UNIVERSITY OF ALBERTA

SPECIAL PURPOSE SIMULATION FOR TOWER CRANE CONSTRUCTION OPERATIONS MANAGEMENT

BY

BRADFORD J. A. APPLETON ©

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This thesis is dedicated to my wife Amy for her love, affection, and encouragement to successfully complete my graduate degree,

And

To my parents. Jack and LaVern Appleton for their encouragement and continued support throughout my entire education.

ABSTRACT

Historically, simulation tools have only been used and understood by the academic community. Special Purpose Simulation (SPS) techniques have introduced computer modeling to the construction industry, resulting in reduced model development time and a user-friendly environment. This Thesis presents a new approach to handling process interaction for computer simulation modeling using *priority rating logic*, which is used to represent leading resource non-cyclic construction operations. The use of priority rating logic control for model process interaction is implemented through the development of a SPS tower crane template. On-site management of the tower crane resource is based on prioritized work tasks that need to be performed within a set period of time. Traditional SPS modeling techniques use *relationship logic links* to represent the logic contained in the modeled system. As the number of work tasks increases for the tower crane resource, the model complexity using traditional simulation techniques becomes unmanageable, resulting in limited acceptance by industry practitioners. The tower crane template uses priority rating logic to replace the relationship logic links. Evaluation of the tower crane operations at the Electrical and Computer Engineering Research Facility (ECERF), being constructed in Edmonton, is used as a generic case study. The ECERF case study is modeled using both the relationship logic links and priority rating logic control modeling approaches. The results from the two models are used to illustrate the advantages and viability of using the priority rating logic modeling approach for tower crane operations.

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1 BACKGROUND AND OBJECTIVES

1.1 OVERVIEW

The state-of-the-art in discrete-event computer simulation has traditionally modeled repetitive construction activities using *relationship logic links* for model process interaction. For example, modeling an earthmoving operation is defined by a distinct cyclic pattern: load, travel, unload, and return travel. These events are logically linked using arrows or relationship logic links, which drives the logical process interaction flow in the simulation model. As a leading resource, the tower crane process interaction consists of a set of activities that need to be completed by the specified tower crane resource, given a certain time frame and urgency. Each lift activity has a scheduled arrival time and a set priority based on activity criticality in relation to the other existing activities in the system. Therefore, the tower crane special purpose simulation (SPS) model must use a linear process interaction approach that represents the tower crane construction operations.

According to Pristker (1986), computer simulation is defined as the process of designing a mathematical-logical model of a real world system and experimenting with the model on a computer. Until recently, computer simulation has only been a tool for academia due to the complexity of model development for industry practitioners. The state-of the-art uses graphical modeling and special purpose simulation (SPS) tools, which results in a simplified modeling environment that reduces the amount of programming and development time required to create a simulation model. SPS is a computer-based environment built to enable a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain in a manner where symbolic representation, navigation schemes within the environment, creation of model specifications, and reporting are completed in a format native to the domain itself. By using SPS tools to create an industry specific modeling environment, computer simulation provides many advantages for the industry practitioner including wider acceptance and use in practical settings (AbouRizk 1998). SPS tools isolate the user from the low level constructs and presents a modeling interface that more closely represents the actual system, resulting in a more effective simulation environment. (Hajjar and AbouRizk 1996).

The success of SPS tools has led to the development of *Simphony* (Hajjar and AbouRizk 1999), a simulation platform for building general and special purpose simulation tools. Simphony "greatly simplifies the SPS tool development process and standardizes the simulation, modeling, analysis and integration features of such tools. The result is a complete environment that tailors to the needs of both novice and advanced simulation tool developers and users" (Hajjar and AbouRizk 1999). Developers can use Simphony to create highly flexible simulation models that support graphical, hierarchical, modular, and integrated modeling with great ease.

Construction simulation is a great decision-making tool that allows the user to analyze various scenarios in the pre-construction phase of the project. It allows analysts and construction industry personnel to experiment with different construction technologies and estimate their possible consequences and impact on scheduling and costs (Ruwanpura 2001).

This research has produced a special purpose simulation application for tower crane management operations using Simphony. During the development phase of the SPS tower crane template, restrictions using traditional *relationship logic links* for process interaction for a leading resource are identified, and the use of *priority rating logic* control is successfully implemented yielding a template that is simple to use and representative of the tower crane construction domain. A generic case study will be used to contrast the difference between the two modeling approaches and to validate the SPS tower crane template output using priority rating logic process interaction control.

1.2 RESEARCH OBJECTIVES

The objective of this research is to develop an alternate method of modeling process interaction for the computer simulation of a leading resource. Using this methodology, a SPS template is implemented for tower crane construction operations yielding a modeling environment that is representative of the tower crane construction domain. To achieve these objectives, the following steps are identified.

1. Understand the day-to-day management techniques currently used for tower crane operations.
2. Develop a special purpose simulation template for tower crane construction operations management on construction sites. In order to create a model that is

representative of the tower crane construction domain, use *priority rating logic* control to drive the lift activity process interaction by the tower crane resource.

3. Validate the replacement of traditional *relationship logic links* with priority rating logic control. The new model must yield comparable results and simplify model development for the end user.

1.3 Research Methodology

The research was conducted in three phases to accomplish the stated objectives. For the first phase, the tower crane at the Electrical and Computer Engineering Research Facility at the University of Alberta, was monitored for a 7-month period from April to November, 2000. This time was used to develop a greater understanding of the tower crane schedule, activity prioritization and selection schemes, delays, and lift activity hook-times. In conjunction with PCL Constructors Inc., information regarding the tower crane operations was collected from project superintendents and coordinators, who oversaw the day-to-day management of the tower crane resource. Other tower crane construction sites visited include the University of Alberta Hospital Expansion Project and the Northern Alberta Institute of Technology (NAIT) Information and Communications Technology Centre (ICTC).

During the second phase, a special purpose simulation tool for tower crane construction operations management was developed. After studying the tower crane lift selection process in phase one, it was decided that the traditional methods representing process interaction within the model had to be modified. Traditional modeling techniques use relationship links to represent the logic contained in the modeled system. As the number of work tasks increases for the tower crane, the model complexity using traditional simulation techniques becomes unmanageable, resulting in limited acceptance by industry practitioners. To overcome this problem the SPS tower crane template introduces *priority rating logic* using prioritized work package modeling elements to represent each activity being performed by the tower crane (i.e. formwork, concrete placement, rebar delivery, etc.). Using priority rating logic for model process interaction simplifies model development for the industry practitioner when modeling a leading resource.

The third phase uses the Simphony common template and the SPS tower crane template to validate priority rating logic using a generic case study. The common template uses relationship logic links for process interaction while the SPS tower crane template uses priority rating logic. The purpose of this phase is to verify that all process interaction constraints from the common template model are upheld using the SPS tower crane template.

1.4 THESIS ORGANIZATION

Chapter 2 provides a summary of the state-of-the-art in computer simulation for tower crane applications. This section also briefs the reader in the use of expert systems and 3D CAD models as a decision support tool for crane operations.

Chapter 3 reviews the current day-to-day management techniques used by field personnel on the construction site.

Chapter 4 discusses the design and development of the SPS tower crane template. It includes the template criteria and a full description of each modeling element and its function. Section 4.2 briefs the criteria to be included in the tower crane template and introduces the concept of *priority rating logic* control. Rules and criteria are established where priority rating logic control should be applied.

Chapter 5 uses the Electrical and Computer Engineering Research Facility (ECERF) at the University of Alberta campus as a case study to validate the use of priority rating logic for model process interaction. To do this, the Simphony common template and the SPS tower crane template are used to model the ECERF case study comparing the use of relation logic links to priority rating logic respectively. Benefits of using the SPS tower crane template are discussed, and the result of the two models analyzed. This chapter also outlines the data collection methods used for model parameter input.

Chapter 6 uses the SPS tower crane template to perform model scenario analysis, which can be used as a valuable decision support tool. By running various scenarios, the practitioner will better understand the sensitivity of the modeled tower crane system.

Chapter 7 describes the conclusions, contributions, and recommendations for further research.

2 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter presents a summary of the state-of-the-art development in the following areas:

1. Computer simulation,
2. Tower crane simulation applications, and
3. Other crane decision support systems.

Section 2.2 presents the summary of computer simulation algorithms and modeling techniques. Section 2.3 briefs the use of tower cane simulation tools, applications developed, and the degree of industry implementation. Section 2.4 provides a summary of crane decision support tools used for crane selection using expert systems and 3D modeling techniques.

2.2 STATE-OF-THE-ART REVIEW IN CONSTRUCTION SIMULATION

"Construction simulation is a powerful tool that can be used by a construction company for a number of tasks such as productivity measurement, risk analysis, resource planning, design and analysis of construction methods, and site planning" (Sawhney et al. 1998). Computer simulation is the process of designing a mathematical-logical model based on a real system and experimenting with the model on a computer (Pritsker 1986). These experiments, or simulations, can be used for design, procedural analysis, and performance assessment. A model is an abstraction from a system, defined as a collection of items from a circumscribed sector of reality that is the object of study (Pritsker 1986). Using computer simulation techniques the practitioner defines the boundaries of the system and the level of modeling detail.

Early simulation required the practitioner to build a simulation model by writing code using computer-programming languages (i.e. FORTRAN, PASCAL, etc.) and experimenting by directly manipulating the computer program (Ruwanpura 2001). Creating simulation models using direct programming code results in stand-alone models that have little flexibility, are costly and time consuming to build, and are difficult to implement in industry. The next phase of simulation uses graphical modeling to create, manipulate and link a number of generation modeling elements familiar to the system domain. A detailed introduction to the history of simulation is found in Kreutzer (1986).

2.2.1 Simulation Modeling

Simulation model development is classified by the underlying algorithm of the developed system. Three algorithms are typically used for construction simulation modeling: (AbouRizk and Hajjar 1998)

1. Discrete-event simulation algorithms. Uses "next event processing" of activities based on logical relationships between process components and availability of resources. Systems modeled using this approach are dynamic in nature.

2. Static simulation algorithms are driven by prescribed processing flow, which is not dependent on time or interaction of resources.
3. Continuous, or time dependent algorithms often represented with a system of equations or mathematical models and then solved for steady state performance using differentiation, integration or by approximation.

Discrete-event and static simulation algorithms are the most commonly used for construction simulation applications. Discrete-event simulation is used when analyzing the logic of a construction production system. According to Hajjar and AbouRizk (2000), discrete-event simulation views a model as a set of events and transitions. Entities represent the active elements of the model as they travel throughout the event network and trigger transformations (Hajjar and AbouRizk 2000). Non-intrinsic static algorithms are used for applications such as range estimating.

In the construction phase of any project certain decisions must be made regarding the intended progress of the work. Usually, decisions are made by considering a variety of scenarios that express what is known about the operation and what can be done with resources in work task sequences. Simulation is a valuable tool used to run project scenarios, establish a feasible work plan, and allow assessment of the adequacy of a resource allocation to the operation. (Halpin 1977)

Halpin (1977) introduced simulation software called CYCLONE (CYCLic Operations NEtwork). CYCLONE is an example of a discrete-event simulation algorithm used to analyze the movement of resource units around the site, which has led to the wide acceptance of construction-process modeling. (Sawhney et al. 1998) Using a set of graphical elements, the CYCLONE format is used to model construction situations by considering the repetitive activities of the job site and the cyclic movement of the production system. The introduction of CYCLONE as a construction simulation tool has spurred substantial research in construction simulation. Ensuing research has focused on the enhancement of the basic system functionality (Ruwanpura 2001), which has resulted in a number of simulation advancements using CYCLONE simulation constructs. Examples of simulation research that has stemmed from CYCLONE are:

- INSIGHT (Paulson et al. 1987). INSIGHT (INteractive SImulation using GrapHics Techniques) uses collected time data from videotapes of field construction operations. The purpose of INSIGHT is to make it more economical to collect production time data in the field and to make powerful simulation analysis and design techniques available on microcomputers at the field-office level.

- COOPS (Liu, L.Y. 1991). COOPS (Construction Object-Oriented Process Simulation System) is a simulation package developed to model discrete-event systems. The package contains queue, activity, and flag controls that are similar in design and function to the controls found in CYCLONE.

- STROBOSCOPE (Martinez and Ioannou 1994). STROBOSCOPE (State and ResOurce Based Simulation of COnstruction ProcEsses) is a programming language designed for the simulation of processes common to construction engineering. Using model elements similar in appearance and function to CYCLONE, STROBOSCOPE uses attributes that consider uncertainty for any aspect (not just time), such as the quantities of resources produced or consumed.

- DISCO (Huang et al. 1994). DISCO (Dynamic Interface for Simulation of Construction Operations) provides a graphical environment in which modeling and simulation of construction operations can be conducted in an interactive fashion. DISCO is written in Microsoft Visual Basic language using the CYCLONE modeling methodology.

CYCLONE is a powerful tool that has paved the way to wider acceptance of construction-process simulation in the academic community, but has had limited use by the construction industry practitioner. "This failure is partly due to the inherent complexity of general simulators and their inability to abstract the underlying modeling fundamentals" (Hajjar et al. 1998). In order to facilitate the use of computer simulation by industry practitioners, Hajjar et al. (1998) propose a framework for building environments tailored to the specific requirements of a given industry domain known as special purpose simulation (SPS). SPS is defined as "a computer-based environment built to enable a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain in a manner where symbolic representations, navigation schemes within the environment, creation of model specifications, and reporting are completed in a format native to the domain itself" (AbouRizk and Hajjar 1998). SPS provides the framework for computer simulation acceptance in the construction industry. Hajjar and AbouRizk (1996) state, "By making the model environment specific for a given industry many advantages are gained including wider acceptance and use in practical settings. SPS tools help bring simulation to the desks of construction engineers who have little or no experience with simulation theory." By isolating the user from the low level constructs and presenting a model interface that more closely represents the actual system, the overall environment becomes more effective. (Hajjar and AbouRizk 1996)

When developing SPS modeling tools the developer must adhere to five conditions satisfying SPS methodology: (Hajjar et al. 1998)

(1) The user must be able to build models using constructs native to the domain itself.

(2) The simulation results must be presented in a manner that is familiar and easy to read by a user who is not proficient in simulation or statistical theory.

(3) The user interface must be highly visual with minimal requirements for manual coding.

(4) The tool must be able to integrate with other modules such as databases and estimating systems.

(5) The tool design must be highly scalable in that the addition of new modules and constructs should be seamless.

Using this methodology, several stand-alone SPS simulation packages have been developed that are intuitive, user-friendly, and easy to use by construction engineers. Examples of such systems include WITNESS and SIMFACTORY (Mathewson 1989), Ap2Earth (Hajjar and AbouRizk 1996), CSD (Hajjar et al. 1998) and CRUISER (Hajjar and AbouRizk 1998). A major drawback of these stand-alone systems is the large initial time investment required for their development, which hinders the application of the SPS-based approach to other construction operations (Hajjar and AbouRizk 1999).

The successes and limitations of stand-alone SPS tools led to the development of *Simphony*, a simulation platform for building general and special purpose simulation tools, developed under the Natural Science and Engineering Research Council (NSERC)/ Alberta Construction Industry Research Chair Program in Construction Engineering and Management. According to Hajjar and AbouRizk (1999), Simphony is a Microsoft Windows based computer system developed with the objective of providing a standard, consistent, and intelligent environment for both the development and utilization of construction SPS tools. Simphony "greatly simplifies the SPS tool development process and standardizes the simulation, modeling, analysis and integration features of such tools. The result is a complete environment that tailors to the needs of both novice and advanced simulation tool developers and users" (Hajjar and AbouRizk 1999). For a detailed introduction to Simphony, refer to Hajjar and AbouRizk (1999).

Following the development of Simphony, several general and special purpose simulation (SPS) tools have been developed. Examples of SPS templates developed in Simphony include: Range Estimating, Project Scheduling, Earth Moving, Aggregate Crushing, Site Dewatering, and Tunneling operations. Recently the Simphony SPS tunneling template was successfully implemented by the City of Edmonton Public Works Department to analyze various construction scenarios logically and expeditiously. (Er et al. 2000)

2.3 Tower Crane Simulation Applications

The purpose of this section is to review the extent of research conducted on tower crane simulation in the field of construction. "Cranes are considered to be the most expensive and frequently-shared resources on the construction site"(Liu 1995). In practice, cranes are managed based on demand and urgency in the field. As a result, simulation models for tower crane construction operations require complex relationships to accurately model the lift sequence required for the numerous activities occurring on a construction site.

Liu (1995), created a discrete-event simulation model using COOPS (Liu 1991) to model a crane operation example where a "contractor is planning to use a tower crane to support the steel erection operation of a construction project. The crane is used to load and lift the steel members into position while ironworkers bolt members together" (Lui 1995). The crane is also used to support calls from other operations such as unloading delivery trucks. As mentioned earlier, COOPS is a simulation package that follows the object-oriented simulation methodology used in CYCLONE (Halpin 1977).

2.4 Other Crane Decision Support Systems

2.4.1 Expert Systems

This section explores research using knowledge-based expert systems as a decision support tool for crane activities. The majority of work performed using expert systems is specific to mobile crane selection for single lift configurations. Expert systems use a rule-based approach to analyze each movement of the crane in detail and check the clearance, capacity, reach, and location for various crane types. This type of decision support systems is used when planning single crane lifts that are high risk and complex. Examples of such systems include: CRANE ADVISOR (Al-Hussein et. al. 1995), NEXPERT (Vargheses 1992), PRECISE (Karl and Gary 1993), CRANES (C. Cooper 1987) and LOCRANE (Warszawski 1990). A detailed introduction of expert systems can be found in E.C. Payne and R.C. McArthur (1990).

Zhang et al. (1999) use expert systems to optimize the location of tower cranes. The system runs three models testing for three criterions in the following order: location generation model, task assignment model, and optimization model. The location generation model uses the crane lift capacity and required tasks to derive the "feasible" lifting area. The larger the feasible area, the more easily a task can be performed. This stage of the model also checks for the closeness of tasks on the jobsite. The task assignment model looks at each crane individually to ensure that one crane is not overburdened while others are idle. The optimization model is applied to each crane one by one to find an exact location in terms of hook transport time in three dimensions.

Based on balance workloads and lowest possibility of conflict, the model converges to yield an optimal tower crane location(s). (Zhang et al. 1999)

2.4.2 3D CAD Modeling

3D CAD programs have been developed for crane selection optimization and lift sequencing. Kenji et al. (1996) developed an object-oriented model used to describe each building element. The output for the model yields the type and positioning of a crane for a specific construction operation based on the location and attributes of the surrounding building elements. Williams and Bennett (1996) introduced ALPS (Automated Lift Planning System), which is a graphical crane and rigging simulation tool used when simulating heavy lifts. Using a library of cranes contained in the system, ALPS allows the user to graphically simulate an entire lift sequence. Al-Hussein (1999) presents a computer-integrated system for crane selection and on-site utilization that incorporates a database system, an optimization module, a 3D CAD module and a 3D animation module. Other examples of 3D CAD modeling programs include Cope (Lin et al. 1996) and HeLPS (Wolfhope 1991).

2.5 CONCLUSION

This chapter discusses the development of special purpose simulation (SPS) modeling techniques in construction, tower crane simulations applications, and other crane decision support systems developed primarily for mobile crane selection for single lift configurations. Aside from the work presented by Liu (1995), little work has been done using discrete-event simulation techniques to model the various tasks included in the tower crane production system. Liu (1995) uses COOPS, a stand-alone simulation package to simulate the tower crane operations for a limited number of crane related tasks for a specified construction site.

CYCLONE (Halpin 1977) and Simphony (Hajjar and AbouRizk 1999) both use object-oriented simulation tools to model construction operations, where two tasks and/or operations are logically linked using relationship logic links. As the number of work tasks for the crane resource increases, modeling the crane operation using relationship logic links becomes more complex and increasingly difficult to represent. This results in the limited use of simulation modeling by industry practitioners for tower crane operations management. This thesis describes a SPS template that facilitates a user-friendly tower crane SPS environment and minimizes the use of complex links and relationships, thus allowing industry experts to easily model a tower crane production system, quantify crane utilization and times associated with each lifting activity, and optimize the production system using scenario analysis. This research addresses this need by developing a SPS application for tower crane management operations that replaces traditional relationship logic links with the *priority rating logic* control. The result in a tower crane template that is simple to use and representative of the tower crane construction domain.

3 CURRENT DAY-TO-DAY MANAGEMENT TECHNIQUES FOR THE TOWER CRANE

3.1 BACKGROUND

The purpose of this Chapter is to allow the reader to develop an understanding of the day-to-day tower crane management techniques used by site superintendents, which must be considered for the development of the proposed tower crane SPS template. It is critical that a developer understand the specified construction operation when developing a simulation template. The tower crane is the leading resource on the construction site and directly affects the completion of critical activities on the project schedule.

The information in this section is based on site interviews with the project managers and/or coordinators who work for PCL Constructors Inc., and provide project management services at various commercial construction sites in the Edmonton, Alberta, Canada region. This Chapter focuses on PCL tower crane management practices and site operations. The interviewees include Paul Knowles and Mario Belini.

3.2 TOWER CRANE RESOURCE

Tower cranes can be erected in multiple configurations to yield various heights, reaches, and capacities. Each of the tower cranes can either be anchored to a concrete foundation or a portable undercarriage on rails providing lateral movement to the tower crane. The travel speeds for hoisting, radial, and horizontal trolley movement varies for each crane type.

Each tower crane has a hoisting engine that governs hoisting speed for the crane. Depending on the tower crane, the hoisting engine will have 3 to 4 gears yielding a specific line speed and capacity for each gear. For hoisting, the highest gear is only used for extreme elevation changes, such as a high-rise building. Horizontal movement is provided by a trolley located on the underside of the boom, which has speeds ranging from 8 to 80 meters per minute. The rotational motion of the tower crane has speeds ranging between 0.6 to 0.8 revolutions per minute depending on the type of tower crane selected. If the tower crane is anchored on a track, the track traveling speeds range from 25 to 30 meters per minute. Tower crane track movement is an isolated activity that is not done simultaneously with scheduled lifting activities. For this reason the crane relocation using tracks is not considered in the proposed SPS tower crane template.

In 1988 PCL conducted a time study which found that line speeds for raising and lowering loads can affect some of the crane operations, but are usually only a significant factor on very high projects (i.e. high-rise buildings). Line speeds will affect such operations as concrete placing and erection of structural steel or pre-cast concrete. They will not usually affect the productivity of forming operations (PCL 1988).

3.3 Tower Crane Processes

As mentioned above, the tower crane has three types of movement considered for each lift: radial, vertical, and horizontal. Depending on the building type, one or all of the lifting movements are considered when calculating each lift delay. For a low rise building or an underground parkade, the time delay equates to the single largest duration associated with the hoisting, radial, or horizontal movement. For a mid-rise or high-rise building the tower crane must clear the building envelope which results in a time delay equal to the hoisting delay plus the largest duration associated with the radial or horizontal movement. By definition a low-rise building is used for structures less than two floors, mid-rise buildings are between 2-6 floors, and high-rise building are for structure elevations greater than 6 floors. Typically the time to perform a lift from the source location to the assigned destination is approximately equal to the time required to return empty from the destination back to the source location.

3.4 Current Tower Crane Management

In order to gain a better understanding of the day-to-day management techniques used to manage the tower crane on site, interviews have been conducted with site superintendents at various PCL construction sites. For the sites visited, PCL is under contract with the client to provide project management services for the projects and all sub-trade contactors work under the supervision of the project manager (PCL). The project managers' (PCL) site resources include the tower crane, project superintendent, project coordinator and various site supervisors. The tower crane is the leading resource on the site, which is to say that the completion of critical activities depend on the schedule management of the tower crane. This section will describe the current tower crane management philosophy used by the site superintendents performing project management services.

3.4.1 *Primary Crane Responsibility*

Typically the tower crane focuses on a particular work activity (i.e. one sub-trade activity). which has priority over other activities occurring on the site. For example, the primary responsibility of the tower crane may be erecting structural steel. Based on the steel erection contract. the steel sub-trade contractor has full use of the crane during the standard workday hours and is under no obligation to release the tower crane for use by secondary sub-trades on site.

3.4.2 *Secondary Crane Responsibility*

Optimization of the job schedule requires that the other sub-trades have use of the crane to lift equipment and materials to the various locations on the site. These sub-trades are defined as secondary sub-trades. The project management firm is responsible for managing the crane for all secondary sub-trades on site and will schedule secondary lifts at the following times: before hours, after hours. lunch breaks. coffee breaks, and weekends. Using this system. the crane operator will typically work from 630hrs to 1730hrs (11 hrs/day) on Monday through Friday and approximately 8hrs on Saturday.

3.4.3 *Superintendent requires notice of all secondary lifts*

The rule of thumb for scheduling a secondary lift is to notify the site superintendent 2-3 days in advance of the required lift. If a lift is required right away the superintendent decides if the lift will jump the queue. The superintendent and the primary sub-trade will also work together to allow some high priority secondary lifts to occur during standard workday hours. The site superintendent and foreman, who are in charge of tower crane management, have a global understanding of various activities on the project and the urgency or priority that each activity has on the overall schedule.

3.5 CONCLUSIONS

The purpose of this chapter is to allow the reader to develop an understanding of the day-to-day tower crane management techniques used by site superintendents, which must be considered for the development of the proposed tower crane SPS template. The crane management system outlined requires goodwill and patience by all parties on site. All sub-trades need to be flexible in understanding that their scheduled lift may need to be rescheduled for a lift of higher priority. This means that the primary sub-trade may need to release the tower crane during workday hours allowing for secondary lifts of higher priority to be performed. Critical to the project success, personnel in charge of tower crane management must have an understanding of the priority level of each activity and how it affects the overall project schedule. Cooperation and flexibility between all parties cannot be overemphasized as large commercial projects can have as many as 30 to 60 sub-trades on the site at any given time, who all contribute to the successful completion of the job.

4 DEVELOPMENT OF A SPECIAL PURPOSE SIMULATION (SPS) TOWER CRANE TEMPLATE

4.1 INTRODUCTION

The purpose of this chapter is two fold: 1) to establish a criteria for the SPS tower crane template that introduces a new method of handling simulation modeling process interaction using priority rating logic control; and 2) to develop a SPS tower crane template using priority rating logic control.

The proposed initiative of using special purpose simulation (SPS) computer modeling to perform hook-time analysis on tower cranes was put forward by PCL construction, which owns and operates various tower cranes. AbouRizk and Hajjar (1998) state that SPS can be defined as a "computer-based environment used to enable a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain in a manner where symbolic representations, navigation schemes within the frame work, creation of model specifications, and reporting are completed in a format native to the domain itself." This chapter outlines the development of the proposed SPS tower crane template. Section 4.2 discusses the criteria to be included in the tower crane template and introduces the concept of *priority rating logic* control. Rules and criteria are established where priority rating logic control should be applied. Section 4.3 summarizes the proposed tower crane model, the work element, analytical capabilities and the tower crane SPS template flow chart. Section 4.4 discusses how abstract factors are handled. Section 4.5 describes in detail the purpose of each modeling element in the SPS tower crane template. Section 4.6 concludes by discussing the purpose and objectives of the SPS tower crane template.

4.2 SPS TOWER CRANE TEMPLATE CRITERIA

4.2.1 Priority Rating Logic Control

Priority rating logic process interaction is defined by an event or activity that is processed based on scheduled arrival time and event priority setting. The use of priority rating logic control is an alternative method of handling model process interaction for computer simulation. Priority rating logic applies the use of prioritized work tasks/events with object-oriented simulation and Special Purpose Simulation (SPS) concepts. The result is a valuable modeling approach that can be used for a specified group of construction domains. Priority rating logic control should be considered when simulating the operations of a leading resource on a construction site. It is important to note that using the priority rating logic approach for computer simulation model process interaction does not replace the use of relationship logic links, but provides an alternate approach for simulation development that can be used for the modeling of a leading resource. For example construction domains that have a repetitive sequence of activities, logic represented by relationship logic links are very successful (i.e. earthmoving, tunneling, etc.). The problem with using relationship logic links when modeling a leading resource such as a tower crane operation is the complex logic relationships that result.

When simulation a leading resource for a specified construction domain, the use of priority rating logic control simplifies simulation model development and use by industry practitioners. The use of priority rating logic control is a valuable tool that should be considered when the following conditions are present:

1. Modeling a key resource that dramatically affects the other processes in the construction operation.
2. High number of trades competing for a key resource.
3. Functions of the key resource are repetitive.

For tower crane operations, each activity occurring in the modeled system does not follow a distinct repetitive process flow, but rather consists of a number of distinct activities that move linearly through the crane model. Each tower crane activity is performed based on urgency and demand within the modeled system. As the number of lifting activities increases for the tower crane, the model complexity using traditional relationship logic links becomes unmanageable resulting in limited implementation by industry practitioners. The proposed tower crane template lift sequencing will be established using *priority rating logic control.* This means that for each lift selected, the tower crane will choose the lifting activity with the highest priority that is currently available in the model. The use of priority rating logic control verses traditional relationship logic links simplifies the tower crane-modeling domain. By replacing relationship logic links with priority rating control during the development of the SPS tower crane template the, following benefits are achieved:

1. Establishes a modeling environment that is easy to create and manipulate by a novice practitioner,
2. Reduces development time for new tower crane construction models, and
3. Prevents the tower crane models from escalating in complexity as the number of lifting activities increase.

4.2.2 Geographical Layout and Movements

Each model will perform movement calculations based on the model footprint, which is constructed using crane, source, and destination elements. *Work Elements* are to be created inside the source element (source child level), which specifies the origin of each work package lift. Knowing the location of each element, the simulation model will calculate the following movement delays for each lift: (1) last lift destination to new Work Element source location, and (2) existing Work Package source to assigned destination for each lift. Each lift delay is based on a combination of hoisting, radial, and/or horizontal movements.

4.3 PROPOSED TOWER CRANE SIMULATION MODEL

In the PCL time study (1988) a time-lapse video was used to monitor tower crane activities (formwork, steel erection, column erection, etc.). The time-lapse videos were monitored to quantify productivity rates that could be used for planning and scheduling future tower crane activities under similar conditions (PCL 1998). Using the proposed

SPS tower crane template, the user can produce productivity standards for various tower crane activities. The proposed SPS template can also be used to quantify risk associated with variation due to radial speed, hoisting speed, horizontal speed, and hookup/unhook delay times.

Using *Simphony*, developed by Hajjar and AbouRizk (1999), a special purpose simulation (SPS) template using priority rating logic control has been created to model short durations in the tower crane schedule (1 day – 1 month) in order to optimize the tower crane production cycle and day-to-day management techniques. The tower crane template schedules lifts based on the geographical locations of the crane, source, and destination elements and by using Work Elements that represent a set of lifts for a particular activity. Each Work Element is broken down into separate entities called Work Packages (WP), which represent a set of uninterrupted lifts to be performed by the tower crane. The Work Element' has the following attributes: Work Element Description, Quantity of WP, WP Arrival Time, Time Between WP Arrivals, Number of Lifts per WP, WP Priority Rating (1-5), Assigned Crane, and Assigned Destination. Based on the work element priority rating and crane availability, the designated crane will select and perform a specified WP. The input parameters and functions of each element contained in the SPS tower crane template will be discussed in detail in the subsequent sections. Using this approach, the SPS template analyzes the tower crane production cycle to optimize crane utilization, crane lift schedule, work prioritization, and crane location. The following points describe in detail the analytical capabilities of the SPS tower crane template.

1. *Crane Utilization Check.* For a critical portion of the schedule, the crane production cycle can be modeled, yielding the overall crane utilization. Using lift priority settings, crane location, and arrival times, the crane utilization can be analyzed.

2. *Production System Sensitivity Analysis.* Alterations to the model can be used to help the practitioner understand the sensitivity of the specified production system.

3. *Hook Time Analysis.* By isolating a specific lifting activity, the SPS tower crane template can be used to help the practitioner better understand a specific lifting activity in order to improve system efficiency. For example, modeling the removal of 'Fly Forms' on a commercial building project in order to yield the crane hours allotted to formwork.

4. *Scenario Analysis.* When modeling the tower crane production cycle, the practitioner can experiment with different scenarios. Each scenario provides a simple, efficient and simple and cost-effective method of reducing waste in the modeled system.

Figure 4-1 is a flow chart describing in detail the logic that is followed by the SPS tower crane template while modeling tower crane operations.

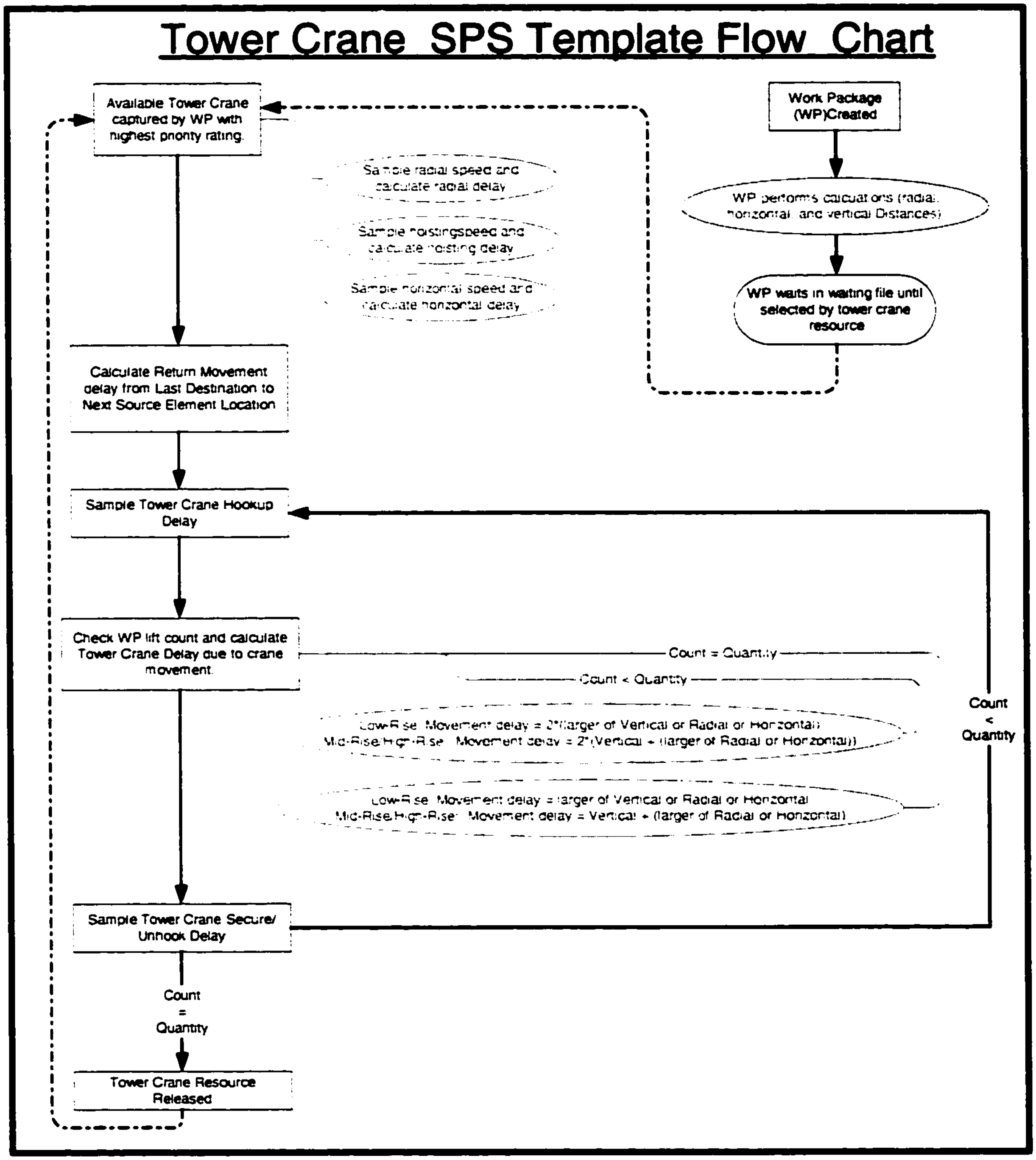


Figure 4-1 SPS Tower Crane Flow Chart

As illustrated above, the model consists of Work Packages (WP) that are competing for the tower crane resource in order to be completed. Each WP is created at a source location and has a designated tower crane, destination location, and priority setting. At WP creation the radial, horizontal, and vertical distances are calculated that will be traveled when selected by the tower crane. Next, the WP is queued in a waiting file until the tower crane resource is available. When the tower crane resource becomes available it selects a WP from the waiting file that has the highest priority rating (1-low, 5-high). At WP capture, the crane samples speeds that will be applied to the radial, horizontal, and vertical distances that were pre-calculated when the WP was created. The following steps describe the movement delays that are performed for each WP:

1. Tower crane selects WP from waiting file with highest priority rating.
2. Tower crane moves from the last destination location to the source location of the captured WP.
3. Delay assigned for WP lift hookup time.
4. The count (number of lifts performed) is compared to the quantity of lifts required to complete the WP.
    a. If Count < Quantity. Crane takes 1 lift to the designated destination and then returns to source location.
    b. If Count = Quantity. Tower crane takes the final lift to designated destination and waits.
5. Delay assigned for WP lift unhook/secure time.
6. If Count < Quantity, return to (3). If Count = Quantity, go to (7).

7. Tower crane resource is released. WP is completed.
8. If WP(s) located in waiting file, go to (1).
9. Finished Simulation

4.3.1 Assumptions and Limitations

During the development of the SPS Tower crane template, the following assumptions and limitations of the proposed template are identified.

<u>Assumptions</u>

- Tower crane movement speeds are the same for both loaded and return WP movements.
- The tower crane does not use its high gear for hoisting.
- WP quantities, hookup/unhook times, arrival time, and time between arrivals can be entered as distributions.
- Tower crane is not relocated during the modeled period.

<u>Limitations</u>

- WP priority ratings are set as integer values.
- User must manually transfer tower crane, source and destination locations from the drawings.
- Only Constant, Uniform, Triangular, Normal, Exponential and Beta type distributions can be entered.
- Each WP Element can only be transported once (source to destination).

4.4 ACCOUNTING FOR ABSTRACT FACTORS USING SPS

According to AbouRizk and Hajjar (1998), "the use of special purpose simulation tools can provide a 'happy medium' between the need for accurate modeling and the desire for reduced levels of effort and complexity." Rather than develop a general-purpose simulation framework requiring high degrees of abstraction, it was found to be more effective to develop SPS tools that solve the entire problem at hand, thus enabling the SPS template to be adopted as an effective tool by the end user (AbouRizk and Hajjar 1998).

By creating SPS template elements that provide flexibility and are simple to use, the end user can manipulate the elements to represent abstract factors that are essential to the accuracy of the modeled system. An example of this would be the implementation of learning curve effects for repetitive lifts in the construction process. To accomplish this the user can separate a work element into two parts: the first element with hookup/unhooking productivities reflecting the slower rates experienced as a result of learning curve effects, and the second element reflecting the post learning curve hookup/unhooking productivities for the remainder of the work package activities.

4.5 SPS TOWER CRANE MODELING ELEMENTS AND FUNCTIONS

This section will describe in detail each modeling element along with its function in the SPS tower crane template. Figure 4-2 illustrates the five elements from the SPS tower crane template used to create a construction model layout. Elements containing general-purpose elements at the child level must be selected from the *User Element Library*. The remaining elements can be selected from the *Modeling Elements Toolbox*. An introduction to general-purpose constructs and the user elements library using the Simphony environment can be found in Mohamed and AbouRizk (2001). The following lists the SPS tower crane template elements and their origins.

<u>Created From Modeling Elements Toolbox</u>

1. Parent Element
2. Source Element
3. Destination Element

<u>Created From User Elements Library</u>

4. Tower Crane Element
5. Work Element

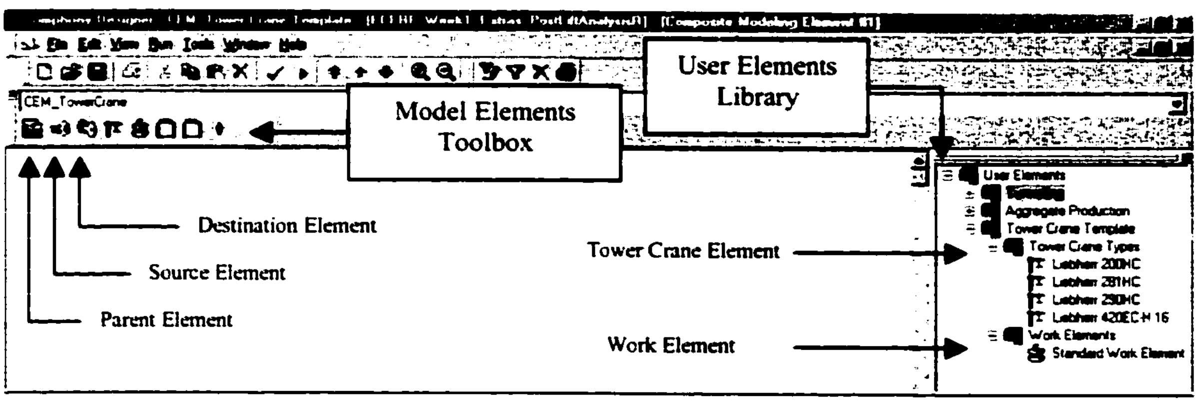


Figure 4-2 Tower Crane Template Elements

4.5.1 Parent Element

The parent element is used to access the tower crane model layout, enter input parameters, and access global statistics that affect the model as a whole. As shown in Figure 4-3, when the parent element child level is opened an axis is created at the origin of the window indicating a reference point for all subsequent element locations.

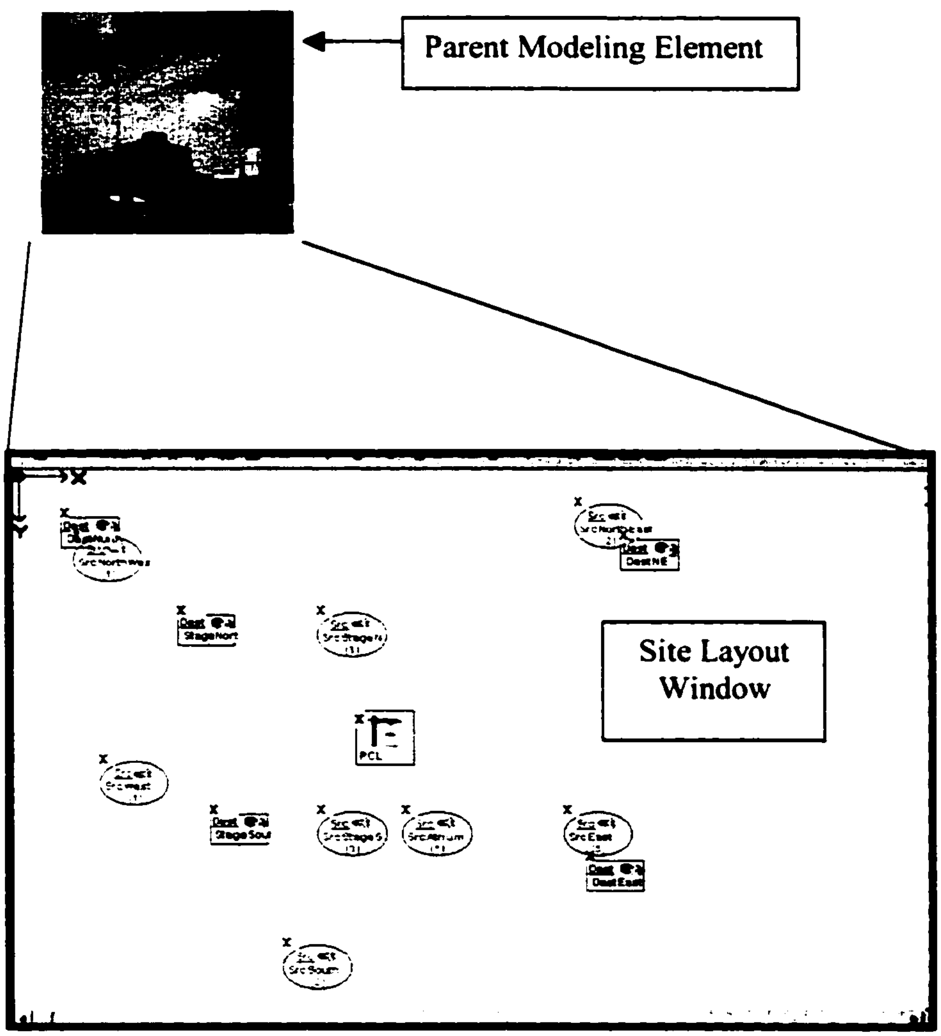


Figure 4-3 Parent Element and Model Layout

The attributes of the parent element include the scale to be used for the site layout window (i.e. footprint), the number of working hours per working day, and the building type classification. The statistics available for review are the total duration in working days and working hours for the specified model. The function of model statistics is to show the duration needed to perform a specified number of WP contained in the model and to allow the project manager to alter the layout, priority setting, or schedule in order to optimize the model.

As illustrated in Figure 4-4, the user must specify the building type as either a low-rise, mid-rise, or high-rise building type. The time delay for a low-rise building is equal to the single largest duration associated with the hoisting, radial, or horizontal movement. For a mid-rise or high-rise building the tower crane must clear the building envelope which results in a time delay equal to the hoisting delay plus the largest duration associated with the radial or horizontal movement.

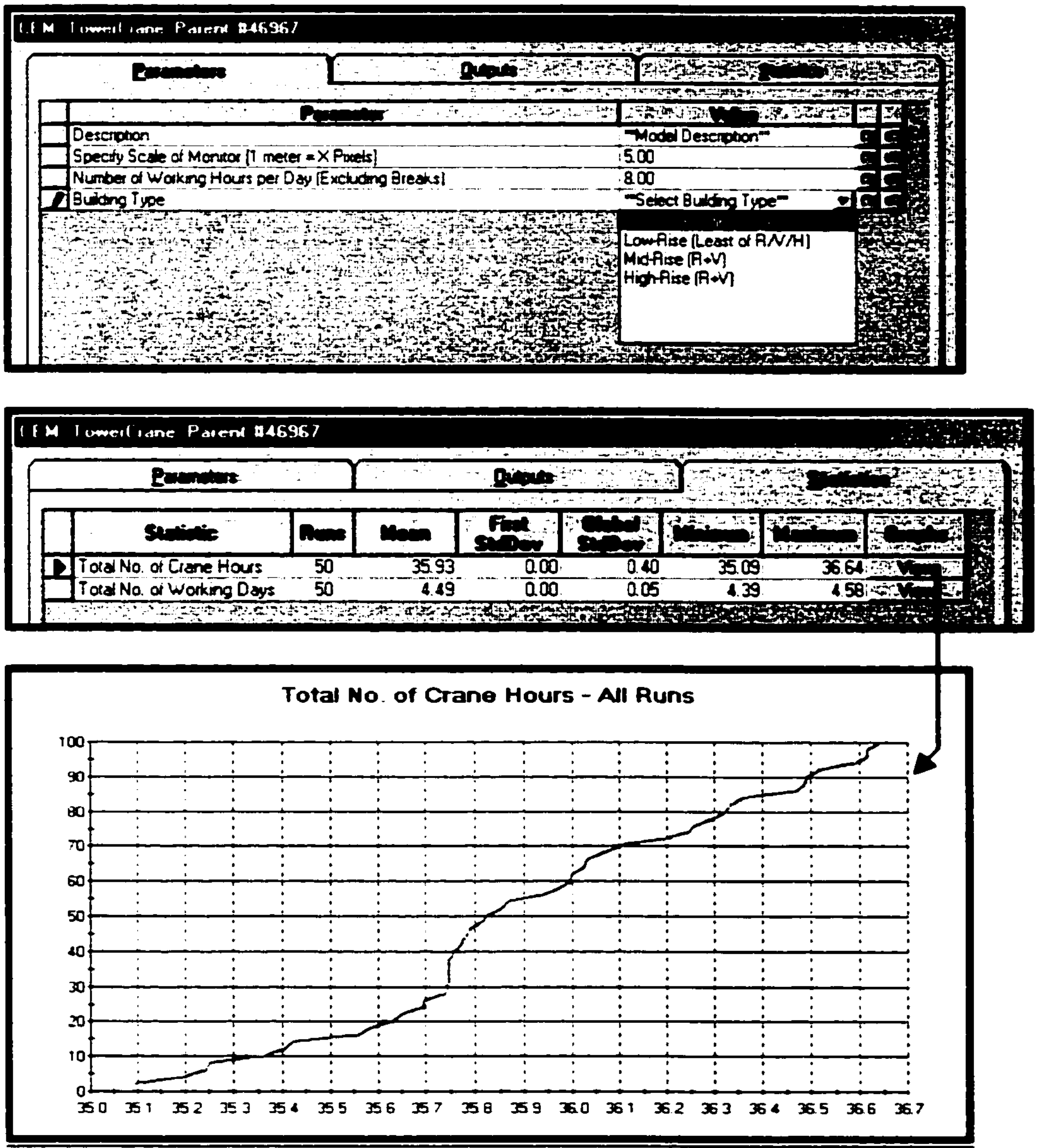


Figure 4-4 Tower Crane Parent Element (parameters, statistics, graphs)

4.5.2 Source Element

The source element is used to represent the geographic location where the tower crane lifts originate on the construction site. When the source element is created in the layout window, the user must enter the source description, x-coordinate, and y-coordinate as input parameters. The coordinates of the source element are used to calculate radial, vertical, and horizontal delays. Figure 4-5 illustrates the number of work elements created in the source child window as displayed on the source element icon.

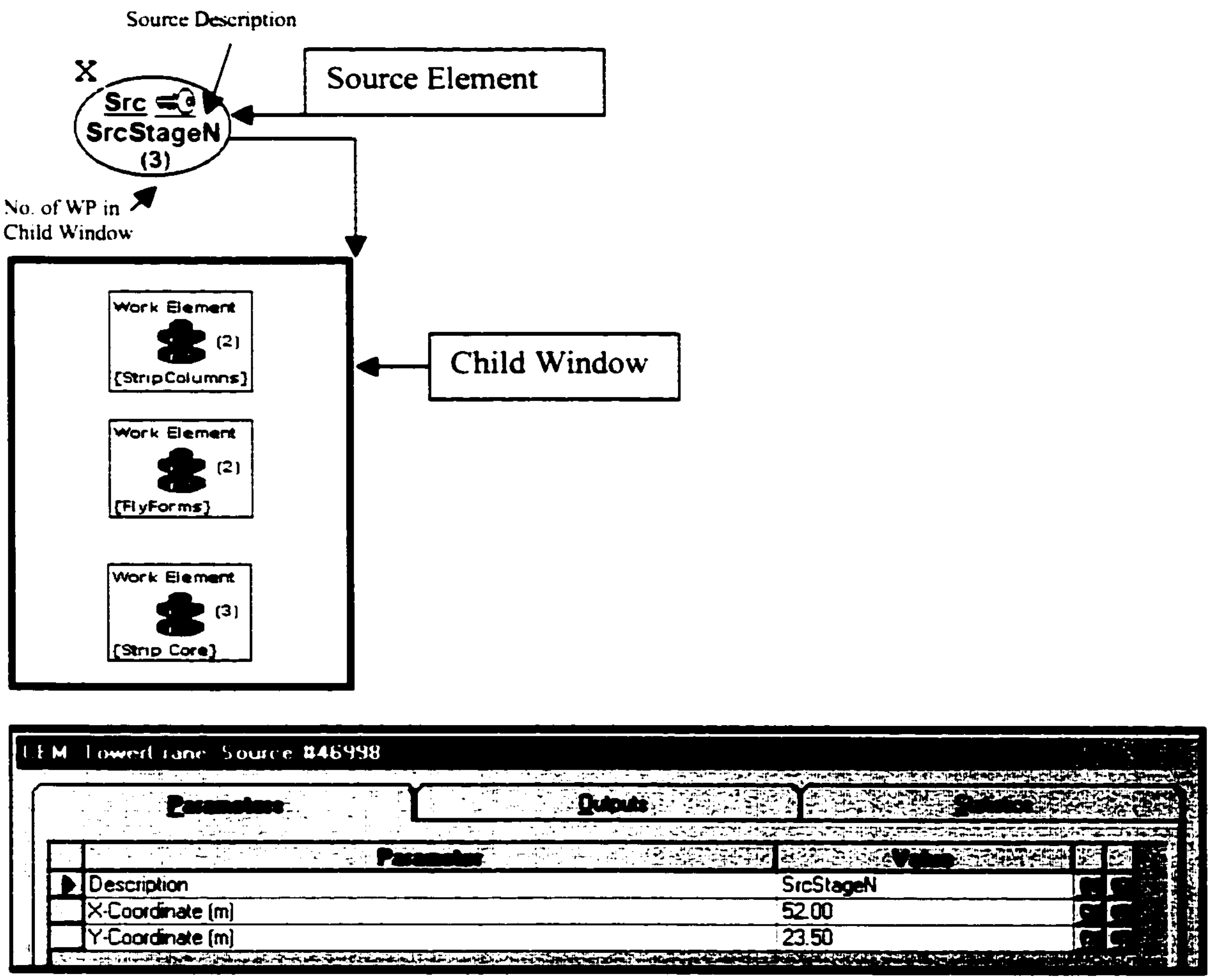


Figure 4-5 Source Element (input parameters, child window)

4.5.3 Destination Element

The destination element is used to represent the geographic location where the tower crane completes each lift for a given work package. When the destination element is created in the model window, the user can enter the description, x-coordinate, and y-coordinate as input parameters for the element (see Figure 4-6). The coordinates of the destination element are used to calculate radial, vertical, and horizontal delays. When the delay for each lift is calculated, the model recognizes whether a lift is the last for a particular work package. If it is the final lift, the crane will find the next source location and calculate the delay based on the required movement.

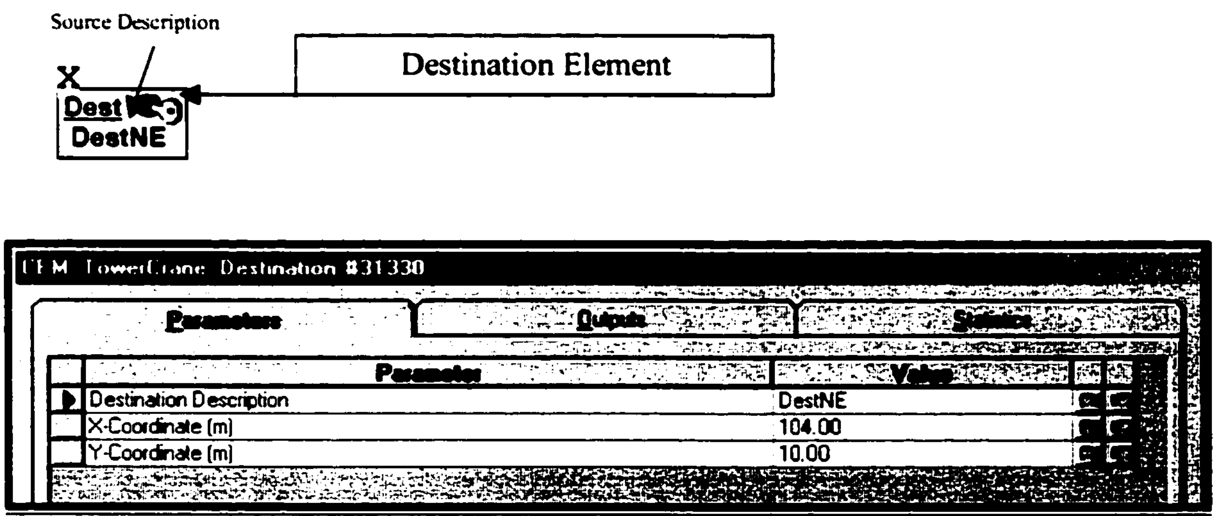


Figure 4-6 Destination Element (input parameters)

4.5.4 Tower Crane Element

One or more tower crane elements can be created in the simulation model. Since the specifications for each tower crane is typically not easily accessible, a library of cranes that are frequently used are stored in the User Element Library, as shown in Figure 4-7. Each tower crane selected from the user element library specifies the crane's maximum reach, rotation speed, hoisting speed, and horizontal speed. After a tower crane element has been selected from the user element library, the user must input a crane name (to be used for work element parameters), x-coordinate, and y-coordinate for each crane element. The coordinates of the tower crane element along with the source and destination coordinates for a given work element are used to calculate radial, vertical, and horizontal delays.

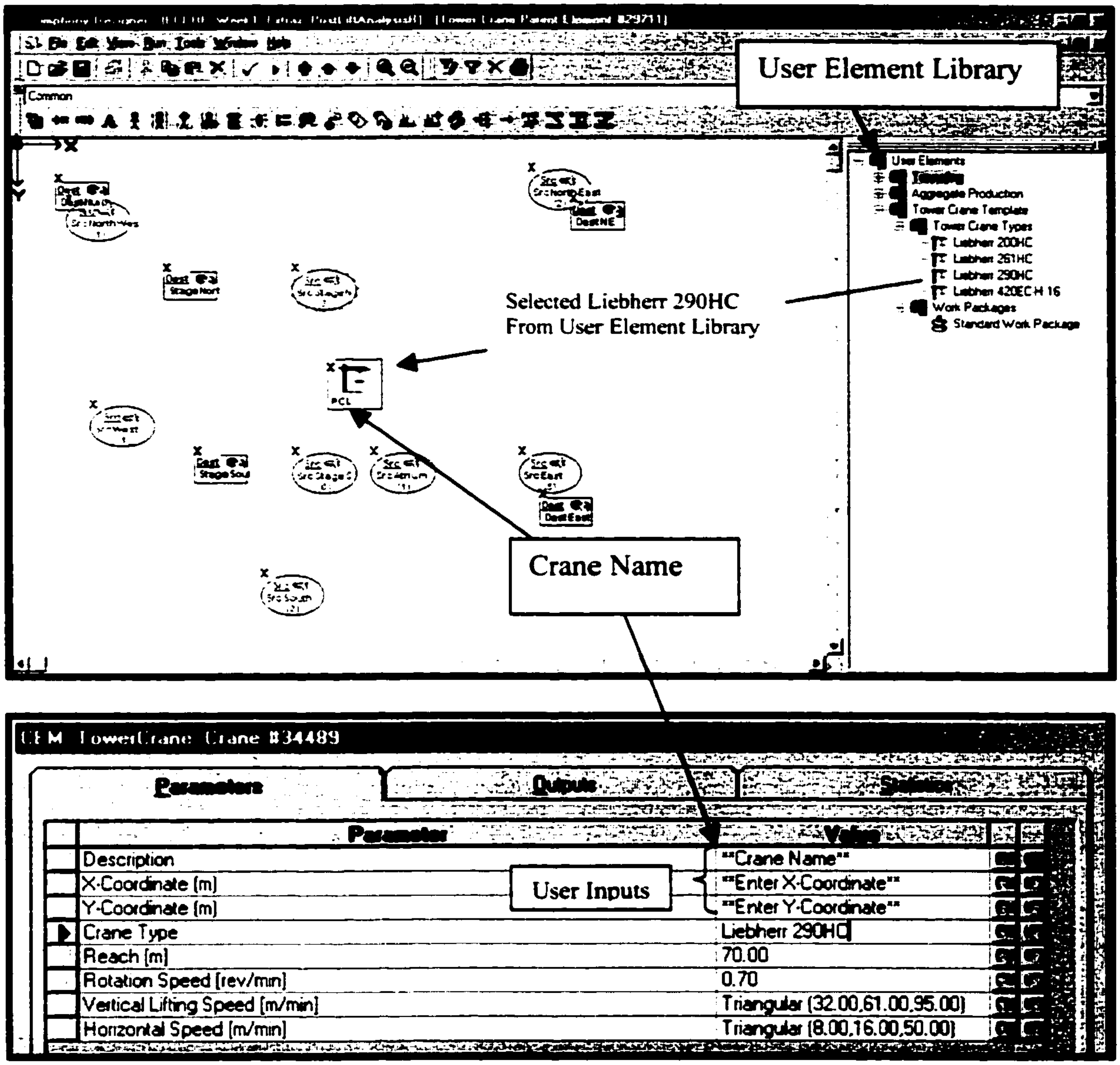


Figure 4-7 Tower Crane Element (user element library, parameters)

The tower crane element provides the user with statistical information regarding the utilization of the crane resource, which is used for system decision support. Figure 4-8 illustrates how the tower crane resource utilization is accessed.

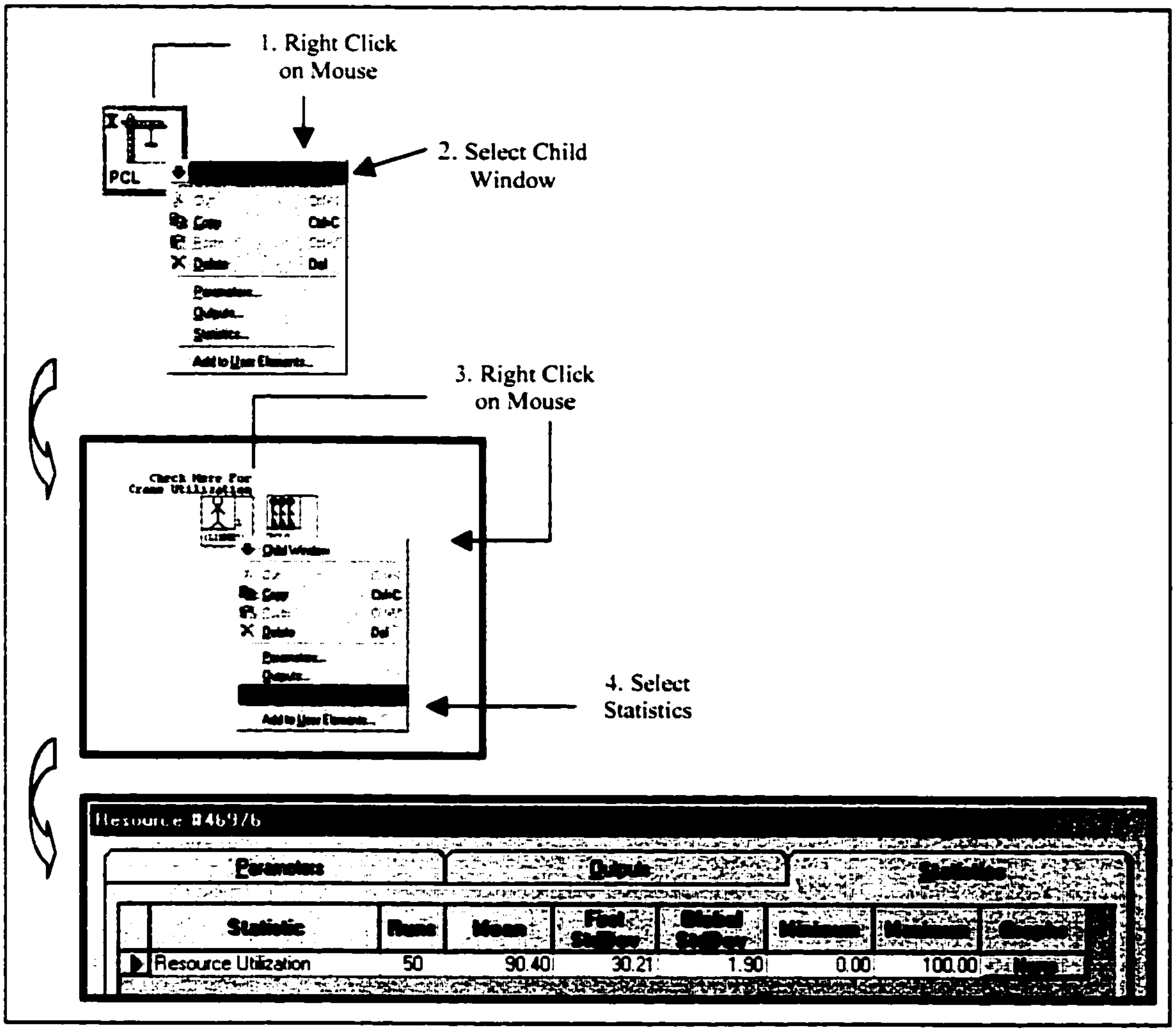


Figure 4-8 Tower Crane Resource Utilization Statistics

4.5.5 Work Element

The work element drives simulation in the SPS tower crane template. Figure 4-9, illustrates the lower level elements constructed using the Simphony general-purpose template known as common elements. The common elements are used to create entities, capture resources, calculate delays, and record statistics for the model. The advantage of using common elements for modeling, rather than programming code, is to enable a practitioner with background in simulation techniques greater flexibility when adjusting simulation events and processes (Mohamed and AbouRizk 2001). Using the SPS tower crane template the user, isolated from the low level constructs, is presented with a modeling interface that more closely represents the actual system.

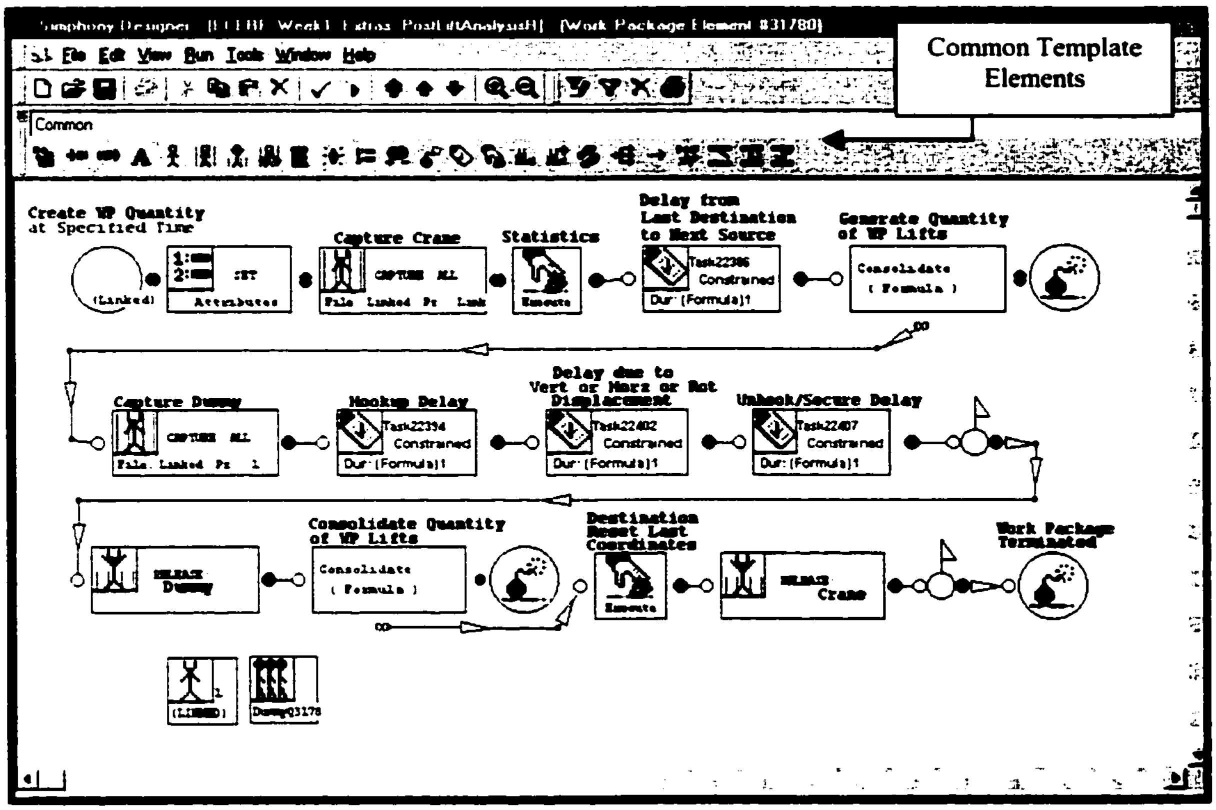


Figure 4-9 Work Element Child Window (simulation with common template elements)

Each work element contains one or more Work Packages (WP) representing a set of lifts to be performed without interruption by the specified crane resource. Each WP lift experiences time delays due to: hookup, securing, vertical distance, crane location, and destination location. For a detailed introduction to the work element parameters refer to Table 4-1. Figure 4-10 illustrates the work element icon and parameters as displayed in Simphony.

As discussed earlier, work elements drive simulation through the implementation of *priority rating logic* control for model process interaction. Priority rating logic control means each lift activity has a scheduled arrival time and a set priority, based on activity criticality in relation to the other existing activities in the system. Using this method, the process interaction logic represented by traditional relationship logic links is replaced with specific arrival times and priority ratings that control activity logic and performance.

Table 4-1 Work Element Parameter Description Summary

Work Element Parameters	Comments
Description	Description displayed on work element. Used to provide easy identification of work element type.
Lift Type	Used to define work element lift type category when placed in User Elements Library.
Quantity of Work Packages	This feature specifies the number of WP with similar parameters thereby reducing the number of required work elements to be created by user. Each time a WP is completed the crane is released at which time the next WP of highest priority is selected.
Time of First WP Arrival (Simtime in hours)	Specifies the arrival time for the first WP of a given work element.
Time Between WP Arrivals (min)	This feature is used if the user has indicated a 'Quantity of Work Packages' greater then one. The 'Time Between WP Arrivals' represents the time lapse before a WP re-occurs. An example of this is concrete delivery where, five trucks deliver concrete, *trucks arrive every 20-30 minutes* and each truck fills 4-5 crane buckets.
Number of Crane Lifts per WP	Represents the number of lifts to complete a WP. When a WP is selected by a crane resource, the resource is not released until all lifts are completed.
Priority of Work Task	Each work element is given a rating between one and five, where a rating of five represents high priority. Each time the crane resource is released it looks for the next available WP with the highest priority rating.
Time Required to Hookup (min)	The duration in minutes expected to hookup lift to the crane.
Time Required to Secure and Unhook (min)	The duration in minutes expected to secure/unhook lift to the crane.
Vertical Lift Distance (m)	The elevation change from lift source to destination. Used to calculate delay associated with hoisting for each lift.
Crane Selection	Specifies the crane resource to perform WP from list of created crane modeling elements in model layaout.
Destination	Specifies the WP destination from list of created destination modeling elements in model layout.

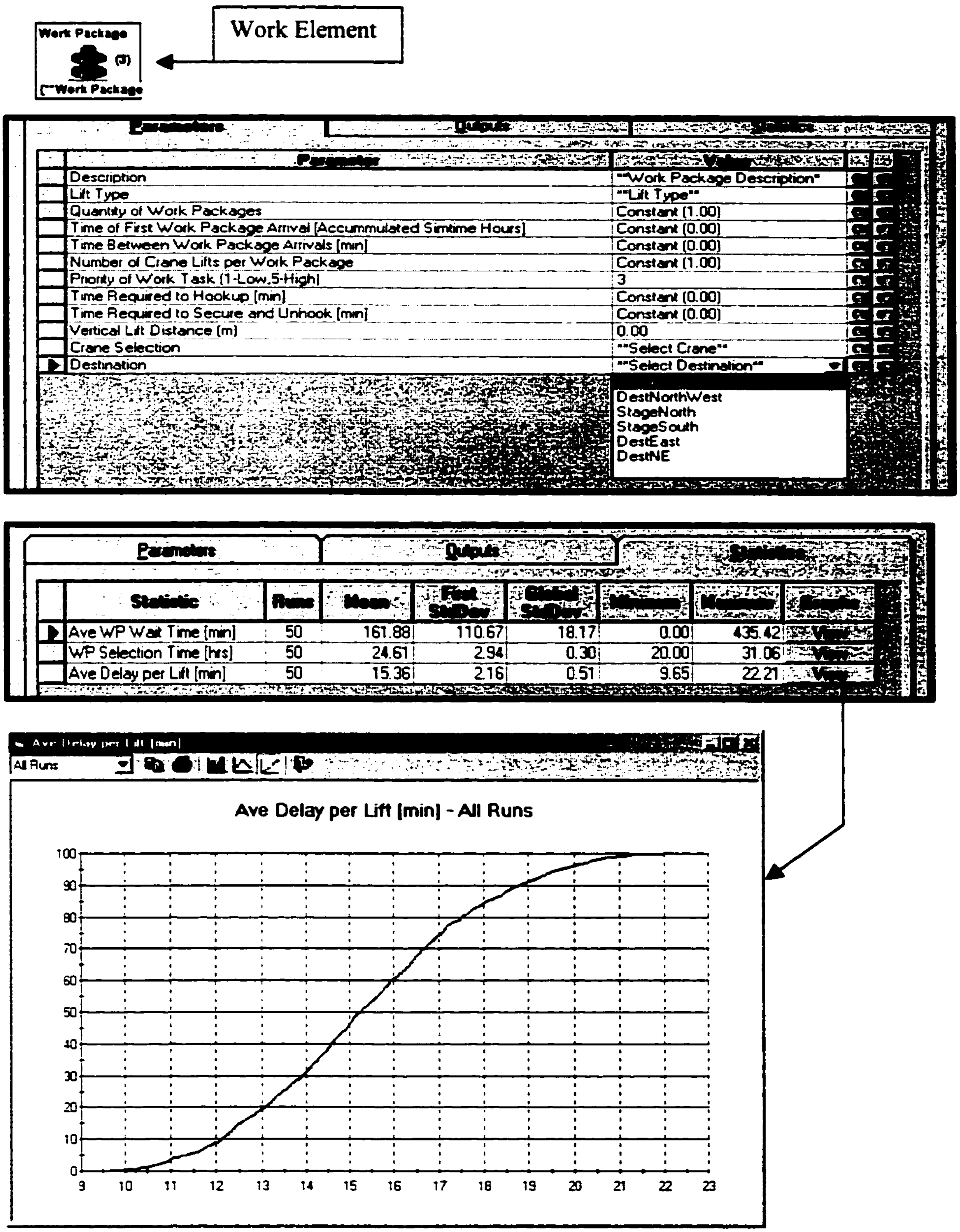


Figure 4-10 Work Element (parameters, statistics, graph)

4.6 CONCLUSIONS

The SPS tower crane template outlined in this chapter has been developed in conjunction with PCL construction to consider tower crane hook-time analysis and day-to-day management operations. Traditional computer simulation modeling techniques use relationship logic links to represent the logic contained in the modeled system. As the number of work tasks increases for the tower crane, the model complexity using traditional simulation techniques becomes unmanageable, resulting in limited acceptance by industry practitioners. To overcome this problem the SPS tower crane template introduces priority rating logic control. When simulation a leading resource for a specified construction domain, the use of priority rating logic control simplifies simulation model development and use by industry practitioners. The use of priority rating logic control is a valuable tool that should be considered when the following conditions are present:

1. Modeling a key resource that dramatically affects the other processes in the construction operation.
2. High number of trades competing for a key resource.
3. Functions of the key resource are repetitive.

The SPS tower crane template administers the priority rating logic concept by using prioritized Work Package (WP) elements representing each activity being performed by the tower crane (i.e. formwork, concrete placement, rebar delivery, etc.). Each work element specifies the quantity of WP, arrival time of first WP, time between WP arrivals, number of crane lifts per WP, WP priority rating, desired crane, and desired destination locations. This simulation approach simplifies tower crane modeling techniques to be implemented by the industry practitioner.

The design and development of the SPS tower crane template has been presented for the analysis of tower crane construction management. The graphical design of the modeling elements depicts the construction layout, allowing an expert end user in construction, not familiar with simulation, to create a model with ease (Ruwanpura 2001). The SPS tower crane template analyzes the crane production cycle to optimize crane utilization, crane lift schedule, work prioritization, and crane location. The following points describe in detail the analytical capabilities of the SPS tower crane template.

1. *Crane Utilization Check.* For a critical portion of the schedule, the crane production cycle can be modeled, yielding the overall crane utilization. Using lift priority settings, crane location, and arrival times, the crane utilization can be analyzed.

2. *Production System Sensitivity Analysis.* Alterations to the model can be used to help the practitioner understand the sensitivity of the specified production system.

3. *Hook Time Analysis.* By isolating a specific lifting activity, the SPS tower crane template can be used to help the practitioner better understand a specific lifting activity in order to improve system efficiency. For example, modeling the removal of 'Fly Forms' on a commercial building project in order to yield the crane hours allotted to formwork.

4. *Scenario Analysis.* When modeling the tower crane production cycle, the practitioner can experiment with different scenarios. Each scenario provides a simple, efficient, and cost-effective method of reducing waste in the modeled system.

Through the development of the SPS tower crane template using Simphony and the priority rating logic approach, a tower crane construction scenario can be easily modeled to represent a real situation. Priority rating logic control specifies that lift activity arrival times and priority ratings dictate tower crane lift selection. The use of priority rating logic control verses traditional relationship logic links simplifies the tower crane modeling domain, which results in the following advantages:

1. Establishes a modeling environment that is easy to create and manipulate by a novice practitioner,
2. Reduces development time for new tower crane construction models, and
3. Prevents the tower crane models from escalating in complexity as the number of lifting activities increase.

By using distribution data received from historical information, observed field data, and industry experts, each simulation run represents the completion of the model layout based on varying site conditions. Simulation gives the user an accurate picture of the amount of risk associated with the project as a whole based on the variability/risk associated with each modeling element.

5 VALIDATION OF SPS TOWER CRANE TEMPLATE USING PRIORITY RATING LOGIC CONTROL

5.1 INTRODUCTION

The purpose of this chapter is to compare two modeling methods and verify that priority rating logic control is a viable replacement for the relationship logic links used by traditional object-oriented simulation techniques. To do this, a generic project will be used as a case study to illustrate the merit in using priority rating logic control for simulating tower crane operations. Section 5.2 introduces the Electrical and Computer Engineering Research Facility (ECERF) constructed on the University of Alberta campus. Using the ECERF project as a case study, two models are developed using Simphony's common and SPS tower crane templates. The benefits of using the priority rating logic control for the SPS tower crane template will be discussed based on the results of the case study.

5.2 CASE STUDY: ELECTRICAL AND COMPUTER ENGINEERING RESEARCH FACILITY (ECERF)

The Electrical and Computer Engineering Research Facility (ECERF) is a seven-storey building constructed on the University of Alberta campus. The ECERF building is the first phase of a two-phase project. The building will house offices for professors and graduate students, and state-of-the-art research laboratories. There is one crane located east of the ECERF structure. PCL is the contractor in charge of site supervision and concrete formwork construction for the erection of the sub/superstructure for the ECERF building. The primary tower crane activity on site is concrete formwork, using a slab fly-form system. The only secondary sub-trade on site is the rebar contractor.

The construction of each floor for the ECERF building is done in two stages. Each stage takes two weeks to complete and occupies approximately half of the floor layout (typical floors 2-7). On any given week the crane is performing lift activities on both stage locations. Table 5-1 outlines the tower crane production cycle over a five-day (1 week) period, and the tower crane activities associated with each stage. As illustrated in Table 5-1, stage 1 work consists of slab rebar and concrete work while stage 2 work consists of column and core work, as well as the relocation of slab fly-forms. In the proceeding weeks, the tower crane production cycle is unchanged as the work simply progresses through each stage. For the purposes of this case study, the computer simulation will model a one-week period representing the production cycle for the tower crane.

Table 5-1 ECERF Tower Crane Production Cycle

ECERF Building Tower Crane Production Cycle		
	Stage 1 - Week One(South) (21m elevation)	**Stage 2 - Week Two(North) (21m elevation)**
Monday	Rebar Delivery (4-5,7:30AM,45-80min,1lift,25-40min,4) [From SrcEast]	Set Rebar in Column Forms (18-22,7:30AM,0,1lift,4-5min,3) [From SrcWest] Pour Column Forms (2trucks,12:30PM,40-50min,4buckets,9-12min,3) [SrcSouth] Fly Core Forms (7-8pcs,2:30PM,6-7min,1lift,10-12min,3) [From SrcNorthEast]
Tuesday	Rebar Delivery (3-4,7:30AM,1-2hrs,1lift,25-40min,4) [From SrcEast]	Rebar to Cores (4,7:30AM,20,1lift,25-35min,3) [From SrcEast] Close Core Forms (7-8pcs,1:30PM,0.0,1lift,10-12min,2) [From SrcNorthEast] Strip Column Forms (18-22,2:30PM,3-4min,1lift,3-4min,2) [To NorthWest Corner]
Wednesday	Rebar Delivery (1-2,9:00AM,1.5-3hrs,1lift,25-40min,4) [From SrcEast]	Pour Core (4-5trucks,8:30AM,15-20min,4-5buckets,4.5-7min,3) [From SrcSouth] Fly Slab Forms (28?forms,12:30PM,8-9min,1lift,Tri[9,14,21]min,2) [Floor to Floor]
Thursday	****Pour Slabs - No Crane Activity****	Strip Core Formwork (14-16pcs,11:00AM,4.5-5.5min,1lift,4-5min,3) [ToNorthEastCorner]
Friday	Fly Column Forms (18-22,7:30-830AM,8-12min,1lift,6-12min,3) [From SrcNorthWest]	
Work Package Descripton (*No. of WorkPackages,Time of First WP, Time between WP, No. Lifts per WP, Duration of Lift,Priority*) [From/To]		

Figure 5-1 shows the east face view of the ECERF building at the completion of the concrete superstructure. Figure 5-2 shows the west face of the ECERF structure while the concrete slab is curing for stage two of the fifth floor. Figure 5-3 shows the slab fly forms as they are being released from the slab. Placement, preparation, and removal of slab fly forms are the primary activities occurring during the tower crane production cycle. Using the jacking device, as shown in figure 5-4, the legs of the fly-form are unloaded and lowered from the underside of the slab. The legs of the slab fly-form are then raised and rollers are placed to transport the form to the edge of the building for tower crane access.

Figure 5-1 East View of Electrical and Computer Engineering Research Facility (ECERF)

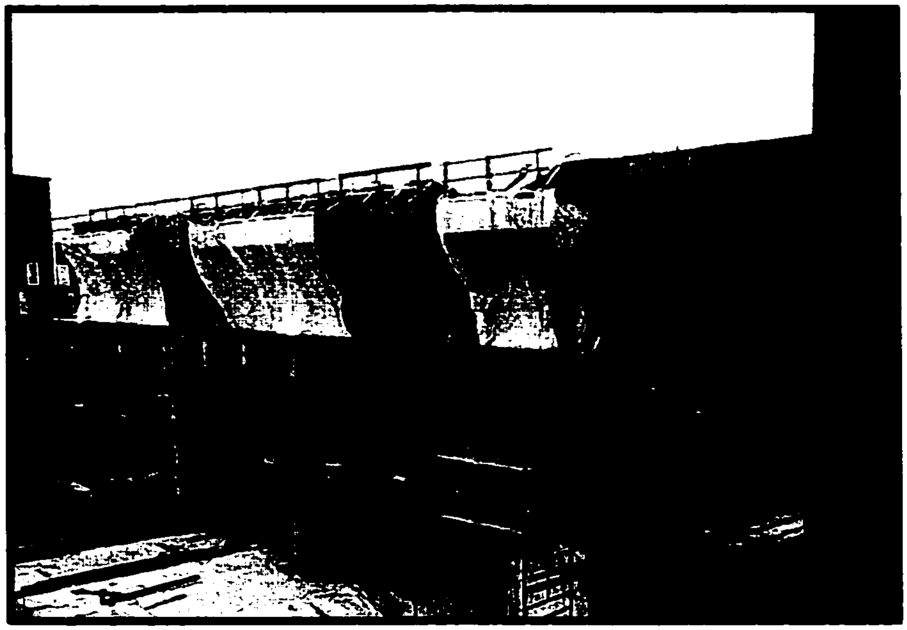


Figure 5-2 ECERF Building Concrete Slab Construction

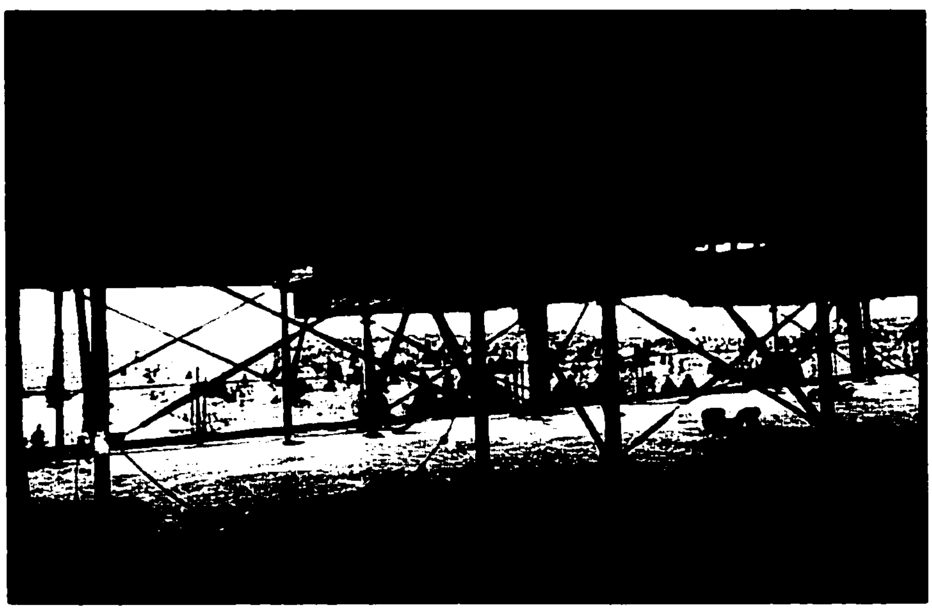


Figure 5-3 Slab Fly Forms Used For ECERF Building Floor Construction

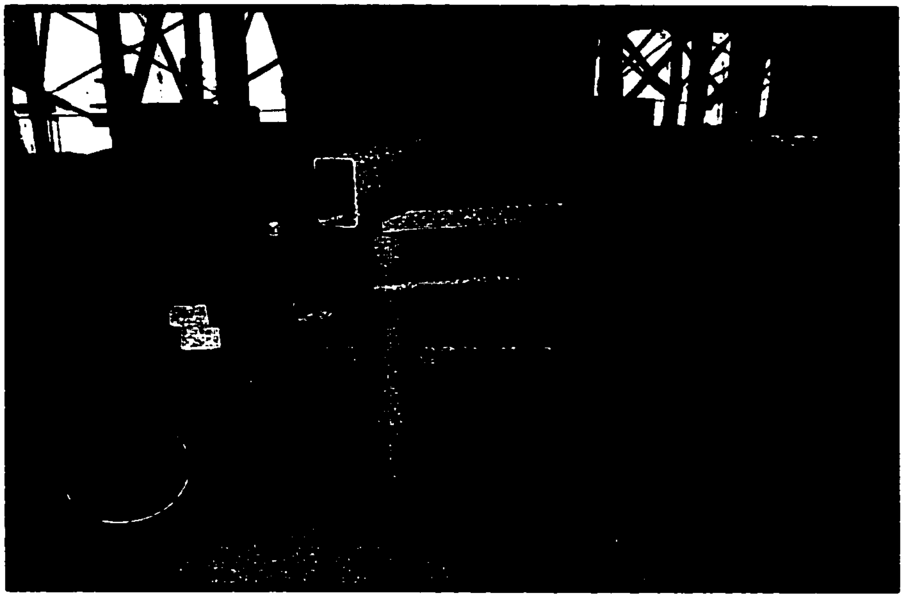


Figure 5-4 Portable Jack Used for Slab Fly Form Transport

5.2.1 Data Collection

Data collection for the ECERF case study is received from two sources: observed field data and expert experience. Field data is an important tool used to quantify activity durations and interaction for a given construction domain. Expert experience data is received from industry practitioners who have extensive field experience. Often, expert data is more reliable for simulation model input as it is reflective of the numerous conditions that can randomly occur on a construction site. Observed field data is only representative of site conditions that have occurred during the observed period. In all cases, the field data is used to confirm information received from industry experts.

Before commencing the development phase of the SPS tower crane template, the tower crane activities at the ECERF construction site were monitored for a 7-month period from April to November, 2000. This time was used to develop a greater understanding of the tower crane schedule, activity prioritization and selection schemes, delays, and activity hook-times. Much of the information regarding activity prioritization and selection schemes was received from the project superintendent and coordinator, who oversaw the day-to-day management of the tower crane. Other information was received from site visits to the University of Alberta Hospital Expansion Project and the Northern Alberta Institute of Technology (NAIT) Information and Communications Technology Centre (ICTC), as well as several meetings with the chief engineer and the manager of purchasing and equipment at PCL Constructors Inc.

Observed field data is divided into two categories: "All Activities" and "Slab Fly-Form Removal." For "All Activities," the crane is monitored for 1 to 2 hour intervals to gain a better understanding of the tower crane selection process and the durations associated with each lift activity. "Slab Fly-Form Removal" data records the cycle time for each slab fly-form lift, which is a complex activity that includes a number of sub-tasks (see Figure 5-6). For each lift cycle, the following detailed information is recorded:

A. Turning radius in degrees,

B. Connect time,

C. Release time,

D. Calculated transport time and travel time,

E. Description of lift activity, and

F. Grid line location.

Figures 5-5 and 5-6 illustrate sample field data sheets used to monitor the tower crane activities for "All Activities" and "Slab Fly-Form Removal" respectively. For detailed field data information, see Appendix A.

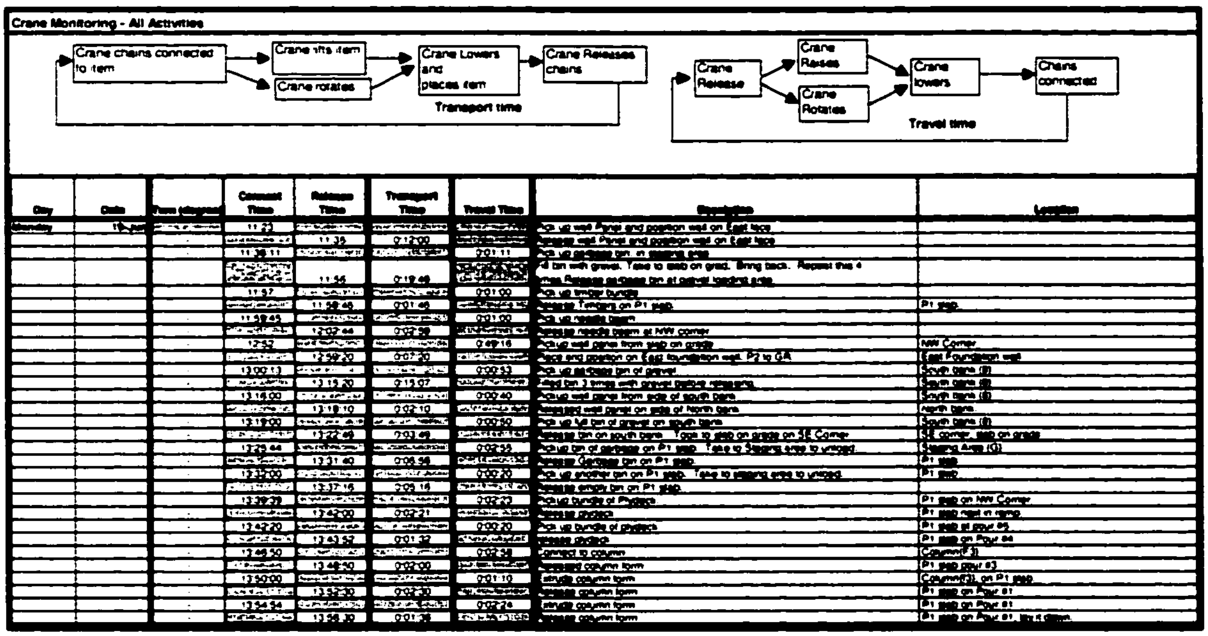
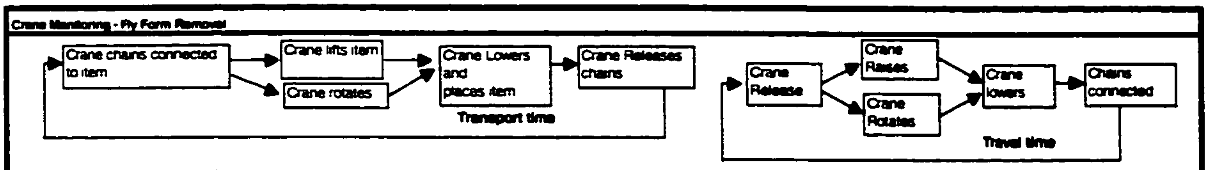


Figure 5-5 Sample Field Data Sheet - All Activities



Fly Form Removal Notes
1 Crane connects 2 chains on end of form just protruding from lower floor of building.
2 Pull fly form straight out so two legs are suspended in mid air while remaining two legs remain on floor
3 Guy gets of Fly form supported by Crane and floor to connect remaining chain to crane with a chain slack adjuster tool.
4 After chain length are altered Fly form completely move off floor and transported.

Day	Date	Turn (degrees)	Connect Time	Release Time	Transport Time	Travel Time	Description	Location
Tuesday	25-Oc		13:05:00				Connect to fly form from L4 (6legs)	L4 AY G6 (From E ledge)
		0		13:24:10	0:19:10		Fly form to L5 (for L6 Pour)	L5 at F5
		90 CW	13:26:00			0:01:50	Connect to fly form from L4 (4legs)	L4 at J5 (from S ledge)
		0		13:34:30	0:08:30		Fly form to L5 (for L6 Pour)	L5 at H- Slab
		180 CCW	13:36:45			0:02:15	Connect to Fly form sitting on Main slab (being repaired) (4legs)	Main at C7
		180 CW		13:44:20	0:07:35		Straight lift - Fly form to L5 (Pour L6)	L5 at H4

Figure 5-6 Sample Field Data Sheet - Slab Fly-Form Removal

The collected field data is used to quantify hook-time durations for slab fly-form and concrete placement activities and verify expert experience data. In conjunction with Paul Knowles, ECERF site project coordinator, the production cycle has been defined and all remaining activity information collected. Some of the missing activity hook-time durations include: rebar delivery, garbage bin disposal, and column and core form movements. Table 5-1 (page 49) documents the ECERF tower crane production cycle and lift hook-time for all lift activities.

5.2.2 ECERF Simulation Model using Simphony *Common Template*

The Simphony common template is a general-purpose simulation tool that enables the practitioner to model a system using process interaction concepts. Model development using the common template requires the user to have background in simulation techniques. The template includes elements for handling hierarchical modeling, entity creation and routing, resources, statistics, activities, and tracing. (NSERC 2000) The common template is used to model the ECERF tower crane production cycle using *relationship logic links* to represent the process interaction between modeling elements.

The major activities occurring on the project are separated into categories: rebar deliveries, slab work, pour slabs, column work, core work, and miscellaneous work. Computer simulation using the common template is a powerful tool for advanced users, providing flexible constructs that can be easily manipulated to represent virtually any construction process. The drawback of using the common template for simulating tower crane operations is the complex relationships that result from having a multiple number of lifting activities that are not driven by process events but rather driven by priority ratings between activities and controlled by entity arrival times. That is to say that once a work package is selected by the crane resource it is unaffected by any other work packages or entities that are present in the model. The only prerequisite for tower crane selection is that the specified work package has arrived at the source location and that it is the highest ranked work package waiting in the model.

The Simphony common template model shown in Figure 5-7 illustrates the level of complexity required to model the ECERF project using relationship logic links. Some of the drawbacks experienced during the development of the common template ECERF tower crane model are outlined as follows:

1. The development phase of the model is time consuming, requiring excessive relationship links and coding by the user.
2. The model will change dramatically when applied to a new project.
3. A novice simulation user cannot easily modify the model.
4. The model is difficult to track and understand.

Many construction operation systems (i.e. earthmoving, tunneling) can be broken down to a set of repetitive activities that drive production. Using the relationship logic links approach demonstrated by the Simphony common template is very successful in modeling these systems. However, using the common template to model tower crane operations is laborious and impractical for the industry practitioner.

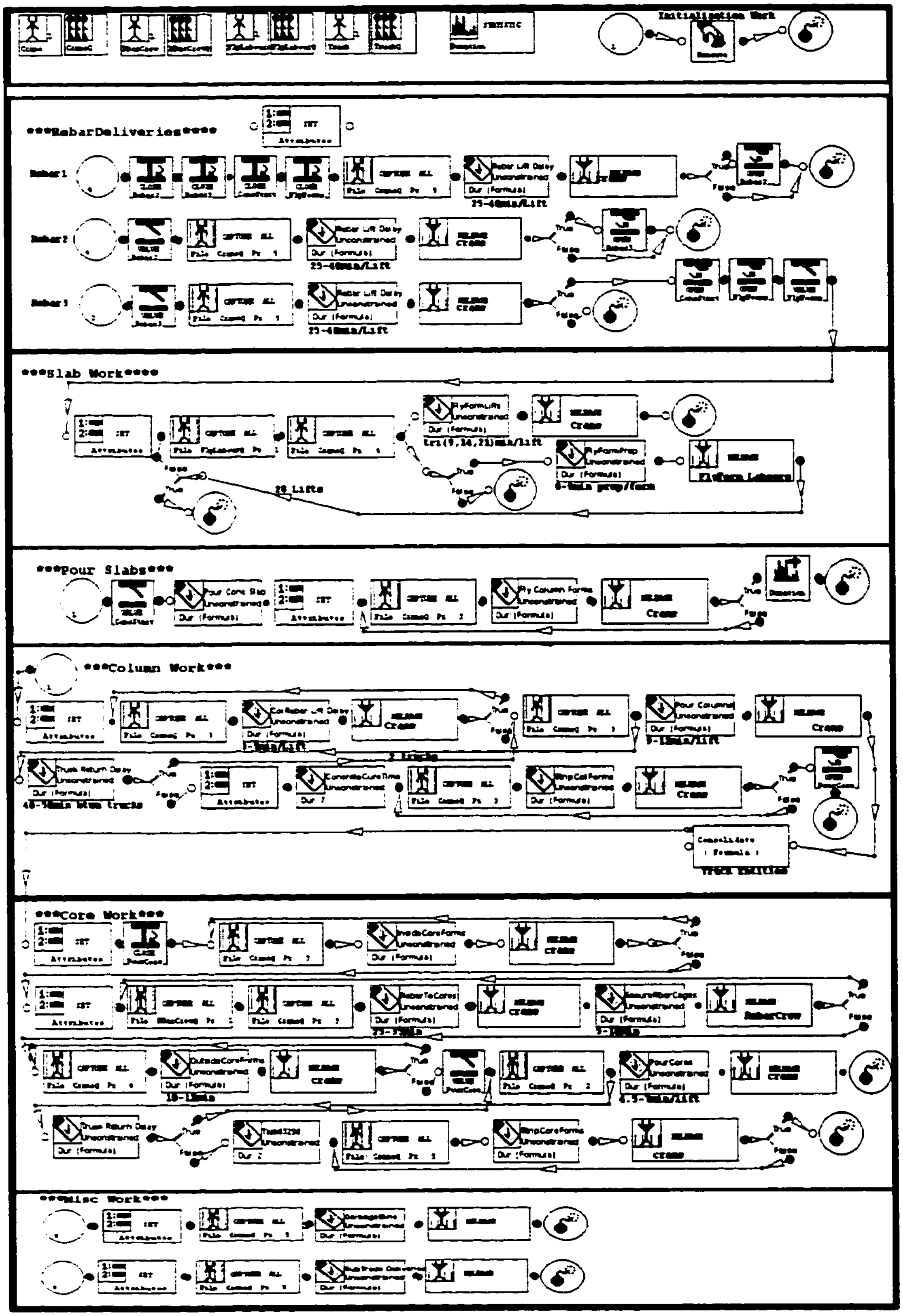


Figure 5-7 ECERF Common Template Simphony Model

5.2.3 ECERF Simulation Model using Simphony SPS Tower Crane Template

As discussed in Chapter 4, the creation of a model using the SPS tower crane template is based on the geographical locations of the crane, source, and destination elements on the model layout (i.e. footprint). Figure 5-8 shows the element locations in relation to the ECERF building layout and the staged construction zones used for each floor. Including the 10-meter buffer zone in the x and y direction, the precise location of each modeling element is found in Table 5-2. At the source child level, work packages have been created for each tower crane activity represented in Table 5-1. Data used for unhook and hookup delays were gathered in the field and expert opinion received from the ECERF job superintendent.

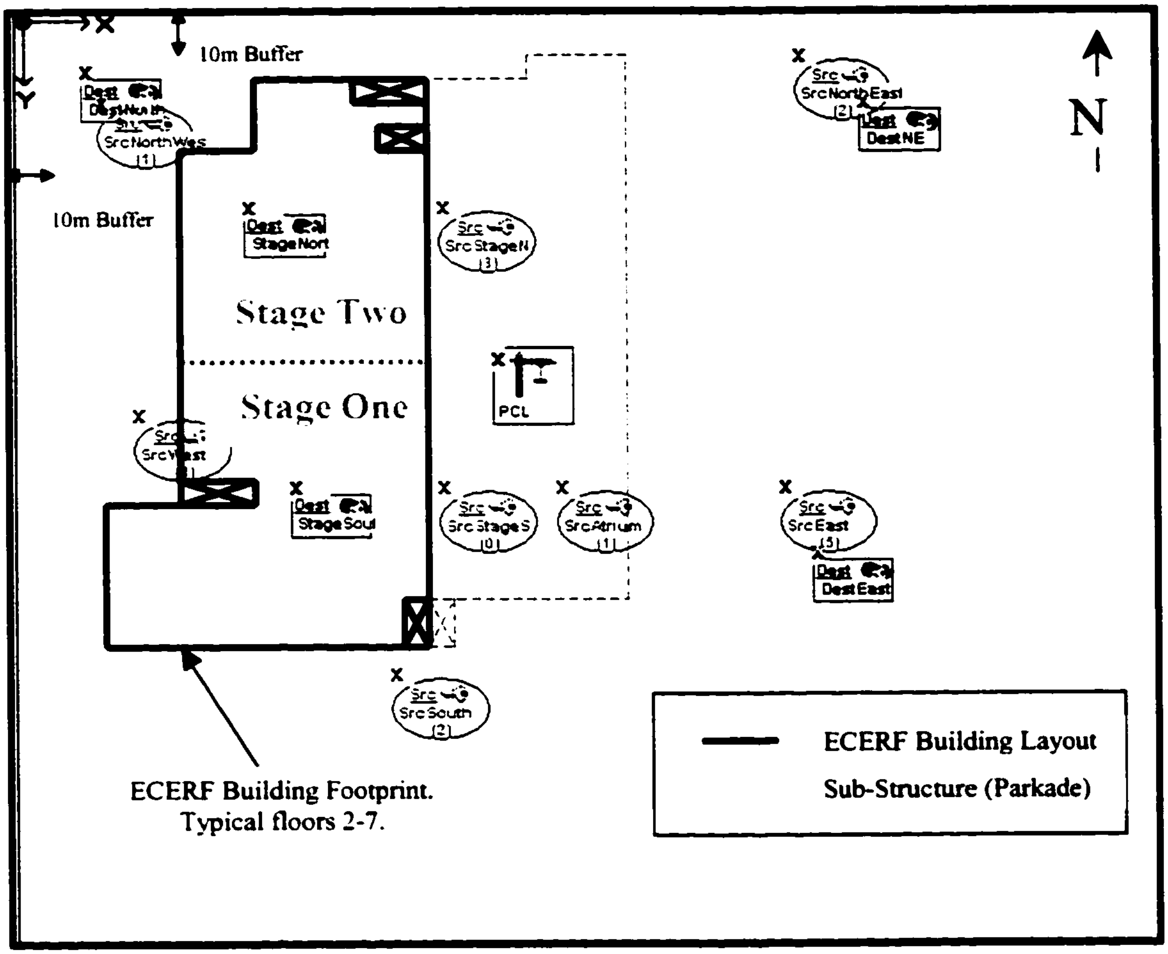


Figure 5-8 ECERF Building Floor Footprint and Model Elements (typical floors 2-7)

Table 5-2 ECERF Modeling Element Coordinates

Locations	X [m]	Y [m]
SrcNorthWest	10.00	10.00
SrcWest	14.50	50.50
SrcNorthEast	94.00	4.00
SrcAtrium	66.44	59.50
SrcSouth	46.00	83.50
SrcEast	94.00	59.50
DestStageNorth	28.00	23.50
DestStageSouth	33.50	59.50
DestNorthEast	104.00	10.00
DestNorthWest	8.00	6.00
SrcStageN	52.00	23.50
SrcStageS	52.00	59.50
CraneLocation	58.65	43.19
Note: North and West Boundries have a 10m Buffer Zone.		

Once all the information was gathered regarding the tower crane production system for the ECERF project, setting up the SPS tower crane model was simple and straightforward. The following inferences were made while developing the ECERF model using the SPS tower crane template:

1. Parameters needed for each work package are representative of the tower crane construction domain, which results in a transference of knowledge that is effortless for site personal.
2. Creating site footprint is a useful tool that helps the practitioner envision the actual construction layout. Required information is drawn directly from site drawings.

3. Using *priority rating logic*, the development phase of the tower crane template is simple and efficient. Priority rating logic uses work package priority ratings and arrival times to control logic in the modeled system.
4. Model is very flexible, which encourages scenario analysis by the practitioner (See Chapter 6).
5. By isolating the user from the low level constructs and presenting a model interface that more closely represents the actual tower crane system, the overall environment is simple to understand.

Each of these advancements described above contributes to a broadening of computer simulation framework in the field of construction. As the results will demonstrate, the SPS tower crane template produces results similar to the common template approach, thus demonstrating the viability of replacing relationship logic links used by the common template with priority rating logic control for modeling process interaction.

5.2.4 Results

Each of the simulation models described above is run for 50 iterations to simulate the various conditions reflected by the input parameters. Table 5-3 shows the results for the total number of crane hours and crane utilization for the common and SPS tower crane template ECERF models.

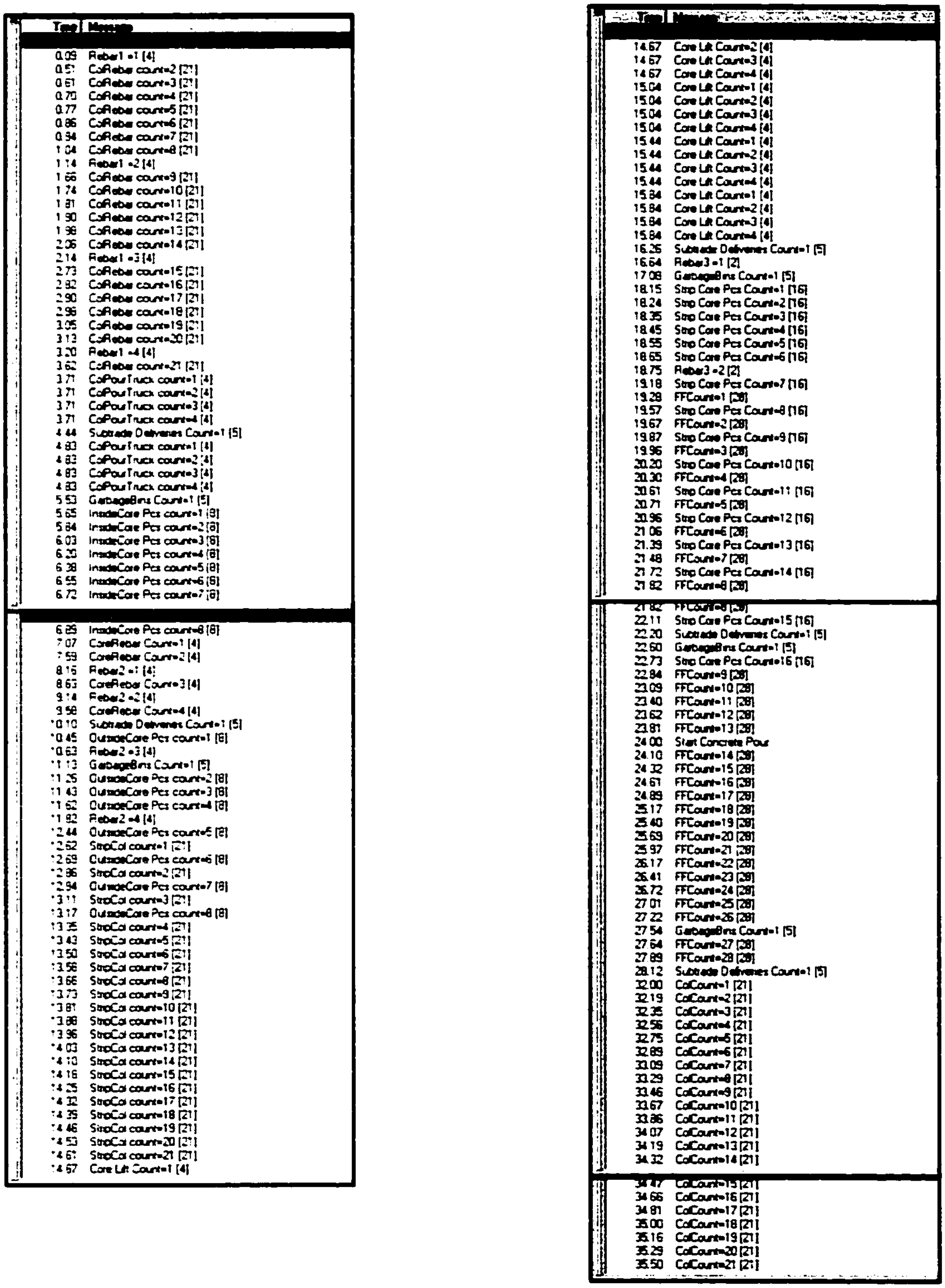
Table 5-3 ECERF Case Study - Model Verification Results

		Simphony Template Description	
		General Purpose - Common Template	SPS Tower Crane Template
Number of Simulation Runs		50	50
Total No. of Crane Hours	Mean	35.5	36.1
	Std. Dev	0.2	0.35
	Min	35.1	35.4
	Max	35.78	36.81
Tower Crane Utilization	Mean	89.2	90.1
	Std. Dev	0.95	1.97
Total No. of Crane Hours % Difference		[illegible]	
Tower Crane Utilization % Difference		[illegible]	

Due to greater flexibility in the SPS tower crane model, dynamic quantities for columns, core forms, and rebar deliveries have been entered for the work package input parameters, whereas the common template model only uses static quantities. This explains why the results show a tighter standard deviation for the common template results.

The duration for each lift used in the common template model includes hookup, unhook, and crane movement delays, whereas the SPS tower crane model requires the practitioner to input the hookup and unhook delays as the crane movement is calculated separately in the model. Much of the lift delay information received from the ECERF site supervisor included hookup, unhook, and movement delays. In order to alleviate this problem, hook-time analysis is performed using the SPS tower crane template to isolate the crane movement delay between the source and destination elements for each specified lift activity (i.e. hookup/unhook delays excluded). Using these results, the hookup/unhook delay for the SPS template is extracted from the original data. Although this provides an accurate estimate for the unhook/hookup times for the SPS template, it results in a slight variation in the total number crane hours and crane utilization when comparing two ECERF models. The percent difference found in the total number of crane hours and tower crane utilization is 1.7 and 1.0 respectively.

To ensure model compatibility, each lift activity performed by the tower crane has been tracked for the common and SPS tower crane templates in Figures 5-9 and 5-10 respectively.



Time	Message
0.09	Rebar1 =1 [4]
0.51	CoRebar count=2 [21]
0.61	CoRebar count=3 [21]
0.70	CoRebar count=4 [21]
0.77	CoRebar count=5 [21]
0.86	CoRebar count=6 [21]
0.94	CoRebar count=7 [21]
1.04	CoRebar count=8 [21]
1.14	Rebar1 =2 [4]
1.66	CoRebar count=9 [21]
1.74	CoRebar count=10 [21]
1.81	CoRebar count=11 [21]
1.90	CoRebar count=12 [21]
1.98	CoRebar count=13 [21]
2.05	CoRebar count=14 [21]
2.14	Rebar1 =3 [4]
2.73	CoRebar count=15 [21]
2.82	CoRebar count=16 [21]
2.90	CoRebar count=17 [21]
2.98	CoRebar count=18 [21]
3.05	CoRebar count=19 [21]
3.13	CoRebar count=20 [21]
3.20	Rebar1 =4 [4]
3.62	CoRebar count=21 [21]
3.71	CoPourTruck count=1 [4]
3.71	CoPourTruck count=2 [4]
3.71	CoPourTruck count=3 [4]
3.71	CoPourTruck count=4 [4]
4.44	Subtrade Deliveries Count=1 [5]
4.83	CoPourTruck count=1 [4]
4.83	CoPourTruck count=2 [4]
4.83	CoPourTruck count=3 [4]
4.83	CoPourTruck count=4 [4]
5.53	GarbageBins Count=1 [5]
5.65	InsideCore Pcs count=1 [8]
5.84	InsideCore Pcs count=2 [8]
6.03	InsideCore Pcs count=3 [8]
6.20	InsideCore Pcs count=4 [8]
6.38	InsideCore Pcs count=5 [8]
6.55	InsideCore Pcs count=6 [8]
6.72	InsideCore Pcs count=7 [8]
6.85	InsideCore Pcs count=8 [8]
7.07	CoreRebar Count=1 [4]
7.59	CoreRebar Count=2 [4]
8.15	Rebar2 =1 [4]
8.63	CoreRebar Count=3 [4]
9.14	Rebar2 =2 [4]
9.58	CoreRebar Count=4 [4]
10.10	Subtrade Deliveries Count=1 [5]
10.45	OutsideCore Pcs count=1 [8]
10.63	Rebar2 =3 [4]
11.13	GarbageBins Count=1 [5]
11.25	OutsideCore Pcs count=2 [8]
11.43	OutsideCore Pcs count=3 [8]
11.62	OutsideCore Pcs count=4 [8]
11.92	Rebar2 =4 [4]
12.44	OutsideCore Pcs count=5 [8]
12.62	StrpCol count=1 [21]
12.69	OutsideCore Pcs count=6 [8]
12.86	StrpCol count=2 [21]
12.94	OutsideCore Pcs count=7 [8]
13.11	StrpCol count=3 [21]
13.17	OutsideCore Pcs count=8 [8]
13.35	StrpCol count=4 [21]
13.43	StrpCol count=5 [21]
13.50	StrpCol count=6 [21]
13.58	StrpCol count=7 [21]
13.66	StrpCol count=8 [21]
13.73	StrpCol count=9 [21]
13.81	StrpCol count=10 [21]
13.88	StrpCol count=11 [21]
13.96	StrpCol count=12 [21]
14.03	StrpCol count=13 [21]
14.10	StrpCol count=14 [21]
14.16	StrpCol count=15 [21]
14.25	StrpCol count=16 [21]
14.32	StrpCol count=17 [21]
14.39	StrpCol count=18 [21]
14.46	StrpCol count=19 [21]
14.53	StrpCol count=20 [21]
14.61	StrpCol count=21 [21]
14.67	Core Lift Count=1 [4]
14.67	Core Lift Count=2 [4]
14.67	Core Lift Count=3 [4]
14.67	Core Lift Count=4 [4]
15.04	Core Lift Count=1 [4]
15.04	Core Lift Count=2 [4]
15.04	Core Lift Count=3 [4]
15.04	Core Lift Count=4 [4]
15.44	Core Lift Count=1 [4]
15.44	Core Lift Count=2 [4]
15.44	Core Lift Count=3 [4]
15.44	Core Lift Count=4 [4]
15.84	Core Lift Count=1 [4]
15.84	Core Lift Count=2 [4]
15.84	Core Lift Count=3 [4]
15.84	Core Lift Count=4 [4]
16.25	Subtrade Deliveries Count=1 [5]
16.64	Rebar3 =1 [2]
17.08	GarbageBins Count=1 [5]
18.15	Strp Core Pcs Count=1 [16]
18.24	Strp Core Pcs Count=2 [16]
18.35	Strp Core Pcs Count=3 [16]
18.45	Strp Core Pcs Count=4 [16]
18.55	Strp Core Pcs Count=5 [16]
18.65	Strp Core Pcs Count=6 [16]
18.75	Rebar3 =2 [2]
19.18	Strp Core Pcs Count=7 [16]
19.28	FFCount=1 [28]
19.57	Strp Core Pcs Count=8 [16]
19.67	FFCount=2 [28]
19.87	Strp Core Pcs Count=9 [16]
19.96	FFCount=3 [28]
20.20	Strp Core Pcs Count=10 [16]
20.30	FFCount=4 [28]
20.61	Strp Core Pcs Count=11 [16]
20.71	FFCount=5 [28]
20.96	Strp Core Pcs Count=12 [16]
21.06	FFCount=6 [28]
21.39	Strp Core Pcs Count=13 [16]
21.48	FFCount=7 [28]
21.72	Strp Core Pcs Count=14 [16]
21.82	FFCount=8 [28]
22.11	Strp Core Pcs Count=15 [16]
22.20	Subtrade Deliveries Count=1 [5]
22.60	GarbageBins Count=1 [5]
22.73	Strp Core Pcs Count=16 [16]
22.84	FFCount=9 [28]
23.09	FFCount=10 [28]
23.40	FFCount=11 [28]
23.62	FFCount=12 [28]
23.81	FFCount=13 [28]
24.00	Start Concrete Pour
24.10	FFCount=14 [28]
24.32	FFCount=15 [28]
24.61	FFCount=16 [28]
24.89	FFCount=17 [28]
25.17	FFCount=18 [28]
25.40	FFCount=19 [28]
25.69	FFCount=20 [28]
25.97	FFCount=21 [28]
26.17	FFCount=22 [28]
26.41	FFCount=23 [28]
26.72	FFCount=24 [28]
27.01	FFCount=25 [28]
27.22	FFCount=26 [28]
27.54	GarbageBins Count=1 [5]
27.64	FFCount=27 [28]
27.89	FFCount=28 [28]
28.12	Subtrade Deliveries Count=1 [5]
32.00	CoCount=1 [21]
32.19	CoCount=2 [21]
32.35	CoCount=3 [21]
32.56	CoCount=4 [21]
32.75	CoCount=5 [21]
32.89	CoCount=6 [21]
33.09	CoCount=7 [21]
33.29	CoCount=8 [21]
33.46	CoCount=9 [21]
33.67	CoCount=10 [21]
33.86	CoCount=11 [21]
34.07	CoCount=12 [21]
34.19	CoCount=13 [21]
34.32	CoCount=14 [21]
34.47	CoCount=15 [21]
34.66	CoCount=16 [21]
34.81	CoCount=17 [21]
35.00	CoCount=18 [21]
35.16	CoCount=19 [21]
35.29	CoCount=20 [21]
35.50	CoCount=21 [21]

Figure 5-9 Activity Tracking - Common Template

Time	Message
0.04	RebarDeliver1
0.47	Column Rbar
0.56	Column Rbar
0.64	Column Rbar
0.70	Column Rbar
0.78	Column Rbar
0.85	Column Rbar
0.93	Column Rbar
1.01	Column Rbar
1.09	Column Rbar
1.17	RebarDeliver1
1.73	Column Rbar
1.80	Column Rbar
1.87	Column Rbar
1.94	Column Rbar
2.02	Column Rbar
2.11	Column Rbar
2.19	RebarDeliver1
2.73	Column Rbar
2.80	Column Rbar
2.88	Column Rbar
2.95	Column Rbar
3.20	RebarDeliver1
4.01	Subtrade Delivery
4.35	Pour Columns
4.51	Pour Columns
4.67	Pour Columns
4.85	Pour Columns
5.04	Pour Columns
5.22	Pour Columns
5.38	Pour Columns
5.54	Pour Columns
5.74	Garbage Bins
5.83	Garbage Bins
6.01	Inside Core Forms
6.23	Inside Core Forms
6.45	Inside Core Forms
6.65	Inside Core Forms
6.85	Inside Core Forms
7.06	Inside Core Forms
7.27	Inside Core Forms
8.02	RebarDeliver2
8.59	Rebar to Cores
9.03	Rebar to Cores
9.47	Rebar to Cores
10.01	RebarDeliver2
10.57	Subtrade Delivery
11.05	Garbage Bins
11.17	Garbage Bins
11.28	Rebar to Cores
11.83	RebarDeliver2
13.02	Outside Core Forms
13.22	Outside Core Forms
13.41	Outside Core Forms
13.62	Outside Core Forms
13.81	Outside Core Forms
14.01	Outside Core Forms
14.20	Outside Core Forms
14.40	Outside Core Forms
14.60	StripColumns
14.69	StripColumns
14.79	StripColumns
14.88	StripColumns
14.94	StripColumns
15.02	StripColumns
15.10	StripColumns
15.18	StripColumns
15.26	StripColumns
15.37	StripColumns
15.45	StripColumns
15.53	StripColumns
15.64	StripColumns
15.78	StripColumns
15.89	StripColumns
15.97	StripColumns
16.08	Subtrade Delivery
16.52	Garbage Bins
16.61	Garbage Bins
16.72	StripColumns
16.80	StripColumns
16.90	StripColumns
17.03	Pour Cores
17.11	Pour Cores
17.21	Pour Cores
17.31	Pour Cores
17.40	Pour Cores
17.50	Pour Cores
17.59	Pour Cores
17.68	Pour Cores
17.79	Pour Cores
17.89	RebarDeliver3
18.44	Pour Cores
18.54	Pour Cores
18.64	Pour Cores
18.75	Pour Cores
18.85	Pour Cores
18.96	Pour Cores
19.07	Pour Cores
19.19	Pour Cores
19.28	Pour Cores
20.01	FlyForms
20.31	FlyForms
20.56	FlyForms
20.91	FlyForms
21.18	FlyForms
21.40	FlyForms
21.62	FlyForms
21.94	FlyForms
22.21	Subtrade Delivery
22.68	Garbage Bins
22.79	Garbage Bins
22.87	FlyForms
23.10	FlyForms
23.45	FlyForms
23.72	FlyForms
24.05	FlyForms
24.33	FlyForms
24.59	FlyForms
24.88	FlyForms
25.22	FlyForms
25.48	FlyForms
25.72	FlyForms
25.99	FlyForms
26.27	FlyForms
26.53	FlyForms
26.79	FlyForms
27.08	Strip Core
27.19	Strip Core
27.28	Strip Core
27.39	Strip Core
27.49	Strip Core
27.59	Garbage Bins
27.74	Garbage Bins
27.81	Strip Core
27.94	Strip Core
28.04	Subtrade Delivery
28.46	Strip Core
28.57	Strip Core
28.67	Strip Core
28.76	Strip Core
28.85	Strip Core
28.96	Strip Core
29.09	Strip Core
29.19	FlyForms
29.49	FlyForms
29.75	FlyForms
30.07	FlyForms
30.40	FlyForms
32.57	Fly Columns
32.73	Fly Columns
32.87	Fly Columns
33.03	Fly Columns
33.22	Fly Columns
33.40	Fly Columns
33.53	Fly Columns
33.74	Fly Columns
33.92	Fly Columns
34.09	Fly Columns
34.23	Fly Columns
34.44	Fly Columns
34.59	Fly Columns
34.74	Fly Columns
34.85	Fly Columns
35.03	Fly Columns
35.17	Fly Columns
35.29	Fly Columns
35.50	Fly Columns

Figure 5-10 Activity Tracking - SPS Tower Crane Template

Overall, Table 5-3 and Figures 5-9 and 5-10 illustrate a correlation between the two modeling approaches. That is to say, modeling using priority rating logic has been compared to the traditional modeling approach using relationship logic links, yielding the same results in less time with greater flexibly and ease. This is a significant finding as it demonstrates that priority rating logic provides a more effective methodology of modeling a leading resource without compromising any logic constraints and rules that exist using traditional simulation methods.

5.3 CONCLUSION

This chapter validates priority rating logic as a viable replacement for the relationship logic links used by traditional object-oriented simulation techniques. The ECERF Building located on the University of Alberta campus has been modeled using both the Simphony common template and SPS template. The ECERF case study is a generic project used to illustrate the merit of using priority rating logic control for simulating tower crane operations.

Each simulation model is run for 50 iterations to simulate the various conditions represented by the input parameters. The total number of crane hours and crane utilization for both models is approximately 36 hours and 90%, respectively. When comparing the two methods, the percent error between the common and SPS tower crane models was found to be less than 1.7%, and confirm the actual schedule in the field. Refer to Table 5-3 for a detailed summary of the model results.

Additionally, modeling tower crane operations using the SPS tower crane template provides many benefits, such as: 1) the parameters needed for each work package is representative of the tower crane construction domain, 2) creating the site footprint helps the practitioner envision the actual construction layout, 3) required information is drawn directly from site drawings, 4) using priority rating logic during the development phase of the tower crane template is simple and efficient, 5) the model is very flexible which encourages scenario analysis by the practitioner, and 6) by isolating the user from the low level constructs and presenting a model interface that more closely represents the actual tower crane system, the overall environment is simple to understand.

Each of these advancements described above contributes to a broadening of computer simulation framework in the field of construction. Each model accurately models the activity selection process performed by the tower crane while using different modeling approaches. The results verify that the two ECERF case study models have valid results and demonstrate that using priority rating logic control can accurately model tower crane operations while still maintaining traditional modeling logic constraints.

6 SPS TOWER CRANE TEMPLATE SCENARIO ANALYSIS

6.1 INTRODUCTION

This Chapter demonstrates how the SPS tower crane template can be used as an effective tool for decision support using scenario analysis. Using the SPS tower crane template and the ECERF building case study described in Chapter 5, various scenarios are used to help the practitioner better understand the modeled tower crane production system. Section 6.2 establishes a base case scenario, which represents the actual production cycle used on site. Section 6.3 documents scenarios that isolate changes to the system, including rebar delivery priority setting, change rebar staging area, relocate crane resource, relocate source element, increase number of slab fly forms, and increase the time between arrivals for the fly form work package. Each scenario applied to the ECERF base case helps the practitioner better understand the sensitivity of the tower crane production system.

6.2 ECERF MODEL BASE CASE RESULTS

The Simphony model described in the previous Chapter describes the current layout used for floor formwork construction at the ECERF building site. As shown in Table 6-1, the model generated 50 runs, yielding the 80^{th} percentile, mean, standard deviation, minimum, and maximum for the "total crane hours." The mean and standard deviation for the "tower crane utilization" are also shown. The percentile value is used as an indication of the probability of exceeding (or not exceeding) a given threshold value

(Ahuja et al. 1994). The 80th percentile, compared to the mean, is of greater interest as it more accurately reflects the desired risk by a practitioner for construction works. Based on Monte Carlo Simulation techniques, multiple simulation runs are performed yielding a normal distribution for the total tower crane hours. From the normal distribution, the practitioner can produce a cumulative distribution function (CDF) illustrating the desired percentiles. Figure 6-1 illustrates the CDF graph for the ECERF base case scenario. For a detailed introduction to Monte Carlo Simulation see Chapter 16 of Ahuja et al. (1994).

Table 6-1 ECERF Base Case Simulation Results

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Base Case	50	36.32	35.93	0.40	35.09	36.64	90.40	1.90

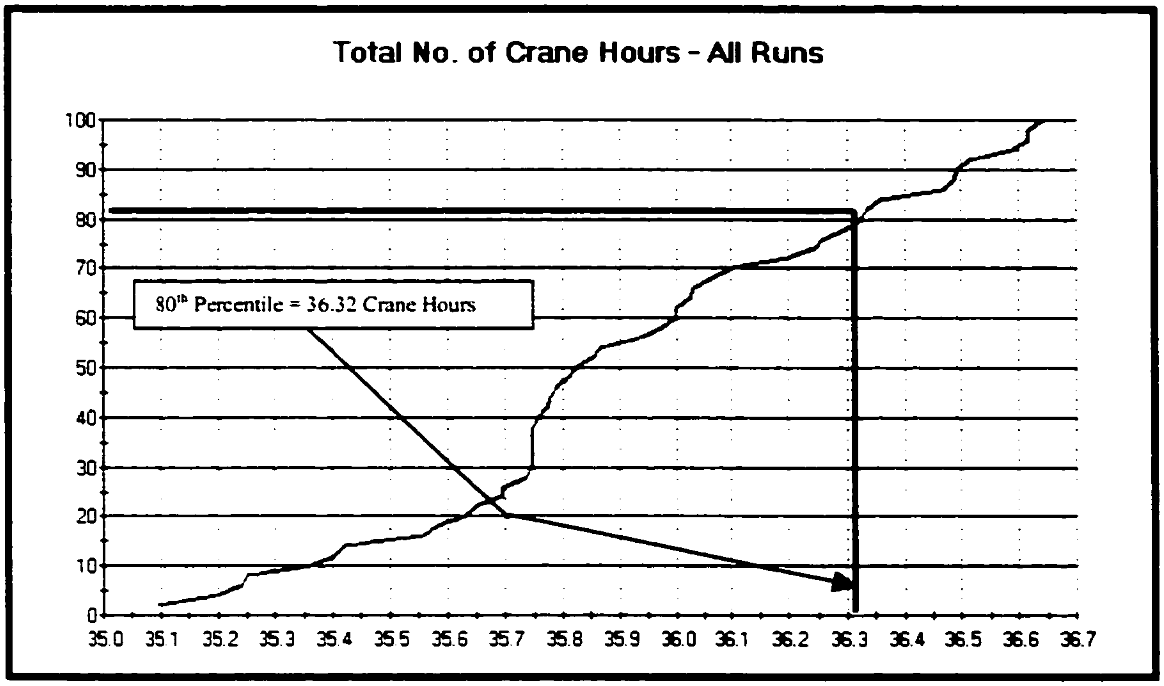


Figure 6-1 ECERF Base Case - Cumulative Density Function (CDF)

6.3 ECERF TOWER CRANE SCENARIO ANALYSIS

Using scenario analysis to illustrate the cause and effect of changes to the tower crane production system gives the practitioner an idea of the system's effectiveness. For example, a change to one of the modeling elements may affect the crane utilization and/or total crane hours. Looking at the production cycle for the ECERF building case study we can see that the utilization of the crane is at approximately 90.4 percent while the total tower crane hours is approximately 36 hours (4.5 days). It is desirable to have the crane utilization at about 90 percent so that anomalies within the production system can be addressed during construction. Each scenario applied to the ECERF base case helps the practitioner better understand the production system.

Scenario 1 – Reduce Priority Setting for Rebar Delivery Work Elements

The priority rating for all rebar delivery work elements is changed from 4 to 1. This translates into a lower priority rating for each rebar delivery work package, which forces longer waiting in the queue. The purpose of this scenario is to understand the effect of priority rating change on the ECERF tower crane production cycle. As expected, the statistics for the rebar delivery work element show a marked increase in work package waiting time, from 2-15 minutes to 52-138 minutes.

Scenario 2 – Change Location of Rebar Staging Area

A subcontractor performs the rebar work at the ECERF building. This sub-contractor uses a staging area to tie rebar cages that are later transported into place by the tower crane. This scenario changes the rebar staging area from the southeast corner of the site to the atrium floor, which provides a concrete slab work surface. The result of changing the rebar staging area has little effect on the total crane hours or the crane utilization for the ECERF production cycle. This indicates that the time delay for rebar lifts is largely attributed to hookup/unhooking time distributions.

Scenario 3 – Relocate Tower Crane Element

In this scenario the tower crane element is moved approximately 9 meters east. The purpose of moving the tower crane element is to determine its effects on the production cycle. The result of relocating the tower crane is a slight decrease (1%) in crane utilization with no change to total crane hours. The ECERF tower crane production cycle contains work packages that have large hookup/unhooking times in comparison to crane movement delays (hoisting, radial, horizontal).

Scenario 4 – Relocate Source Element

This is scenario is similar to scenario 2 except that the x-coordinate and y-coordinate are changed for a specific source element rather than the work elements simply being moved to a new source. In this case, the concrete delivery source location is moved from the south side of the building to the east staging area. The result of this change has minimal effect on the ECERF tower crane production cycle.

Scenario 5 – Increase The Number of Slab Fly-Forms Being Lifted

The ECERF base case analyzes the pouring of concrete for stage one (south side). In stage two the number of slab fly-forms increases from 28 to 33. The result of this scenario reveals that the total crane hours for the production cycle is unchanged but the crane utilization increases. In short, the five additional fly-form lifts are performed without an increase to the total crane hours for the production cycle. Therefore the tower is simply busier with a utilization increase of approximately 4%.

Scenario 6 – Increase The "Time Between Arrivals" For Slab Fly-Forms.

This scenario looks at the effect of altering arrival times for slab fly-forms. The "Time Between Arrivals" parameter represents the time required for a crew to prepare each slab fly-form before the tower crane can perform the required lift. The "Time Between Arrivals" distribution has been increased from 8-9 minutes to 25-45 minutes. The purpose of this scenario is to illustrate the importance of hook-time in the ECERF tower crane production cycle. The total crane hours increases by 1.5 hours and the tower crane resource utilization decreases by 4%.

Each of the scenarios applied to the ECERF tower crane production cycle are listed in Table 6-2.

Table 6-2 ECERF Model Scenario Statistics Summary

Scenario Description	No of Runs	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Base Case	**50**	**36.32**	**35.93**	**0.40**	**35.09**	**36.64**	**90.40**	**1.90**	-
1. Rebar Delivery Priority (1)	50	36.21	35.92	0.41	35.09	36.93	90.38	1.80	WP waiting time changed (2 15min to 52-138min)
2. Change Rebar Staging Area	50	36.25	35.92	0.43	35.26	37.01	90.36	1.57	Rebar staging area changed from SrcEast to SrcAtrium
3. Relocate Crane	50	36.45	36.11	0.39	35.28	36.80	89.23	1.78	Move crane 8.5m East
4. Relocate Source	50	36.32	35.92	0.40	35.09	36.64	90.62	1.82	Move SrcSouth to East staging area. Source used for concrete delivery.
5. Increase No. of Fly Forms (28to33)	50	36.30	35.94	0.38	35.41	36.78	94.11	2.16	Increase no. of forms from 28 to 33
6. Increase 'Time Between Arrivals' for Fly Form WP	50	37.82	37.63	0.31	37.07	38.39	86.19	1.59	Increase TBA from 25-45min

The ECERF tower crane model is an example of an efficient production system. Each scenario applied to the base case either has no effect or results in a decrease in system efficiency. This is the result of using model data collected after project completion, which reflects a tower crane production cycle that has been optimized throughout construction. Notwithstanding, each scenario helps the practitioner gain a greater understanding of the production system and can be applied on similar projects in the future. Using the SPS tower crane template before and during the project construction phase will allow the practitioner to understand, justify, and change the specified tower crane production system yielding a competitive advantage to the user.

6.4 CONCLUSIONS

Scenario analysis is a powerful simulation tool used for construction methods decision support. By applying scenario analysis, the tower crane production system can be optimized by simplifying the organization, avoiding waste, and stimulating employees to improve their own production processes (Melles 1994). Scenario analysis using the SPS tower crane template can help the practitioner understand the crane production cycle and justify any proposed changes that may be needed.

In this chapter, six scenarios are analyzed. Scenarios 1-4 show very little change in total crane hours and crane utilization in comparison with the base case. By changing the priority for rebar delivery, the rebar waiting time increases dramatically. When the rebar delivery source is changed, the crane element is relocated or the source element is relocated, there is minimal effect to the tower crane production system. This indicates that delays associated with tower crane hoisting, radial, and horizontal movements have little affect on the overall ECERF production cycle. In Scenario 5, the number of fly-forms increases from 28 to 33, showing little change in the total crane hours, but does increase the crane utilization from 90.4 to 94.1%. This is an indication that the additional fly-form lifts are performed without increasing the total crane hours for the production system. Scenario 6 adjusts the "Time between Arrivals" for slab fly-form deliveries, which represents the time required for the laborers to release and transport the slab fly-forms to the specified source location. This change results in an increase to the total crane hours and a decrease in the crane resource utilization.

Scenario analysis is a valuable simulation tool used for decision support. Each scenario helps the practitioner gain a greater understanding of the production system to be applied on similar projects in the future, thus providing a competitive advantage for project estimation and performance.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 RESEARCH SUMMARY

This thesis presents an alternate approach for modeling process interaction in construction simulation by replacing traditional *relationship logic links* with *priority rating logic* control when modeling a leading resource operation. The validity of priority rating logic control is illustrated through the design, development, and implementation of the tower crane construction management process using special purpose simulation (SPS). The development of this simulation tool is a result of extensive field observations, the creation of a flexible powerful simulation engine (Simphony), and the successful collaborative research work between PCL Contractors Inc. and the NSERC/Alberta Construction Industry Research Chair in Construction Engineering and Management. The research presented in this thesis can be divided into three phases.

The first phase focuses on developing a clear understanding of the tower crane operations and interaction with other resources on the construction site. The tower crane was monitored for a 7-month period from April to November, 2000. As a result of this field monitoring, the following data was compiled: activity prioritization and selection scheme, activity delays, and lift activity hook-times. Further information regarding activity prioritization and selection schemes was received from the project superintendent and coordinator, who oversaw the day-to-day management of the tower crane. Other tower crane information was received from site visits to the University of Alberta Hospital Expansion Project, the NAIT Information and Communications Technology Centre

(ICTC), and several meetings with the chief engineer and the manager of purchasing and equipment at PCL Constructors Inc. During this phase of research, it became apparent that the traditional method of representing simulation model process interaction was too complex when modeling a leader resource operation.

The second phase of research focuses on the development of a special purpose simulation (SPS) template for tower crane construction operations management. Due to the difficulties of modeling the tower crane operations, it was decided that traditional methods of representing process interaction within the model had to be modified. Traditional modeling techniques use relationship links to represent the logic contained in the modeled system. As the number of work tasks increases for the tower crane, the model complexity using traditional simulation techniques becomes unmanageable, resulting in limited acceptance by industry practitioners. To overcome this problem the SPS tower crane template introduces priority rating logic control using prioritized work package modeling elements representing each activity being performed by the tower crane (i.e. formwork, concrete placement, rebar delivery, etc.). Using priority rating logic for model process interaction is a better representation of the tower crane construction domain and simplifies model development for the industry practitioner.

Priority rating logic control does not replace the use of relationship logic links, but is intended as practical tool to be used when modeling a leader resource operation. The problem with using relationship logic links when modeling a leading resource such as a tower crane operation is the complex logic relationships that result. When simulating a leading resource for a specified construction domain, the use of priority rating logic control simplifies simulation model development and use by industry practitioners. The use of priority rating logic control is a valuable tool that should be considered when the following conditions are present:

1. Modeling a key resource that dramatically affects the other processes in the construction operation.
2. High number of trades competing for a key resource.
3. Functions of the key resource are repetitive.

For tower crane operations, each activity occurring in the modeled system does not follow a distinct repetitive process flow, but rather consists of a number of distinct activities that move linearly through the crane model. Each tower crane activity is performed based on urgency and demand within the modeled system. The use of priority rating logic control verses traditional relationship logic links simplifies the tower crane-modeling domain.

The third phase compares the Simphony common template and the SPS tower crane template to validate priority rating logic control using a generic case study. The common template uses relationship logic links for process interaction while the SPS tower crane template uses priority rating logic. The results of the two models illustrate the advantages of using priority rating logic when model a leading resource operation and yield similar results for the total tower crane hours and crane utilization for the specific tower crane production cycle.

7.2 Summary of Research Contributions

This research has led to the following major contributions:

1. The use of priority rating logic control as an innovative method of handling process interaction modeling for tower crane construction.
2. Development of a flexible special purpose simulation template for tower crane construction operations management.

The development of the SPS tower crane template is based on the geographical site layout and the construction sequence, thus enabling end-users who are not familiar with simulation, but have expertise in tower crane construction, to create a model and experiment by changing the parameter values in the modeling elements. The SPS tower crane template analyzes the crane production cycle to optimize crane utilization, crane lift schedule, work prioritization, and crane location. The following points describe in detail the analytical capabilities of SPS tower crane template.

1. *Crane Utilization Check.* For a critical portion of the schedule, the crane production cycle can be modeled, yielding the overall crane utilization. The crane utilization can be analyzed using lift priority settings, crane location, and arrival times.

2. *Production System Sensitivity Analysis.* Alterations to the model can be used to help the practitioner understand the sensitivity of the specified production system for each Work Package or lifting activity.

3. *Hook Time Analysis.* By isolating a specific lifting activity, the SPS tower crane template can be used to help the practitioner better understand a specific lifting activity in order to improve system efficiency.

4. *Scenario Analysis.* When modeling the tower crane production cycle, the practitioner can experiment with different scenarios. Each scenario provides a simple, efficient and simple and cost-effective method of reducing waste in the modeled system.

Traditional computer simulation modeling techniques use relationship logic links to represent the navigation scheme used for the modeling framework. For construction domains that have a repetitive sequence of activities (i.e. earthmoving, tunneling, etc.), logic represented by relationship logic links is very successful. For tower crane operations, each activity occurring in the modeled system does not follow a distinct process flow. Furthermore, as the number of lifting activities increases for the tower crane, the model complexity using traditional relationship logic links becomes unmanageable resulting in limited implementation by industry practitioners. The developed SPS tower crane template lift sequencing uses *priority rating logic control.* This means that for each lift selected, the tower crane will choose the lifting activity with the highest priority that is currently available in the model. The use of priority rating logic verses traditional relationship logic links simplifies the tower crane model domain. The benefits of using priority rating logic control are as follows:

1. Establishes a modeling environment that is easy to create and manipulate by a novice practitioner,
2. Reduces development time for new tower crane construction models, and
3. Prevents the tower crane models from escalating in complexity as the number of lifting activities increase.

7.3 RECOMMENDATIONS

During the design, development and implementation of the SPS tower crane template using priority rating logic control for model process interaction, the following has been noted as recommendations for further research and development.

1. Other construction domains that are similar in nature to tower crane construction should be identified. The development and implementation of SPS templates for non-cyclic activities using priority rating control will serve as another tool that will aide in the continued success of computer simulation in the field of construction.

2. Figure 4-1 in Chapter 4 shows four tower crane types saved in the User Element Library. The number of tower crane types saved in the User Element Library should be expanded to include a wider range of cranes. Once the User Element Library is complete, development is need to create a database that will allow the practitioner to access each crane type using the tower crane input parameters.
3. The SPS tower crane template needs to be modified and tested using mobile crane configurations. The rising or lowering of the boom for mobile cranes is represented by the horizontal trolley movement on the tower crane. Further research is needed to verify if the mobile crane movement can be represented within the constructs of the SPS tower crane template. If not, a separate SPS mobile crane template may need to be developed.
4. The greatest degree of model uncertainty is associated with the tower crane hookup and unhooking times. The need for accurate data collection is essential to the success of computer simulation. It is recommended that the collection of crane hookup and unhook times be emphasized in order to create a database that can be used to enter accurate data into the simulation models. A sound database of historical information needs to be assembled to reaffirm expert opinion and to produce valid model outputs.
5. The development of an optimization algorithm should be developed within the SPS tower crane template in order to optimize the location of the tower crane based on the geographical locations of the source and destination elements, and the quantity of work packages located in each source location.

Through the research outlined above, simulation in tower crane construction will receive wider acceptance in the construction industry by offering a viable decision support system for construction practitioners.

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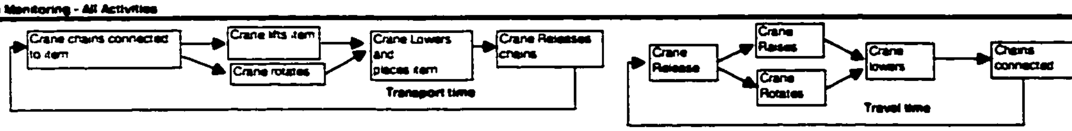
APPENDIX A – TOWER CRANE MONITORING DATA

Crane Monitoring - All Activities



Crane Monitoring - All Activities

Day	Date	Swing (degrees)	Connect Time	Release Time	Transport Time	Travel Time	Description	Location
Monday	19-Jun		11:23				Pick up wall Panel and position wall on East face	
		-		11:36	0:12:00		Release wall Panel and position wall on East face	
		-	11:36:11			0:01:11	Pick up garbage bin in staging area	
		-		11:56	0:19:49		Fill bin with gravel. Take to slab on grad. Bring back. Repeat this 4 times. Release garbage bin at gravel loading area.	
		-	11:57			0:01:00	Pick up timber bundle.	
		-		11:58:46	0:01:46		Release Timbers on P1 slab.	P1 slab.
		-	11:59:45			0:01:00	Pick up needle beam.	
		-		12:02:44	0:02:59		Release needle beam at NW corner	
		-	12:52			0:49:16	Pickup wall panel from slab on grade	NW Corner
		-		12:59:20	0:07:20		Place and position on East foundation wall. P2 to GR.	East Foundation wall.
		-	13:00:13			0:00:53	Pick up garbage bin of gravel	South bank (B)
		-		13:15:20	0:15:07		Filled bin 3 times with gravel before releasing	South bank (B)
		-	13:16:00			0:00:40	Pickup wall panel from side of south bank.	South bank (B)
		-		13:18:10	0:02:10		Released wall panel on side of North bank.	North bank.
		-	13:19:00			0:00:50	Pick up full bin of gravel on south bank	South bank (B)
		-		13:22:49	0:03:49		Release bin on south bank. Take to slab on grade on SE Corner	SE corner, slab on grade.
		-	13:25:44			0:02:55	Pickup bin of garbage on P1 slab. Take to Staging area to unload.	Staging Area (G)
		-		13:31:40	0:05:56		Release Garbage bin on P1 slab	P1 slab
		-	13:32:00			0:00:20	Pick up another bin on P1 slab. Take to staging area to unload.	P1 slab
		-		13:37:16	0:05:16		Release empty bin on P1 slab.	
		-	13:39:39			0:02:23	Pickup bundle of Plydeck	P1 slab on NW Corner
		-		13:42:00	0:02:21		Release plydeck	P1 slab next to ramp.
		-	13:42:20			0:00:20	Pick up bundle of plydeck	P1 slab at pour #5
		-		13:43:52	0:01:32		Release plydeck	P1 slab on Pour #4
		-	13:46:50			0:02:58	Connect to column	Column (F3)
		-		13:48:50	0:02:00		Released column form	P1 slab pour #3
		-	13:50:00			0:01:10	Extrude column form	Column (F3), on P1 slab.
		-		13:52:30	0:02:30		Release column form	P1 slab on Pour #1
		-	13:54:54			0:02:24	Extrude column form	P1 slab on Pour #1
		-		13:56:30	0:01:36		Release column form	P1 slab on Pour #1, lay it down.
Thursday	22-Jun		10:09:30				Rebar Bundles, Off truck	Staging Area (G)
		180 CCW		10:11:31	0:02:01		Rebar Bundle	P1 slab (D4)
		180 CW	10:14:07			0:02:36	Rebar Bundle Off truck	Staging Area (G)
		180 CCW		10:16:40	0:02:33		Rebar Bundle	P1 slab (D4)
		180 CW	10:18:44			0:02:04	Rebar Bundle Off truck	Staging Area (G)
		180 CCW		10:20:38	0:01:54		Rebar Bundle	P1 slab (D4)
		180 CW	10:22:30			0:01:52	Rebar Bundle Off truck	Staging Area (G)
		180 CCW		10:24:15	0:01:46		Rebar Bundle	P1 slab (D4)
		180 CW	10:26:00			0:01:45	Rebar Bundle Off truck	Staging Area (G)
		180 CCW		10:28:15	0:02:15		Rebar Bundle	P1 slab (D4)
		180 CW	10:29:50			0:01:35	Rebar Bundle Off truck	Staging Area (G)
		180 CCW		10:31:06	0:01:16		Rebar Bundle	P1 slab (D4)
		5 CW	10:33:50			0:02:44	Pick up column form	P1 slab (C5)
		-		10:34:24	0:00:34		Lay down column form at same spot.	P1 slab (C5)
		2 CCW	10:35:18			0:00:54	Pick up column form	P1 slab (C5)
		-		10:36:00	0:00:42		Lay down column form at same spot.	P1 slab (C5)
		80 CCW	10:36:50			0:00:50	Pick up column form	P1 slab (D5)
		-		10:37:25	0:00:35		Lay down column form at same spot.	P1 slab (D5)
		35 CCW	10:40:07			0:02:42	Remove P1 Ext wall Panel	F wall (J2)
		10 CCW		10:47:10	0:07:03		Release wall panel. Lay it down.	P1 slab (H3)
		33 CCW	10:50:10			0:03:00	Remove P1 Ext wall form	East side of South stair well. (H5)
		180 CW		10:56:20	0:06:10		Lay down external wall form	P1 slab (C5)
		180 CCW	10:58:27			0:02:07	Remove P1 Ext wall form	East side of South stair well. (J5)
				11:13:35	0:15:08		Lay down external wall form	P1 slab (F4)
Friday	23-Jun		10:28:50				Column form Laying down.	P1 slab (C5)
		15 CW		10:32:58	0:04:08		Place column form	P1 to Gr column (C6)
		60 CCW	10:34:10			0:01:15	Column form Laying down	P1 slab (D4)
		35 CW		10:38:10	0:04:00		Place column form	P1 to GR column (C4)
		180 CW	10:39:50			0:01:40	External Wall panel	East Fwall panel (B8)
		5 CW		10:44:30	0:04:40		External Wall panel	Place on P2 slab (D8)
		35 CW	10:46:20			0:01:50	Pickup timber pieces from carpenters formwork	Staging area (F)
		180 CW		10:48:23	0:02:00		Release on slab	P1 slab (F3)
		15 CCW	10:49:40			0:01:17	Wall panel laying down	P1 slab (H3)
		-		10:55:00	0:05:20		Foundation Wall panel	Place panel on South Ext Wall (J5)
		45 CW	10:58:10			0:03:10	Column form Laying down	P1 slab (E5)
		10 CCW		10:59:40	0:01:30		Release column form	Column (E3)
		-	11:00:30			0:00:50	Column form Laying down	P1 slab (D4)
		130 CW		11:06:25	0:05:55		Place column form	Column (B6)
Tuesday	27-Jun		10:10:00				Connect to outside wall panel on S side of South P1-Gr Stairwell	Fwall P1-Gr (J5)
		30 CW		10:19:40	0:09:40		Place on South bank edge	(J5) laying against slope
		30 CCW	10:20:00			0:00:20	Bracket located at SE corner of S Stairwell	SE Corner of S1 wall (J5)
		180 CW		10:24:50	0:04:50		Release @ NE corner of N Stairwell	(A8)
		270 CCW	10:29:35			0:04:45	Pick up one upright column form	Staging Area (G)
		180 CW		10:32:40	0:03:05		Place on N-Slab. Lay down	P1 Slab (E2)
		90 CCW					Quit to haul concrete buckets	
		[redacted]			0:00:00			P1 Slab (E2)
			11:34:51			11:34:51	Pick up full garbage bin	Staging Area (G)
		165 CCW		11:38:20	0:03:29		Empty bin in garbage (Staging Area (G))	Staging Area (C)
		4 CCW	11:39:40			0:01:20	Pickup corner form in Staging Area	Staging Area (C)
		110 CCW		11:42:50	0:03:10		Release on P1-Slab, lay down	P1 Slab (C5)
		110 CCW	11:44:41			0:01:51	Pickup corner form in Staging Area	Staging Area (C)
		110 CCW		11:47:00	0:02:19		Release on P1-Slab, lay down	P1 Slab (C5)
		-	11:47:10			0:00:10	Pick Corner form from P1-Slab - Laying down	P1 Slab (C5)
		5 CW		11:50:04	0:02:54		Release	West outside face of N Elev. Shaft (B6)
		5 CCW	11:50:20			0:00:16	Pick Corner form from P1-Slab - Laying down	P1 slab (C5)
		5 CW		11:55:02	0:04:42		Place on W side of N elevator shaft	(B6)
		110 CW	11:57:10			0:02:08	Pick up wall panel	Staging Area (C)
		-		11:59:30	0:02:20		Turn over	Staging Area (C)

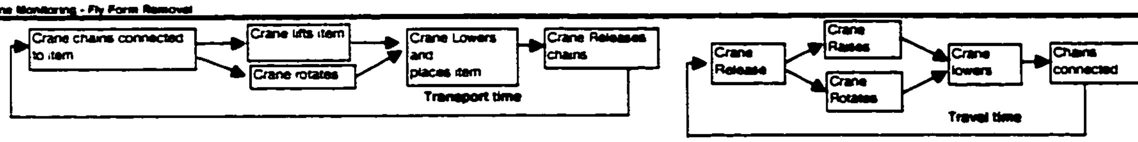
Crane Monitoring - All Activities

[illegible]	[illegible]		13:13:20				Bundle of Rebar (corner pieces)	Staging Area (H)
		15 CW		13:14:32			Release	Staging Area (H1)
		15 CCW	13:15:50			0:01:18	Bundle of Rebar from truck (corner pieces)	Staging Area (H)
		15 CW		13:16:47	0:00:57		Release	Staging Area (H1)
		15 CCW	13:17:27			0:00:40	Bundle of Rebar from truck (corner pieces)	Staging Area (H)
		15 CW		13:20:35	0:03:08		Release	Staging Area (H1)
		15 CCW	13:21:30			0:00:55	Bundle of Rebar from truck (corner pieces)	Staging Area (H)
		15 CW		13:23:22	0:01:52		Release	Staging Area (H1)
		15 CCW	13:24:02			0:00:40	Bundle of Rebar from truck (long bars)	Staging Area (H)
		15 CW		13:26:40	0:02:38		Release	Staging Area (H1)
		15 CCW	13:27:29			0:00:49	Bundle of Rebar from truck (long bars)	Staging Area (H)
		15 CW		13:29:05	0:01:36		Release	Staging Area (H1)
		140 CCW	13:30:16			0:01:11	Wall panel laying down	P1 Slab (D8)
		20 CW		13:41:43	0:11:27		Place on external wall by stairwell	N Wall, inside (A, 4-6) P1-Gr
		130 CW	13:42:55			0:01:12	Bundle of Rebar from truck (long bars)	Staging Area (H)
		15 CW		13:44:00	0:01:05		Release	Staging Area (H1)
		15 CCW	13:44:47			0:00:47	Bundle of Rebar from truck (long bars)	Staging Area (H)
		15 CW		13:47:42	0:02:55		Release	Staging Area (H1)
		15 CCW	13:48:27			0:00:45	Bundle of Rebar from truck (long bars)	Staging Area (H)
		15 CW		13:50:23	0:01:56		Release	Staging Area (H1)
		100 CCW	13:52:50			0:02:27	Bundle of Wood. Misc. All sizes	P1 Slab (C8)
		10 CCW		13:54:15	0:01:25		Place on top of Core shaft formwork	Elev. Shaft @ Gr (B6)
		160 CW	13:56:31			0:01:16	Garbage bin - with gravel	Top of south bars (8)
		13 CCW		13:59:50	0:04:19		Place on slab on grade (A, 8A). Then release	Release @ Slab on grade (F7)
		80 CW	14:01:01			0:01:11	Wall panel laying against S bars	South bars (7)
		110 CCW		14:02:27	0:01:26		Take to Staging Area - Lay down	Staging Area (C)
		190 CCW	14:04:20			0:01:53	Full bundle of Ply decking	P1 Slab (H6)
		15 CW		14:06:00	0:01:40		Place on Gr Slab Formwork	Gr Slab (H3)
		-	14:07:12			0:01:12	W staging area. Prelapsed lumber pieces for Slabs formwork	W Staging Area (H)
		-		14:08:10	0:00:58		Placed on Gr Slab #1	Gr Slab (H3)
		-	14:10:30			0:02:20	Wall Panel	P1 Slab (J - 5)
		30 CW		14:11:45	0:01:15		Release in W staging area	W Staging Area (H)
		30 CCW	14:13:00			0:01:15	Wall panel laying of S bars	S bars (J4)
		30 CW		14:14:23	0:01:23		Release in W staging area	W Staging Area (H)
		30 CCW	14:15:30			0:01:07	Wall panel - laying on S bars	S bars (J4)
		30 CW		14:17:10	0:01:40		Release in W staging area	W Staging Area (H)
		30 CCW	14:18:20			0:01:10	Wall panel - laying against S bars	S bars (J4)
		30 CW		14:20:10	0:01:50		Release in W staging area	W Staging Area (H)
		35 CCW	14:21:21			0:01:11	Wall panel - laying against S bars	S bars (J8)
		146 CCW		14:23:14	0:01:53		Release in E staging area	Staging Area (D)
		146 CW	14:24:30			0:01:16	Wall panel - lay against S bars	S bars (J8)
		35 CW		14:26:30	0:02:00		Release in W staging Area - Lay down	W Staging Area (H)
		45 CCW	14:27:29			0:00:59	Wall panel - laying against S bars	S bars (J8)
		46 CW		14:29:05	0:01:36		Release in W staging Area - lay down	W Staging Area (H)
[illegible]	[illegible]		10:58:07				Help secure a wall panel	(E1)
		-		11:04:18	0:06:11		Help secure a wall panel	(E1)
		180 CCW	11:08:17			0:03:59		Staging Area (G)
		-		11:11:00	0:02:43			Staging Area (G)
		120 CW	11:15:26			0:04:26	Pick up bundle of bars	(G1)
		10 CW		11:16:50	0:01:24		Pick up bundle of bars	(G1)
		120 CCW	11:17:10			0:00:20	Pick up barrel	Staging Area (G)
		120 CW		11:20:32	0:03:22		Release on Gr Slab	(G8)
		120 CCW	11:21:39			0:01:07	Pick up pressure sprayer	Staging Area (G)
		100 CW		11:26:50	0:05:11		Release on Gr Slab	(F4)
		-	11:27:37			0:00:47	Pick up barrel	(G4)
				11:28:49	0:01:12		Release barrel	(G4)
		90 CCW	11:30:10			0:01:21	Pick up bundle of wood	(G8)
		120 CW		11:31:53	0:01:43		Release on Gr Slab Scaffold	(D8)
[illegible]	[illegible]		9:59:56				Bucket of Concrete lifted	South of (J, 5-6)
		3 CCW		10:05:11	0:05:15		Emptied bucket	(J8)
		3 CW	10:07:41			0:02:30	Bucket of Concrete lifted	South of (J, 5-6)
		3 CCW		10:15:43	0:08:02		Emptied bucket	(J8)
		3 CW	10:18:54			0:03:11	Bucket of Concrete lifted	South of (J, 5-6)
		3 CCW		10:21:04	0:02:10		Emptied bucket	(J8)
			10:21:04			0:00:00	Bucket of Concrete lifted	(J8)
		90 CW		10:23:11	0:02:07		Emptied bucket	(E-F, 1-2)
			10:23:11			0:00:00	Bucket of Concrete lifted	(E-F, 1-2)
		37 CCW		10:24:16	0:01:05		Drop off bucket	South of (J, 5-6)
		87 CW	10:24:42			0:00:26	Rebar casing lifted for repositioning	(E-F, 1-2)
				10:27:14	0:02:32		Released	(E-F, 1-2)
		160 CCW	10:28:26			0:01:12	Metal bars lifted	Staging Area (H)
		30 CW		10:29:44	0:01:18		Released	(G8)
		210 CW	10:31:36			0:01:52	Bundle of Wood. Misc. All sizes	(B7)
		10 CW		10:32:56	0:01:20		Released	(C8)
		10 CCW	10:33:41			0:00:45	Metal bars lifted	(B7)
		10 CW		10:35:00	0:01:19		Released	(C8)
		10 CCW	10:35:44			0:00:44	Metal bars lifted	(B7)
		10 CW		10:37:06	0:01:22		Released	(C8)
		10 CCW	10:37:52			0:00:46	Metal bars lifted	(B7)
		10 CW		10:38:57	0:01:05		Released	(C8)
		10 CCW	10:39:36			0:00:39	Garbage bin of wood	(B7)
		90 CW		10:41:23	0:01:47		Released garbage bin	Staging Area (H)
		150 CW	10:43:49			0:02:26	Rebar casing lifted for repositioning	(E-F, 1-2)
				10:44:38	0:00:49		Released	(E-F, 1-2)
		-	10:44:56			0:00:18	Rebar column lifted and positioned (upright)	(E-F, 1-2)
		5 CCW		10:54:47	0:09:51		Released	(F2)
		2 CW	10:55:18			0:00:31	Rebar column lifted and positioned (upright)	(E-F, 1-2)
		2 CW		11:02:52	0:07:34		Released	(E-F, 2)

Crane Monitoring - All Activities

Thursday	27-Jul		10:57:37				Wrapped up bundle of wood	Staging Area (H)
		10 CCW		11:01:01	0:01:24		Released	Staging Area (H)
		10 CW	11:02:45			0:01:44	Wrapped up bundle of wood	Staging Area (H)
		10 CCW		11:04:15	0:01:30		Released	Staging Area (H)
		10 CW	11:05:56			0:01:41	Wrapped up bundle of wood	Staging Area (H)
		10 CCW		11:08:47	0:02:51		Released	Staging Area (H)
		10 CW	11:10:10			0:01:23	Wrapped up bundle of wood	Staging Area (H)
		40 CCW		11:11:40	0:01:30		Released	Staging Area (C)
		40 CW	11:13:28			0:01:48	Wrapped up bundle of wood	Staging Area (H)
		40 CCW		11:15:08	0:01:40		Released	Staging Area (C)
		40 CW	11:17:08			0:02:00	Wrapped up bundle of wood	Staging Area (H)
		40 CCW		11:18:52	0:01:44		Released (Had to prop up bundle because it was right against the truck)	Staging Area (C)
		40 CW	11:22:29			0:03:37	Wrapped up bundle of wood (Positioned wrong initially had to be repositioned)	Staging Area (H)
		40 CCW		11:24:59	0:02:30		Released (Had to prop up bundle because it was right against the truck)	Staging Area (C)
		40 CW	11:28:26			0:03:27	Wrapped up bundle of wood	Staging Area (H)
		30 CCW		11:29:46	0:01:20		Released	Staging Area (H)
		-	11:30:32			0:00:46	Bundle of Wood Misc. All sizes	Staging Area (H)
		150 CW		11:31:50	0:01:18		Released	(E-F, 2)
		30 CW	11:32:16			0:00:26	Rebar bars lifted	(B3)
				11:33:56	0:01:40		Released	(B3)
		25 CCW	11:35:27			0:01:31	Column form lifted	(E2)
		46 CCW		11:39:42	0:04:15		Released	(H2)
		40 CW	11:41:22			0:01:40	Column form lifted	(F2)
		-		11:55:21	0:13:59		Released	(F2)
Monday	14-Aug		11:09:40				Connect to shaft wall panel 2'3" Wide	Main Slab (B3)
		CCW 45		11:11:43	0:02:03		Secure on Ext Wall, Release	(H-8) Main to L1
		CW 46	11:12:30			0:00:47	Pick up Wall Panel	(D-2) Main slab
		CCW 46		11:19:03	0:06:33		Secure on Ext Wall, Release	(G-1) main to L1
		CW 150	11:20:30			0:01:27	Pick up Compressor by service well	(A-8) North Bank staging area
		CCW 180		11:22:05	0:01:35		Release	(F-4) Main slab
		CW 180	11:23:52			0:01:47	Pick up bundle of timber and chips by service wells	(A-8) Services pit
		CCW 180		11:25:41	0:01:49		Release	(F-4) Main slab
		CW 180	11:27:00			0:01:19	Pick up thumper	(A-8) Services pit
		CW 100		11:29:06	0:02:06		Release	East Staging area
		CW 20	11:30:30			0:01:24	Pick up garbage bin	(G-7) Main slab
		CCW 45		11:36:16	0:05:46		Release in garbage bin (large) and return to	Staging Area (C) back to (F4) Main
		CCW 320	11:41:52			0:05:36	Pick up column cage	Main Slab (F-2)
		CCW 46		11:50:33	0:08:41		Place on column (F5)	(F-6) to Main L1
		CW 90	11:52:05			0:01:32	Pick up bundle of old timber	(E-5) Main
		CW 200		11:55:00	0:02:58		Release in Stage Area	(C) Staging Area
Thursday	17-Aug		10:57:39				Wall panel lifted	(B3)
		90 CCW		11:19:33	0:21:54		Wall panel released (and placed)	(G, 1-2)
		100 CCW	11:22:46			0:03:13	Bundle of rebar	Stg Area (H)
				11:24:16	0:01:30		Released	Pour #6 (SE corner)
		150 CW	11:27:02			0:02:46	Wall panel	(F7)
		100 CCW		11:34:17	0:07:15		Wall panel placed and released	(H8)
		80 CW	11:37:02			0:02:45	Wall panel	(E-F, 1)
		10 CCW		11:47:28	0:10:26		Wall panel placed and released	(G, 1-2)
		100 CCW	11:54:21			0:06:53	Second floor - floor panel (put in backwards and had to be redone)	Stg Area (H)
		150 CW		12:10:23	0:16:02		Placed and released	(E-F, 1-5)
Thursday	24-Aug		10:22:15				Bundle of Rebar	Stg Area (H)
		90 CCW		10:24:03	0:01:48		Released on Pour #7 and 8	(C, 8-9)
		90 CW	10:30:55			0:06:52	Scaffolding around column form on Pour #8	(H, 8A)
				10:32:18	0:01:23		Released just behind	(H, 8A)
		-	10:32:43			0:00:25	Stripping column form (1 side)	(H, 8A)
		5 CCW		10:40:01	0:07:18		Released	(H8)
		5 CW	10:42:36			0:02:35	Stripping 2 more sides of column form at once	(H, 8A)
		5 CCW		10:43:58	0:01:22		Released	(H8)
		5 CW	10:44:41			0:00:43	Stripping last side of column form	(H, 8A)
		5 CCW		10:46:41	0:02:00		Released	(H8)
		-	10:48:14			0:01:33	Bundle of Rebar	Stg Area (H)
		90 CCW		10:49:52	0:01:38		Released on Pour #7 and 8	(A, 8-9)
		120 CCW	10:53:03			0:03:11	Rebar column lifted and positioned (upright)	(E1)
		15 CCW		11:15:30	0:22:27		Released	(H1, 1)
		90 CCW	11:24:53			0:09:23	Bundle of Wood Misc. All sizes	Stg Area (H)
		5 CCW		11:25:37	0:00:44		Released	(H8)
		-	11:25:58			0:00:21	1 side of column form lifted for repositioning	(H8)
				11:26:56	0:00:58		Released	(H8)
		120 CW	11:28:17			0:01:21	Rebar column lifted and positioned (upright)	(E1)
		10 CCW		11:40:19	0:12:02		Released	(H1)
Tuesday	29-Aug		12:51:18				Lift Form	Just South of (J8)
		15 CCW		12:56:41	0:05:23		Place on scaffolding in staging area	Stg Area (H)
		-	12:56:41			0:00:00	Supports and stands attached and form lifted	Stg Area (H)
		180 CCW		13:10	0:13:56		Released/placed on pit	(D7)
		165 CCW	13:11:53			0:01:16	Lift Form	Just South of (J8)
		15 CCW		13:15:12	0:03:19		Place on scaffolding in staging area	Stg Area (H)
		-	13:15:12			0:00:00	Supports and stands attached and form lifted	Stg Area (H)
		165 CW		13:49:08	0:33:56		Released/placed on pit	(D-E, 7)
		150 CCW	13:50			0:00:53	Lift Form	Just South of (J8)
		15 CCW		13:54:28	0:04:25		Place on scaffolding in staging area	Stg Area (H)
		-	13:54:28			0:00:00	Supports and stands attached and form lifted	Stg Area (H)
		150 CW		14:07:49	0:13:23		Released/placed on pit	(E7)
		135 CCW	14:09:00			0:01:11	Lift Form	Just South of (J8)
		15 CCW		14:12:11	0:03:11		Place on scaffolding in staging area	Stg Area (H)
		-	14:13:11			0:01:00	Supports and stands attached and form lifted	Stg Area (H)
		135 CW		14:31:56	0:18:45		Released/placed on pit	(E-F, 7)

Crane Monitoring - Fly Form Removal



Fly Form Removal Notes

1. Crane connects 2 chains on end of form just protruding from lower floor of building.
2. Pull fly form straight out so two legs are suspended in mid air while remaining two legs remain on floor
3. Guy gets of Fly form supported by Crane and floor to connect remaining chain to crane with a chain slack adjuster tool.
4. After chain length are altered Fly form completely move off floor and transported.

Day	Date	Turn (degrees)	Connect Time	Release Time	Transport Time	Travel Time	Description	Location
Tuesday	29-Oc		13:05:00				Connect to fly form from L4 (6legs)	L4 AT G6 (From E ledge)
		0		13:24:10	0:19:10		Fly form to L5 (for L6 Pour)	L5 at F5
		90 CW	13:26:00			0:01:50	Connect to fly form from L4 (4legs)	L4 at J5 (from S ledge)
		0		13:34:30	0:08:30		Fly form to L5 (for L6 Pour)	L5 at H- Slab6
		180 CCW	13:36:45			0:02:15	Connect to Fly form sitting on Main slab (being repaired) (4legs)	Main at C7
		180 CW		13:44:20	0:07:35		Straight lift - Fly form to L5 (Pour L6)	L5 at H4
Tuesday	31-Oc		13:24:25				Attach to wall form on E side of N Core	N Core L4 to L5 (G-8)
		30 CW		13:33:30	0:09:05		Place on ground on N side of ETLC	(B) North side of building
		160 CW	13:34:00			0:00:30	Attach to set of I-Beams on Main Slab	(G-6) Main Slab
		160 CCW		13:36:30	0:02:30		Place on suspended platform L2	(B3) L2-Suspend slab
		140 CW	13:37:25			0:00:55	Attach Bundle of timbers for flyforms	South bank ground (7)
		90 CW		13:39:30	0:02:05		Place at L6 Flyforms	L6 (G4)
		-	13:40:50			0:01:20	Pickup heater (Propane)	L6 (G4)
		-		13:41:40	0:00:50		Release heater	L6 (G2)
		-	13:42:40			0:01:00	Pickup heater (Propane)	L6 (64)
[illegible]								
			13:49:00				Pickup bundle flyform legs	L2 (F6)
		100 CW		13:50:40	0:01:40		Release	L5 (D2)
		60 CW	13:53:50			0:03:10	Attach to flyform supporting L5(L4 to L5)	L4 (F6) Flyform L4 to L5
		-		14:06:06	0:12:16		Move to L5-L6 (legs?)	L5(F3) Flyform L5 to L6
		100CW	14:08:30			0:02:24	Attach to flyform supporting L5(L4 to L5)	L4 (D8)
		25 CCW		14:22:30	0:14:00		Move to L5-L6 supporting L6 (2 legs)	L5 to L6 (D8)
		25 CW	14:23:50			0:01:20	Attach to Flyform (L4 to L5) supporting L5 (2legs)	L4 (D8)
		25 CCW		14:43:20	0:19:30		Release on L5 Slab (to support L6)	L5 (D8)

APPENDIX B – SPS TOWER CRANE ALGORITHMS

Parent Element

```
Public Sub CEM_TowerCrane_Parent_OnAfterUpdateParameters(ob As
CFCSim_ModelingElementInstance)


End Sub

Public Function CEM_TowerCrane_Parent_OnCheckIntegrity(ob As CFCSim_ModelingElementInstance)
As Boolean

        If ob("Building_Type")="**Select Building Type**"  Then
                Tracer.TraceEnabled = True
                Tracer.Trace "Must Select a Building Type!"
                CEM_TowerCrane_Parent_OnCheckIntegrity = False
        Else
                CEM_TowerCrane_Parent_OnCheckIntegrity = True
        End If

End Function

Public Function CEM_TowerCrane_Parent_OnCreate(ob As CFCSim_ModelingElementInstance, x As
Single, y As Single) As Boolean

                CEM_TowerCrane_Parent_OnCreate=True
    ob.OnCreate x,y,True
        ob.SetNumCoordinates 2
                ob.CoordinatesX(0)=x
                ob.CoordinatesY(0)=y
                ob.CoordinatesX(1)=x+175
                ob.CoordinatesY(1)=y+175

    ob.AddAttribute "Name","Description",CFC_Text, CFC_Single, CFC_ReadWrite
    ob.AddAttribute "Scale", "Specify Scale of Monitor [1 meter = X
Pixels]",CFC_Numeric,CFC_Single,CFC_ReadWrite,,,".00"
    ob("Scale")="1.0"
    ob.AddAttribute "Hours_Day", "Number of Working Hours per Day (Excluding
Breaks)",CFC_Numeric,CFC_Single,CFC_ReadWrite
                ob("Hours_Day")="8.00"
                ob.AddAttribute "Building_Type","Building
Type",CFC_Text,CFC_ListBox,CFC_ReadWrite
                ob("Building_Type")="**Select Building Type**"
                ob("Building_Type").LimitList=True

                CEM_TowerCrane_Parent_DrawAxis ob

                'Statistics
                ob.AddStatistic "Total_CraneHours","Total No. of Crane Hours",False,True
                ob.AddStatistic "Total_Days", "Total No. of Working Days",False,True

End Function

Public Sub CEM_TowerCrane_Parent_OnDragDraw(ob As CFCSim_ModelingElementInstance)
        ob.OnDraw
End Sub
```

Parent Element(Cont.)

```
Public Sub CEM_TowerCrane_Parent_OnDraw(ob As CFCSim_ModelingElementInstance)

        CDC.RenderPicture "Photo3.bmp",ob.CoordinatesX(0),ob.CoordinatesY(0),175,175
        CDC.ChangeFont "Courier New",11,True,False,False,False


        If ob.Selected Then
                CDC.ChangeLineStyle CFC_DOT,1,RGB(255,0,0)
                CDC.Rectangle ob.CoordinatesX(0)-2,ob.CoordinatesY(0)-
2,ob.CoordinatesX(1)+2,ob.CoordinatesY(1)+2
        End If

End Sub

Public Sub CEM_TowerCrane_Parent_OnListBoxInitialize(ob As CFCSim_ModelingElementInstance, attr
As CFCSim_Attribute, List As Object)

        Select Case attr.Name

        Case "Building_Type"
                List.additem "**Select Building Type**"
                List.additem "Low-Rise (Least of R/V/H)"
                List.additem "Mid-Rise (R+V)"
                List.additem "High-Rise (R+V)"

        End Select

End Sub
Public Sub CEM_TowerCrane_Parent_OnSimulationPostRun(ob As CFCSim_ModelingElementInstance,
RunNum As Integer)

        ob.stat("Total_Days").Collect SimTime*(1/ob("Hours_Day"))
        ob.stat("Total_CraneHours").Collect SimTime
End Sub
Public Sub CEM_TowerCrane_Parent_DrawAxis(ob As CFCSim_ModelingElementInstance)
        Dim NewElement As CFCSim_ModelingElementInstance
        ' delete All child Axis Elements and labels
        For Each NewElement In ob.ChildElements
                If NewElement.ElementType="CEM_TowerCrane_AddAxis" Or
NewElement.ElementType="CEM_TowerCrane_Footprint" Then
                        NewElement.Delete
                End If
        Next
        ' draw coordinate Axis
                Set NewElement=ob.AddElement("CEM_TowerCrane_AddAxis",1,1)
                NewElement.CoordinatesX(0)=0
                NewElement.CoordinatesY(0)=0
        ' draw footprint
                'Set NewElement=ob.AddElement("CEM_TowerCrane_Footprint",1,1)
                'NewElement.CoordinatesX(0)=100
                'NewElement.CoordinatesY(0)=100

End Sub
```

Source Element

```
Public Sub CEM_TowerCrane_Source_OnAfterUpdateParameters(ob As
CFCSim_ModelingElementInstance)
        ob.CoordinatesX(0)= (ob.Attr ("X_Coordinate"))*ob.Parent("Scale")
        ob.CoordinatesY(0)= (ob.Attr ("Y_Coordinate"))*ob.Parent("Scale")
        ob.CoordinatesX(1)= (ob.Attr ("X_Coordinate")*ob.Parent("Scale"))+65
        ob.CoordinatesY(1)=        (ob.Attr ("Y_Coordinate")*ob.Parent("Scale"))+55

        ob.OnDraw
End Sub

Public Function CEM_TowerCrane_Source_OnCreate(ob As CFCSim_ModelingElementInstance, x As
Single, y As Single) As Boolean

                CEM_TowerCrane_Source_OnCreate=True
    ob.OnCreate x,y,True

                If ob.Parent.ElementType <> "CEM_TowerCrane_Parent" Then
                        MessagePrompt "This element is only allowed as child of the Crane Parent
Element !"
                        CEM_TowerCrane_Source_OnCreate = False
                        Exit Function
                End If

                ob.SetNumCoordinates 2
                ob.CoordinatesX(0)=x
                ob.CoordinatesY(0)=y
                ob.CoordinatesX(1)= x+65
                ob.CoordinatesY(1)= y+55

                ob.AddAttribute "Name","Description",CFC_Text, CFC_Single, CFC_ReadWrite
                ob("Name")=""
                ob.AddAttribute "X_Coordinate","X-Coordinate (m)",CFC_Numeric,   CFC_Single,
CFC_ReadWrite
                ob.AddAttribute "Y_Coordinate","Y-Coordinate (m)",CFC_Numeric,   CFC_Single,
CFC_ReadWrite
                ob.AddAttribute "WP_count","",CFC_Numeric,CFC_Single,CFC_Hidden
                ob("WP_count")=0


End Function

Public Sub CEM_TowerCrane_Source_OnDragDraw(ob As CFCSim_ModelingElementInstance)
        ob.OnDraw
End Sub

Public Sub CEM_TowerCrane_Source_OnDraw(ob As CFCSim_ModelingElementInstance)
        'ob.OnDraw True

        CDC.Ellipse
ob.CoordinatesX(0),ob.CoordinatesY(0)+10,ob.CoordinatesX(0)+60,ob.CoordinatesY(0)+50
        CDC.RenderPicture "Source.bmp",ob.CoordinatesX(0)+30,ob.CoordinatesY(0)+15,16,12
        CDC.ChangeFont "Courier New",16,True,False,False,False
        CDC.ChangeTextColor (89)
```

Source Element(Cont.)

```
        CDC.TextOut ob.CoordinatesX(0),ob.CoordinatesY(0),"X"
        CDC.ChangeFont "Arial",12,True,False,True,False
        CDC.TextOut ob.CoordinatesX(0)+11,ob.CoordinatesY(0)+14,"Src"
        CDC.ChangeFont "Arial",12,True,False,False,False
        CDC.TextOut ob.CoordinatesX(0)+4,ob.CoordinatesY(0)+26,ob("Name")
        CDC.ChangeFont "Arial",11,True,False,False,False
        CDC.TextOut ob.CoordinatesX(0)+25,ob.CoordinatesY(0)+38,"(" & ob("WP_count") &")"



        If ob.Selected Then
                CDC.ChangeLineStyle CFC_DOT,1,RGB(255,0,0)
                CDC.Ellipse ob.CoordinatesX(0)-
2,ob.CoordinatesY(0)+8,ob.CoordinatesX(0)+62,ob.CoordinatesY(0)+52
        End If

End Sub

Public Sub CEM_TowerCrane_Source_OnSimulationInitialize(ob As CFCSim_ModelingElementInstance)
        ob.CoordinatesX(0)= (ob.Attr ("X_Coordinate"))*ob.Parent("Scale")
        ob.CoordinatesY(0)= (ob.Attr ("Y_Coordinate"))*ob.Parent("Scale")
        ob.CoordinatesX(1)= (ob.Attr ("X_Coordinate")*ob.Parent("Scale"))+65
        ob.CoordinatesY(1)=       (ob.Attr ("Y_Coordinate")*ob.Parent("Scale"))+55

End Sub
```

Destination Element

```
Public Sub CEM_TowerCrane_Destination_OnAfterUpdateParameters(ob As
CFCSim_ModelingElementInstance)

        ob.CoordinatesX(0)= (ob.Attr ("X_Coordinate"))*ob.Parent("Scale")
        ob.CoordinatesY(0)= (ob.Attr ("Y_Coordinate"))*ob.Parent("Scale")

        ob.OnDraw

End Sub

Public Function CEM_TowerCrane_Destination_OnCreate(ob As CFCSim_ModelingElementInstance, x
As Single, y As Single) As Boolean

                CEM_TowerCrane_Destination_OnCreate=True
    ob.OnCreate x,y,True

                If ob.Parent.ElementType <> "CEM_TowerCrane_Parent" Then
                        MessagePrompt "This element is only allowed as child of the Crane Parent
Element !"
                        CEM_TowerCrane_Destination_OnCreate = False
                        Exit Function
                End If

                ob.SetNumCoordinates 1
                ob.CoordinatesX(0)=x
                ob.CoordinatesY(0)=y

                ob.AddAttribute "DestName","Destination Description",CFC_Text, CFC_Single,
CFC_ReadWrite
                ob.AddAttribute "X_Coordinate","X-Coordinate (m)",CFC_Numeric,   CFC_Single,
CFC_ReadWrite
                ob.AddAttribute "Y_Coordinate","Y-Coordinate (m)",CFC_Numeric,   CFC_Single,
CFC_ReadWrite
                'ob.AddAttribute "Elevation", "Destination Elevation
(m)",CFC_Numeric,CFC_Single,CFC_ReadWrite
                ob("DestName")=""
End Function

Public Sub CEM_TowerCrane_Destination_OnDragDraw(ob As CFCSim_ModelingElementInstance)
        ob.OnDraw
End Sub

Public Sub  CEM_TowerCrane_Destination_OnDraw(ob As CFCSim_ModelingElementInstance)

        CDC.Rectangle
ob.CoordinatesX(0),ob.CoordinatesY(0)+12,ob.CoordinatesX(0)+50,ob.CoordinatesY(0)+40
        CDC.RenderPicture "Destination.bmp",ob.CoordinatesX(0)+30,ob.CoordinatesY(0)+14,18,12
        CDC.ChangeFont "Courier New",16,True,False,False,False
        CDC.TextOut ob.CoordinatesX(0),ob.CoordinatesY(0),"X"
        CDC.ChangeFont "Arial",12,True,False,True,False
        CDC.TextOut ob.CoordinatesX(0)+2,ob.CoordinatesY(0)+13,"Dest"
        CDC.ChangeFont "Arial",12,True,False,False,False
        CDC.TextOut ob.CoordinatesX(0)+5,ob.CoordinatesY(0)+25, ob("DestName")
```

Destination Element(Cont.)

```
        If ob.Selected Then
                CDC.ChangeLineStyle CFC_DOT,1,RGB(255,0,0)
                CDC.Rectangle ob.CoordinatesX(0)-
2,ob.CoordinatesY(0)-10,ob.CoordinatesX(0)+52,ob.CoordinatesY(0)+42
        End If

End Sub

Public Sub CEM_TowerCrane_Destination_OnSimulationInitialize(ob As
CFCSim_ModelingElementInstance)

        ob.CoordinatesX(0)= (ob.Attr ("X_Coordinate"))*ob.Parent("Scale")
        ob.CoordinatesY(0)= (ob.Attr ("Y_Coordinate"))*ob.Parent("Scale")

End Sub
```

Crane Element

```
Public Sub CEM_TowerCrane_Crane_OnAfterUpdateParameters(ob As
CFCSim_ModelingElementInstance)

        ob.CoordinatesX(0)= (ob.Attr ("X_Coordinate"))*ob.Parent("Scale")
        ob.CoordinatesY(0)= (ob.Attr ("Y_Coordinate"))*ob.Parent("Scale")

        ob.OnDraw

End Sub

Public Function CEM_TowerCrane_Crane_OnCreate(ob As CFCSim_ModelingElementInstance, x As
Single, y As Single) As Boolean

                CEM_TowerCrane_Crane_OnCreate=True
    ob.OnCreate x,y,True

                If ob.Parent.ElementType <> "CEM_TowerCrane_Parent" Then
                        MessagePrompt "This element is only allowed as child of the Crane Parent
Element !"
                        CEM_TowerCrane_Crane_OnCreate = False
                        Exit Function
                End If

                ob.SetNumCoordinates 1
                ob.CoordinatesX(0)=x
                ob.CoordinatesY(0)=y

                ob.AddAttribute "Name","Description",CFC_Text, CFC_Single, CFC_ReadWrite
                ob("Name")="**Name Crane**"
                ob.AddAttribute "X_Coordinate","X-Coordinate (m)",CFC_Numeric,  CFC_Single,
CFC_ReadWrite
                ob.AddAttribute "Y_Coordinate","Y-Coordinate (m)",CFC_Numeric,  CFC_Single,
CFC_ReadWrite
                ob.AddAttribute "Type","Crane Type",CFC_Text,CFC_Single,CFC_ReadWrite
                'ob.AddAttribute "Capacity", "Capacity [Tons]",
CFC_Numeric,CFC_Single,CFC_ReadWrite
                ob.AddAttribute "Reach", "Reach [m]", CFC_Numeric,CFC_Single,CFC_ReadWrite
                ob.AddAttribute "Rotation_Speed","Rotation Speed
[rev/min]",CFC_Numeric,CFC_Single,CFC_ReadWrite
                ob.AddAttribute "Vertical_Speed","Vertical Lifting Speed
[m/min]",CFC_Distribution,CFC_Single,CFC_ReadWrite
                ob.AddAttribute "Horizontal_Speed", "Horizontal Speed
[m/min]",CFC_Distribution,CFC_Single,CFC_ReadWrite
                ob.AddAttribute "DestX","DestX",CFC_Numeric,CFC_Single,CFC_Hidden
                ob.AddAttribute "DestY","DestY",CFC_Numeric,CFC_Single,CFC_Hidden
                'ob.AddAttribute "HorzD","Horz",CFC_Numeric,CFC_Single,CFC_Hidden

End Function

Public Sub CEM_TowerCrane_Crane_OnDragDraw(ob As CFCSim_ModelingElementInstance)
        ob.OnDraw
End Sub

Public Sub CEM_TowerCrane_Crane_OnDraw(ob As CFCSim_ModelingElementInstance)
```

Crane Element(Cont.)

```
        CDC.Rectangle
ob.CoordinatesX(0),ob.CoordinatesY(0),ob.CoordinatesX(0)+50,ob.CoordinatesY(0)+50
        CDC.RenderPicture "crane.bmp",ob.CoordinatesX(0)+10,ob.CoordinatesY(0)+2,30,30
        CDC.ChangeFont "Courier New",16,True,False,False,False
        CDC.TextOut ob.CoordinatesX(0),ob.CoordinatesY(0),"X"
        CDC.ChangeFont "Arial",12,True,False,False,False
        CDC.TextOut ob.CoordinatesX(0)+3,ob.CoordinatesY(0)+35, ob("Name")

        If ob.Selected Then
                CDC.ChangeLineStyle CFC_DOT,1,RGB(255,0,0)
                CDC.Rectangle ob.CoordinatesX(0)-2,ob.CoordinatesY(0)-
2,ob.CoordinatesX(0)+52,ob.CoordinatesY(0)+52
        End If

End Sub

Public Sub CEM_TowerCrane_Crane_OnSimulationInitialize(ob As CFCSim_ModelingElementInstance)
        ob.CoordinatesX(0)= (ob.Attr ("X_Coordinate"))*ob.Parent("Scale")
        ob.CoordinatesY(0)= (ob.Attr ("Y_Coordinate"))*ob.Parent("Scale")
        ob.Attr("DestX")="0"
        ob.Attr("DestY")="0"

End Sub

Public Sub CEM_TowerCrane_Crane_OnSimulationInitializeRun(ob As
CFCSim_ModelingElementInstance, RunNum As Integer)
        'ob.Attr("HorzD")="0"
End Sub
```

Work Element

```
Public Function CEM_TowerCrane_Work_Package_OnCheckIntegrity(ob As
CFCSim_ModelingElementInstance) As Boolean

'Check if Work Package Crane is not Selected
        If ob("Crane_Selection")="**Select Crane**" Or ob("Destination")="**Select Destination**"
Then
                Tracer.TraceEnabled=True
                Tracer.Trace "Must Select a Crane & Destination!  " & " [See Work Package: " &
ob("Package_Name") &"]"
                CEM_TowerCrane_Work_Package_OnCheckIntegrity = False
        Else
                CEM_TowerCrane_Work_Package_OnCheckIntegrity = True
        End If

End Function

Public Function CEM_TowerCrane_Work_Package_OnCreate(ob As CFCSim_ModelingElementInstance,
x As Single, y As Single) As Boolean

                CEM_TowerCrane_Work_Package_OnCreate=True
    ob.OnCreate x,y,True

                If ob.Parent.ElementType <> "CEM_TowerCrane_Source" Then
                        MessagePrompt "This element is only allowed as child of the Source Element !"
                        CEM_TowerCrane_Work_Package_OnCreate = False
                        Exit Function
                End If

                ob.Parent("WP_count")=ob.Parent("WP_count")+1

                ob.SetNumCoordinates 2
                ob.CoordinatesX(0)=x
                ob.CoordinatesY(0)=y
                ob.CoordinatesX(1)=x+80
                ob.CoordinatesY(1)=y+65

                ob.AddAttribute "Package_Name","Description",CFC_Text, CFC_Single,
CFC_ReadWrite
                ob.AddAttribute "Lift_Type","Lift Type",CFC_Text,CFC_ListBox,CFC_ReadWrite

                ob.AddAttribute "WPQuantity","Quantity of Work
Packages",CFC_Distribution,CFC_Single,CFC_ReadWrite,,,"0"
                ob.AddAttribute "Arrival", "Time of First Work Package Arrival [Accummulated
Simtime Hours]",CFC_Distribution,CFC_Single,CFC_ReadWrite
                ob.AddAttribute "BetwnArrivals","Time Between Work Package Arrivals
[min]",CFC_Distribution,CFC_Single,CFC_ReadWrite
                ob.AddAttribute "Quantity","Number of Crane Lifts per Work
Package",CFC_Distribution,CFC_Single,CFC_ReadWrite

                ob.AddAttribute "Priority","Priority of Work Task (1-Low,5-
High)",CFC_Text,CFC_ListBox,CFC_ReadWrite
                ob("Priority")="3"
                ob.AddAttribute "Hookup","Time Required to Hookup
[min]",CFC_Distribution,CFC_Single,CFC_ReadWrite
```

Work Element(Cont.)

```
                ob.AddAttribute "Unhook","Time Required to Secure and Unhook
[min]",CFC_Distribution,CFC_Single,CFC_ReadWrite
                ob.AddAttribute "Lift_Elevation", "Vertical Lift Distance
(m)",CFC_Numeric,CFC_Single,CFC_ReadWrite
                ob("Priority").LimitList= True
                ob.AddAttribute "Crane_Selection","Crane
Selection",CFC_Text,CFC_ListBox,CFC_ReadWrite
                ob("Crane_Selection")="**Select Crane**"
                ob("Crane_Selection").LimitList=True
                ob.AddAttribute "Destination","Destination",CFC_Text,CFC_ListBox,CFC_ReadWrite
                ob("Destination")="**Select Destination**"
                ob("Destination").LimitList=True

                ob.AddAttribute "Dst","Find Dest Coordinates",CFC_Object,CFC_Single,CFC_Hidden
                ob.AddAttribute "Crne","Find Crane
Coordinates",CFC_Object,CFC_Single,CFC_Hidden
                ob.AddAttribute "SrcD","Distance from Source to
Crane",CFC_Numeric,CFC_Single,CFC_Hidden
                ob.AddAttribute "DestD","Distance from Destination to
Crane",CFC_Numeric,CFC_Single,CFC_Hidden
                ob.AddAttribute "OppD","Distance from Source to
Destination",CFC_Numeric,CFC_Single,CFC_Hidden
                ob.AddAttribute "Rotation","Required rotation from Source to
Destination",CFC_Numeric,CFC_Single,CFC_Hidden

                ob.AddAttribute "EntityCount","",CFC_Numeric,CFC_Single,CFC_Hidden
                ob.AddAttribute "MDelay","",CFC_Numeric,CFC_Single,CFC_Hidden
                ob.AddAttribute "HDelay","",CFC_Numeric,CFC_Single,CFC_Hidden
                ob.AddAttribute "RetDelay","",CFC_Numeric,CFC_Single,CFC_Hidden
                ob.AddAttribute "Sample","",CFC_Numeric,CFC_Single,CFC_Hidden
                ob.AddAttribute "FirstWP","",CFC_Numeric,CFC_Single,CFC_Hidden
                ob.AddAttribute "LiftSample","",CFC_Numeric,CFC_Single,CFC_Hidden
                ob.AddAttribute "Accum_LiftTime","Accumulated Work Element Lift Time
[hrs]",CFC_Numeric,CFC_Single,CFC_ReadOnly

                'Statistics
                ob.AddStatistic "Waiting","Ave WP Wait Time [min]",False,True
                ob.AddStatistic "Selection_Time","WP Selection Time [hrs]",False,True
                ob.AddStatistic "Ave_LiftDelay","Ave Delay per Lift [min]",False,True
                ob.AddStatistic "WE_LiftTime","Total Work Element Lift Time [hours]",False,True

End Function
Public Sub CEM_TowerCrane_Work_Package_OnDelete(ob As CFCSim_ModelingElementInstance)
        ob.Parent("WP_count")=ob.Parent("WP_count")-1
End Sub

Public Sub CEM_TowerCrane_Work_Package_OnListBoxInitialize(ob As
CFCSim_ModelingElementInstance, attr As CFCSim_Attribute, List As Object)

        Select Case attr.Name

        Case "Destination"
                Dim Dest As CFCSim_ModelingElementInstance
                List.additem "**Select Destination**"
```

Work Element(Cont.)

```
        For Each Dest In ob.Parent.Parent.ChildElements
                        If Dest.ElementType="CEM_TowerCrane_Destination" Then
                                List.AddItem Dest("DestName")
                        End If
                Next

        Case "Priority"
                List.additem "1"
                List.additem "2"
                List.additem "3"
                List.additem "4"
                List.additem "5"

        Case "Crane_Selection"
                Dim crane As CFCSim_ModelingElementInstance
                List.additem "**Select Crane**
                For Each crane In Elements
                        If crane.ElementType="CEM_TowerCrane_Crane" Then
                                List.AddItem crane("Name")
                        End If
                Next
        End Select
End Sub

Public Sub CEM_TowerCrane_Work_Package_OnDragDraw(ob As CFCSim_ModelingElementInstance)
        ob.OnDraw
End Sub

Public Sub CEM_TowerCrane_Work_Package_OnDraw(ob As CFCSim_ModelingElementInstance)

        CDC.Rectangle ob.CoordinatesX(0),ob.CoordinatesY(0),ob.CoordinatesX(1), ob.CoordinatesY(1)
        CDC.RenderPicture "bolt.bmp",ob.CoordinatesX(0)+ 24,ob.CoordinatesY(0)+18,30,30
        CDC.ChangeFont "Arial",12,True,False,False,False
        CDC.TextOut ob.CoordinatesX(0)+3,ob.CoordinatesY(0)+50, "{" & ob("Package_Name") & "}"
        CDC.TextOut ob.CoordinatesX(0)+3, ob.CoordinatesY(0) +3, "Work Element"
        CDC.TextOut ob.CoordinatesX(0)+60, ob.CoordinatesY(0)+25, "(" & ob("Priority") & ")"

        If ob.Selected Then
                CDC.ChangeLineStyle CFC_DOT,1,RGB(255,0,0)
                CDC.Rectangle ob.CoordinatesX(0)-2,ob.CoordinatesY(0)-
2,ob.CoordinatesX(1)+2,ob.CoordinatesY(1)+2
        End If

End Sub

Public Sub CEM_TowerCrane_Work_Package_OnSimulationInitialize(ob As
CFCSim_ModelingElementInstance)

ob("EntityCount")=0


'Find Specified Destination Element Location
Dim elmnt As CFCSim_ModelingElementInstance
        For Each elmnt In Elements
```

Work Element(Cont.)

```
                If elmnt.ElementType="CEM_TowerCrane_Destination" Then
                        If elmnt("DestName") = ob("Destination")Then
                                Set ob("Dst").Reference= elmnt
                        End If
                End If
        Next

'Find Crane Element Location
Dim crane As CFCSim_ModelingElementInstance
        For Each crane In Elements
                If crane.ElementType="CEM_TowerCrane_Crane" Then
                        If crane("Name") = ob("Crane_Selection") Then
                                Set ob("Crne").Reference= crane
                        End If
                End If
        Next

'Find Required Calculation Distances
Dim SrcD As Single
Dim DestD As Single
Dim OppD As Single
Dim Rotation As Single
Dim X1,Y1,X2,Y2,X3,Y3 As Single

        'Source Coordinates
        X1= ob.Parent("X_Coordinate")
        Y1= ob.Parent("Y_Coordinate")
        'Crane Coordinates
        X2= ob("Crne").Reference("X_Coordinate")
        Y2= ob("Crne").Reference("Y_Coordinate")
        'Destination Coordinates
        X3= ob("Dst").Reference("X_Coordinate")
        Y3= ob("Dst").Reference("Y_Coordinate")

        'Find Distance from Source to Crane equal to SrcD
        SrcD = ((X2-X1)^2 +(Y2-Y1)^2)^0.5
        ob("SrcD")= SrcD
        'Find Distance from Destination to Crane equal to DestD
        DestD = ((X2-X3)^2 +(Y2-Y3)^2)^0.5
        ob("DestD")= DestD
        'Find Distance from Destination to Source equal to OppD
        OppD = ((X1-X3)^2 +(Y1-Y3)^2)^0.5
        ob("OppD")= OppD
        'Use Law of Cosines to find angle of Crane Rotation
        Dim Z As Single
        Z = ((SrcD^2+DestD^2-OppD^2)/(2*SrcD*DestD))
        Rotation = Atn(-Z / Sqr(-Z * Z + 1)) + 2 * Atn(1)
        ob("Rotation")=Rotation
'MessagePrompt "Source:" & ob.Parent("Name") & ",OppD:" & OppD & ", DestD:" & DestD & ", SrcD:"
& SrcD & ", Rot:" & Rotation
End Sub

Public Sub CEM_TowerCrane_Work_Package_OnSimulationInitializeRun(ob As
CFCSim_ModelingElementInstance, RunNum As Integer)
```

Work Element(Cont.)

```
        ob("EntityCount")=0
        ob("Accum_LiftTime")=0

'Sample Arrival time of First Work Package
        ob.Attr("FirstWP")= ob.Attr("Arrival")

'Sample the number of work packages and round the value
Dim Q As Single
        Q = ob.Attr("WPQuantity")
        'MessagePrompt "random sample = " & Q
        Q=Round(Q,0)
        'MessagePrompt "rounded = " & Q
        ob.Attr("sample")=Q

End Sub

Public Sub CEM_TowerCrane_Work_Package_OnSimulationPostRun(ob As
CFCSim_ModelingElementInstance, RunNum As Integer)
        ob.stat("WE_LiftTime").Collect ob.Attr("Accum_LiftTime")

End Sub
```