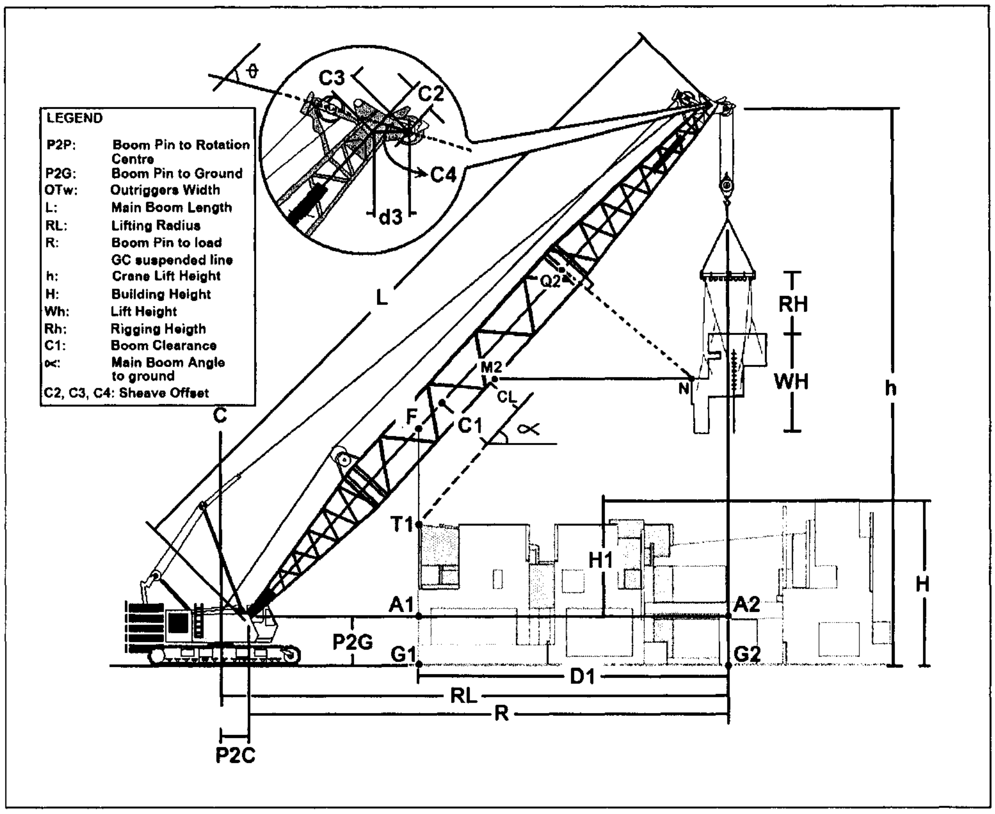

Figure 12: Components of the crane selection system, elevation view

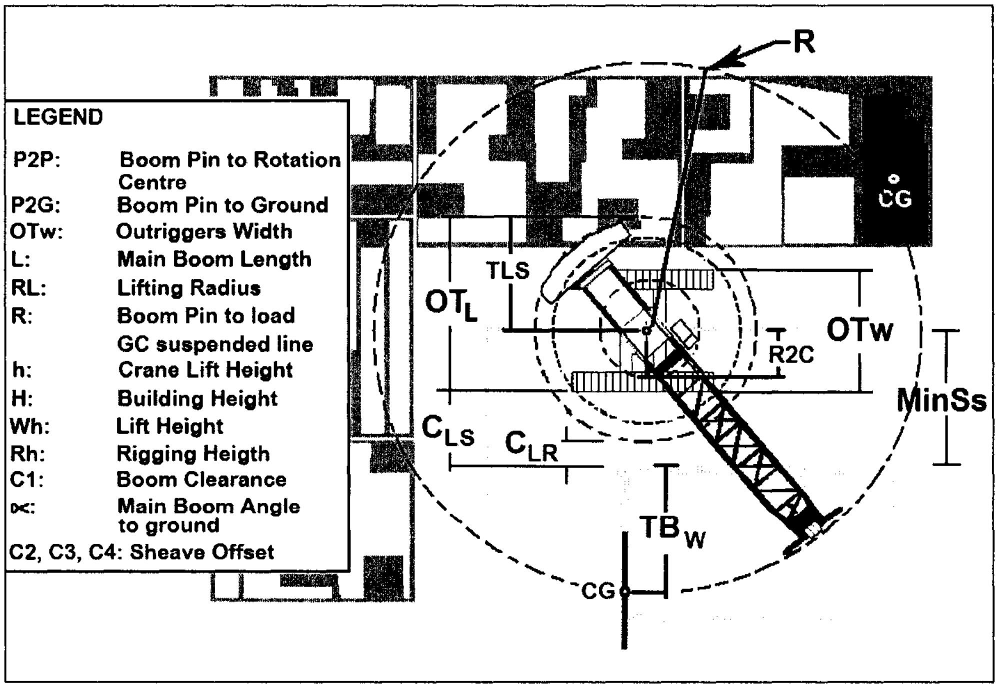

Figure 13: Components of the crane selection system, plan view

$$GC \geq TW = LW + RW \quad (1)$$

where:

$R_W = H_W + SL_W + SP_W$

GC = gross capacity

Tw = total weight

L_W = lift or object weight; and

Rw Rigging weight (which includes H_W = hook block weight, SL_W = Slings weight; and SP_W = spreader beam weight). For this case, Rw is set to be equal to the system default value, a 10% of the lift weight (Lw) is used as common practice, but after defining its final weight, the user is able to change it. Users also have the option to select from the existing list of rigging hardware or specify the weight used for the lift under consideration.

$$C_{LR} = R - (TB_W + R2C) \quad (2)$$

$$C_{LR} = R - (TB_W + \tfrac{1}{2}\, OT_L) \quad (3)$$

$$C_{LS} = MinS_S - \tfrac{1}{2}\, OT_W \quad (4)$$

$$C_{LS} = MinS_S - TLS \quad (5)$$

$$MaxR \geq (C_{LR} + C_{LS}) + R2C + TLS \quad (6)$$

$$MaxR \geq (C_{LR} + C_{LS}) + R2C + \tfrac{1}{2}\, OT_L \quad (7)$$

$$MaxR \geq (C_{LR} + C_{LS}) + R2C + TLS \quad (8)$$

$$C_{LF} = MaxR - (C_{LR} + R2C + TLS) \quad (9)$$

$$C_{LF} = MaxR - (C_{LR} + R2C + \tfrac{1}{2}\, OT_L) \quad (10)$$

The formulations for lifts performed only on the main boom are considered for this case study, as illustrated in Figures 12 and 13. The algorithm considers the detailed geometry of each crane in its calculation including sheave offsets (C_2 and C_3) from the centerline of the main boom. To select a mobile crane, contractors need to know the following three main geometrical variables: main boom length (L), main boom angle to ground (α) and the crane's lifting radius (R). 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 (L) as a function of its angle to ground (α), 2) the main boom length (L) as a function of the crane's lifting radius (R) and 3) the crane's lifting radius (R) as a function of the main boom angle to ground (α).

This section describes the formulation in which the boom length (L) is expressed as a function of the main boom angle to the ground (α). The formulation below accounts for the boom/building clearance constrains (C_L). Considering the geometric parameters shown in Figures 12 and 13, it is possible to express (L) as shown in Equation 11.

$$L = \frac{C_1 \, Sin\,\alpha + D_1 - [C_4 \, Cos\,(\phi - \alpha)]}{Cos\,\alpha} + \frac{H_1 + C_1 \, Cos\,\alpha}{Sin\,\alpha} \qquad (11)$$

To find the optimum boom length L (i.e. minimum L and its associated maximum load capacity), the first and the second partial derivatives of (L) with respect to (α) are determined.

$$\frac{\partial L}{\partial \alpha} = \frac{C_1 \, Sin^2\alpha - D_1 \, Sin^3\alpha - C_4 \, Sin\,\phi \, Sin^2\alpha - C_1 \, Cos^2\alpha - H_1 Cos^3\alpha}{Sin^2\,\alpha \, Cos^2\,\alpha} = 0 \qquad (12)$$

Equation 12 is a complex equation to solve. However, it can be simplified by transforming it into a polynomial of (*t*), where (*t*) is set equal to tan(α/2), which is provided in Equation 13.

$$\frac{\partial L}{\partial \alpha} = \frac{C_1(1+t^2)^2 - 2D_1t(1+t^2)}{(1-t^2)^2} - \frac{C_4Sin\phi(1+t^2)^2}{(1-t^2)^2} - \frac{C_1(1+t^2)^2}{(2t)^2} - H_1\frac{(1-t^2)(1+t^2)}{(2t)^2} = 0$$

(13)

Equation 13 can be further simplified to take the form shown in Equation 14.

$$\frac{\partial L}{\partial \alpha} = (3C_1 - 4C_4Sin\phi + 2H_1)t^3 + (5C_1 - 4C_4Sin\phi + H_1)t^2 + (3C_1 - 2H_1)t + (C_1 - H_1) = 0$$

(14)

Equation 14 is more manageable mathematically. Knowing all the variables involved, one could solve for (t) by means of iterations and by subsequently ensuring that $\frac{\partial^2 L}{\partial \alpha^2} < 0$. Knowing that t = tan (α/2), an (α) value that satisfies the condition for the optimum boom length (L) can then be determined.

Maximum and Minimum Lift Radii: The optimization module of the algorithm provides an easy-to-use environment for calculating the maximum and minimum radii associated with the optimum lift configuration(s) 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 "Selectomatic." However, their angles to the ground are subject to change when the lifting radius changes. Considering the crane geometry and that the lift is to be performed on its boom, the objective function can be set as shown in Equation 15. The objective here is to optimize the lifting radius (i.e., to determine the minimum and the maximum radii (R_{min} and R_{max})). This is carried out by using a macro, which activates MS Solver twice; once to determine the maximum (R) value and a second time to determine the minimum (R) value. It should be noted that the parameters used in the equations of this section (i.e., Equations 15-19) are shown in Figures 12 and 13.

$$Min/Max.\ \ Radii\ \ R = \pm P2C + (L + C_3)\ Cos(\alpha) \qquad (15)$$

The optimization process is then carried out using the objective function (Equation 7), subjected to the set of constraints represented in Equations 15-19. It should be noted that these equations account for all clearances and constraints imposed by the lift, crane and site. This includes boom clearance to buildings (Equation 16), minimum hook clearance (Equation 17), load clearance to boom (Equation 18) and carrier clearance to buildings (Equation 19).

$$G1F \geq \{H + [T1F * Cos(\alpha)]\} \qquad (16)$$

$$[L + C_3\ Sin(\alpha)] \geq (H + W_h + R_h + Min_{-CL}) \qquad (17)$$

$$NM_2 \geq [(NQ_2) \div Cos(\alpha)] \qquad (18)$$

$$[0.5 * L + C_3)Cos(\alpha)] \geq [(\pm P2C + 0.5 * OT_W + D1)] \qquad (19)$$

Based on the results obtained from this interface, the next step was to choose the crane capable of performing the work, while minimizing mobility complications and considering operation costs, availability and accessibility parameters. A Manitowoc Crawler Mounted Crane 888 (230 tonnes) was selected [Web 5].

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. The spreadsheet developed in this module can be applied to any case involving the lifting of any type of load by using a crawler crane. The requirements, as explained later on, are: The type of crane and its reach capacity, the load location and its final position. As an example, the spreadsheet for phase 1C is shown in Figures 14 and 15. 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, Figure 15). The coordinate system started from the left bottom corner of the project (Quadrant C, Figure 6). The final X and Y locations relative to the center of gravity of each panel are shown in Figure 14. For the calculations in Step 3, it was necessary to determine the distance of the crane to the final location of each panel by using the Equations 20 and 21.

offset x(m)	8.9				
offset y(m)	8.9				
X min(m)	0.0				
X max(m)	23.5				
Y min(m)	0.0				
Y max(m)	36.3				
PHASE	1C	FINAL POSITION OF THE CRANE			
X pos (m)	5.96	Min Momemtum	169	X(m)	0
Y pos (m)	24.10			Y(m)	24.1046

PANEL #	THICKNESS (m)	WIDTH (m)	HEIGHT (m)	x (m)	X From Crane (m)	y (m)	Y From Crane (m)	AREA (m2)
21	0.21	8.3	3.6	14	23.4	4	13	18
22	0.21	5.3	4.9	14	23.4	11	20	21
23	0.21	[illegible]	8.9	[illegible]	23.4	19.2	24	39
24	0.21	3.1	8.9	14	23.4	19.5	28	19
25	0.21	2.6	8.9	16	24.6	20.0	29	22
26	0.21	7.2	5.0	14	23.4	24	33	29
27	0.21	10.3	2.3	9	18.2	22	31	15
28	0.21	8.3	3.6	5	13.7	4	13	21
29	0.21	[illegible]	5.0	[illegible]	13.7	11	20	24
30	0.21	5.0	9.1	5	13.7	15	24	31
31	0.21	3.3	[illegible]	5	[illegible]	19	27	[illegible]
32	0.21	7.5	9.3	0	9.0	14	23	43
33	0.21	[illegible]	[illegible]	2	[illegible]	12	21	[illegible]
34	0.21	3.4	1.2	0	9.0	23	32	4
35	0.21	[illegible]	[illegible]	0	9.0	19	28	[illegible]
36	0.21	6.1	8.8	3.0494	12.0	22.31	31	34

Figure 14: Optimization model spreadsheet, part A

$$X form\ Crane\ = Offset\ X + X \quad (20)$$

$$Y form\ Crane\ = Offset\ Y + Y \quad (21)$$

Where:

Offset X, Offset Y = Offset distances measured from the edge of the footings to the center of rotation.

Figure 15 shows the calculations made in the optimization model, which is explained in detail in Step 3. Rx and Ry (Equations 22 and 23 respectively) represent the radii of the final location of the crane to the final location of the panel, with the crane sitting on the X-axis or Y-Axis. Mx and My (Equations 24 and 25) are the product of the radii in X or Y and the panel weights. In the same spreadsheet, the maximum values are shown at the bottom of each calculation.

Rx = [(Xpos – X from Crane)^2 + (Ymin-Y form Crane)^2]^0.5 (22)

Ry = [(Ypos – Y from Crane)^2 + (Xmin-Y form Crane)^2]^0.5 (23)

where:

Xpos, Ypos, = Iterated crane location along the X or Y axis;

Xmin, Ymin = Coordinate values of where the quadrant starts.

PANEL	Rigging (Ton)	Panel Weight (Ton)	WEIGHT (Ton)	Rx (m)	Ry (m)	Mx (Ton.m)	My (Ton.m)
DW5	2.5	9.605	12.1	6.6	7.9	80	95
DW4	2.5	11.245	13.7	8.0	7.2	111	100
DW3	2.5	21.15	23.7	9.1	7.1	214	169
DW2	2.5	10.385	12.9	10.2	7.3	131	93
DN2	2.5	11.675	14.2	10.5	7.6	149	108
RW2	2.5	15.7	18.2	11.3	7.6	205	138
GN1	2.5	11.35	13.9	10.2	6.0	142	82
SCE2	2.5	11.205	13.7	4.6	5.4	63	73
SCE1	2.5	12.85	15.4	6.6	4.3	101	67
GE1	2.5	16.81	19.3	7.8	4.2	151	81
GE2	2.5	[illegible]	10.5	8.7	4.3	[illegible]	47
GW2	2.5	23	25.5	7.0	2.8	179	71
GS1	2.5	[illegible]	20.6	6.5	3.6	135	74
GW1.1	2.5	2.2	4.7	9.9	3.7	46	17
GW1	2.5	19.42	21.9	8.5	3.0	186	65
GN3	2.5	26.05	28.6	9.7	4.2	277	121
MAX			28.55	11.3	8	277	169

Figure 15: Optimization model spreadsheet, part B

The structural design included a panel installation sequence, which could not be modified (Figure 16). 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, B, C and D as shown in Figure 17. 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.

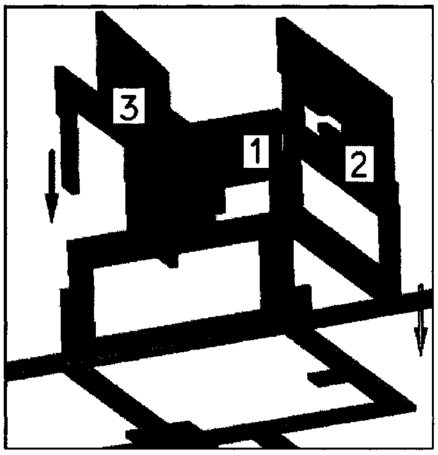

Figure 16: 3D Model, panel installation sequence

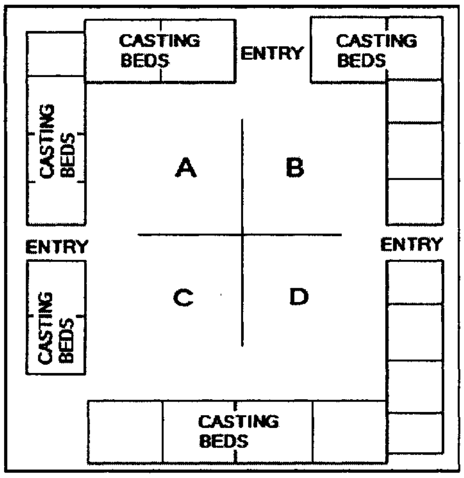

Figure 17: Casting slabs, case study

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 x 12.80 m to 15.84 x 15.84 m (42 x 42 ft to 52 x 52 ft), covering a total area of 4316 m^2 or 46,459 sq ft (Figure 6). 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 Figure 18.

Step 3: Optimization Model and Panel Layout: The objective was to calculate the minimum of the maximum momentums for each subset of panels while varying the crane location along the rectangular path around the house. By utilizing a min max model, the lifting position selected will ensure the capability to lift the subset of panels without having to relocate the crane. The developed spreadsheet used a quadratic optimization model. The momentum theory was applied to the model, satisfying equations 24 and 25.

offset x(m)	8.9
offset y(m)	8.9
X min(m)	0.0
X max(m)	23.5
Y min(m)	0.0
Y max(m)	36.3
PHASE	1C
X pos (m)	5.96
Y pos (m)	24.10

Iterating Parameters

FINAL POSITION OF THE CRANE

Min Momemtum	169	X(m)	0
		Y(m)	24.1046

Final Location

PANEL #	THICKNESS (m)	WIDTH (m)	HEIGHT (m)	x (m)	X From Crane (m)	y (m)	Y From Crane (m)	AREA (m2)	PANEL	Rigging (Ton)	Panel Weight (Ton)	WEIGHT (Ton)	Rx (m)	Ry (m)	Mx (Ton.m)	My (Ton.m)
21	0.21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
22	0.21	5.3	4.9	14	23.4	11	20	21	DW4	2.5	11.245	13.7	8.0	7.2	111	100
23	0.21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
24	0.21	3.1	8.9	14	23.4	19.5	28	19	DW2	2.5	10.385	12.9	10.2	7.3	131	93
25	0.21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
26	0.21	7.2	5.0	14	23.4	24	33	29	RW2	2.5	15.7	18.2	11.3	7.6	205	138
27	0.21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
28	0.21	8.3	3.6	5	13.7	4	13	21	SCE2	2.5	11.205	13.7	4.6	5.4	63	73
29	0.21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
30	0.21	5.0	9.1	5	13.7	15	24	31	GE1	2.5	16.81	19.3	7.8	4.2	151	81
31	0.21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
32	0.21	7.5	9.3	0	9.0	14	23	43	GW2	2.5	23	25.5	7.0	2.8	179	71
33	0.21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
34	0.21	3.4	1.2	0	9.0	23	32	4	GW1.1	2.5	2.2	4.7	9.9	3.7	46	17
35	0.21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
36	0.21	6.1	8.8	3.0494	12.0	22.31	31	34	GN3	2.5	26.05	28.6	9.7	4.2	277	121
								406	MAX			28.55	11.3	8	277	169

Minimum Momentum

Figure 18: Final Crane Location on construction site

$$Mx = F.Dx \qquad (24)$$

$$My = F.Dy \qquad (25)$$

where:

M = Momentum;

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 favourable 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, Figure 19 shows the momentum results exerted on the crane by altering the crane's location along the path. Appendix A shows the graphs for the different phases.

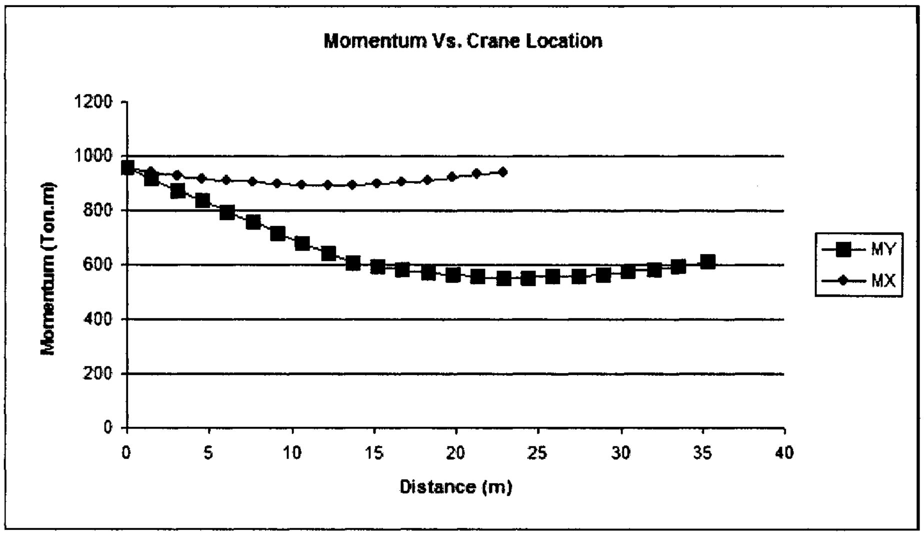

Figure 19: Momentum Vs. Crane location on-site

The path that the crane can follow by varying its location in accordance with the installation sequence is shown in Figure 20. 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.

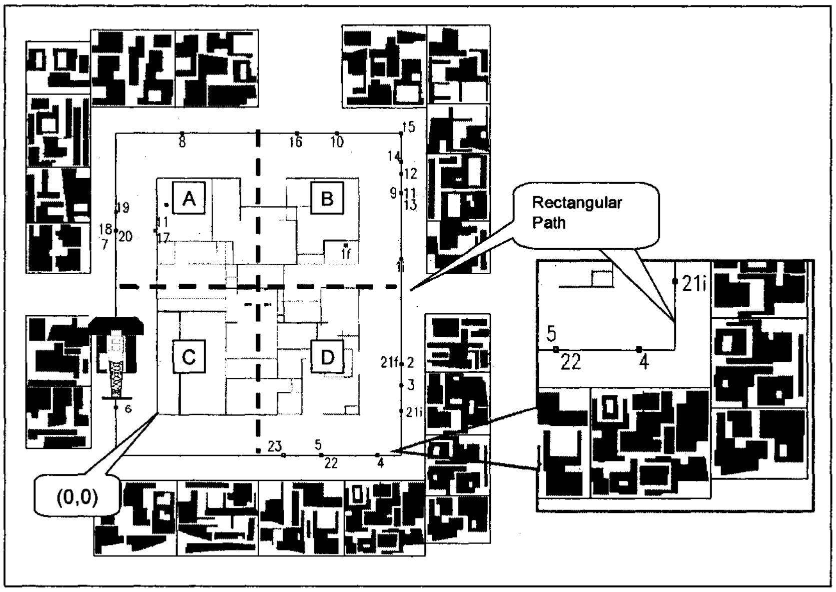

Figure 20: Final Crane locations on-site

Solver and Solver Table were applied to obtain the result. As an example, Figure 19 shows the crane's final location. Figure 21 illustrates the quadratic model used in the investigation for targeting 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 by satisfying the objective function in equation 26 and the set of constraints in equations 27-30:

$$Min\ (M_{xi}, M_{yi}) \qquad (26)$$

$$X_i \geq Xmin \qquad (27)$$

$$X_i \leq Xmax \qquad (28)$$

$$Y_i \geq Ymin \qquad (29)$$

$$Y_i \leq Ymax \qquad (30)$$

Where:

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

X_i, Y_i = Iterating values along the rectangular path;

Xmin, Ymin, Xmax, Ymax = Minimum and Maximum path boundaries.

Sensitivity analysis: The reduce gradient in Figure 21 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 can not 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 Figure 21 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 is at the valley of the quadratic equation, where the slope (or rate of change) is zero.

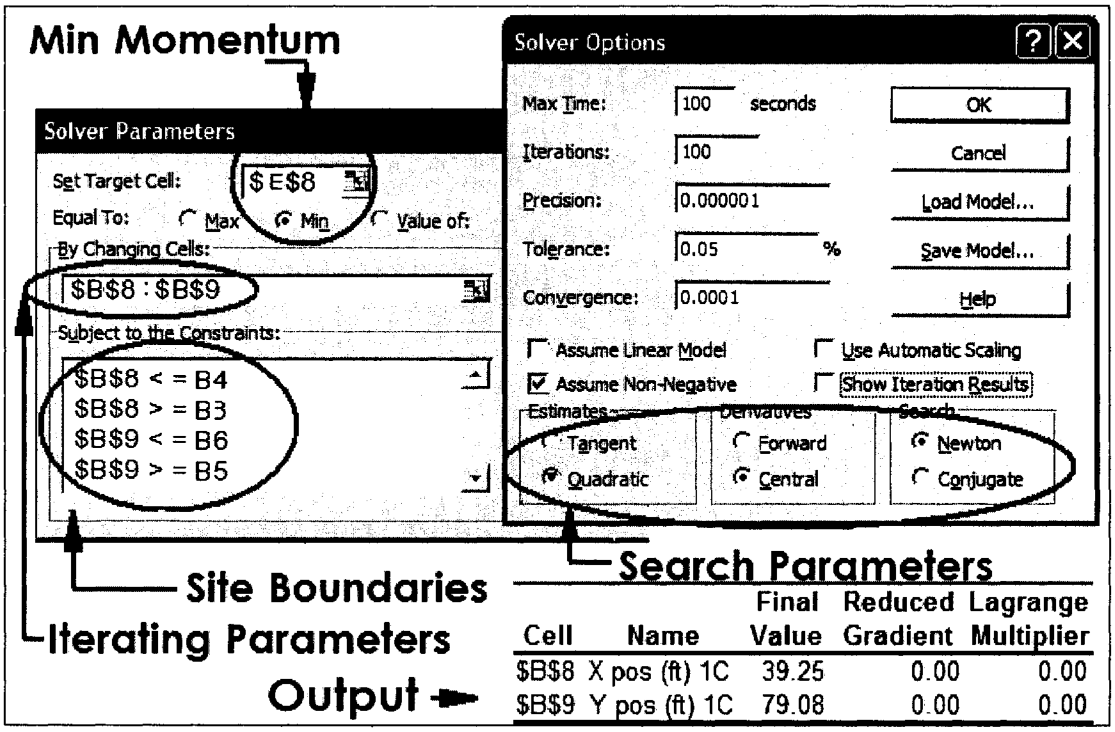

Figure 21: Optimization model dialog box, input and output parameters

4.2.4 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. Based on the panels' shapes, the structural designer had to include strong backs and legs to avoid localized stresses and potential bending and fracturing when the panels are pivoted on their axis of rotation (Figure 22).

Two different models of casting slab shapes were proposed in order to facilitate the lifting process. As shown in Figure 23, 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.

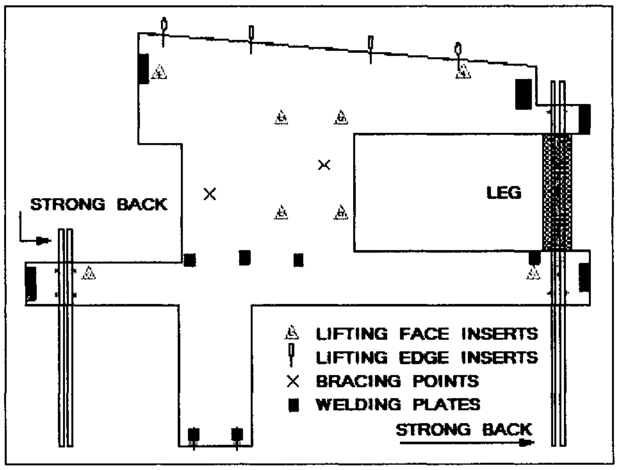

Figure 22: Panel Configuration example, lifting and bracing components

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 **Z** = 0). The concrete panels were tilted from lift inserts (as explained in 4.4.4). The location of this lift inserts were determined by the structural engineer; they were placed in the panel in order to maintain the center of gravity aligned with the main line of the crane (rigging) and in order to keep horizontal the bottom of the panel.

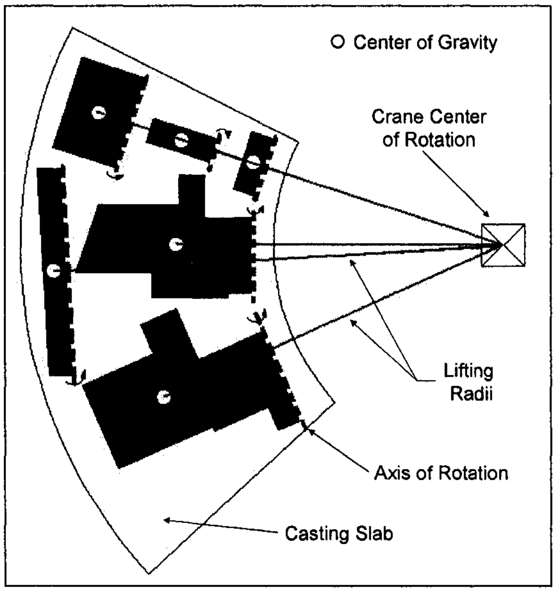

Figure 23: Circular casting slab

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 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 Figure 24, the panels are closer to each other, which use less space.

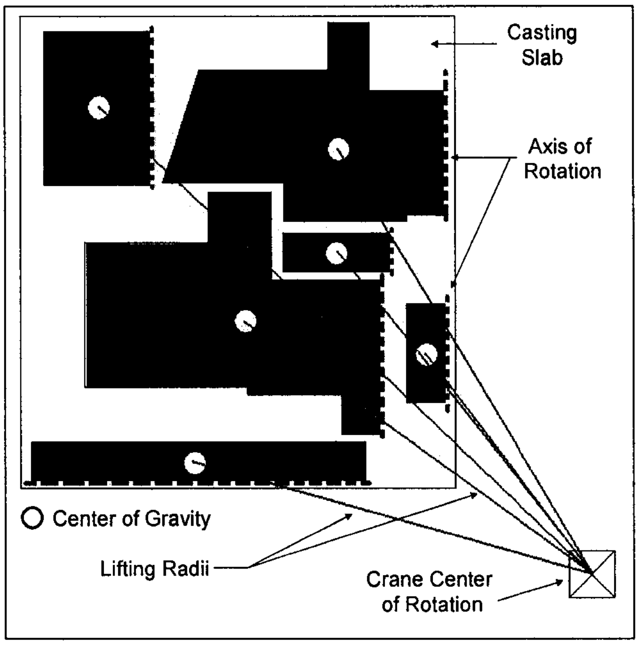

Figure 24: Rectangular casting slab

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 Figure 25.

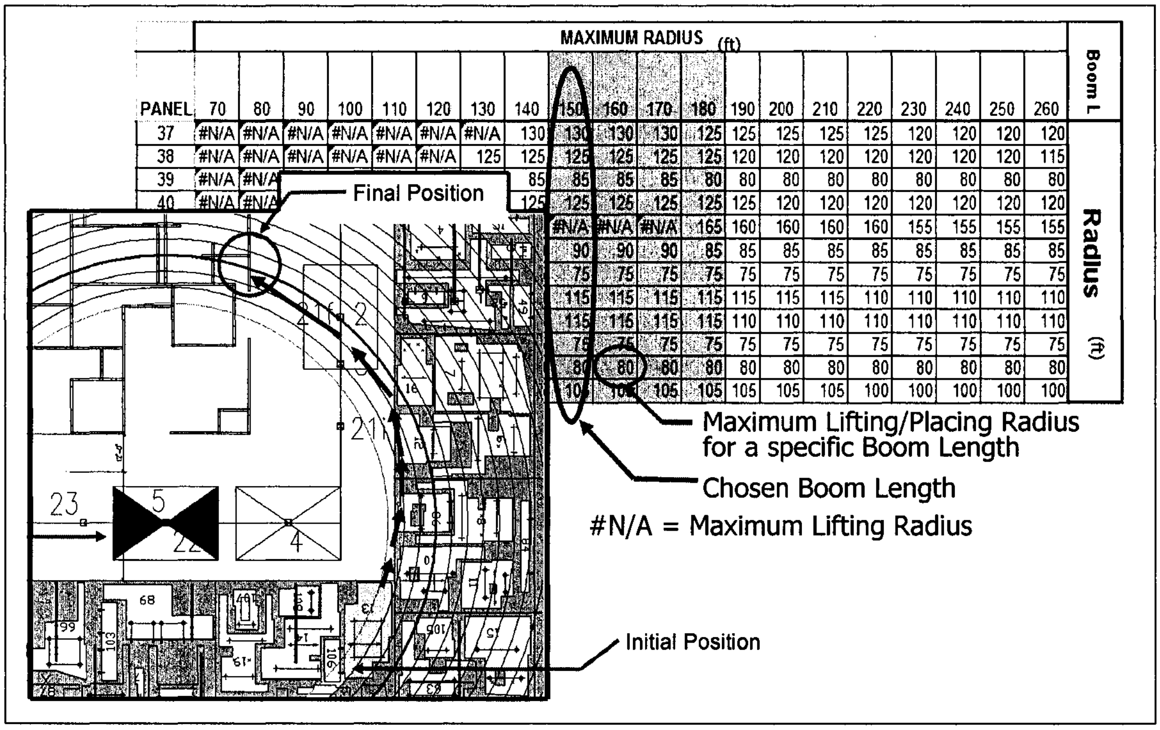

Figure 25: Lifting radii per boom length

The construction site layout was drawn in AutoCAD (Figure 20). 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.

4.2.5 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. Figure 26, shows the complete 3D model of the facility made in AutoCAD.

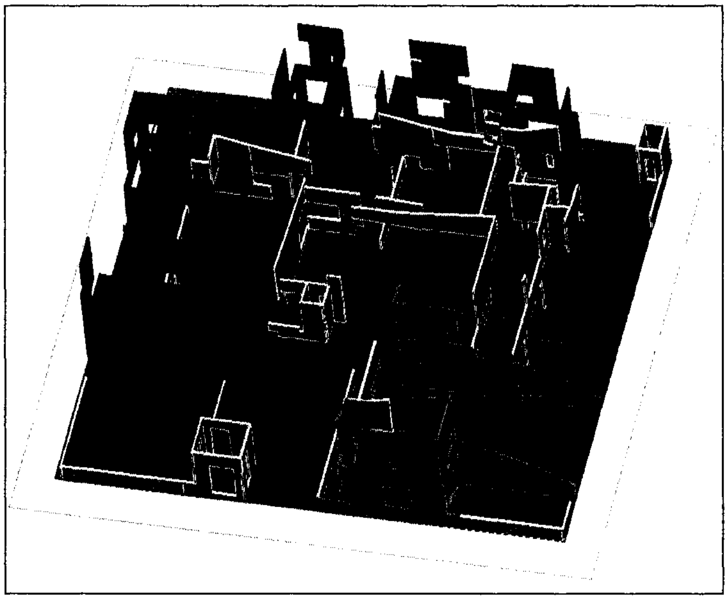

Figure 26: 3D AutoCAD model, case study

A special requirement, when constructing with Tilt-up, is the need to pivot the panel from its base without dragging it (Figure 27). 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 design 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.

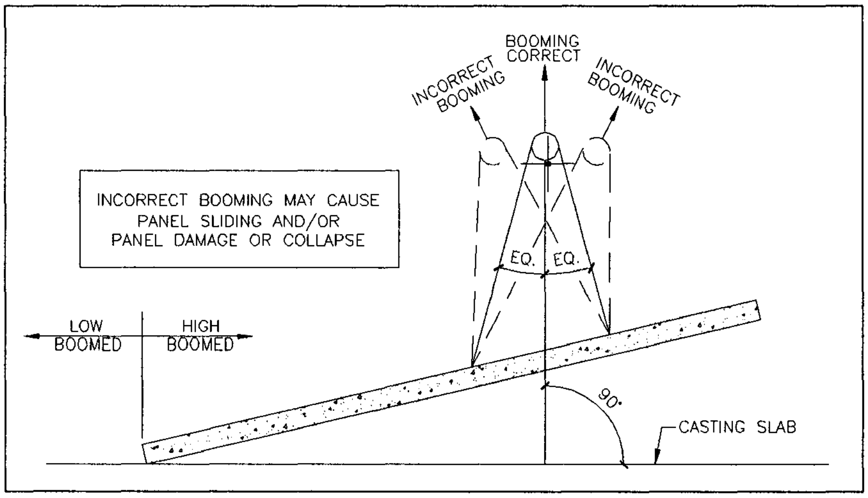

Figure 27: Proper tilting of the concrete panels on the casting slab

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 installation, 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 Figure 28, 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.

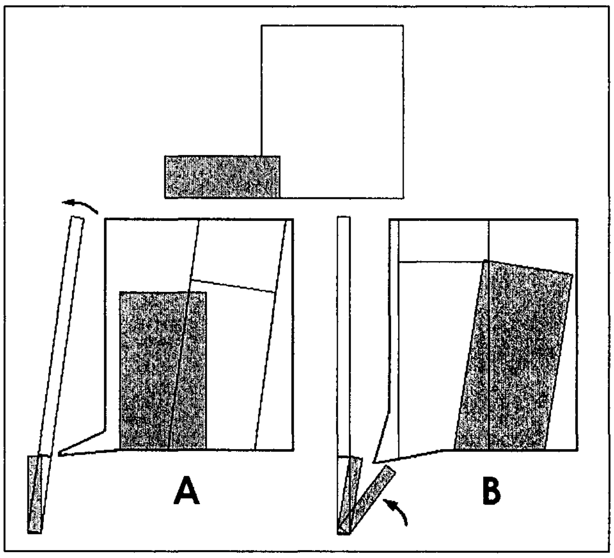

Figure 28: Proper installation sequence

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 1x1x1 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 m to 9.75 m (18 ft to 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.

Four frame samples of one panel animation have been included in this paper (Figure 29). 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, B and 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 pre-defined specifications.

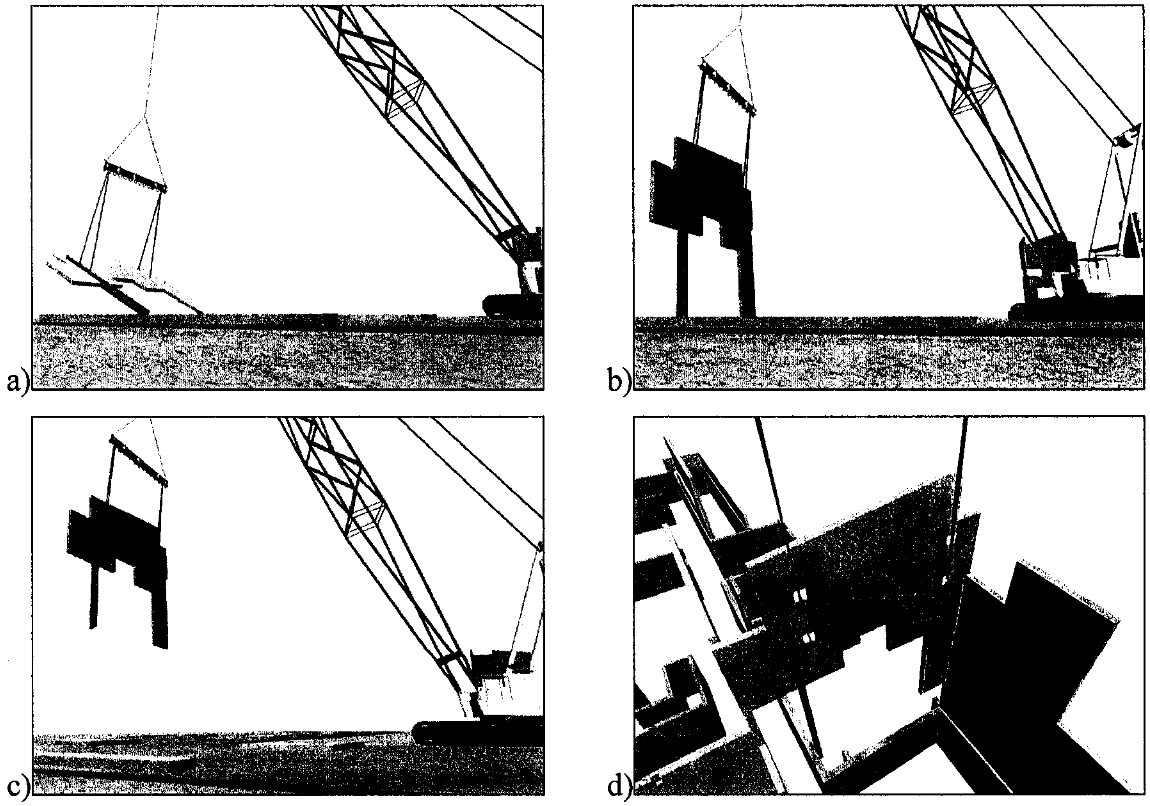

Figure 29: Frame views from the 3D animation of lifting a panel

4.3 Concrete Finishing Analysis

4.3.1 Objective

Precision played an important roll in the construction of the case presented in this thesis, based on the joint connections and the materials used. The first challenge was pouring and casting of the panels: measures had to be in place to minimize the concrete tendency to shrink due to climate humidity and mix characteristics.

The second challenge was to fit the concrete panels, cast on-site, with the maximum joint tolerance of 1.27 cm (0.5 in) or 63.5mm for each panel (0.25 in). The actual construction obtained the maximum benefit by constructing and testing a structure with similar features: knowledge was gathered from the correction of flaws discovered in the mock-up model, which was constructed based on engineering knowledge and trial-and-error. Different materials were tested in order to select the most effective concrete mix (over 500 m^3 of concrete was needed to pour the 108 concrete panels that compose the facility). To optimize each step in the construction process and to improve the final product, the mock-up model was also used to test different materials. As show in Table 1 (Seaviewcorp Inc., 2005), eleven elements with different variables were tested in order to analyze the actual construction.

Due to the considerable investment for constructing the actual facility, the mock-up model was intended to address as many questions as possible. All of the eleven elements listed in Table 1 affected somehow the quality of the final product of the construction. For instance, the surface of the concrete panels has a direct relationship with the construction of the concrete slabs; the curing compound; the type of chairs used; the type of bond breaker; the concrete mix and the type of vibration method. The plastic chairs were important to test to due the marks that they can leave on the concrete surface. These elements are required to support the rebar in order to avoid its contact with the bottom floor; in order to eliminate the marks, low density plastic chairs were needed in order to obtain floatation effect by pushing up the rebar and avoiding their contact with the floor. The architectural design required high quality aesthetic surface on the panels; the structural design required perpendicularity in corners and sides in order to allow interlocking the concrete panels as it will be explain later in this paper. Shape accuracy is extremely important for this complex facility, which called for a maximum panel-to-panel joint tolerance of only 1.27 cm (0.5 in) or 63.5 mm for each panel (0.25 in), often in 90-degree joints between panels. This demands flat casting slabs and precise formwork.

The purpose of describing the construction method used in the case study is to demonstrate the accuracy and tolerance challenges related to pouring casting slabs for tilt-up panels. The challenge was to aim at precise floor flatness and levelness of the casting slabs in order to achieve the owner's quality expectations and the structural requirements. The formwork is the second key to ensuring the quality production of the concrete panels in regards to the surface smoothness. Due to the variety of types of construction concrete materials that could be used for the structure, the mock-up model was also used to test and determine which materials would provide the results expected by the owner.

The structural designer relied on the results of the mock-up model analysis in order to determine the concrete mix design and reinforcement needed for the concrete panels. Three types of concrete mixes with the same structural resistance were tested in order to select the mix that provides the best finished surface. The mock-up model was constructed using concrete panels that complied with the actual shapes, interlocking at 90 degrees. The mock-up model was also used to verify the underlying assumption; the surface quality of the actual panels is the same or close to the surface quality for the casting slabs.

4.3.2 Proposed Methodology

The goal of the proposed methodology, which is illustrated in Figure 30, is to describe a construction process specific to precast tilt-up panels including site preparation, pouring and casting procedures, and final finishing. Due in part to the inherent complexity of the case and the high quality required by the owner and the architectural design, a mock-up model was designed and built to minimize imperfections of the finishing and installation process. Many characteristics were explained during the conceptual planning and feasibility analysis phase. As illustrated in Figure 30, many parameters were considered for the project including space constraints, materials, forms and lessons learned from the errors obtained from the mock-up report. There were many uncertainties to address, especially those involving the smoothening of the panels, which is why a smaller model was constructed to address the effect of material selection for the finishing quality and the erection procedure. It is of interest to mention here, the structural design was expected to be modeled based on the type of concrete mix that could provide the best finishing.

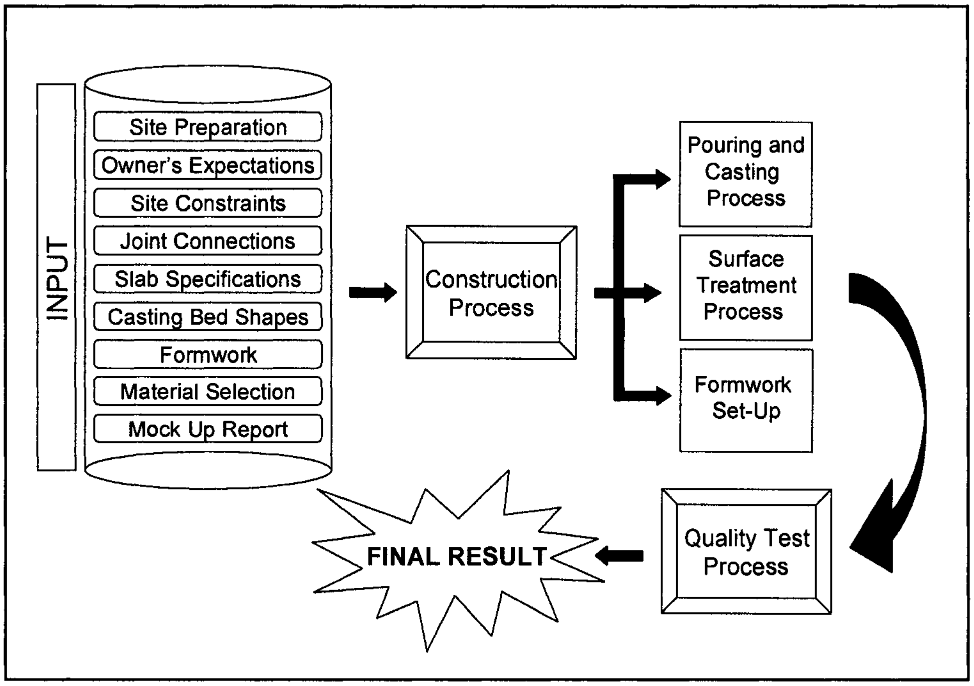

Figure 30: Proposed methodology, concrete finishing analysis

Lessons were learned from the mock-up model for the finishing quality, and the process of erecting the structure. Table 1 (Seaviewcorp Inc., 2005) details the elements tested, the variables for each and the possible solutions or suggested changes obtained; this was documented and detailed in a report, which was prepared with the assistance of a third party consultant.

Mock-Up Model Findings

Different materials were tested in order to obtain high quality results. Four different types of chairs were tested, showing marks on the external panels' surfaces, demanding research for a better product. In addition, the contractor is faced with the challenge of delivering a flat and smooth concrete surface for acid staining later in the process. "Bug Holes," "Honey combs" and voids have to be eliminated to meet the owner's expectations in both quality and architectural aesthetics. Three out of four concrete mixes failed this test as shown in Figure 31.

Figure 31: Panel Imperfections, mock-up model

The mock-up model was successful in providing the following insights, among many, for the final construction:

- Accuracy can be improved by leveling and flattening the casting slabs with screed machines. A point elevation measurement device (Dipstick), which is a device that measures elevations on surfaces with an accuracy of 5/10,000 of an inch (Face Construction Technologies Inc., 2005), was used to check the F-Numbers (which will be described in detail later in this thesis). One of the casting slabs used in the mock-up model was tested, producing a F_L of 10.83. With this unsatisfactory level of accuracy, the concrete panels barely fit together. F-Numbers ranging the values of 55 to 65 and 45 to 50 (for floor flatness (F_F) and floor levelness (F_L) respectively) were suggested for the actual construction (the calculations of these numbers will be described later in this paper). Casting over joint controls was also not accepted, since they left visible marks on the panel surfaces.

- Shape precision for the concrete panels can be improved by cutting the formwork on-site (Table 1). Tolerance guidelines, listed in Table 2, were determined to be used for the actual construction.
- A concrete mix with plasticizer, self leveled and self compacted must be used in order to reduce bug holes and cracks as shown in Figure 31.
- A curing compound is necessary to enhance the finishing quality (Table 1). A double-silicon seal coat should be applied to separate the casting slabs from the panels.

4.3.3 Construction Process

The complex nature of this project posed a challenge to optimize the construction process. Erecting tilt-up panels is not a widely used technique for residential construction, especially for buildings with panels that have irregular shapes. The formwork utilized for the construction of the panels is not reusable, as each panel is completely different. The panels must also be poured in short succession for quality purposes (to ensure that the mix would be the same in a large set of panels with the same texture and aggregate color). Evaluating the constraints before tilting up each panel not only reduced cost, time and labor, but the installation was made safely and provided an acceptable tolerance level. Several layouts with different casting slab shapes and different panel locations were proposed and experimented with during the planning stage. To avoid cracks and fissures, the geotechnical engineer required that the crane, should keep a minimum distance of 3.65 m or 12 ft from the foundation walls. One of the main reasons for leaving such a distance between the crane and the structure was the weight pressure that would be exerted by the crane against the footing and the basement walls. The casting slab sizes range from 12.80 x 12.80 m (42 x 42 ft) to 15.84 x 15.84 m (52 x 52 ft). The total casting slab area was 4,316 m^2 (46,458 sq ft). Layouts were arranged according to space constraints, maintaining square shapes to avoid concrete cracks.

The site was graded with a bulldozer and a 15.24 cm (6 in) stone base layer was place to avoid future settlement. A rolling vibrator was used to compact the layer until it reached 95% compaction. This compaction percentage was obtained based on the permeability test using the maximum dry density of the material. If the material is compacted at a higher rate or lower rate, it will expand/shrink, damaging the casting slab.

The minimum joint separations between casting slabs was set at 2.54 cm (1 in), the joint separations were placed to create rectangular shapes; some of the casting slabs did not match the previously defined panel layout specifications, but ultimately the ratio between width and height was never less than 0.94. The minimum acceptable separation between the panel forms was set at 20.32 cm (8 in) to allow for tilt-up.

A) Construction of Casting slabs – The casting slabs used a 250 kg/cm^2 (3,500 psi) concrete mix and did not require reinforcing due to their thickness (10 cm or 4 in) and time of pouring (in spring). A laser screed machine with a 3.65 m (12 ft) arm flattened and leveled the concrete. While the concrete was poured, the laser screed machine ensured the flatness and levelness of the slab. An automatic laser control system provided an accurate finishing through the use of electro-hydraulic controls. Two laser receivers, each mounted at the end of the screed head, receive multiple signals from a transmitter, providing automatic control to the work.

Recently, a wide variety of concrete curing and finishing products have become available for construction projects. In this case study, the bond breaker (Nox-Crete, 2003) was the product used to cure, seal and harden the casting slabs based on the results and the guidelines obtained from the mock-up model.

The bond breaker fulfilled the construction requirements in terms of quality finishing, concrete bonding and suitability for the ambient temperature conditions during the casting process. This product allows constructors to improve the smoothness and hardness of concrete surfaces, and it also allows the separation between two concrete surfaces. Since the smoothness factor played such an important role for panel surface finishing; eliminating the porosity and the voids on the casting slabs, the quality expectations became somewhat achievable. The treatment process began once the casting slabs had solidified; after preparing the chemical mix, the operator sprayed the solution over the slabs. For quality assurance purposes, the casting slabs were sprayed with the bond breaker within a 30-minute window (Nox-Crete, 2003). Areas that had dried in the elapsed time period had to be sprayed again to provide a homogeneous result.

Next, the puddles were swept away to create a uniform effect on the casting slabs. Water was then hosed over the surface to help the chemical solution penetrate into the concrete surface. At the same time, the residue was removed with a broom to avoid stains. The casting slabs were poured during spring and to obtain a high-quality finish on the interior faces of the panels, it was necessary to apply three coats of the bond braking compound. The first one was used to cure the concrete slabs, and the second and third coats were required to facilitate the separation of the concrete panels from the casting slabs (Figure 32) (Nox-Crete, 2004).

The bond breaker requires less water during cold weather conditions which is a primary consideration in the curing process. To guarantee quality, the bond breaker exceeded the moisture retention requirements by ASTM as indicated in the reference. However, the chemical solution did not work as it was intended: some surface flaws were discovered after tilting up the panels.

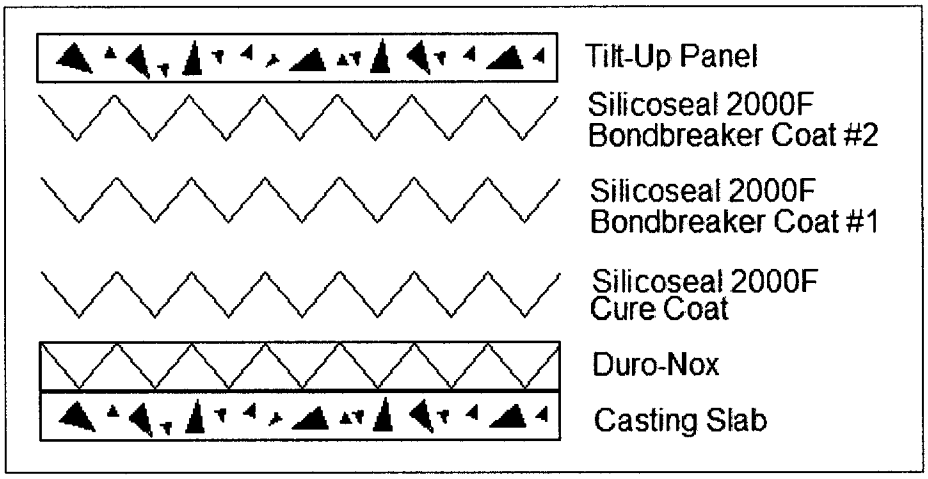

Figure 32: Bond Breaker coats (Nox-Crete, 2005)

B) Formwork Setup – After testing the flatness and levelness of the casting slabs, the panels were outlined with chalk. The Rule of 3-4-5 was used to trace squared angles. By tracing two perpendicular lines from the same origin with 3 and 4 m (or ft), the length measure from their final ends have to have 5 m (or ft); this helps to check at the same time the squareness. Measurements were also taken during and after the panels were formed to verify the final dimensions. Weyerhaeuser's timberstrand LSL concrete form boards, which come in 19.20 m (40 ft) lengths, were used to build the formwork; this lumber comes with final dimensions of 5.08 x 20.32 cm (2 x 8 in nominal size). As seen in Figure 33, the lumber used, enabled depth and leveling accuracy of the concrete mix inside the formwork. In order to avoid the bending on the forms generated by the concrete, 20.32x20.32 cm (8"x8" nominal size) shoes were installed every 91.44 cm (3ft), nailing them against the casting slab and the side forms as well.

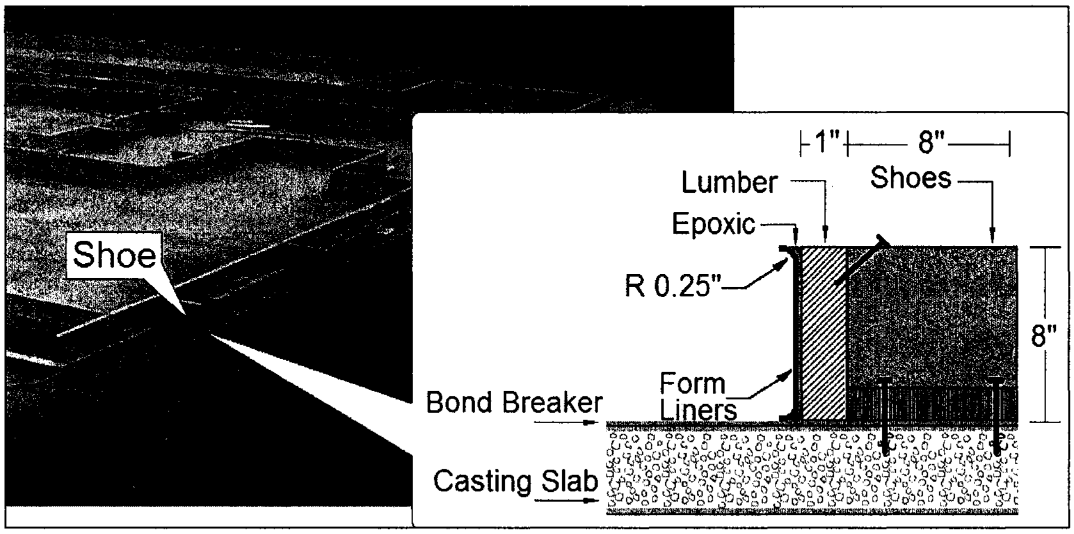

Figure 33: Formwork configuration

C) Construction of the Tilt-up Panels: The corners and joints were mitered for better finishing, and the lumber on the inside surface of the formwork was covered with polystyrene to provide smooth edges on the panels. The top and bottom of the panels were tapered with a 0.635 cm (0.25 in) radius of polyester form, excluding windows and doors. Shoes were nailed to the lumber and concrete slabs to avoid any bending of the lumber after pouring the concrete. The spacing between the shoes did not exceed 1.2 m (4 ft).

4.3.4 Quality Testing Process

After completing the construction process of casting and finishing the casting slabs, it was necessary to measure the flatness and levelness of the casting slabs. The curing compound, as specified by the producer, necessitated 72 hours to dry and then, the graph profile of the casting slabs using a point elevation measurement device (Dipstick) (Face Construction Technologies, 2005) was determined. This method was used in accordance with the specifications of the ASTM E1155-96 procedure "Standard Test Method for Determining F_F Floor Flatness and F_L Floor Levelness Numbers." (American Society for Testing and Materials, ASTM, 1996). The ultimate F_F and the F_L goals for this project were set high between the value ranges of 70 to 80 and 45 to 55, respectively. Floor Flatness (F_F) and Floor Levelness (F_L) are called "F-Numbers" and are determined by the ASTM E 1155-96 procedure. These numbers can be calculated as explained in the cited reference and briefly described here in order to provide continuity.

The main reason for calculating the F-Values of the casting slabs is for the need to control the accuracy of flat surfaces in response to special structural and architectural demands. As specified by the American Concrete Institute ACI 117 and by the Canadian Standards Association CSA A23.1, the F-Values measure how bumpy and inclined or tilted a surface is. The F_F measures the slope between two points, spaced at 30.48 cm (1ft); the F_L measures the slope between two points, spaced at 304.8 cm (10ft). The ranges for these F-Numbers are shown in Table 3 (Face Construction Technologies, Inc., 2005).

Table 3 F-Number Ranges

F-Number	in	mm
10	0.625	15.88
30	0.208	5.29
50	0.125	3.175
70	0.089	2.27
90	0.069	1.76
100	0.063	1.59

It is crucial to have flattened and leveled casting slabs in order to construct side forms perpendicular to them due to the concrete panel connections. When the panels interlock, they have to have the ability to fit; if the sides are not perpendicular or close to a perpendicular angle, it would be impossible to connect them. If the casting slabs have enough flatness and levelness, the joint connection of 6.35 mm (0.25 in) of each panel (or a total of 1.27 cm or 0.5 in, between two panels) will be enough to allow such interactions. The worst case scenario is shown in Figure 34a, when both sides have non-perpendicular ends. The inclination in the casting slab is due to low F_F and F_L numbers. Figure 34b shows the correct side angles due to high casting slab F-Numbers.

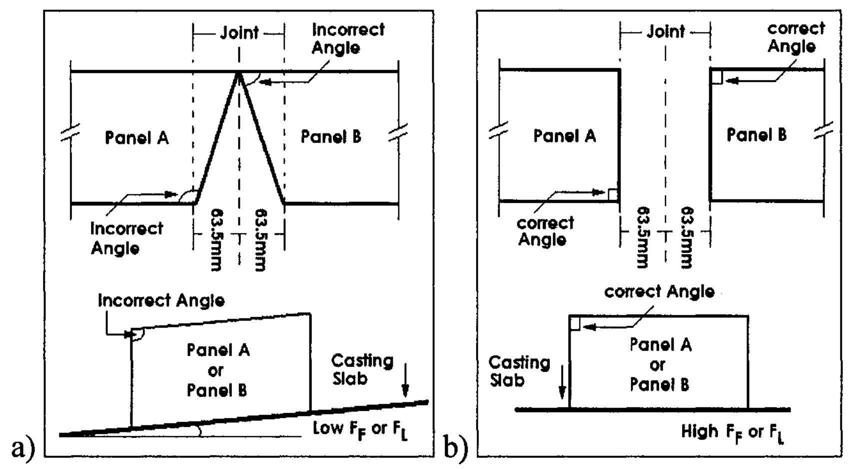

Figure 34: a) Low casting slab F-Numbers, b) High casting slab F-Numbers

The procedure to obtain these F-Numbers involves the following sequence: 1) Trace straight lines along the casting slab; 2) Measure with a point elevation measurement device (Dipstick), the point elevations every 30.48 cm (12 in) along the traced line; 3) Calculate the difference between two adjoining points (repeat this step along 10 points for a total length of 304.8 cm (10 ft)); and 4) Perform statistical analysis with the standard deviation method to obtain F-Numbers (ASTM, 1996). The procedure used to mark the lines follows the requirements from the ASTM E1155-96 procedure and is illustrated in Figure 35; the first two letters in the tag indicate the line orientation (i.e., EW = East to West), and the last digit indicates the order for the lines drawn on the panel.

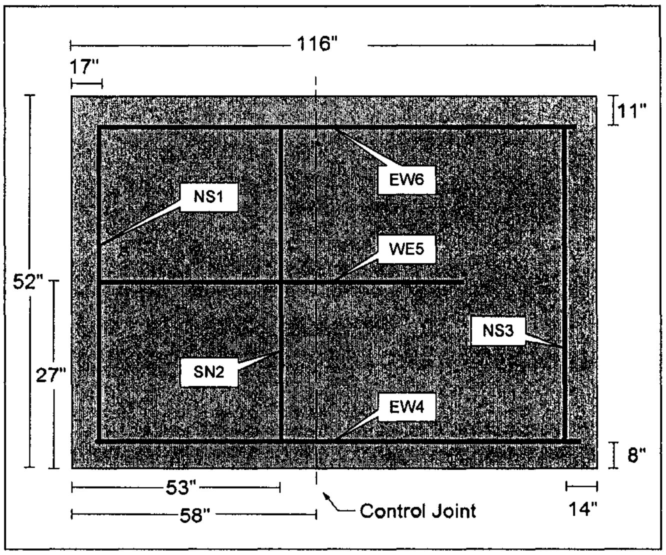

Figure 35: F_F and F_L measurement procedure, Section 1

For the case study, several measurements were taken to analyze the F-Numbers along the casting slabs, covering the entire area. The results are presented in Tables 1, to 6 in Appendix A. Figure 35 shows the traced paths in Section 1. It was useful to tag them to avoid misunderstandings when calculating the final numbers. Depending on the length of the paths, a different number of measurements were taken as indicated in Tables 1B to 6B. The results were obtained satisfying Equation 31 (ASTM, 1996).

$$F_{F1+2} = (F_{F1})*(F_{F2})*[(r_{q1} + r_{q2})/(r_{q2}*F_{F1}^2 + r_{q1}*r_{q1}F_{F2}^2)]\text{^}0.5 \quad (31)$$

where:

F_{Fi} = the floor flatness

r_{qi} = the number of measurements

Once the measurements were taken with the point elevation measurement device (Dipstick) from the casting slabs, the F_F and F_L results were calculated and plotted as shown in Figures 36 and 37, respectively (Face Construction Technologies Inc., 2005).

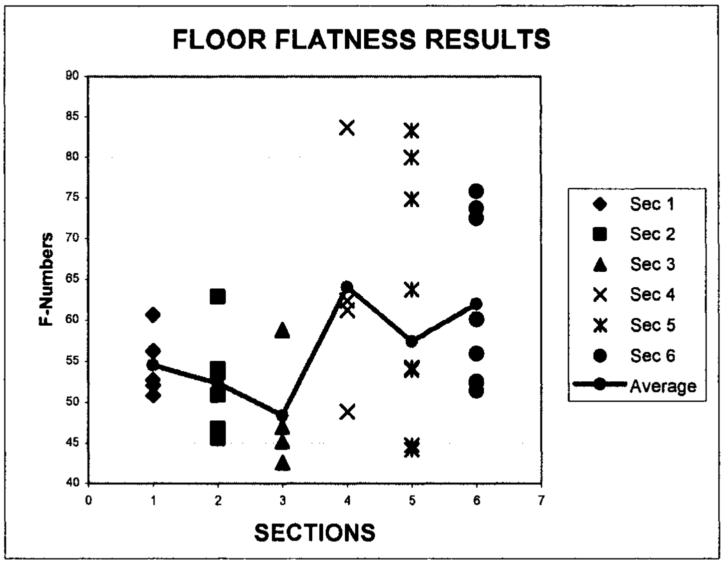

Figure 36: Floor Flatness results

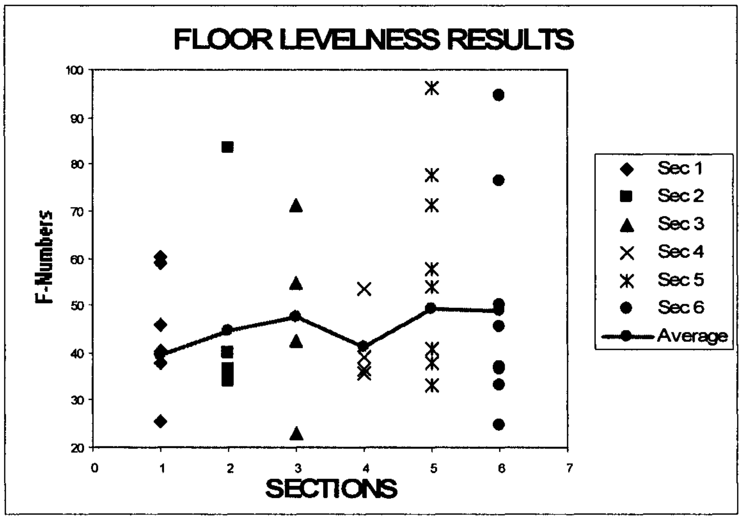

Figure 37: Floor Levelness results

Between 40 and 48 measurements were taken along the traced lines on each section of the casting slabs. For Section 3, 30 measurements were taken due to its smaller size. The procedure stated in the ASTM E 1155-96 was used to calculate the average of the F-Numbers.

The composite results for the casting slabs are shown in Table 4, where each result is compounded with the next adjacent section (in this case, six sections), producing final values of 56.39 and 44.31 for the F_F and F_L numbers, respectively.

Table 4 Composite F-Number Results

Composition	F_F	F_L
Sec 1 & Sec 2.	53.5	41.54
Previous & Sec 3.	52.06	42.83
Previous & Sec 4.	54.82	42.34
Previous & Sec 5.	55.30	43.42
Previous & Sec 6.	**56.39**	**44.31**

The expected high numbers of $F_F = 75$ and $F_L = 50$ were not accomplished, but the results were within the acceptable range of quality. A low F_F value means that the surface of the casting slabs would have irregular bumps or dips. An F_F accuracy of 56.39 implies that the casting slab surface had a height difference of 2.8 mm in 304.8 cm (approximately 1/9 inch in 10 ft). As shown in Figure 34a, this height difference between two points will produce an inclination on the casting slab. For the F_L, the casting slab had an inclination of 3.58 mm in 304.8 cm (approximately 1/7 inch in 10 ft).

Using the maximum panel length of 10.67 m (35 ft), the maximum dips or bump that would be obtained is 9.8 mm for the F_F and 12.53 mm for the F_L. The inclination angle obtained with these two values is not higher than 5.3×10^{-2} degrees; now using a concrete panel thickness of 203.2 mm (8 in), the maximum side opening will be 1.86×10^{-1} mm. This value does not represent more than 3% of the maximum joint panel requirement (6.35 mm or 1/4 in) as show in Figure 34a. The F-Numbers of 75/50 (for F_F and F_L respectively) were not required for the structural design as explained before, but for aesthetic. The F_F has to be higher that the F_L since it is calculated on a shorter distance (30.48 cm or 1ft); so if is lower, the surface will have more dips and bumps. An assumption was made that the side of the panel facing the casting slab will have the same F_F and F_L. The F-Numbers were not calculated on the concrete panels' top surface, which is the interior face; any inclination on the internal face of the panel does not affect the structure. The approach for the construction was to cast the concrete panels outdoors. Due to the following:

1) Doing the work in a controlled environment could increase the F-numbers, but by a small margin, however at a higher cost due to the transportation cost and labor performance. Due in part to the sheer-size of about 20-panels; transportation of these panels could have been if not impossible; it could be at a very high cost of delivery that would include relocating power lines and other abstractions in the road. The concrete panels were as wide as 10.70 m (35 ft).

2) The expected increase of the F-numbers would not justify the incurred cost for labor and transportation and would not add marginal value to the end product as described before; and,

3) Unless the panels are cast on steal sheets, the reusability of concrete slabs could cause imperfection after the first use, therefore a casting slab with sufficient size that allows for all the panels to be cast was a preferred option, this option would not be acceptable by any manufacturer. The imperfections obtained by casting on-site the concrete panels are attributed the methods used for their construction such as: the laser-skid limitations, the environment, and the concrete shrinkage.

For the panels' layout on the casting slabs, measurements were repeated three times to verify the correct dimensions of each panel. The forms were measured several times in different days from their inside surface, to ensure that the perpendicular angles between the floor and the lumber were not changing over time. After the panels were verified, the next step was to install the reinforcing and rebar required for the structure, including chairs, weld plates, lifting hardware (such as hooks and lifting points) and electrical ducts. Due to the constant rainfall, each finished form was covered with a plastic layer to avoid puddles and dirt. From this process, the team discovered that it is better to cover the forms using a sloped plastic layer rather than a flat one in order to shed the panel from water. It was impossible to completely avoid the deposition of moisture and dirt on the forms, making it necessary to clean them periodically to neutralize fungus and remove excess mud. Some difficulties were encountered during the cleaning process: some panels required more steel reinforcement, which left small gaps between the bars, interfering with the reach of the cleaners to the casting slabs. Air compressors were used with lower air pressure in order to avoid damage to the surface and removal of the bond breaker.

4.4 Bracing Spatial Analysis

4.4.1 Objective

This module focuses on spatial analysis of the bracing system for tilt-up constructions and tolerable clearances between the lifted panel and the on-going structure. The 3D and

4D-models that were developed in the previous stages were used to minimize the time spent on installation. The models were also used to minimize the expense of constructing temporary support materials that would be used during the placement of concrete panels such as steel braces, concrete deadmen and foundation walls. The project's greatest challenges were ensuring the requisite high joint connection accuracy of 1.27 cm panel to panel (half an inch) and the task of building the structure in accordance with architectural and engineering demands.

4.4.2 Panel Design

Due to the complexity of the structural design, most of the panels had to be reinforced with a lot of rebar in order to avoid bending and cracking during the lifting process; some of them had to use strong backs to minimize stresses during the lifting process as well. Since the panels are tilted from the lift inserts, the entire weight is going to be dangling from two, four or eight points; the surface finishing can be affected if cracks take place. As shown in Figure 38, most of the panels had to have more reinforcement along openings and legs. The panels had a vertical reinforcement with 1.5875 cm diameter rebar every 45.72 cm (#5 @ 18 in) and a horizontal reinforcement with 1.27 cm diameter rebar every 45.72 cm (#4 @ 18 in). In addition, every opening required two 1.5875 cm diameter (#5) rebar along the perimeter and next to each opening. For the panels with legs and long span beams, additional reinforcement was used to control shearing and bending stresses [Web-4]. To control deflections and depending on the panel size and configuration, the panel thickness ranged from 20.32 cm (8 in) to 27.94 cm (11 in). The mix used to cast the panels was self consolidated concrete with a 28-day compressive strength of 5000 psi.

Figure 39a presents a sample of the panels with long legs and cutoffs. The design of 8 panels could have been modified in order to avoid the use of strong backs. Some of the panels incorporated a bottom beam to join the legs and, and as seen in Figure 39b, such configuration would eliminate the use of external structural members for the lifting process.

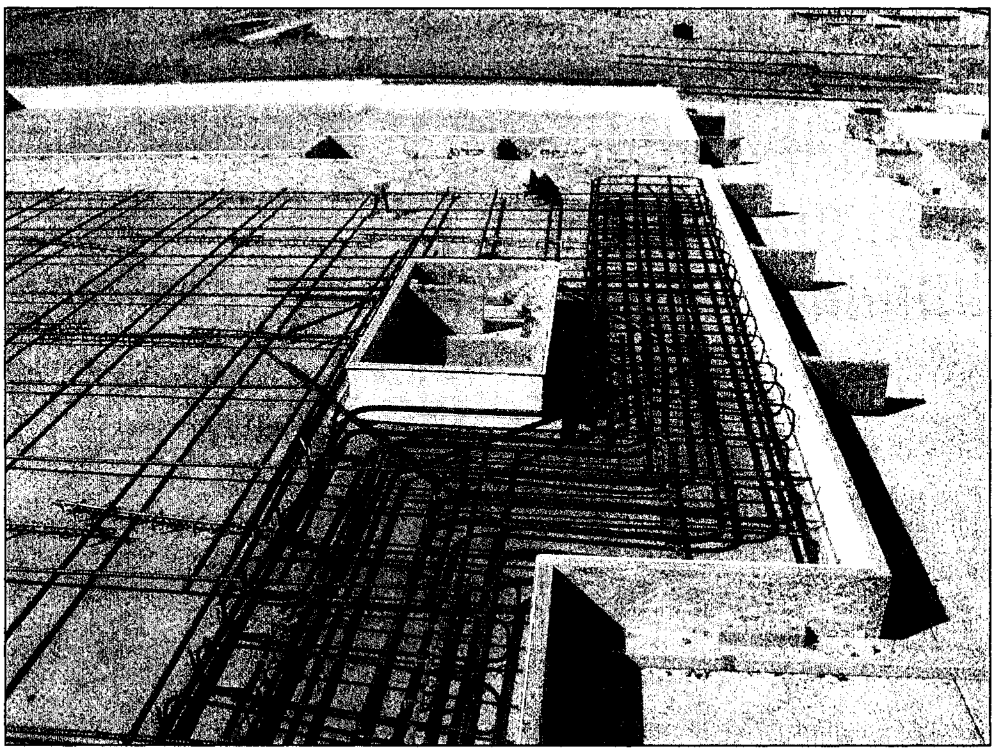

Figure 38: Panel rebar example, case study

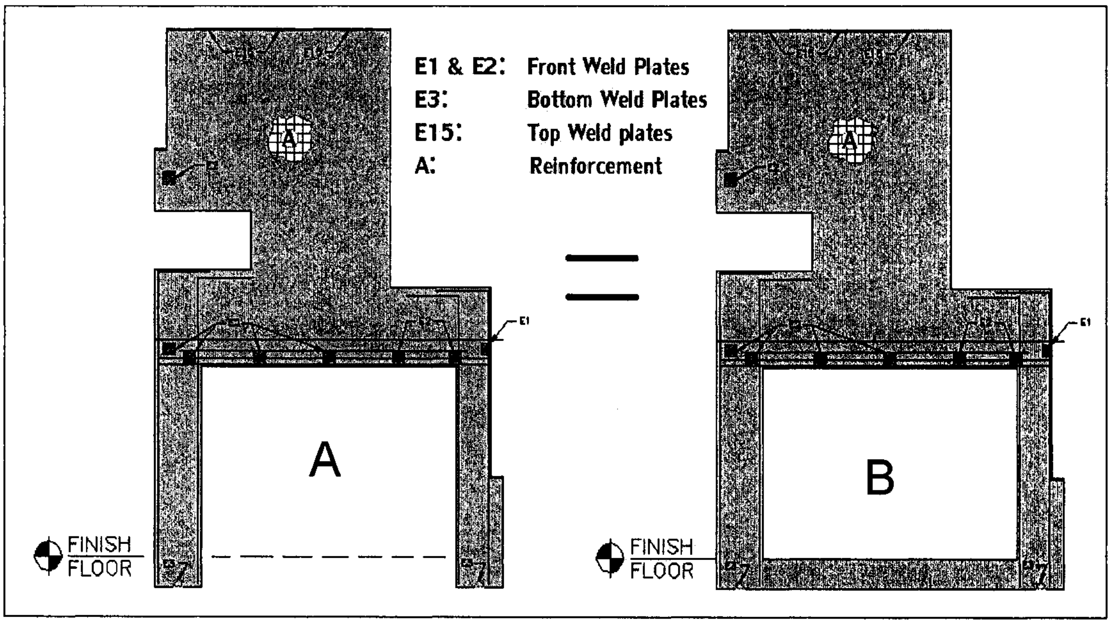

Figure 39: Panel allowable modifications, case study

4.4.3 Proposed Methodology

In order to minimize material expenditure and installation time, a structured procedure was followed to achieve expectations and to provide possible solutions regarding space constraints and brace maneuverability. As can be seen in Figure 40, information was gathered from the mock-up model, the 3D (CAD) model and the bracing requirements for each of the panels. Utilizing a spreadsheet, data was managed to produce a complete list of the material needed, including spatial locations, amount of concrete deadmen and brace types. A 4D model and computer animations were incorporated at the end of the exercise to show possible constraints during the installation procedure. With the help of Common Point 4D (Common Point Inc., 1999) and Microsoft Project, the 4D model showed, in sequence, a plan of how the panel installations were to proceed, allowing managerial decisions to be based on planned solutions before every lift.

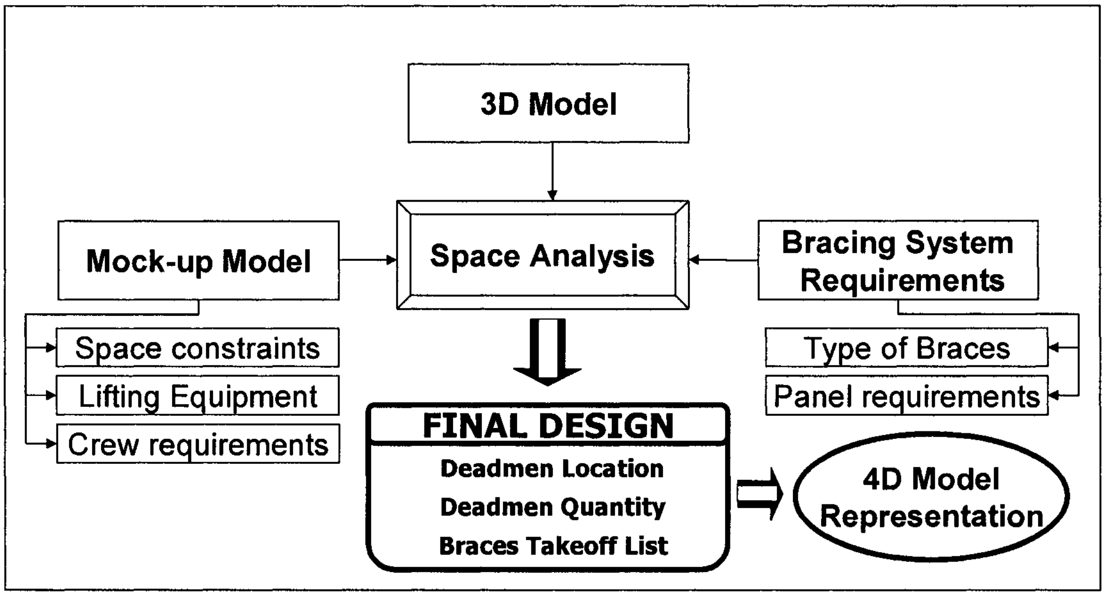

Figure 40: Proposed Methodology, bracing spatial analysis

The installation procedure of the concrete panels required for this project was sorted upon structural needs. The facility was subdivided into four areas with two lifting phase sequences. The two lifting phases were organized in such a way that the pier panels in each area had to be installed first. Then, the light panels that enclosed and connected the entire structure were set on top. In the first phase, the four areas worked independently from each other; this fact provided the opportunity to maximize the equipment utilization and crew adaptation by starting with a sector with less operational demands.

Due to the uniqueness of the project, the crew had to be introduced to the operation before it started. This was conducted by implementing the following two steps: first, creating computer animations (Manrique, et al 2005) and, second, analyzing the bracing procedure with the installation manager, which is the focus of this module. DSI

Engineering designed the concrete panels, provided brace types and dimensions, and anchor locations. By the time the installation procedure took place, the slab's desired grade on top of the foundation walls was not poured, forcing a reanalysis of the anchor location of the bracing system. In order to start with the analysis, the following four modules were utilized: the bracing system, the 3D model, the 4D model and the mock-up model results.

Bracing System. The braces required for the job had the following four constraints:

- Inclination angle between the floor and the brace: 40-60 degrees.
- Maximum opening angle from the perpendicular of the panel: 5 degrees.
- Brace nominal sizes: 4.26 m (14ft), 6.70 m (22 ft), and 9.75 m (32 ft).
- Maximum Brace extension/contraction: ± 5inches (Figure 41).

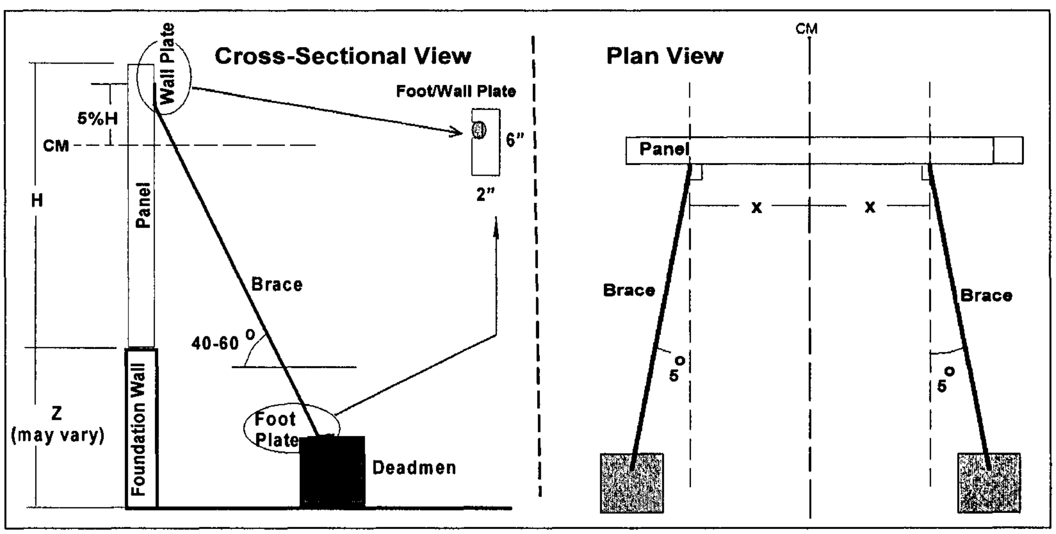

Figure 41: Bracing requirements, case study

In order to minimize the force exerted by the wind pressure on the steel brace, the wall plate of the steel brace is located at 2/3 of the maximum height of each panel. As show in Figure 42, if momentum is calculated at the bottom of the concrete panel, the longer the lever the less force will be necessary to stabilize the concrete panel. If less force is applied to the steel brace, the demand of material strength will be lower.

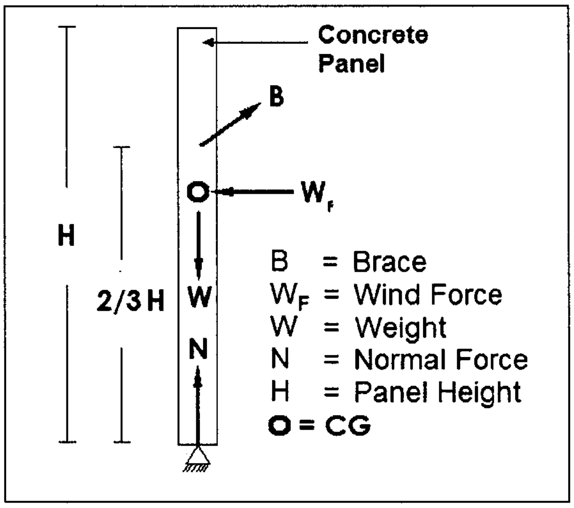

Figure 42: Free Body Diagram

The braces had to be anchored to both the panels and the deadmen/foundation walls with 1.9 cm (¾ inch) diameter expansion bolt heads that had a length of 12.7 cm (5 inch). Most of the panels, due to the absence of the slab being on grade, had to be anchored to concrete deadmen with a max volume of 0.76 m^3 (1.05 CY). See Figure 43.

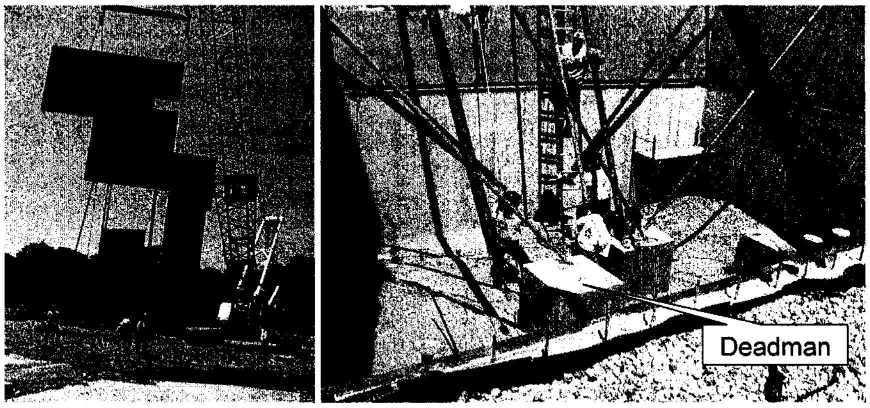

Figure 43: Bracing the concrete panels

3D Model. The constraints mentioned before, regarding the bracing, were modified based on the crew installation experience and the 3D model to find the possible location for the foot slabs (Figure 44). The maximum opening angle of the panel from the perpendicular angle was exceeded in order to minimize the amount of deadmen. Then, the foot plate of the brace was anchored to the foundation wall or footing, depending upon the scenario. In order to keep the brace angle range between 40 to 60 degrees with respect to the floor, 9.75 m braces (32 ft) were used for some of the panels. Using CAD, the final location of the foot plate/deadmen was found, simplifying the installation procedure (Figure 44).

4D Model. Due to the considerable number of braces required to support the concrete panels in certain sectors of the construction site, and because of the possible space interruptions between braces when installing the panels, a 4D model was developed based on the structural sequence and the crew's adaptability to the process.

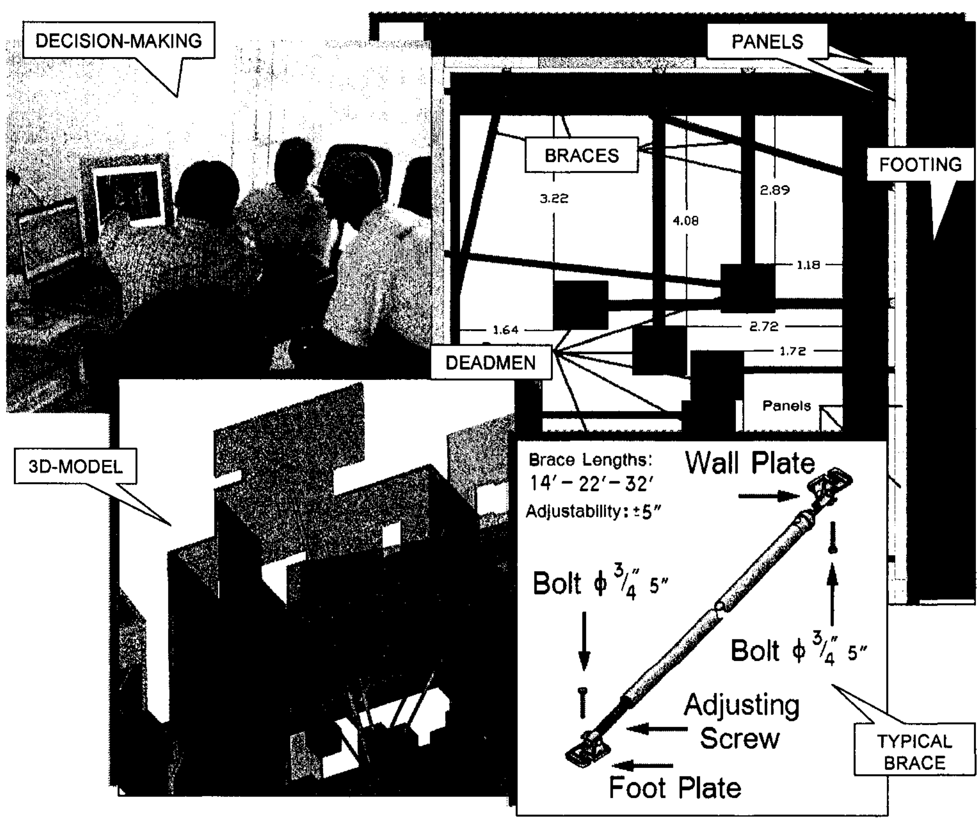

Figure 44: 3D Model analysis

During the simulation process with the 4D model, 18 the braces had to be relocated because of the spatial interference between braces, the lack of space for deadmen and the difficulty of installation.

Unforeseen circumstances, such as multiple deadmen in a row, were managed using a Jersey barrier, which is a pre-cast concrete barricade used to separate lanes of traffic. Figure 45 shows the software interface (Common Point 4D), which combines information from the schedule (MS Project) and the 3D model (CAD Model), providing as output a 4D model that shows the installation process through time.

Bearing in mind the constraints related to minimum clearances between the lifted panel and the on-going structure, the length and location of the braces on the panels were tested with an animation process (Manrique, et al 2005). Both models showed possible errors during the installation procedure, but the development of computer animations demands more time, compared to utilizing 4D models.

4.4.4 Lifting Operation

Based on the panel shapes, structural configuration and architectural design, the panels had to be tilted-up using four different lifting procedures, which were determined by the designing engineering firm. Complications arose when applying the requirements for the rigging system.

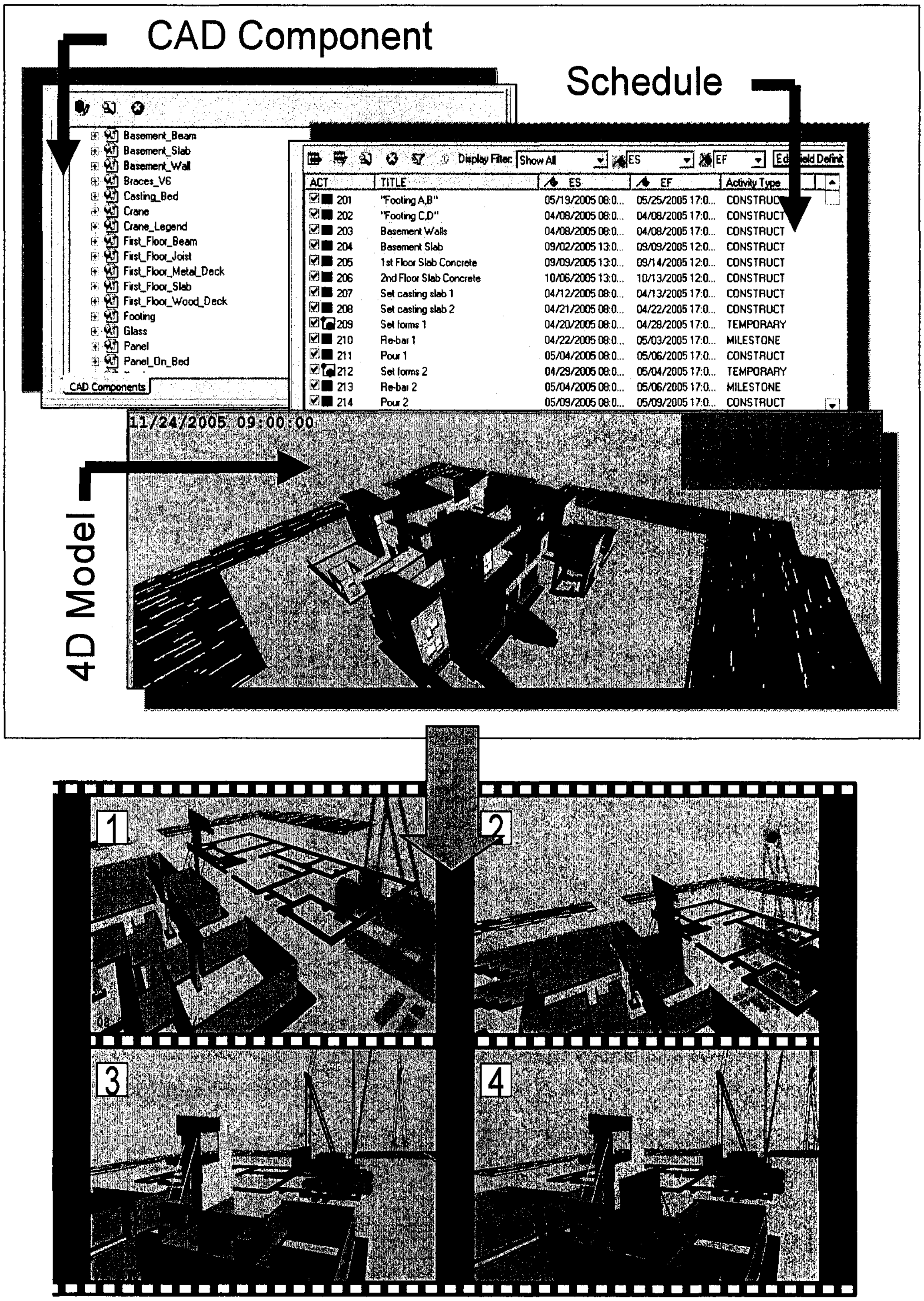

Figure 45: 4D Model, panel installation sequence

As can be seen in Figure 46, minimum sling lengths were to be applied to each panel depending on the panel size, amount of lifting points and their location and separation in the panel. In order to avoid cracks around these points, the spreader bar had to have a width close to the length separation between them; this allows for the force vectors to be decomposed in just one vector pointing upwards. Due to the irregularity of the concrete panels, these lifting points were not always under the same axel, making the panel weight vector to be decomposed into two forces, and at the same time, making the calculation for the rigging system undetermined. For panels with two and four lifting points, the three mathematical equations (sum of forces in the x and y directions, and momentum around a point) were enough to determine the sling lengths. However, when the panels had eight lifting points, the variables increased to eight and could not be determine with the same mathematical equations. A graphical method was applied to calculate such lengths, but a mathematical model should be used to acquire a better precision. The width of the spreader bar needs also to be evaluated; it has to have a length as close as possible to the length separation of the lifting points. Most of the panels had a different lifting point separation, making the exercise even more difficult. Something that should be considered during the design stage of tilt-up concrete panels is standardization. Again, the uniqueness of the project demanded such approach; however, the on-site performance will be increased by applying nominal separations. Most of the panels were both pivoted and lifted from the face inserts, but some of them had special lifting sequences. Although physics is not integrated into the computer animation model, the animation is a means to establish the rotation angles that the crane operator can utilize to lift the panel in accordance with the pre-defined specifications, which benefits the project by showing clearance problems and installation constraints.

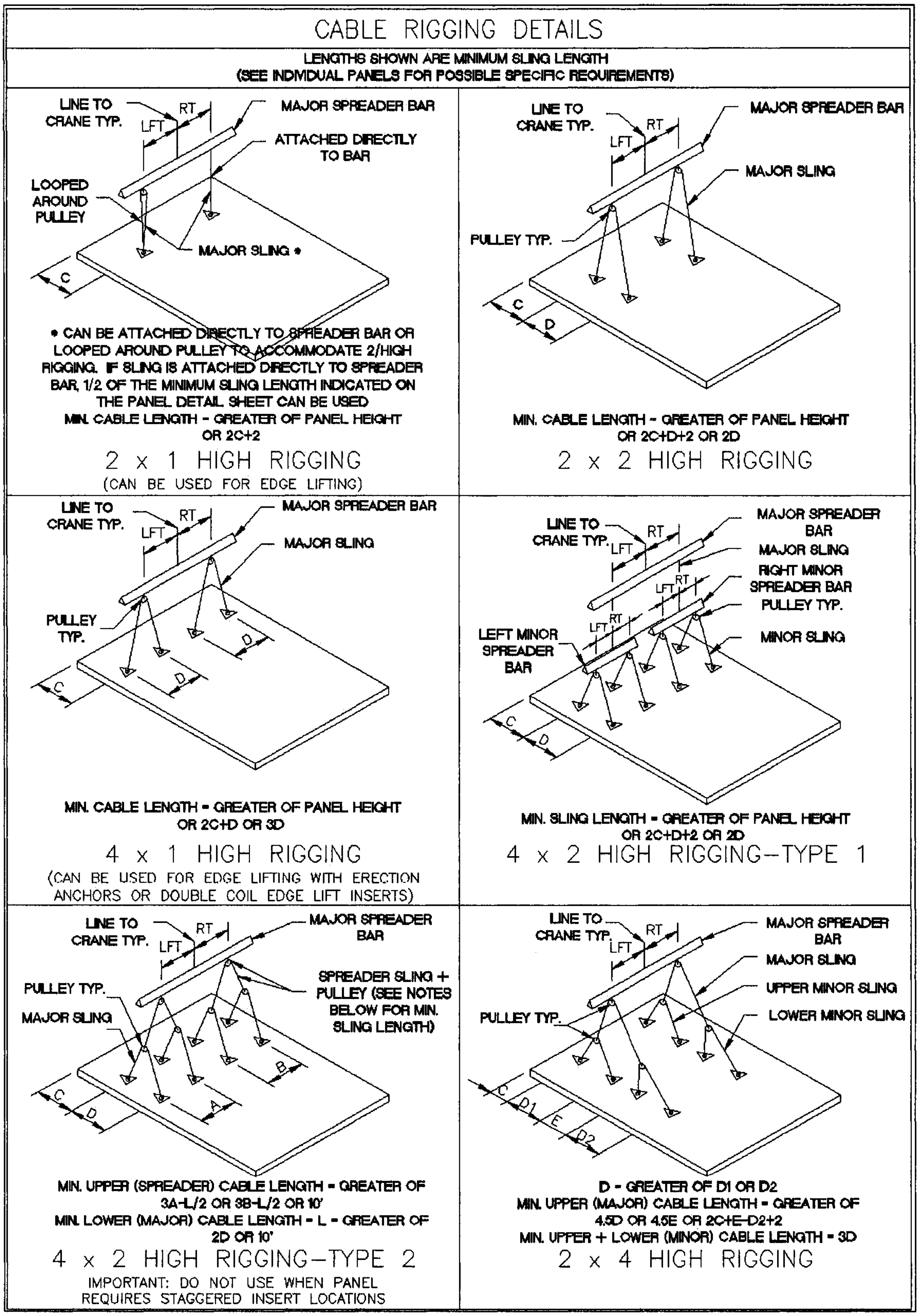

Figure 46: Cable rigging details, [Web-4]

4.4.5 Construction Schedule

The construction schedule was managed in 15 work packages as listed in Figure 47 and more in detail in Appendix C "Construction Schedule". Before the installation took place, the schedule was made according to the results obtained from the Mock-up model. There were many uncertainties regarding the lifting process; the panels lifted in the Mock-up model had only a third in height of the final concrete panels and all of them contemplated 2 and 4 lifting points (for the final construction, some of the panels had 8 lifting points). Due to the lack of knowledge in regards to the installation time expended for each panel, a rule of thumb was applied in order to determine the duration for the lifting process (Table 5):

Table 5 Panel Installation Duration

# Lifting Points	Strong back?	Duration (Hrs)
2	No	1
4	No	1.5
4	Yes	2
8	No	2.5
8	Yes	3

In average, 4 to 5 panels were installed in an 8-Hr working day. The information listed in Table 5 more or less had a fair approximation to the installation process. During the construction process, the schedule was updated according to specific modifications and the activity elapsed times.

	Title	Duration	Start	Finish
1	General Conditions	5 days	3/15/2005	3/21/2005
2	⊞ Site Work	297 days	3/15/2005	5/04/2006
9	⊞ Concrete	131 days	4/08/2005	10/10/2005
54	⊞ Panel Repair	40 days	9/12/2005	11/04/2005
58	⊞ Masonry	37 days	2/14/2006	4/05/2006
63	⊞ Steel	85.5 days	8/24/2005	12/21/2005
110	⊞ Carpentry	124 days	9/14/2005	3/06/2006
126	⊞ Thermal & Moisture Protection	215.5 days	3/15/2005	1/11/2006
137	⊞ Doors & Windows	144 days	8/16/2005	3/03/2006
147	⊞ Finishes	281 days	3/15/2005	4/12/2006
162	⊞ Conveying Systems	45 days	1/13/2006	3/17/2006
166	⊞ Mechanical	103.5 days	7/25/2005	12/15/2005
173	⊞ Plumbing	115 days	3/15/2005	8/23/2005
177	⊞ Storm Plumbing Rough-in	58.5 days	9/27/2005	12/16/2005
181	⊞ Sanitrary Rough-In	144 days	9/27/2005	4/14/2006
188	⊞ Electrical	228 days	6/15/2005	5/01/2006

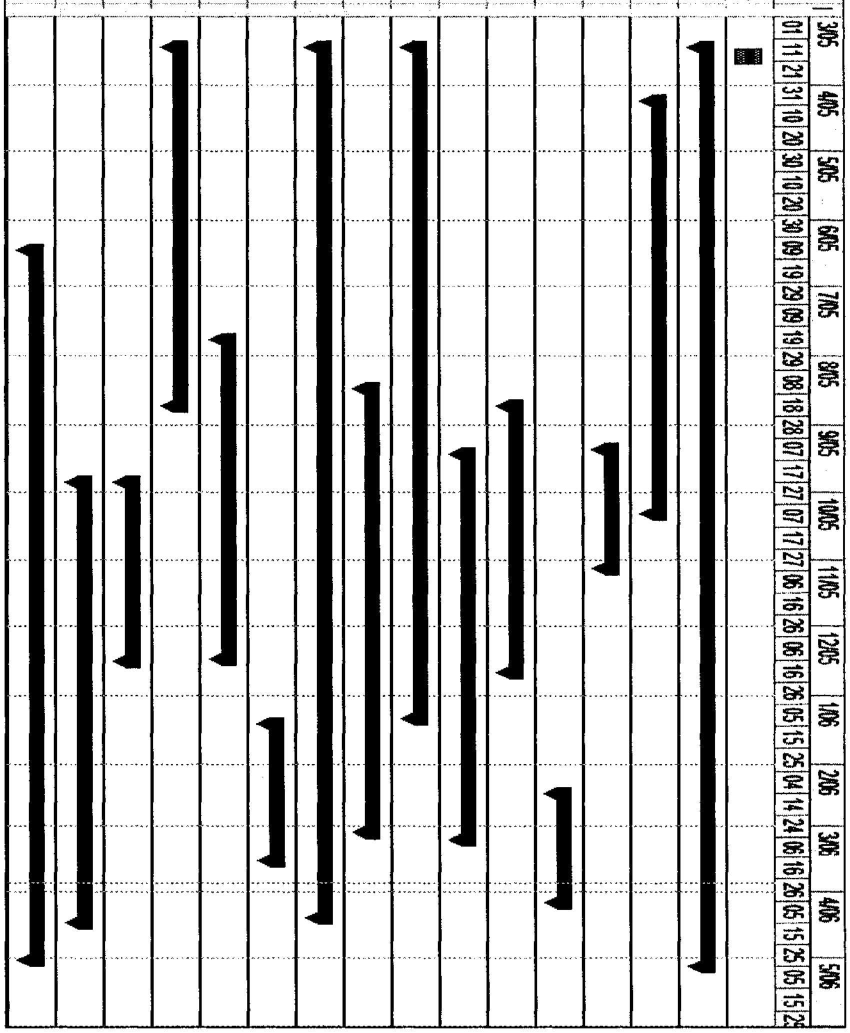

Figure 47: Main Construction Work Packages, case study

The erection of the panels started on June 15/06 and ended on July 27/06 for a total of 30 working days or 43 regular days. Due to the location of the construction site, no activities were allowed during the weekends and between 5:00 pm to 7:00 am, making the installation process more expensive. An error was encountered during the installation of the first 7 panels in regards to the center lines of the building. Due to this adversity, the installation had a delay of 2 days and those 7 panels had to be reinstalled again to their correct location. When the basement was constructed, the as-built dimensions were never updated. An old version of the basement layout was used to trace the center lines of the facility, having and error of 5.04 cm (2 in) in the East-West orientation of the house. The 3D Model was not updated as well, having to modify such error for the layout of the following panels. Fortunately, due to the width of the basement walls (30.48 cm or 12 in), the panels were replaced without any major inconvenient.

Chapter 5: Findings and Limitations

5.1 Findings

Due to the use of optimization modeling and 3D/4D modeling, Tables 6 and 7 describe in detail the advantages encounter.

Table 6. Optimization Modeling Vs. Traditional Methods

CRITERIA	OPTIMIZATION MODELING	TRADITIONAL METHOD
Equipment selection	The developed algorithm chooses from a database different types of cranes that are able to perform the lift; these cranes are sorted based on their rental cost. The selection is fast due to the computer capacity to perform many operations per second. The result is show in a dialog box, listing the type of crane, the boom length, the crane capacity, etc.	The lifting analysis required for each concrete panel can be done by utilizing the lift capacity charts for several cranes in order to obtain the equipment that is able to perform the lifting. Spatial constraints in regards to building clearances can be time consuming; the crane and boom selection are also time consuming activities.
Equipment location	An optimization process was run in order to locate the crane on strategic locations, allowing the lift of a subset of panels without the need of relocation. These lifting points helped to organized a plan for the installation procedure, allowing contractors to have a define schedule for the operation.	An exact location for the crane will be hard to obtain if more panels are needed to be lifted from the same spot. A lifting analysis has to be performed for each concrete panel in order not to exceed the crane capacity.
Equipment mobilization	Due to a planned lifting sequence and crane location, unnecessary crane mobilizations were reduce by maximizing its capacity according to its maximum lifting radii. In total, 3 panels had to be installed by mobilizing the crane.	Without a crane location for a subset of panels, the crane has be relocated every time a new panel has to be lifted.
Construction site layout	The concrete panels were placed on the casting slabs according to the crane location and the crane lift capacity. The panels were placed close to their final location, obtaining a 14% in concrete savings	Once again, the relationship between the crane location and its maximum capacity will determine the construction layout. Without these 2 elements, a final construction site layout would be difficult to design in order to save material and facilitate the installation procedure

Table 7. 3D/4D Modeling Vs. Traditional Methods

CRITERIA	USE OF 3D/4D	TRADITIONAL METHOD
Lifting sequence	Computer visualization enhances the lifting sequence by showing the possible constraints for erecting the concrete panels. Due to the software capacity for measuring distances, 3D and 4D determined if the panels fit or not according to their lifting sequence	Without the use of computers, it becomes hard to analyze spatial issues in regards the lifting sequence. In fact, the structural designer could not realize the interferences between panels by modifying the lifting sequence.
Panel Tilting	3D animations helped to determine the 3 basic movements the crane operator had to do in order to lift every panel according to the structural design in order to avoid dragging movements and additional solicitations to the panels. 3D animations worked as a learning tool to avoid errors during the installation process.	It is hard to conceive how the panels had to be tilted without a guideline. The lifting process has to rely on the crane operator's expertise. Possible interferences and spatial constraints can not be analyzed. Historical data will be required for a better understanding of the project
Bracing installation	The use of CAD and 3D animations helped to determine the final location of the brace end plate. It was possible to decide were to locate the deadmen in the case were no foundation wall/footing were available. Material was also optimized by avoiding the use of unnecessary deadmen.	The use of construction drawings can help to locate the final position of the brace end plates. However, it will become time consuming to understand spatial interferences in a 2D environment.
Decision making	A better understanding of the project was achieved by watching the 3D animations and 4D models. The installation and bracing managers became aware of the possible installation failures by looking the installation of any panel at the computer screen in many different angles. The idea was transmitted efficiently.	An idea of the situation can be obtained by analyzing construction drawings. It becomes hard to express the installation process by imagining it. Decisions can be made; however, uncertainty can arise in regards to space constraints.
Scheduling	Due to the complexity of the panels shapes, the 3D animations helped to determine the amount of hours that any panel could take for its installation. Due to the high equipment cost and labor, it was necessary to determine the possible amount of days the operation would take.	Experience can determine with a high degree of accuracy the amount of hours per panel needed for its installation. However, due to the complexity of the project, it could become hard to schedule the time installation
Rigging system	The calculation of the sling lengths became undetermined due to the amount of lift inserts needed per panel. With the use of CAD and the dimensions of the spreader bars, it was possible to obtain the sling lengths.	The use of trigonometric calculations will be required in order to obtain the sling lengths. However, due to the amount of lift inserts per panel, an iteration process has to be done.
On-site interference	Due to the panel and brace dimensions, on-site interferences can be obtained during the bracing process. 3D and 4D shown these interferences and decisions were made in order to avoid any collision or rework during the installation	Once again, it becomes hard to imagine an installation sequence; braces would not fit correctly and rework would be needed in order to support the panels.
Safety	Due to the advantage for visualizing the installation procedure, the installation and bracing crew were located according the installation needs. No accidents were presented	A safety plan can be provided for the construction process, achieving good results. However, mistakes can arise due to the lack of visualizing spatial constraints

5.2 Limitations

3D Studio Max is a powerful interface that allows users to animate 2D and 3D models. However, the program was time consuming during the development of the 3D animations, and improvements can definitely 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 position to their final position [Williams II and Kuriger, 1997]. In this case, the initial position was the crane location with the boom, rigging and slings at a certain instant in a coordinate system. The trajectory delineated the lifting maneuvers and the final position was ultimately the desired position of the panel.

Imperfections were encountered during the tilt-up process. Most panels did not exceed an imperfection area of 1.61 cm^2 (0.5 in^2), but some notable errors were found in the concrete panels. As shown in Figure 48(a), the concrete panel dragged out a chunk of the casting slab with a surface area of 248 cm^2 (38.5 in^2). As shown in Figure 48(b), an area of 345 cm^2 (53.5 in^2) on the concrete panel became attached to the casting slab. In general, the Silicoseal 2000F functioned well as a bond breaker and the surface quality suited the owner's expectations. All the procedures applied in the construction and installations of the formwork were conducted in accordance with the structural engineer's specifications, but mistakes were still made in the casting of panels with an inclined upper edge. One of the features included in the architectural design was an inclined roof to divert storm water into collecting pipes. Therefore, the upper edge of the panels had to correspond with the angle of the roof. Fortunately, these mistakes will be covered by the roof, but for future constructions, it would be better to revise such details to enhance the quality of the construction.

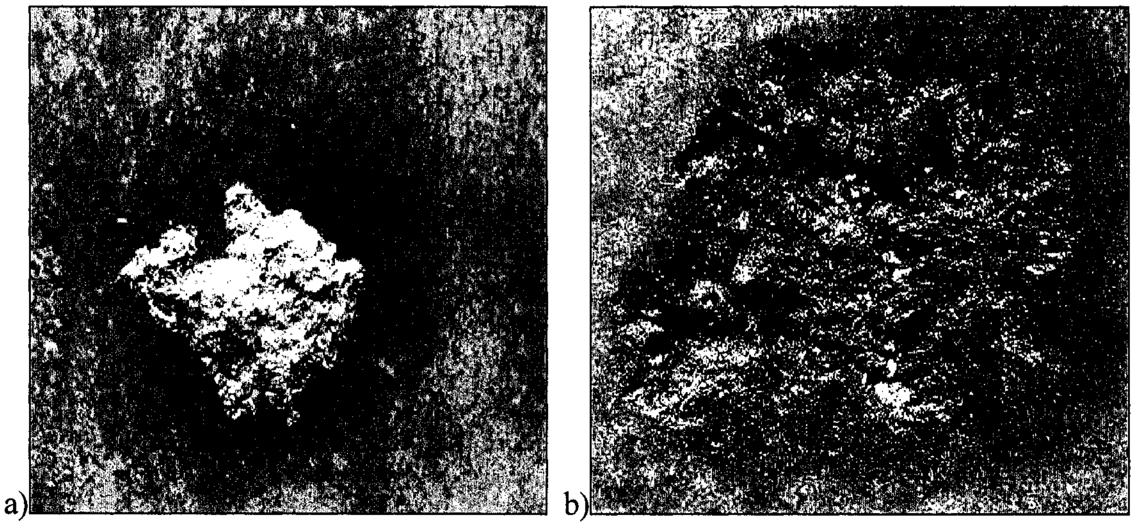

Figure 48: Errors encountered, concrete dips and bumps

Due to an incorrect interpretation of the construction drawings, the maximum error encountered was a height difference of 1.91 cm (0.75 in). When the carpenter organized the layout of the panels, he mistakenly increased the final length of the inclined top ends. Although the surface inclination was correct, the total length was wrong. In total, 17 panels had misaligned appearances, an example of which is shown in Figure 49.

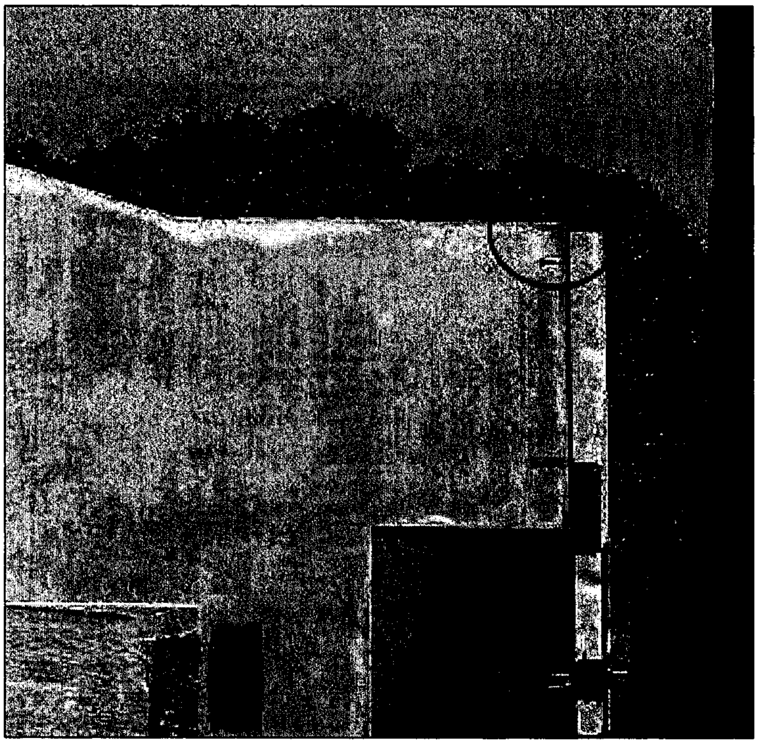

Figure 49: Panel Misalignment

Chapter 6: Conclusions

6.1 General Conclusions

This thesis presents a methodology used to construct a challenging project with a unique construction method that contained a low joint tolerance and a high level of accuracy. Therefore, the need for precise equipment utilization could not be ignored. Each of the 108 panels was animated using 3D Studio Max. This software exposed possible constraints, beginning with the tilt-up process for every panel and ending with their final placement. All the requirements for tilting the panels were included in the animation.

Based on the optimization model, all the panels were cast in close proximity to minimize the cost of the casting slabs and the traveling requirements of the crane. As a result, the gaps between most of the panels were narrow, which demanded accuracy in the tilt-up process. The location of the panels was managed by the use of CAD tools and optimization models, which helped to minimize the use of concrete for casting slabs. In this case, a concrete savings of 14% was produced in regards to these casting slabs; this implied a reduction in construction time, equipment utilization and material and labor expenses. The layout of the construction site allowed for casting the 108 concrete panels in one round, avoiding the construction of new casting slabs that would imply a delay in the lifting process, increase the rental cost of the crane and raise the allotted budget for the lifting and installation crews. The computer animations revealed which types of movements minimized errors in the tilt-up process. Animating this procedure using 3D Studio Max was useful.

This project was noteworthy because it applied the precision-focused methods of commercial building construction on a residential scale. It is not common for flatness and levelness to be so crucial in the making of casting slabs. In this case, these factors were imperative for flush interlocking of the rectangular edges of the panels. A small deviation from perpendicularity would manifest itself in a noticeable imperfection at the junctions between panels. In addition to the structural prerogatives, this project also necessitated smooth surfaces on the concrete panels to facilitate the architect's vision of a uniform exposed surface.

Based on the analysis results from this construction process, developers can incorporate precision planning concerning materials selection and management into traditionally inaccurate techniques. To obtain a smooth concrete surface, many parameters must be taken into consideration. The type of backfill, concrete mix, joint controls, ambient temperatures and casting procedures are some of the factors that can affect the smoothness of a tilt-up panel. Acceptable levels of flatness and levelness need to be determined to meet maximum tolerances.

The case study explains how to build casting slabs for tilt-up panels with a high-quality finishing. More than 4,300 m^2 (45,210 sq ft) of concrete was cast in the construction site of this complex structure. Analyzing the results obtained in the case study following the ASTM E1155-96 procedure illustrated the maximum error encountered was below 3% of the maximum joint tolerance. Errors related to surface smoothness were also encountered after erecting the panels. This problem was possibly related to the difficulty of cleaning the casting slabs before the concrete was poured for the panels. Due to the puzzle-like shapes of the panels, the structural design required a high amount of reinforcement to avoid bends and cracks. As a result, it was impossible to reach, clean and spray some of the inner areas on the bottom of the panels.

3D models (CAD Spatial analysis) and 4D models were used to plan, ahead of construction time, a complicated tilt-up installation process regarding the bracing system. A systematic model was developed to minimize material expenditure (concrete deadmen) and to obtain the final bracing location in 3D space. Due to the accuracy requirements, every lift was analyzed on the computer screen before the actual construction. This provided directions to the lifting/bracing crew during installation. Errors were encountered during the installation of the first seven panels due to a misplacement of center chalk lines. As a result, the installed panels had to be removed, re-installed and re-braced.

The results obtained for the installation process are as follow: twenty seven 0.74 m^3 concrete deadmen, two Jersey Barriers and 126 steel braces were used. With the systematic model, it was possible to save 99 concrete deadmen and facilitate the bracing regarding the installation process. The 4D model demonstrated to the crew possible alternatives to deal with during the installation process and helped to make managerial decisions in advance.

A spatial constraint solution can be made by re-adapting the bracing position on the panel (wall plates) and by minimizing the use of deadmen via an optimization model. The lack of time and predefined structural requirements made it hard to develop an approach other than the one presented in this thesis.

5.2 Research Contributions

This research generated the following contributions:

1. The use of 3D CAD Models helped to ensure efficacy, efficiency and precision in the decision making process, which allowed the Project Manager to relay with better information.
2. 4D Models were integrated into the project schedule with 3D CAD objects in such way that it helped both the installation and bracing crews to have a better understanding of the project before its start.
3. Optimization, based on mathematical algorithms and spreadsheets, was the key to analyzing and selecting the crane. These optimization models helped to choose the most convenient equipment with the lowest cost and maximum capacity for the job. The panel installation process was finished in 43 days, with an average of 4 panels per day. These algorithms can be applied in general to any lifting procedure with minor modifications; the parameters needed to start any analysis are the space constraints, load weights and equipment availability.
4. The lifting process was optimized by developing mathematical functions that reduced the crane displacements along the construction site layout. According to the results obtained, 22 lifting points were determined and only 3 times the crane had to travel with a concrete panel. The benefits by including algorithms and 3D/4D modeling are fully described in Chapter 5.

5. The use of CAD tools helped to reduce the amount of concrete used for the casting slabs by 14%. According to the results obtained from a mock-up model, a 250 kg/cm^2 concrete mix was used for the concrete slabs.
6. The analysis of the process for the floor flatness and levelness documented in this thesis allows improvements by future constructors who wish to build similar projects where laser screed machines are used, where there is a need for a high level of concrete finishing quality.
7. 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.
8. The use of spatial analyses helped to optimize the bracing process by allowing the contractors to identify possible constraints, final bracing locations and material utilization.

5.3 Recommendations for Future Work

1. The use of 3D animation modeling methods demands a significant amount of time during the development stage. Future research should consider incorporating a syntax that would allow an individual to make changes, on the same computer sequence, but in a shorter period of time. A 3D animation executes a sequence that is pre-established by the user, eliminating the option of performing any other type of kinematics. Time can be saved by allowing the

user to manipulate a pre-established sequence "on the run" (i.e. computer games) or, by generating a sequence of movements that will target the final point from the initial point. Such a syntax would minimize equipment usage by obtaining a time efficient path in order to connect 2 points in a 3D space [Shihchung and Miranda, 2005].

2. Construction layouts are one of the most important designs that a constructor can aquire before the erection takes place; an automation processes using generic algorithms (GA's) should be incorporated to define material location and equipment mobilization [Osman, et al 2003]. For the case study presented in this thesis, a layout was designed according to the space constraints and construction needs, using an optimization model for the lifting process. However, enhancements to the presented procedure can be developed in order to further minimize the use of space and material. During the layout design stage, the use of an optimization model regarding the crane location and lifting capacities, and CAD facilitated the placement determination of the casting slabs and the concrete panels, but an automation process could be developed in order to connect the optimization model and the CAD tool. Future research should incorporate GA's and a technique that would provide fast results with the use of minimum construction space.

3. The approach used to calculate the sling lengths for the case study was based on a graphical CAD method. Due to time constraints, the sling lengths were not calculated using a systematic approach. The sling lengths should be obtained by mathematical algorithms that could provide the exact solution. When designing

tilt-up concrete panels, designers should keep in mind that standard separations between lifting points will reduce the use of spreader bars. At the same time, this will reduce confusion during on-site installation. Future research need be conducted to implement a model that, depending on the lifting case, could provide a graphical solution with the exact sling lengths.

4. 4D models are useful tools that increase 3D visualization allowing analysis of the construction activities through time. The 4D models, as explained before, link the construction schedule with the CAD layers and generate the installation process according to the activity time frames. Unfortunately, a 4D model does not detect if an element is crossing another in a 3D environment. Future research need be conducted to incorporate a system that could tell if activities that are taking place are interfering spatially with others.

5. Due to the complexity of the bracing system, a spatial analysis was performed to obtain the final locations of the braces. This approach was conducted according to the structural requirements of the panels, saving 99 concrete deadmen by nailing the brace ends to footings and foundation walls whenever possible, and by sharing a deadman between two or more braces. This analysis was made with the bracing and installation managers, but enhancements can be made in order to obtain an automated answer that would check for better set ups. An algorithm need be developed in future research in order to avoid human errors and for the sake of convenience through a complete and effective spatial analysis.

5.4 Process Guidelines

1. If the construction methodology that is going to be used is not common to the Construction Organization, mockup models should be developed in order to minimize risks and uncertainties.
2. Prior testing is always recommended with construction products. As an example, the bond breaker used for the construction project worked most of the time with a high degree of quality. However, dust and excessive moister decreased its capacity to separate concrete surfaces, which produced errors during the tilting of the panels.
3. Due to weather conditions, it is recommended that the period between forming, reinforcing and concreting should be short in order to avoid the need for people to clean the inside of the forms. For this project, almost a month passed between the forming and concreting. This increased the amount of dust build-up and the need to drain rain water from the forms. An approach was considered in order to cover the forms as explained before, but it did not completely prevent the water filtrations.
4. When possible for any tilt-up construction project, it's better to have a slab on grade that will allow the bracing crew to nail the end of the braces against it. This will save the use of extra concrete (deadmen) to support the panels during the installation stage.
5. It is recommended to measure the final dimensions of the concrete panels after casting them due to potential concrete shrinkage. It is also recommended to use

the final measurements in a 3D model to understand space changes and make decisions prior to lifting.

6. As-built measurements need to be compared and checked with the 3D Model in order to avoid installation errors. It is recommended after building different stages of the main structure, to update the construction drawings and computer models. This procedure can be enhanced with surveying, providing the final measurements for joists, beams, trusses, and windows.

APPENDIX A:

SPREADSHEETS

offset x	29.25															
offset y	29.25															
X min	0.00															
X max	98.75															
Y min	93.83															
Y max	196.25															
PHASE	1A	FINAL POSITION OF THE CRANE														
X pos (ft)	81.42	Min Momemtum		4.295	X	52.16666502			ft							
Y pos (ft)	152.15				Y	196.250			ft							

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
37	8	28.2	9.9	35	64	106	106	112.5	ES2	5	21	26	91.9	79.2	2388	2058
38	8	15.6	17.5	56	85	106	106	224.3	LS1.1	5	22.43	27	90.3	96.6	2477	2651
39	8	16.0	32.3	52	81	114	114	474.3	LW1	5	47.43	52	81.9	89.8	4295	4707
40	8	16.0	17.1	48	77	114	114	220.9	RW1	5	22.09	27	82.0	85.6	2223	2318
41	8	9.0	11.8	41	70	117	117	105.8	RW3	5	10.58	16	79.8	78.6	1244	1225
42	8	13.4	33.5	45	74	122	122	430	SS1	5	43	48	74.6	80.2	3580	3850
43	8	23.0	34.1	38	67	141	141	550	SW2	5	55	60	57.5	68.3	3451	4095
44	8	11.3	34.1	38	67	127	127	258.2	SW3	5	25.82	31	70.4	71.7	2169	2209
45	8	14.5	21.5	57	87	144	144	269	SE2	5	26.9	32	52.6	87.0	1678	2774
46	8	29.6	35.4	57	87	152	152	542.9	SE1	5	54.29	59	44.4	86.6	2633	5134
47	8	24.6	36.9	45	75	167	167	496.5	SN1	5	49.65	55	30.4	76.0	1659	4155
48	8	15.0	28.6	38	67	160	160	310.3	SW1	5	31.03	36	39.4	67.7	1419	2437
									MAX			60.00	91.9	97	4,295	5,134

Spreadsheet 1. Crane Location Optimization Model, Phase 1A

offset x	29.25	
offset y	29.25	
X min	83.666	
X max	168.25	
Y min	97.66	
Y max	196.25	
PHASE	1B	**FINAL POSITION OF THE CRANE**
X pos (ft)	126.5	Min Momemtum 3,539 — X 168.25 ft
Y pos (ft)	156.1666661	Y 156.167 ft

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
49	8	12.7	5.4	90	90	137	137	68.6	LN2	5	6.8	11.8	69.6	80.6	821	951
50	8	31.0	17.4	96	96	125	125	328.8	LE2.1	5	32.8	37.8	77.2	78.6	2918	2969
51	8	17.9	4.8	105	105	113	113	86	MN2.2	5	8.6	13.6	86.0	76.6	1169	1041
52	8	7.0	13.5	115	115	109	109	44.3	VW2	5	4.43	9.43	87.9	71.3	829	672
53	8	31.6	31.5	123	123	106	106	453.1	VS1	5	45.31	50.31	90.3	67.4	4544	3393
54	8	17.5	31.5	139	139	115	115	295.9	VE1	5	29.59	34.59	82.1	50.6	2839	1751
55	8	24.7	31.5	127	127	123	123	474.6	VN1	5	47.46	52.46	73.6	53.4	3860	2801
56	8	16.6	13.5	98	98	146	146	96.6	KS2	5	9.66	14.66	57.6	71.3	845	1045
57	8	20.0	31.5	99	99	167	167	363.3	KN2	5	36.33	41.33	40.6	70.4	1679	2908
58	8	20.3	31.5	108	108	156	156	485.1	KE1	5	48.51	53.51	44.0	59.9	2355	3206
59	8	30.3	30.4	89	89	156	156	396.6	KW1	5	39.66	44.66	54.9	79.2	2451	3539
60	8	20.7	27.9	97	97	106	106	336.8	LS2	5	33.68	38.68	94.9	87.1	3673	3371
61	8	16.6	31.5	115	115	115	115	290.5	VW1	5	29.05	34.05	82.4	67.8	2807	2308
62	8	20.0	31.5	99	99	146	146	301.4	KS1	5	30.14	35.14	57.2	70.3	2008	2469
									MAX			53.51	94.9	87	4,544	3,539

Spreadsheet 2. Crane Location Optimization Model, Phase 1B

offset x	29.25				
offset y	29.25				
X min	0				
X max	77.25				
Y min	0				
Y max	119.25				
PHASE	1C	FINAL POSITION OF THE CRANE			
X pos (ft)	39.00	Min Momemtum	3,630	X	0 ft
Y pos (ft)	79.08			Y	79.0833324 ft

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
21	8	27.1	11.8	48	76.8	14	43	[illegible]	DW5	5	19.21	24.21	57.1	84.9	[illegible]	[illegible]
22	8	17.4	16.1	48	76.8	36	65	225	DW4	5	22.49	27.49	75.3	78.0	2069	2145
23	8	10.3	29.0	48	76.8	49.6	79	423	DW3	5	42.3	47.3	97.6	76.8	[illegible]	[illegible]
24	8	10.3	29.0	48	76.8	64.1	93	208	DW2	5	20.77	25.77	100.7	78.1	2595	2012
25	8	8.4	29.0	51	80.6	65.7	95	[illegible]	DN2	5	23.35	28.35	103.6	[illegible]	[illegible]	[illegible]
26	8	23.6	16.3	48	76.8	78	107	314	RW2	5	31.4	36.4	113.5	81.7	4133	2974
27	8	33.9	7.7	30	59.7	73	102	162	GN1	5	22.7	27.7	104.8	64.1	[illegible]	1775
28	8	27.2	11.8	16	44.9	14	43	224	SCE2	5	22.41	27.41	43.2	57.7	1185	1582
29	8	18.8	19.6	16	44.9	37	66	[illegible]	SCE1	5	25.7	30.7	66.4	46.7	[illegible]	[illegible]
30	8	16.3	29.9	16	44.9	51	80	336	GE1	5	33.62	38.62	80.2	44.9	3098	1735
31	8	10.8	15.4	16	44.9	61	90	167	GE2	5	16.7	21.7	90.4	46.1	1961	[illegible]
32	8	24.6	30.5	0	29.6	46	75	460	GW2	5	46	51	75.4	29.9	3843	1525
33	8	16.6	30.5	0	37.2	39	68	363	GS1	5	36.26	41.26	68.1	38.8	[illegible]	[illegible]
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
35	8	22.5	30.5	0	29.6	61	91	388	GW1	5	38.84	43.84	91.2	31.8	[illegible]	[illegible]
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
								4367	MAX			57.10	113.5	85	5,850	3,630

Spreadsheet 3. Crane Location Optimization Model, Phase 1C

offset x	29.25
offset y	29.25
X min	69.50
X max	168.25
Y min	0
Y max	147.660
PHASE	1D
X pos (ft)	122.4
Y pos (ft)	66.50002413

FINAL POSITION OF THE CRANE

Min Momemtum	3,971	X	168.25	ft
		Y	37.250	ft

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
6	8	20.0	30.6	134	134	38	67	314.1	JE1	5	31.41	36	68.2	34.3	2485	1247
7	8	24.7	30.6	122	122	48	77	602.5	JN1	5	60.25	65	76.9	47.4	5019	3093
8	8	20.0	30.6	124	124	28	58	339.7	JS1	5	33.97	39	57.6	44.8	2245	1746
9	8	11.5	4.0	139	139	51	80	46	BE3	5	4.6	10	82.0	32.7	787	314
10	8	27.5	20.2	139	139	70	99	317.8	BE2	5	31.78	37	100.5	44.1	3696	1621
11	8	15.2	16.5	131	131	57	86	222	BS1	5	22.2	27	86.2	41.6	2345	1130
12	8	16.0	16.5	131	131	89	119	218.4	BN1	5	21.84	27	118.9	64.0	3191	1719
13	8	14.1	30.0	119	119	89	119	383.2	BN2	5	38.32	43	118.6	71.5	5139	3098
14	8	20.8	30.0	139	139	77	106	378.2	BE1	5	37.82	43	107.7	49.7	4612	2130
15	8	20.1	25.1	83	83	37	67	414	MW2	5	41.4	46	77.5	85.6	3594	3971
16	8	11.0	21.3	88	88	48	77	210.3	MS3	5	21.03	26	84.3	81.1	2195	2112
17	8	2.7	12.3	98	98	18	47	28.3	NN2	5	2.83	8	52.7	72.6	413	569
18	8	18.0	29.5	99	99	9	38	251	NE1	5	25.1	30	44.7	74.5	1344	2242
19	8	17.3	30.6	91	91	0	30	280.5	NS1	5	28.05	33	43.1	85.6	1426	2830
20	8	18.0	30.6	83	83	9	38	354.2	NW1	5	35.42	40	55.2	90.1	2229	3643
									MAX			65.25	118.9	90	5,139	3,971

Spreadsheet 4. Crane Location Optimization Model, Phase 1D

offset x	29.25
offset y	29.25
X min	0.00
X max	119.25
Y min	60
Y max	196.25
PHASE	2A
X pos (ft)	98.500
Y pos (ft)	106.000

FINAL POSITION OF THE CRANE

Min Momemtum	4.837	X	69.24999906	ft
		Y	196.250	ft

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
69	8	37.8	19.3	69	98	106	106	486	LS1 2	5	48.6	53.6	90.3	98.5	4837	5280
80	8	31.1	7.1	32	61	73	73	203	GN2	5	28.5	33.5	128.7	69.1	4311	2315
72	8	18.6	14.4	87	116	96	96	202.4	RE3	5	20.24	25.24	101.5	116.7	2561	2944
95	8	40.1	4.9	0	12	146	146	195.4	EW2	5	19.54	24.54	99.6	42.1	2445	1033
91	8	20.5	15.5	0	12	116	116	189.1	EW1	5	18.91	23.91	117.6	16.0	2811	383
70	8	16.1	20.5	55	84	97	97	187.3	DW1	5	18.73	23.73	99.9	84.9	2371	2015
79	8	14.5	17.1	16	45	66	66	185.9	GE3	5	18.59	23.59	140.5	59.9	3313	1412
97	8	46.4	4.0	24	36	82	82	185.7	EPN1	5	18.57	23.57	130.6	43.4	3077	1023
93	8	16.7	15.5	13	25	114	114	185	EE1	5	18.5	23.5	110.6	25.9	2597	609
92	8	16.5	15.5	9	21	122	122	170.9	EN1	5	17.09	22.09	107.6	26.1	2378	576
96	8	33.0	4.9	17	29	167	167	161.1	SN2	5	16.11	21.11	76.0	67.0	1603	1416
90	8	13.0	15.5	7	19	106	106	152	ES1	5	15.2	20.2	120.6	18.5	2436	374
71	8	18.9	13.3	48	77	99	99	139.5	RW4	5	13.95	18.95	99.5	77.1	1885	1460
94	8	21.1	4.8	27	39	122	122	101	EN2	5	10.1	15.1	95.1	42.2	1436	638
78	8	7.7	12.7	51	81	89	89	90.6	DN3	5	9.06	14.06	108.4	82.3	1524	1157
77	8	7.0	12.7	51	81	97	97	86.5	RN1	5	8.65	13.65	101.2	81.1	1381	1108
									MAX			53.60	140.5	117	4,837	5,280

Spreadsheet 5. Crane Location Optimization Model, Phase 2A

offset x	29.25						
offset y	29.25						
X min	60						
X max	168.25						
Y min	97.66						
Y max	196.25						
PHASE	2B	FINAL POSITION OF THE CRANE					
X pos (ft)	95.99999979	Min Momemtum	2.317	X	96.00	ft	
Y pos (ft)	130			Y	196.250	ft	

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
[illegible]	8	26.0	19.4	96	96	134	[illegible]	120.3	LE1.2	5	32	37	62.6	72.3	2317	2677
102	8	42.4	4.8	139	139	145	145	203.2	VE2	5	20.32	25.32	66.6	33.2	1687	841
[illegible]	8	18.6	9.8	105	105	113	113	185.7	MN2.1	5	18.57	23.57	83.7	65.5	1974	1544
100	8	30.9	14.2	73	73	146	146	155.3	MN3	5	15.53	20.53	54.9	96.5	1127	1981
75	8	[illegible]	9.2	96	96	116	116	[illegible]	LE1.1	5	14.4	19.4	80.6	73.7	1563	1429
101	8	28.8	4.8	125	125	167	167	138	KN1	5	13.8	18.8	41.1	57.0	773	1072
74	8	[illegible]	9.8	92	92	137	137	[illegible]	LN1	5	7.4	12.4	59.4	76.1	736	944
									MAX			37.00	83.7	96	2,317	2,677

Spreadsheet 6. Crane Location Optimization Model, Phase 2B

offset x	29.25
offset y	29.25
X min	0
X max	77.25
Y min	0
Y max	78.25
PHASE	2C
X pos (ft)	29.58333297
Y pos (ft)	46.8

FINAL POSITION OF THE CRANE

Min Momemtum	633.08	X	0	ft
		Y	17.550	ft

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
98	8	33.8	4.0	0	29.6	18	47	135	GW4	5	16.4	21.4	46.8	29.6	1002	633
99	8	10.0	4.0	5	34.3	0	30	40	SCS1	5	4	9	29.9	38.3	270	346
									MAX			21.40	46.8	38	1,002	633

Spreadsheet 7. Crane Location Optimization Model, Phase 2C

offset x	29.25
offset y	29.25
X min	50.00
X max	198.25
Y min	0
Y max	126.917
PHASE	2D
X pos (ft)	112.50
Y pos (ft)	70.00

FINAL POSITION OF THE CRANE

Min Momemtum	4,562	X	112.50	ft
		Y	-29.25	ft

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
63	8	24.7	29.6	113	113	78	107	377.4	BW1	5	37.74	43	106.8	93.1	4562	[illegible]
89	8	34.4	17.0	65	65	41	70	373	DS1	5	37.3	42	84.8	133.2	3585	5633
64	8	19.3	30.6	115	115	[illegible]	67	[illegible]	[illegible]	5	31.5	37	67.0	83.3	[illegible]	[illegible]
67	8	35.8	25.1	65	65	28	57	271.4	MS1.1	5	27.14	32	74.0	133.8	2377	4301
83	8	48.3	7.8	83	83	[illegible]	95	[illegible]	DE1	5	26.45	31	98.3	115.4	[illegible]	[illegible]
66	8	16.6	30.6	91	91	18	47	258.8	NN1	5	25.8	31	51.5	109.4	1585	3369
86	8	12.2	16.2	121	127	54	83	167	BE4	5	16.7	22	84.7	72.2	[illegible]	[illegible]
68	8	16.6	13.1	91	91	28	57	145	MS1.2	5	14.5	20	60.6	107.7	1181	2101
105	8	11.8	12.5	133	133	0	30	123.2	KGS2	5	12.32	17	36.1	76.6	[illegible]	[illegible]
88	8	9.1	13.5	92	92	23	52	120.8	MW1	5	12.08	17	55.6	107.5	950	1835
103	8	24.7	4.9	139	139	18	48	120.5	KGE2	5	12.05	17	54.3	63.7	[illegible]	[illegible]
81	8	29.8	4.0	98	98	80	110	117.5	MN5	5	11.75	17	110.6	107.9	1853	1807
108	8	9.3	12.5	134	134	8	37	112.5	KGN1	5	11.25	16	42.5	72.6	[illegible]	[illegible]
87	8	14.6	12.4	107	107	41	70	101.1	MS2	5	10.11	15	70.1	91.3	1060	1379
65	8	23.7	25.2	99	99	29	58	101	NE2	5	[illegible]	33	59.9	99.6	[illegible]	[illegible]
85	8	21.3	5.6	113	113	58	88	97.7	BW2	5	9.77	15	87.6	87.5	1294	1293
104	8	8.8	12.5	139	139	4	33	86	KGE1	5	8.65	14	42.2	76.0	[illegible]	[illegible]
84	8	29.1	2.7	98	98	48	77	78.6	RTS1	5	7.86	13	78.3	100.9	1008	1298
107	8	8.8	12.5	129	129	4	33	72.1	KGW1	5	7.21	12	37.3	78.1	[illegible]	[illegible]
82	8	16.0	5.0	87	87	74	103	68.5	RE2	5	6.85	12	106.4	116.1	1260	1376
106	8	13.2	4.9	121	121	0	30	64.4	KGS1	5	6.44	11	30.7	87.5	[illegible]	1001
									MAX			42.74	110.6	134	4,562	5,633

Spreadsheet 8. Crane Location Optimization Model, Phase 2D

		MAXIMUM RADIUS (ft) PHASE 1A																				Boom L (ft)
PANEL	R REQ (ft)	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	
37	92	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	130	130	130	130	125	125	125	125	125	120	120	120	120	Radius (ft)
38	90	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	125	125	125	125	125	125	120	120	120	120	120	120	120	115	
39	82	#N/A	#N/A	85	85	85	85	85	85	85	85	85	80	80	80	80	80	80	80	80	80	
40	82	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	125	125	125	125	125	125	120	120	120	120	120	120	120	
41	80	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	165	160	160	160	160	155	155	155	155	
42	75	#N/A	#N/A	#N/A	90	90	90	90	90	90	90	90	85	85	85	85	85	85	85	85	85	
43	58	#N/A	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	
44	70	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	120	120	115	115	115	115	115	115	115	110	110	110	110	110	
45	53	#N/A	#N/A	#N/A	#N/A	#N/A	115	115	115	115	115	115	115	110	110	110	110	110	110	110	110	
46	44	#N/A	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	
47	30	#N/A	#N/A	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	
48	39	#N/A	#N/A	#N/A	#N/A	105	105	110	105	105	105	105	105	105	105	105	100	100	100	100	100	

Spreadsheet 9. Boom Selection, Phase 1A

		MAXIMUM RADIUS (ft) PHASE 1B																				Boom L
PANEL	R REQ (ft)	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	
49	81	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	180	180	175	175	175	170	170	170	Radius (ft)
50	79	#N/A	#N/A	#N/A	#N/A	105	105	105	105	105	105	100	100	100	100	100	100	100	100	100	100	
51	77	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	170	170	170	165	165	160	165	160	
52	71	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	190	190	190	185	185	185	180	
53	67	#N/A	#N/A	85	85	85	85	85	85	85	85	85	85	85	85	85	85	80	80	80	80	
54	51	#N/A	#N/A	#N/A	#N/A	#N/A	110	110	110	110	110	110	110	105	105	105	105	105	105	105	105	
55	53	#N/A	#N/A	85	85	85	85	85	85	85	85	85	80	80	80	80	80	80	80	80	80	
56	71	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	165	165	165	160	160	160	160	155	
57	70	#N/A	#N/A	#N/A	#N/A	100	100	100	100	95	95	95	95	95	95	95	95	95	95	95	95	
58	60	#N/A	#N/A	85	85	85	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	
59	79	#N/A	#N/A	#N/A	95	95	95	95	95	95	90	90	90	90	90	90	90	90	90	90	90	
60	87	#N/A	#N/A	#N/A	#N/A	105	105	105	100	100	100	100	100	100	100	100	100	95	95	95	95	
61	68	#N/A	#N/A	#N/A	#N/A	#N/A	110	110	110	110	110	110	110	110	105	105	105	105	105	105	105	
62	70	#N/A	#N/A	#N/A	#N/A	#N/A	110	110	110	110	110	105	105	105	105	105	105	105	100	105	100	

Spreadsheet 10. Boom Selection, Phase 1B

		MAXIMUM RADIUS (ft) PHASE 1C																				Boom L
PANEL	R REQ (ft)	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	
21	85	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	135	135	135	135	130	130	130	130	130	125	125	125	125	Radius (ft)
22	78	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	125	125	125	125	125	125	120	120	120	120	120	120	120	115	
23	77	#N/A	#N/A	#N/A	90	90	90	90	90	90	90	90	90	90	85	85	85	85	85	85	85	
24	78	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	130	130	130	130	130	125	125	125	125	125	120	120	120	
25	82	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	125	125	125	120	120	120	120	120	120	120	115	115	115	115	
26	82	#N/A	#N/A	#N/A	#N/A	105	105	105	105	105	105	105	105	105	105	100	100	100	100	100	100	
27	64	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	125	125	125	125	125	125	120	120	120	120	120	115	115	115	
28	58	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	125	125	125	125	125	125	120	120	120	120	120	120	120	115	
29	47	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	120	120	115	115	115	115	115	115	115	110	110	110	110	110	
30	45	#N/A	#N/A	#N/A	#N/A	105	105	105	100	100	100	100	100	100	100	100	100	95	95	95	95	
31	46	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	140	140	140	140	140	135	135	135	135	135	135	130	
32	30	#N/A	#N/A	85	85	85	85	85	85	85	85	85	85	85	85	85	80	80	80	80	80	
33	39	#N/A	#N/A	#N/A	#N/A	100	100	100	100	100	95	95	95	95	95	95	95	95	95	95	95	
34	40	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	190	190	190	185	185	185	180	
35	32	#N/A	#N/A	#N/A	95	95	95	95	95	95	95	95	95	90	90	90	90	90	90	90	90	
36	46	#N/A	#N/A	80	80	80	80	80	80	80	80	80	75	75	75	75	75	75	75	75	75	

Spreadsheet 11. Boom Selection, Phase 1C