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Methodology for the economic assessment of construction innovation

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Methodology for the Economic Assessment of Construction Innovations: Simulation of Structural Steel Erection

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Abstract

This thesis presents the methodology and results of the analysis of the economic impact of selected advanced construction technologies for the erection of steel structures. The research was conducted at the National Science Foundation's Center for Advanced Technologies for Large Structural Systems (ATLSS) as part of project ADC-11, Economic Assessment of an Integrated Building System. The objectives of this research are to develop a methodology to systematically evaluate construction innovations, and to apply it to assess advanced construction technologies for structural steel erection. The methodology consists of three models which together simulate the specific tasks necessary for the erection of steel structures. The first model is a representation of the process flow of the tasks and activities required for the structural steel erection process. The second model estimates the duration of tasks by using resource combinations and production rates adjusted to site conditions. The third model merges the first two models to provide a dynamic simulation, providing the daily status of a project. Duration, cost and safety requirements are addressed in this third model. The simulation methodology is used to assess eight advanced construction technologies for structural steel erection. The detailed changes that these technologies might bring are examined and compared to a baseline scenario of a prototype building erected by standard methods. The results provide insights into the cost, scheduling and safety implications of each technology. Opportunities for future research and development to improve structural steel erection are also identified. Future research should be directed towards programming the models with an object-oriented language, and expanding the simulation to include other construction activities.

Chapter 1

Introduction

Despite its reputation for slow technological change, innovations are frequently introduced into the construction process. Recent studies have concluded that construction is being reshaped by new technologies. The construction industry has responded to requirements to reduce costs and improve quality through utilizing its skilled labor, specifically through innovating on-site (Slaughter, 1993). Some construction tasks are relatively well structured and sufficiently repetitive to be automated or robotized. It is strongly believed that with higher automation of the construction industry, productivity, cost, quality and safety can be improved. The research problem addressed in this thesis is how to assess the economic impacts of utilizing these innovations. In particular, this thesis studies the economic benefits of utilizing advanced construction technologies in the structural steel erection process.

The economic assessment of construction technologies may be treated with different approaches. Classical economic analyses for the benefits and costs, such as initial investment, maintenance and operation for a given time horizon and minimum accepted rate of return, have been used for the assessment of new technologies

(Warszawski, 1990). Other authors have used prior-use evaluation models for the economic analyses (Neil, Salomonsson and Skibniewski, 1993). In this thesis, the systems approach will be used to assess the economic impact of utilizing eight different structural steel construction technologies.

Structural steel erection is a process that depends on many decisions made on the design and fabrication of the structure. Therefore, this research emphasizes establishing relationships between design, fabrication, safety and management with all tasks of the erection process. As part of the Advanced Integrated Building System (AIBS) project at the ATLSS Research Center at Lehigh University, this thesis shows that construction innovations can be assessed by using three simulation models which integrate issues of productivity, cost and safety. The AIBS concept provides the means to design, fabricate, and erect cost-effective building systems with a focus on providing a computer-integrated systems approach. The long-term intent of this program is to lead to a family of structural systems with enhanced fabrication and erection characteristics, an automated construction system incorporating power tools capable of transporting, positioning, and/or connecting construction materials at the job site, and sensor systems which gather and process information for the successful conclusion of the construction process as well as the monitoring of building life-cycle performance (ATLSS, 1990).

1.1 Objectives

One of the objectives of this thesis is to develop a methodology to systematically assess the economic impact of using new construction technologies. The need for such a methodology has become apparent since innovations are often assessed empirically by experienced construction professionals, thereby introducing uncertainty to the assessment. Field trials is another method of assessing innovations. However these trials usually involve high risk.

Another objective of this thesis is to apply the models to assess eight construction technologies which enhance the current methods of erecting structural steel. The assessment is done for duration, cost and safety. Each of the technologies is compared to a baseline case which simulates the construction of a prototype building erected using standard methods. The eight technologies are: the ATLSS Connector, a self-aligning connector; the Stewart Platform, a remotely controlled panel which gives additional degrees of freedom to cranes; the Mighty Jack, a hoisting equipment that sets beams; the Auto-Claw, Auto-Clamp, and Mighty Shackle Ace, crane attachments used in the unhooking tasks at construction sites; the Shear Stud Welder, a programmed equipment which automatically welds shear studs; and a welding robot used in the field to weld beam flanges to columns.

1.2 Research Significance

Three contributions to project planning are presented in this thesis. First, structural steel erection is examined in minute detail to accurately model the impact of using new technologies. Second, the models capture the dynamics and complexity of activities performed on-site. Finally, the models explicitly incorporate safety measures that comply with OSHA regulations.

The approach used to assess new construction technologies with the three simulation models is a systematic methodology that enables the objective analysis of construction innovations. The models complement existing project planning and control techniques, such as scheduling, cost estimation and cost control, while representing the dynamics on the site. The models are flexible and can adapt to the characteristics of different projects. Appropriate production rates for different tasks that the technologies may introduce to the process flow of construction activities are easily adjusted.

The assessment that results from utilizing the models consists of the main issues considered in construction economics: duration, cost and safety. By assessing technologies in this proposed way, the impacts of introducing new technologies on the operational dynamics of construction activities can be identified. Modifications to emerging technologies can also be identified. Finally, the need for new technologies for the automation of certain tasks can be recognized.

1.3 Research Approach

The research approach used in this thesis was to analyze and model detailed tasks associated with specific construction activities in the structural steel erection process. The research thus required the identification of tasks and task interrelationships, resources, production rates and site factors. Other aspects such as safety and structural stability were incorporated into the analysis of the dynamics of the erection process. To capture all this richness present at the sites, this research heavily relied upon site observations and collaboration with industry experts.

The structural steel erection process was finally simulated with a set of three models which capture the intricate processes present at the site. The term *simulation* denotes the representation of the dynamic flow of activities in the erection process.

1.4 Research Results

The results of this thesis consist of the development of the three models, the presentation of the economic impact from utilizing each of the construction technologies, and the identification of opportunities for future research and development.

The models which were developed are: a representation of the process flow describing the sequence of tasks in structural steel erection of buildings, a productivity/resource tabulation of time estimates for the activities in the erection process, and a dynamic interrelation of daily task times combined with safety and stability constraints to simulate the erection process. A safety module included in the third model was developed to compute a danger index which is used to compare the safety performance of each of the technologies.

Each of the models has its limitations and must be complemented with the other models. The process flow model, which deals with the description of all of the detailed tasks in structural steel erection, does not produce a quantifiable output. This lack of output resulted in the development of the second model which quantifies all structural components like bolts, inches of weld, members, deck sheets and bays. A spreadsheet containing a list of production rates and resource components computes the time needed to perform each of the stages. These computations are based on the linear expression:

$$T=P\bullet N,$$

in which P, the production rate at which a specific activity is performed, and N, the number of elements to be set in the referenced activity, are multiplied to obtain the duration, T, of performing the activity. Although this second model does provide an output, the output is said to be *static*. The computed times are merely a series of times that have been grouped into the major stages of the erection process. The times do not reflect the daily overlap and relationships of the activities at the site. This limitation is, however, overcome with the third model which uses the output of the second model and the conceptual guidance of the first model to obtain the daily and *dynamic* simulation of all the activities.

This thesis presents the results of assessing eight advanced construction technologies which enhance the standard method of structural steel erection. The eight technologies can generally be viewed as beneficial to the steel construction process. They all represent higher concerns in safety, and in some cases induce lower costs as compared with the current methods of erecting structural steel. The magnitude of these savings, and the implications for changes to the dynamic process differ among the technologies. The ATLSS Connector, for example, performed efficiently in the duration, cost and safety analyses. The Mighty Jack also exhibited benefits, specifically in the duration and cost aspects. Finally, all the technologies showed higher safety than the standard methods of erection.

New directions in research should focus in modifying current technologies and in identifying new automation techniques. Discussion on how each of the technologies can provide insight into the identification of other activities that can be automated is presented in Chapter 5.

1.5 Organization of Thesis

The background literature presented in Chapter 2 concentrates on erection procedures, construction simulation, and safety guidelines. Chapter 3 discusses the methodology used in this research, and describes the data collection through interviews with industry experts and site visits. The models providing the systematic means for the assessment of new construction technologies are presented in Chapter 4. The assessment of eight advanced construction technologies for structural steel erection is presented in Chapter 5. As a baseline for comparison, the models are used to assess the erection of a prototype building under standard methods of construction. Then each of the technologies is analyzed with respect to the baseline case. Finally, the conclusions are presented in Chapter 6. Supplementary information is available in the appendices. Appendix A includes the flow model. Appendix B includes the productivity/resource model spreadsheet. Appendix C includes another spreadsheet used for the dynamic daily simulation model. Finally, Appendix D lists the names of industry members who contributed in the development of this research.

Chapter 2

Background

The need for a systematic procedure for comparing technological alternatives has prompted developments in several fields. Different methods to compare the use of certain alternative technologies examine the impact of these technologies on construction processes and flows (Warszawski, 1990). Experimenting with the models developed in this research can provide understanding of the operational use of several construction technologies. This understanding may be achieved without actually testing a given technology on the field, thus making the simulation of construction activities extremely valuable when it comes to the assessment of different alternatives for a given structure.

The primary background required for this research is the understanding of the standard procedures, tools, equipment and methods for erecting steel structures. Several texts proved invaluable in the formulation of the flow diagram and the productivity/resource models. For the development of the safety module of the third model, industrial safety manuals were extremely helpful. Other background information which addressed quantitative and qualitative aspects of construction work was found in reports published by the Construction Industry Institute. A report to the Construction

Industry Institute presents a methodology for identifying automation opportunities in construction. The methodology is based on literature search, field data collection and industry experts interviewing (Tucker *et al.*, 1990). This research uses such a methodology for the development of the three simulation models.

The following sections of this chapter discuss the information sources utilized in this research under three different topics: construction simulation, structural erection, and industrial safety.

2.1 Construction Simulation

Progress in the development and application of computer-aided design and engineering packages has been prodigious over the last decade. Advancements in computer hardware have made three-dimensional representation of designed elements possible, and increasingly the design specifications are directly transferred and used in the fabrication and manufacturing of the components. This has held true in many industries, including steel fabrication, where many repetitive actions like cutting steel members to length have been automated. Unlike manufacturing, however, construction *in situ* is not as repetitive and must respond to changing site conditions that are absent in manufacturing environments. Therefore, the potential economies that can be gained from the application of CAD/CAE packages in construction cannot be directly extrapolated from those observed in some manufacturing industries.

Simulation is the representation of the dynamic flow of production processes. Simulation models provide insight into the nature of real systems, and are a means to evaluate alternatives. Research on computer-based simulation models for construction processes has developed along several themes. The first is characterized by the cyclic activities in construction. A commercially available simulation model, MicroCYCLONE, developed by D.W. Halpin at Purdue University, has been used in several simulation analyses (Vanegas, Bravo, and Halpin, 1993; Cheng and O'Connor, 1993; and Huang and Halpin, 1993). The cyclic activities are modelled through subroutines; and by defining the tasks, processes and associated resources, this simulation model allows analysis of alternative construction procedures with time as the dynamic element. The efficiency of the resource use is also a primary factor of concern. This type of simulation model, however, relies heavily upon the repetition of certain activities, thereby more closely resembling manufacturing processes. In addition, this type of simulation is concentrated on the efficiency of the resources employed rather than the specifics of the design, in which specific components (*e.g.* members, decking sheets, bolts, welds) need to be fully described.

A second theme for construction simulation models has been the expansion of three-dimensional graphical representations to include the construction processes themselves, rather than only the design of the facility (Stouffs *et al.*, 1993). Several applications of this type of simulation particularly explore issues such as clearances for the installation of large equipment. The placement of the hoisting equipment and the sequence of assembly of building elements can be evaluated through these simulation studies. At this point, these simulations can only be laboriously assembled from still images from the CAD/CAE package. This problem will probably be corrected over time. In addition, this type of simulation assumes a certain set of resources and uses a pre-established general sequence. Moreover, it focuses on the construction process alone rather than in conjunction with the exploration of design alternatives.

The third theme for construction simulations examines the flow of activities with their associated required resources using object-oriented modeling (Oloufa, 1993). The linking of design and construction for resource utilization is also addressed in this type of model (Tommelein, Carr, Odeh, 1994). This type of simulation does allow the modeling of non-repetitive activities, related to different types of resources. Tying the description of the system to the resources provides a certain accuracy, but may not be as flexible when the nature of the resources themselves shifts dramatically or may be unknown, such as with a new technology that significantly alters the flow of an activity.

While many of these simulation models provide vital output for the comprehension and control of the construction of facilities, most of them appear to exclude a significant portion of traditional simulation theory, the probability functions for the input variables. In construction-related areas, the most popular application of these probability-based simulation models have been for cost contingency and other measures of capital risk (Newnan, 1980; Marshall, 1988). The expansion of this probability-based approach to the sequence of events as well as the utilization of resources is an area currently unexploited.

2.2 Structural Steel Erection

The primary sources of information on structural erection that were used in this research are technical references for professionals in the industry. One category of reference material provided information about the processes for the erection of steel structures. The second category provided both data and analysis methods of construction productivity.

The references for steel erection were relatively plentiful (Oppenheimer, 1960; Rapp, 1968; Cherry, 1974; Allen, 1985; Hart *et al.*, 1976; Peurifoy, 1958; Schueller, 1990; and Taranath, 1988). Interestingly, many of the texts written over thirty years ago were still accurate in their description of the process and tools used in steel erection. Two in particular (Oppenheimer, 1960; and Rapp, 1968) provided detailed descriptions of the site activities for steel erection. Additional references provided insight into the daily activities of structural steel erection:

> "...the flow of fabrication, transportation from the shop to the site, accessibility of site, the handling of materials, the size and location of the storage space on the site, the energy supply sources, the process of assembly, the capacity and position of the erection equipment, the availability of local materials and construction expertise." (Schueller, 1990)

Others provided a view into the potential difficulties in collecting data and following the flow process of the tasks at a site:

> "trying to follow the activities of every worker at the site may seem unattainable. The different gangs [...] are in each others' way; [...] the plumber-ups dispute among themselves [...] , and the connectors argue with

> each other, [...] and while it is interesting to work with
> these differences, it is also slow." (Cherry,1974)

Still other references emphasized the interaction between the fabrication and erection activities, and the advantages of each (Allen, 1985).

Additional sources provided necessary information for the early estimation of productivity in steel erection (Drewin, 1982; Business Roundtable, 1985, 1986, 1987; Silver, 1986; Oglesby *et al.*, 1989; Thomas, Horner and Smith, 1990; and Thomas and Kramer, 1988). Some of these parameters are analyzed in the determination of a factored productivity described in Chapter 4. One source specifically mentions the following variables in the measurement of productivity in construction: "size of project, material used, quality requested, location, type of project, climate, skills, resources and the union" (The Business Roundtable, 1985).

While the erection process for steel structures is a complex activity that makes use of many different types of resources, the three models developed in this research attempt to provide a systematic approach that incorporates the regular sequence of activities, the specificities of different designs, and the mobilization of resources. Building upon the experience in the industry, this research attempts to replicate the usual and unusual attributes of steel erection.

2.3 Industrial Safety

Construction involves many potential hazards to workers and equipment, such as heat, noise, wind, dust, vibrations, impact and toxic chemicals. Although the Occupational

Safety and Health Administration (OSHA) has been established in the United States to ensure safety, the responsibility ultimately rests with management to provide safe working conditions.

The element of safety is a factor that should be considered in each phase of the design and construction of a project. Safety has become a major concern in all industrial analyses, and has proven to reduce costs. The main conclusion that has been reached is that with a control of safety, productivity and costs will be decreased. Because "the workers are the most valuable asset the company has; and their safety, comfort, welfare and good will are essential to the company's success," this research focuses on the workers' exposure to danger as explained in Chapter 5 (Williams, 1927).

For accident prevention, it is necessary to know how and why accidents occur. To serve these ends, accident statistics must be analyzed by cause of accident. These causes are based upon an analysis of site conditions that are correlated with the occurrence of accidents (Heinrich, 1959). This research bases its safety module on the third model on Heinrich's scale of accident injuries. Most of the accidents can be categorized into any of the ten categories he listed, as indeed the Bureau of Labor Statistics does for its annual industrial accident reports. Percentages of total reported accidents are listed for each of the ten categories.

A proposed safety system indicates that five general variables influence the balance of the safety system: job environment, workman, protection, mechanical-hazard elimination, job conditions. If one of the variables is neglected or is deficient, the entire network is out of balance (Parker and Oglesby, 1972).

Accident costs include medical costs, premiums for compensation benefits, liability, and property loss. Other significant costs include the cost of lost time of the injured employee, the cost of work stoppage of the employees due to an accident, and the lost supervisory time (Oberlender, 1993). Workman's compensation rates have been included in the analyses of the costs when analyzing each of the advanced construction technologies. It will be seen in the assessment of these technologies that with safer technologies, lower costs and higher productivities can be achieved.

Chapter 3

Research Methodology

The methodology used for the development of the models that simulate the structural steel erection process was chosen to solve two main concerns. The first problem to be addressed was the identification and relation of major and minor activities in the erection of a structure. The sequence in which activities occur is the essence of the problem this research tries to analyze. To fully understand the erection process, it is necessary to understand that many activities occur simultaneously. It is common to have two or three activities going on at the same time. For example, while a subcrew is setting the steel, there are other workers who, directed by the supervisor, perform certain activities to prepare the equipment for later use. Similarly, it is common to have three subcrews working in parallel. One subcrew could be setting steel, another one bolting, and even a third one decking. This issue is important in the analysis of idle time which will be discussed in section 3.2.2.

Hopefully, the accurate economic feasibility studies of new construction technologies will trigger changes in the flow of the sequences to achieve lower costs and decrease the time to erect structural steel. The ATLSS Connector, for instance, may induce changes in the flow of activities. For example, it is very attractive to assemble a complete floor of 25 feet by 25 feet with four or six perimetral ATLSS connectors, and then raise the assemblage into position. Bolting would occur on the floor, increasing the productivity and safety. As a matter of fact, this solution was used in a joint project between Lehigh University and Du Pont in New Johnsonville, Tennessee. Three lifts of preassembled floor and roof panels were erected using the ATLSS connectors.

The second problem this research addressed was to obtain the production rates at which the activities and tasks are performed for a given set of resources. In addition to the flow of tasks, productivity rates are needed so that the simulation can include a duration dimension. Establishing production rates is a deterministic method; and to accurately simulate projects, the models must include a probabilistic dimension. A qualitative description of the parameters which may affect productivity is currently being accepted by some companies in addition to the classical time-independent productivity analyses. These effects on productivity are introduced in this research by the use of the parameter factor described in section 4.3.3. The factor is meant to adjust the production rates as the site conditions change throughout the duration of a project.

The approach used to solve these two problems is a methodology using primary information. Feedback from industry experts and direct observation at erection sites were selected as the two main sources of information. Any interaction between design, fabrication, erection and management was considered as a source of information necessary for the creation of the models. Sections 3.1 and 3.2 are each separated into the information regarding the flow of activities and the production rates.

3.1 Industry Members

Information from industry experts was extremely valuable in complementing the initial information that had been gathered from the literature. Two books that deal with the phases of structural steel erection were studied to gather the initial information needed to create the erection flow diagram (Oppenheimer, 1960; Rapp, 1968). The sequences followed at the site today are essentially the same as those discussed in these references over 25 years ago, a reason in itself for considering advanced construction technologies for the erection process.

Table 3.1 lists the industry members that provided the most detailed information. The approach used to collect this information was to mail an initial form of the first two models for comments and revisions by thirty-five industry experts. A complete list of participating experts is included in Appendix C. Following this, the industry members were interviewed about the information they had previously received. Finally, a questionnaire to standardize the collection of information was sent to them.

Designs of a prototype structure with four variations were sent to selected steel fabrication and erection companies to determine the relative costs of fabrication and erection. A detailed description of this prototype building is given in Chapter 5, and it will be used as a baseline for the assessment of the advanced construction technologies. At this point, a brief description suffices. The structural system of the prototype building consists of a series of two-span frames which are four stories high. The frames are orthogonally connected by infill and bracing beams.

Table 3.1: Industry Members

Name	Company	Location
Mr. Robert Abramson	Interstate Ironworks Corporation	Whitehouse, NJ
Mr. Arthur Aubin	Yonkers Contracting Company	Yonkers, NY
Mr. Jim Avery	Havens Steel Company	Kansas City, MO
Mr. Edward Becker	Lehigh University	Bethlehem, PA
Mr. Milt Gore	Du Pont Engineering	Newark, DE
Mr. Tim Horst	Bechtel Corporation	Gaithersburg, MD
Mr. Jay Larson	Bethlehem Steel Corporation	Bethlehem, PA
Mr. John McMahon	Institute of the Ironworking Industry	Washington, DC
Mr. Brett Paddock	Falcon Steel Company, Inc.	Wilmington, DE

The prototype structure variations sent to the companies were: 1) standard bolted connections, with seated connections in the frames and simple connections for the bracing and infill beams between the frames; 2) semi-rigid composite connections using standard shear and seat angles. 3) semi-rigid composite connections using the ATLSS connectors; 4) semi-rigid composite connections using the ATLSS connectors in conjunction with the use during erection of the Stewart Platform. Four companies responded with cost or time estimates. The range of costs for the different alternatives varied with estimates ranging from adding 6 percent to the costs, to saving over 20 percent, with respect to the first alternative.

To explore the rationale behind the variations, interviews with members of the companies that responded indicated that different assumptions were made for the estimates. The need to develop a systematic way of comparing the impact that new technologies might have became apparent at this point. The plans for the prototype building for only the standard connections alternative were sent to a larger sample of fabrication and erection companies. This time they were asked for the determinants of their estimates, such as the way in which they decide erection sequences of activities and their productivity goals. A questionnaire covering several issues which would be conducive to enhancing the models was then formulated. Answers by five industry members which were interviewed in depth provided a verification of the proposed models.

3.1.1 Flow of Erection Process Obtained From Industry Members

Valuable information related to the process of steel erection was collected. Assigning different subcrews to different activities, having the permanent connection activities always lagging behind the erection stage activities, complying with existing OSHA regulations, having parallel occurrence of different stages, providing stability to the structure after completing any erection unit, and using factor productivity in the planning stage prior to construction were invaluable information provided by the industry experts.

The respondents emphasized the importance of specific OSHA regulations. For example, shared bolts and slip bolts are dangerous for the ironworkers, especially if the workers are inexperienced. This means that the use of these bolts should be avoided during the design stage. During erection, OSHA regulations require that a minimum of two bolts be connected at each end of the erected member. This is accounted for in the productivity/resource model. Also, in the scheduling of activities, it should be considered that two levels under the floor on which erection is going on, the deck must be completed. This measure prevents falls from higher elevations than 32 feet.

3.1.2 Production Rates Obtained From Industry Members

From the interviews with industry members, it was concluded that the industry standard is approximately 60 structural members erected in one day by a subcrew consisting of one crane, one crane operator and three ironworkers (two erectors and one person hooking). Other subcrews of two ironworkers are estimated to connect 100 bolts per person per day. Similarly, a different subcrew of two ironworkers can install the decking, welding 2000 studs per day and laying 120 sheets per day.

It was also noted that bolting and welding productivities are dependent on the depth of the beam, since an ironworker sitting at the top flange may not reach the bolt holes on the lower flange. Height of the building is also a factor since materials handling up and down a tall building slows down certain production rates.

3.2 Site Visits

The fifteen visited sites provided an excellent complement to the literature search and to the information provided by the industry experts. Table 3.2 lists the sites and their locations in the order in which they were visited. Different structural systems were encountered, such as pre-engineered gable frames, multi-story buildings, joist and rolled beam composite decks, and tubular columns framed with rolled I-beams. As with the industry members, the objectives for visiting the sites were to gather information on the flow of activities and to collect production rates. Other data collected at each of these sites included a description of the site conditions, the structural system of the facility and safety requirements.

Table 3.2: Visited sites in chronological order

SITE	LOCATION
Lehigh University Indoor Tennis Courts	Bethlehem, PA
Breathalizer Plant	Bethlehem, PA
Church	Bethlehem, PA
Watchtower Parking Garage	Brooklyn, NY
Store	Quakertown, PA
Home Depot	Whitehall, PA
Mutual of America Bank	Manhattan, NY
Chanel Building	Manhattan, NY
MBNA Building	Wilmington, DE
Addition to Sacred Heart Hospital	Allentown, PA
Court House	Allentown, PA
Du Pont Chemical Plant	New Johnsonville, TN
CVS Drugstore	East Stroudsburg, PA
Ashland Chemical	Easton, PA
Martin Marietta Building	Philadelphia, PA

3.2.1 Flow of Erection Process Obtained From Site Visits

After reviewing the literature, interviewing the industry experts and visiting the sites, the units of work were classified as *stages, activities* and *tasks.* The cyclic, sequential and parallel nature of the process became more apparent as the research progressed with the site visits. By the time the Du Pont chemical plant was visited, all the gathered information to that point was verified in the observation of the activities during the erection process.

3.2.2 Production Rates Obtained From Site Visits

The production rates not only depend on the resources, but on the idle times caused by the intricate flow of different tasks and activities. The utilization of resources was carefully analyzed to obtain the production rates of all the tasks and activities. However, when compared to the production rates obtained from the industry experts, the time measurements of several tasks at the sites did not match. It was noted that at the sites, time measurements were recorded for flat production rates; that is, not considering idle time. For example, if during 20 minutes of observation, five beams were erected, a flat production rate of 4.00 minutes per member could be averaged. The information gathered from the industry members suggested that with 60 members erected per day, an equivalent value of 8.00 minutes per member should be observed. Some reference have indicated that idle time could be 25 to 30 percent of the total time (Tucker *et al.*, 1990).

In this research as much as 50 percent has been assumed for idle time. In several of the visited sites it was noted that of the eight-hour workday only four hours were used for erecting steel.

By defining idle time for a given activity as any period of time in which the given activity is not performed, many reasons can be listed to account for the four hours of idle time. In erecting members, the following obstacles can be identified and aggregated as idle time. First, approximately one hour is spent in preparation or cleanup. Every morning workers spend up to 30 minutes preparing equipment which will be needed to start erecting members, and halfway through the morning there is a break of 15 minutes for refreshments. At the end of the day an additional 15 minutes can be accounted for the time to pack equipment. Second, for at least one hour a day the crane is utilized to lift heavy equipment, shakeout material, or at times to reposition itself at a better angle to continue with the erection activity. Third, problems and delays always arise. Fabrication errors, tolerance limitations caused by misalignment of the columns with respect to the beams and the breaking of a hoisting wire, for example, may account for as much as one hour lost. Fourth, the erectors subcrew can be reassigned to other help with activities to which another subcrew has been assigned. Finally, lack of prior planning leaves the supervisor with too many decisions to make as the project unfolds. This last factor can account for another lost hour. In the safety module of the dynamic daily simulation model, the six stages: unloading, shaking out, erecting, plumbing, permanently connecting and decking have been assumed to have idle percentages of the total time of 50 percent, 25 percent, 50 percent, 25 percent, 50 percent and 50 percent, respectively.

3.3 Development and Reliability of the Models

The data collected from the industry members and visited sites were gathered as the models were being developed. These simultaneous endeavors allowed the models to be modified and refined every time that an interview or site visit was conducted. This iterative procedure is one of the aspects that gave the models robustness.

Results of tests for reliability also verify the robustness of the models. The tests included the analysis of a prototype building and of the structure for the indoor tennis court project. The duration of the tennis court project matched the predictions obtained by using the models. In the interviews, certain industry members considered that if the prototype were erected, it would take ten days to complete the six stages of the erection process. The duration estimate obtained by using the models was 9.48 days. The structural system of the indoor tennis court project was modeled with the productivity/resource model. The model performed well, demonstrating the flexibility of the model to adapt to real structures. An estimate of 11.45 days by the model, compared to 12 days that the project actually lasted, was satisfactory.

A sensitivity analysis was conducted on an earlier form of the second model, using the prototype building. The results of a comparison between using the ATLSS Connectors and standard connections show that the durations of tasks in the permanent connections stage were sensitive to variations of the rates at which the tasks of installing and tightening bolts were performed. A single productivity rate was changed at a time, and the total project time was observed to change by a percentage that was recorded in the analysis. This means that the permanent connections stage controls much of the duration of projects.

Other sensitivity analyses on the prototype building were conducted to observe the validity of the models. The productivity/resource model was tested by changing the rate for erecting a member from 6.00 to 7.50 minutes (25%). A change of 4% was observed in the total duration of the project. Similarly, the rates for bolts were increased by 25%, and resulted in a change of 20%. This means that the model is sensitive to changes in the rates of bolting tasks, whereas it is not sensitive to those of setting steel. Future research should focus on obtaining a large sample of data to analyze standard deviations from the mean rate values of production rates to improve accuracy.

Chapter 4

Description of Simulation Models

The purpose of the models presented in this report is to portray the patterns of activities present in the erection sequences of any steel building. It is very common in the construction industry to characterize every project as unique. However, this research identifies the similarities present in different projects. Specific sequences on how to erect a steel structure depend on the project under consideration, which entails the uniqueness referred to above. Nonetheless, different projects have similar sequences which the models try to convey. Three models were developed to capture the decisions, sequences, and use of resources inherent in any project.

The erection of steel structures is a complex process. Once the shop work is completed, the structure must be shipped to the construction site, where activities are performed on and with the members and materials. The sequence of activities is generally uniform, but the action upon each set of structural members depends upon several factors. First, they are defined by the specific details of the structural design. Secondly, they reflect the planned schedule between fabrication, delivery and erection. Thirdly, they respond to available equipment and labor resources on the site. And finally, they must respond dynamically to different conditions on the site, for instance, bad weather or fabrication errors like the misalignment of bolt holes.

Several techniques exist for planning the erection activities, and for providing control mechanisms for their progress. These techniques include cost estimation, project scheduling, progress tracking, cost control accounts, as well as several other methods. The models that have been developed in this research do not seek to replace those techniques but rather to add a new set of capabilities. These simulation models are the basis upon which future research can build an interactive simulation system that will allow designers and erectors to model the construction process for specific projects. Figure 4.1 shows the conceptual interaction of the three models. Note that the construction issues addressed by the models constitute a synthesis of the integration that can be achieved by the systems approach.

Because the sequence of activities at the site follows a general pattern, the erection may be approximated through a diagram that charts the flow of those activities. This flow diagram includes specific points where decisions must be made. The usefulness of the flow diagram is that it reveals the repeated sets of activities, and also provides insight into where disruptions can occur, and how these disruptions can alter the flow of the activities.

The second model provides time estimates for specific building designs, aggregated by the major activities identified in the flow diagram. Using the design details and deciding upon the resources, this model can provide counts for each component of the structure (*e.g.* members, bolts, splice plates), and matches those component counts to production rates for each activity. The result is a total time and cost estimate for a

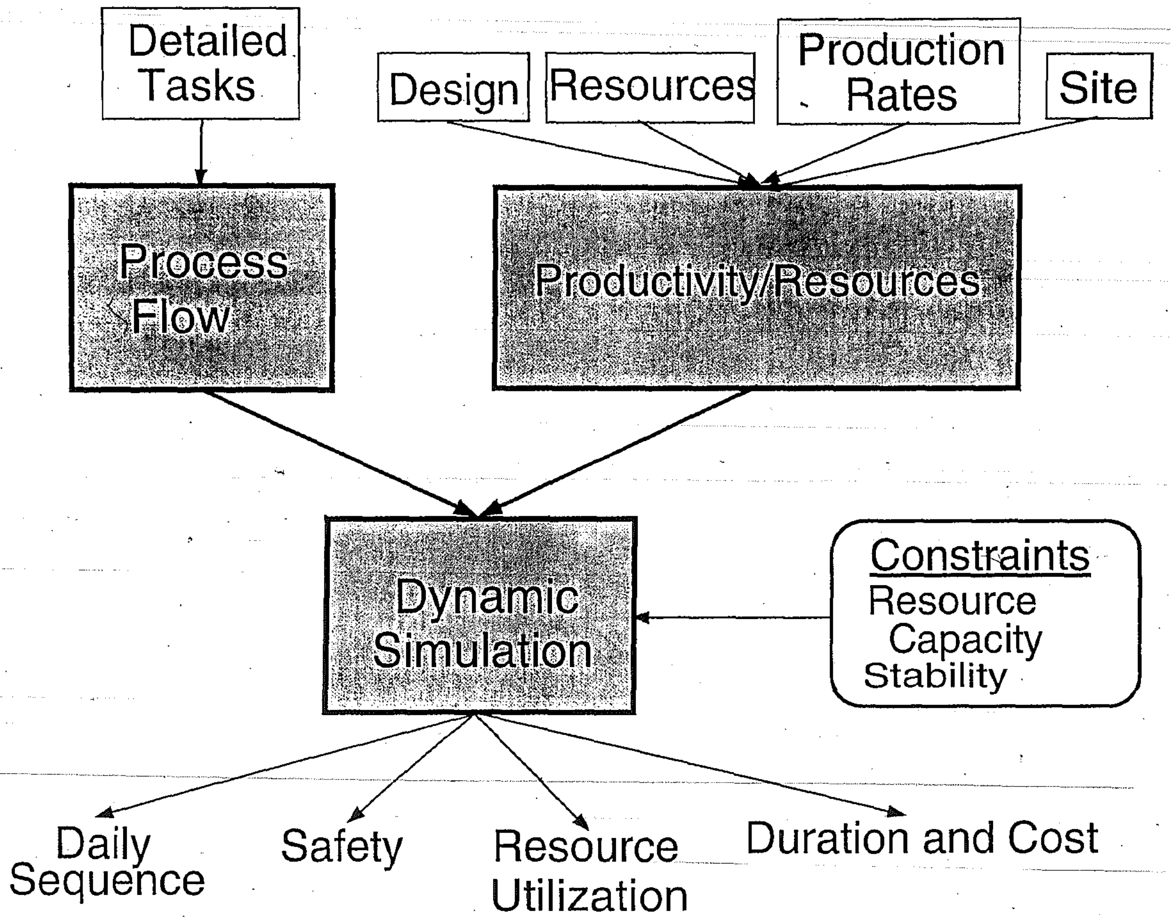


Figure 4.1 Interaction of Simulation Models

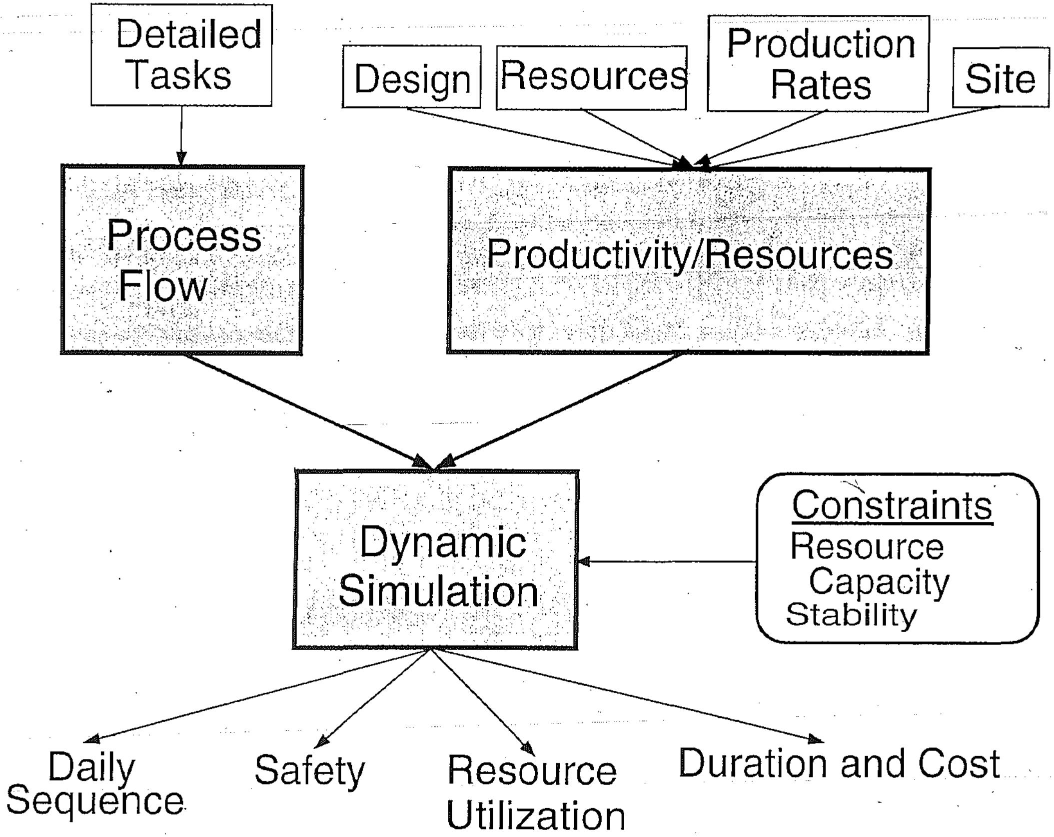


Figure 4.1 Interaction of Simulation Models

specific structural steel erection project.

The third model is a combination of the flow of the activities and the specific attributes of a project, dynamically combined in a time based sequence. This model includes a safety module based on statistics recorded by the Bureau of Labor Statistics (OSHA, 1992). The goal of this model is to represent a daily flow of the project, including the number of members erected and bolted. The direct consideration of resource utilization, the stability of the frame during erection, and safety of the workers is addressed in the model. It is hoped that eventually these models can be replaced with a computer-based program that automates the transfer of information among the models and the full simulation of the steel erection process.

As noted previously, these models were developed to reflect current practice in the United States, and indeed the development relied heavily upon the expertise of the industry and their willingness to aid this research. Observations at several construction sites provided a strong test of the validity and reliability of the models, as shown in Chapter 3. The use of the models is explained in Chapter 5, where they are the basis of an assessment of eight different construction technologies.

4.1 General Description of Structural Steel Erection

For a given erection unit, six stages have been identified: unloading, shaking out, erecting, plumbing, permanently connecting, and decking. Figure 4.2 shows the logical network of these stages. The network contains start-to-finish relationships and also stages

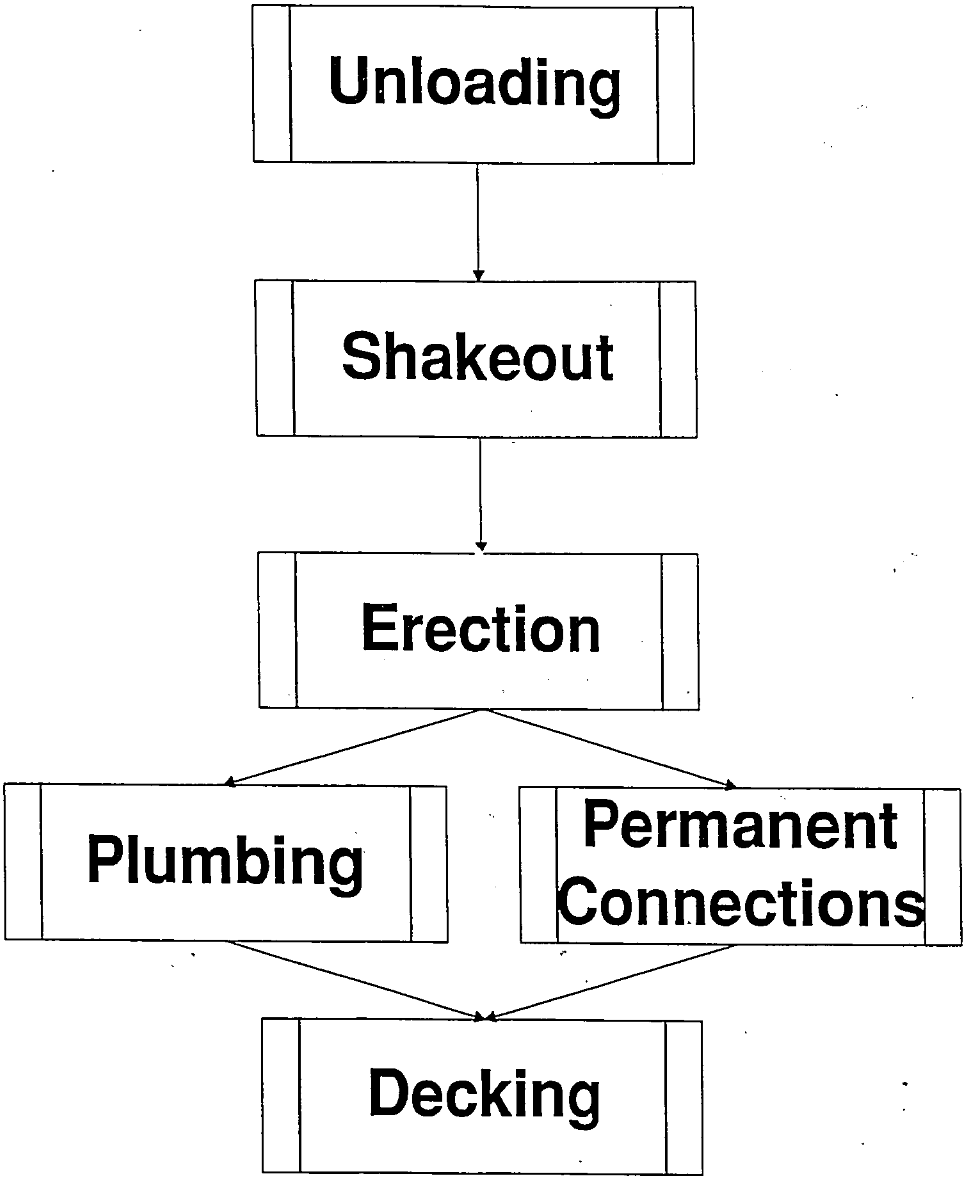


Figure 4.2 Logical Network of Stages

occurring in parallel. These stages are characteristic of each erection unit, and overlap those stages of another erection unit. For example, it is common to have an erection unit being erected while the members of another erection unit are being permanently connected in another part of the site.

Unloading is a priority when making a decision on whether an activity should be interrupted or not. A truck that arrives at the site must be unloaded as soon as possible. While one of the two connectors may stay installing and tightening bolts at the site, and while the decking crew continues its decking procedures, all other workers interrupt their activities and go to unload of the truck. The two erectors get on the truck and hook bundles. The person hooking and other connector unhook the bundles onto the ground. The crane operator swings the crane boom back and forth from the truck to where the unloading is being done. The supervisor and helper aid with any task that requires their presence.

Shakeout is performed the crane operator and the person hooking. The erection stage is interrupted when there is only one crane that must be shared by the unloading, shakeout, and erection stages. Material is untangled or moved from the storage place to a closer place next to where the structure is going to be erected.

Erection is the stage which has been analyzed in greatest depth. During this stage there are activities such as erecting members, correcting any fabrication errors and guying the structure if it is not self-stabilizing when erected. The activity of erecting members can be broken down to several tasks such as hooking, handling, connecting and unhooking.

Plumbing and permanently connecting occur simultaneously. As part of a structure is being plumbed, a worker may even still be installing bolts in that part of the structure. Some bolts may have to be loosened, others removed, or in some cases even tightened so that the plumbing can be achieved. This may seem an unplanned, misuse of time since certain tasks have to be repeated or undone. However, the fabrication tolerances with which the erectors must cope are unavoidable. During plumbing the supervisor and helper with the aid of one of the connectors perform all the tasks. Guying, leveling manually or by the transit are all performed by these workers.

The permanent connections stage consists of only one activity: fully connecting the members. The tasks in this activity are welding, installing bolts and tightening bolts.

The decking stage consists of activities such as lifting the bundle of sheets to the appropriate floor level, cutting and laying the sheets, welding the studs, and installing safety devices like perimetral wires.

4.2 Erection Flow Diagram Model

The erection of steel structures involves the six distinct stages. However, depending upon the availability of resources (labor and equipment), work may be proceeding at different stages in separate locations of the structure. For instance, while the first units are being decked, other units are being plumbed and permanently connected. At the same time even other units are being erected.

The sequence of activities at a site has been approximated by the erection flow diagram model. The structure of this model is based on a specified erection unit, and on the definition of several terms which will be used in this research.

An erection unit is defined as the smallest assemblage of structural members on which the sequencing of activities in the erection process are based. For instance, in the erection of a gable frame warehouse, the construction process is centered on erecting one frame, stabilizing it with guy wires, and then repeating this sequence throughout the length of the warehouse. The erection unit in this case is thus the gable frame. Other structures consist of a rigid frame of several spans and multiple floors. Although the designed structural system is similar to a gable frame, its erection is not necessarily centered around the erection of each frame. Most likely, the erector will form bay assemblages by connecting two columns of one frame with the respective columns of its adjacent frame. Since the columns are usually two floor tiers, the final stabilized assemblage will consist of four columns stabilized by four orthogonal floor beams at the first level and four other at the second level. In this case the erection unit is the bay assemblage consisting of eight beams and four columns. Note that the erection unit is not necessarily the same as the structural system. The infill beams on each of the two levels may or may not be considered as part of the erection unit, depending on the rigidity of the structure.

The other terms that must be defined to understand the structure of the model are: task, activity, and stage. A task is the smallest unit of work an ironworker performs. The grouping of several tasks constitutes an activity. Similarly, a group of activities defines a stage. Thus, in the erection stage of a project, several activities like erecting a member and correcting fabrication errors are performed. Within the activity of erecting a member, there are a series of tasks which flow one after the other. Examples of tasks within the activity of erecting a member are hooking a member, swinging in of the crane, handling of the member in the air, connecting the minimum amount of bolts, unhooking the member, and swinging out of the crane.

Within each stage, the model shows a series of activities which are start-to-finish activities (Figure 4.3). The level of detail has been chosen so that each task is represented in the flow diagram. It is at this level of detail that the cyclic nature of steel construction becomes apparent. For example, in the erection stage, hooking, lifting, maneuvering, connecting and unhooking are start-to-finish tasks that repeat member after member. Keeping track of this repetition would require the use of counters in a future, more sophisticated model. The total number of members that have been erected and the total number of members that need to be erected during the whole project would be tracked by this counting system. An alternative observed in several of the visited sites was hooking and lifting three members together, then connecting and unhooking one by one. In this case the total number of members remains the same while the number of lifts is divided by three.

The model also includes decision diamonds in each stage. As shown in the flow diagram model, these decisions can be external, internal or probabilistic. An example of external decisions is skipping the totality of the shakeout stage if, for a given project, this stage is impossible or unnecessary. For instance, a project may require the erection of members directly from the truck at a congested site in the middle of a city. If the flow

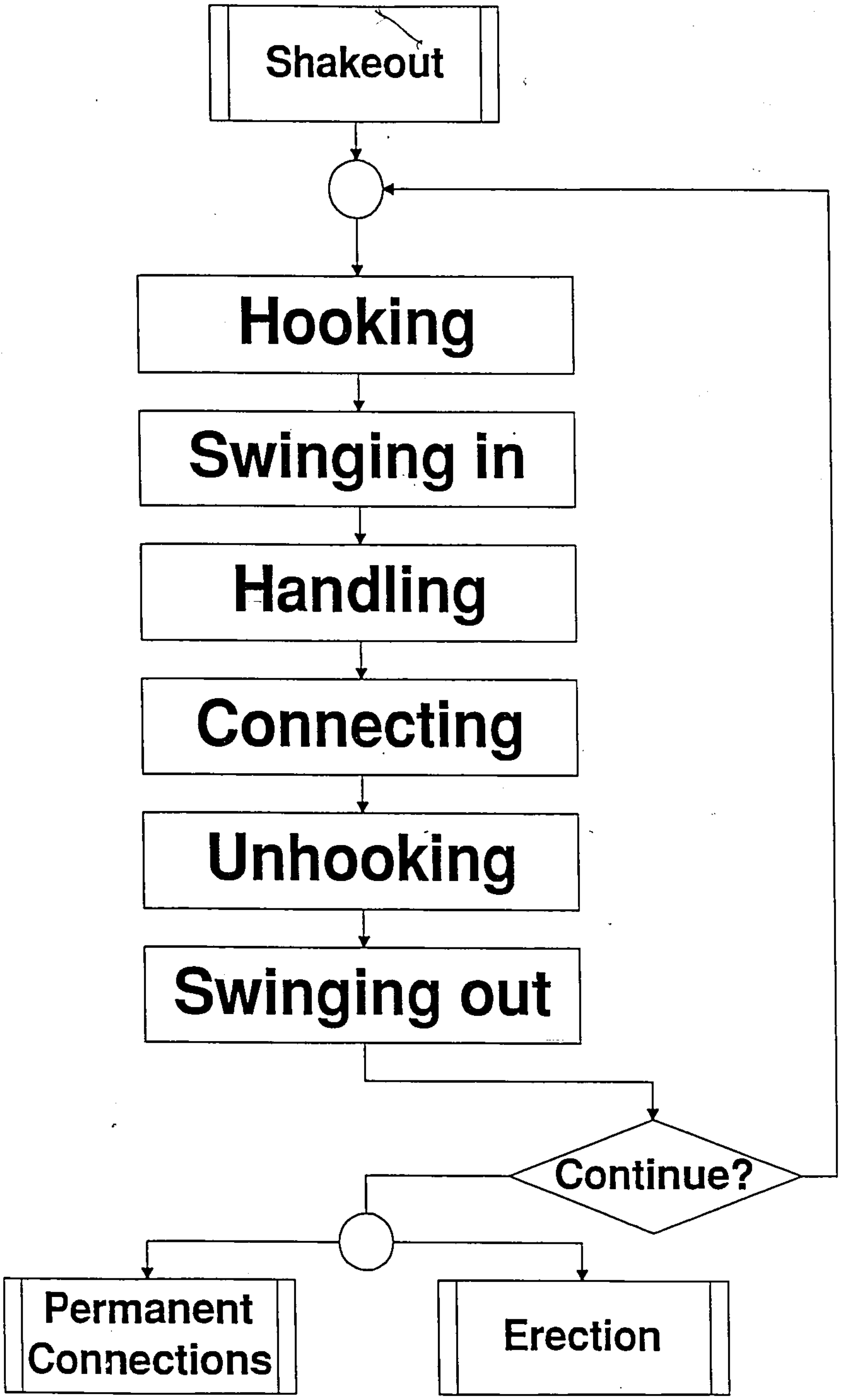


Figure 4.3 Tasks in the Erection of Steel Members

model were to be programmed, these decisions must be specified as part of the input, and thus are named *external.* These decisions, which are made at the office prior to the erection, usually depend on the site factors. These decisions also depend on the selected process of erection and the scheduling of activities made at the office, such as whether floor connections should be made to lift a whole panel of members, and whether plumbing is critical.

Similarly, to count structural design details, internal decisions would keep track of the number of members that have been erected at any time. For instance, a counter could keep track of the number of columns on the first tier. Usually at the end of each stage there is a check to see if all members of an erection unit have been processed in that particular stage. The counters must keep track of this condition. If the check is satisfied, the flow proceeds to the next stage. Otherwise it remains in the same stage but cycles through a series of activities. These checks that appear in decision diamonds are named *internal* because the decisions are made according to the specific project under consideration. That is, they depend on the erection unit and the number of members, bolts, welds, sheets, and studs of the given project. Although these quantities change from project to project, once the quantities are specified, the internal checks would always be performed.

Finally, to represent the random nature of the erection process, different decision diamonds are inserted throughout the flow diagram to more closely represent the simulation of actual construction activities. The *probability* decisions depend on the random nature of the erection process. For example, a member may not have been delivered, the holes of a gusset plate may not align with the holes of the connecting member, or repairs like shimming may not happen at the site. In actual construction, these decisions are made as the erection unfolds, but with a simulation program they could be predicted if enough data were collected to include a probabilistic distribution in the model. The way all these attributes interact can be observed in the flow diagram in Appendix A.

The erection model as a conceptual guidance is thus infinitely adaptable to any project. Different projects could be described by their erection units and specified with certain counters. The model shows the unavoidable patterns reflected in any construction site. When using this model for the evaluation of the problems or benefits that a project may have, the flow reveals possible activities that may have to be performed and points of potential disruptions. This is a conceptual model which reminds the user of what may be encountered at the site. However, the model is limited as it lacks a time dimension and a control over the employed resources. To compensate for this shortcoming, the productivity/resource model was developed.

4.3 Productivity/Resource Model

The productivity/resource model complements the flow model by keeping track of a project's structural quantities, by establishing the resources that will be used for a particular project, and by computing time estimates for the activities. Productivity and resource are related by a simple relation which computes the ratio of output to input. The output is the number of structural quantities that can be set in a given time, or productivity. Conversely the input is the type of resources, both labor and equipment, which are utilized to obtain a given productivity. Thus, when analyzing these two factors, the duration of a project can be estimated. The first model is considered in the structure of the second model, but it is only with the second model that time estimates can be obtained.

To quantify the duration of each of the activities, a spreadsheet was structured in four main sections. The first section quantifies members, connections, plumbing units, decking sheets and any other structural element. The second section is based on the standard production rates of steel erection, and computes actual productivity estimates for the project under consideration, incorporating the influences of site conditions through a productivity factor. The actual estimates are then multiplied by the quantities to obtain the time estimates. The third section displays the total time estimates, T, after carrying out the multiplication for each of the six stages: $F \bullet P_p \bullet N$. A summary which groups the six stages into four major categories is shown as the final result. Unloading and decking have been left alone as single categories, shakeout and erection are grouped into one category, and plumbing and permanently connecting in another category. Finally, in the fourth section an important description of the expected conditions of the project is listed. Direct and indirect costs, project duration, resource utilization, and productivity averages are displayed in three tables.

The input data is shown shaded in each of the tables, whereas the output as discussed above is presented at the end of the spreadsheet computations. Table 4.1 shows

Table 4.1: Input of structural elements

TIME ESTIMATES
-for activities in the steel construction process

[redacted]

STRUCTURAL SYSTEM:

[redacted]

Members

Member		total No. of members	
Columns	[redacted]	21	[redacted]
Girders/supporting beams	[redacted]	56	[redacted]
Bracing beams	[redacted]	48	[redacted]
Filler beams	[redacted]	120	[redacted]
Diagonal braces	[redacted]	0	[redacted]
Steel joists	[redacted]	0	[redacted]
Purlins	[redacted]	0	[redacted]
Trusses	[redacted]	0	[redacted]
		245	Total

*---Zeros must be replaced by ones to avoid division by zero in subsequent tables.

Table 4.1: Input of structural elements

TIME ESTIMATES
-for activities in the steel construction process

DATE: 04/03/95

PROJECT: Prototype Building
WEIGHT: 150 Tons

STRUCTURAL SYSTEM:

A series of rigid frames connected by bracing beams.
four-floor column tiers.
Filler beams in composite action.

Members

Member	Unit	Unit quantity	members/unit	total No. of members	input No. of members(*)
Columns	tier	1	21	21	21
Girders/supporting beams	floor	4	14	56	56
Bracing beams	floor	4	12	48	48
Filler beams	floor	4	30	120	120
Diagonal braces				0	1
Steel joists				0	1
Purlins				0	1
Trusses				0	1
				245	Total

*---Zeros must be replaced by ones to avoid division by zero in subsequent tables.

the input of the structural elements of the prototype building. Appendix B includes the complete productivity/resource model spreadsheet.

4.3.1 Design Characteristics

The purpose of this section is to quantify the structural elements of a design. The numbers of these elements are the parameters which define the duration and cost of a project given a set of resources. Columns, beams, braces, connection types, bolts and decking sheets are all structural elements that must be quantified.

For the data entry of the first section, it is assumed that a preliminary layout of the design is available. Having the layout which contains the structural quantities permits transferring these quantities into the spreadsheet. The more repetitive the structural system, the easier the spreadsheet is to use. This is evident, as the spreadsheet charts were developed such that if a repeating unit is identified (*e.g.* a frame or a bay), just one unit is entered along with the number of times it repeats. A sketch or a detailed blueprint which shows all structural quantities are needed as references. That is, the design must be completed to be able to evaluate its effectiveness.

An evaluation of alternate designs with different structural systems and thus different structural quantities is highly desirable to make comparisons. Different layouts of a same project can be considered, and the most convenient with respect to time and cost would be chosen.

4.3.2 Resources

The purpose of this section is to establish all resources that will be used to erect the structure. The first step is to establish the size and composition of the crew since the equipment is defined with respect to the subcrews. Certain basic equipment is assumed to be utilized. For example, the erection subcrew uses one crane, while the decking subcrew assumes the availability of a shear stud welding gun.

The size of an erection crew varies in the industry from six to twelve ironworkers. For the purposes of this research, a total of eleven different workers were identified by subcrew as shown in Table 4.2.

It is possible in this model to reassign members of a subcrew to another subcrew if the schedule requires it. For example, erection might get too far ahead of the bolting up, and the erection of the second tier may be delayed until the first tier is permanently connected and decked. Safety issues specified by OSHA do not allow erection to continue where more than 32 feet in height of undecked floors are present (OSHA, 1992). To model this situation of reassigning resources, the total number of available ironworkers must be maintained by deleting one subcrew and adding other combinations of subcrews with the same total number of workers. For example, one of each subcrews A, B and D (erection, permanent connections and decking) may be reassigned as two subcrews of type B (permanent connections) and one of type D (decking), by blocking subcrew A. It is assumed in this case that the crane operator and the hooker person remain idle, while the two erectors go to help with the connecting activities.

Table 4.2: Labor resources

Subcrew	Activity	Workers
A	erecting	3 ironworkers, 1 crane operator
B	bolting	2 ironworkers
C	welding	1 ironworkers
D	decking	2 ironworkers
E	supervising	2 ironworkers
Total		11 ironworkers

4.3.3 Production Rates

For new, unfamiliar techniques of erection, increases or decreases in production rates for the activities may vary. Therefore, the purpose of this section is to define the actual production rates that will be used in the calculations of the duration of each of the activities of the project under consideration. In the case that the user wishes to use different rates than the ones proposed, the standard production rates can be replaced. The mechanics of the computations will remain the same, though. In the assessment of the advanced construction technologies, these variations will become apparent.

For most activities, the production rates in Table 4.3 were estimated by member, bolt, or bundles of one element. These production rates also depend on the specific subcrew which performs the activity, so the table is defined for a single subcrew. The objective of arranging this table by single units and subcrews is to allow for adjustments that reflect the decisions made during the erection process of a particular project. If bundles of a higher number of members per bundle are unloaded or shaken out, then the

Table 4.3: Standard production rates

	Output			Input (crew)	
	Unit	Unit Quantity	(min/unit)	Crew	No. of crews
UNLOAD					
Beam	bundle	1	4.00	A	1
Joist/Purlin	bundle	1	4.00	A	1
Column	bundle	1	4.00	A	1
Truss section	bundle	1	4.00	A	1
Diagonal brace	bundle	1	4.00	A	1
SHAKEOUT					
Beam	bundle	1	1.00	A	1
Joist/Purlin	bundle	1	1.00	A	1
Column		1	1.00	A	1
Truss section	bundle	1	1.00	A	1
Diagonal brace	bundle	1	1.00	A	1
ERECT					
Beam	member	1	6.00	A	1
Joist/Purlin	member	1	6.00	A	1
Column	member	1	6.00	A	1
Truss	member	1	6.00	A	1
Diagonal brace	member	1	6.00	A	1
Install bolt	bolt	1	0.50	A	1
PLUMB					
Bay	bay	1	20.00	B	1
Column	column	1	5.00	B	1
PERMCON					
Install bolt on floor	bolt	1	0.25	B	1
Tighten bolt on floor	bolt	1	1.00	B	1
Install bolt at height	bolt	1	0.50	B	1
Tighten bolt at height	bolt	1	2.00	B	1
Install anchor bolt	bolt	1	0.50	A	1
Tighten anchor bolt	bolt	1	2.00	A	1
weld	inch	1	1.50	C	1
DECK					
stud	stud	1	0.25	D	1
deck sheets	sheet	1	4.00	D	1

time estimates used in the production rates are adjusted to represent such a change.

The production rates were calculated from on-site observations, and corrected by the parallel occurrence of activities. The unloading activity is assumed to occur by bundle, taking 4.00 minutes per bundle to set the blocking, hook on the hoist, lift the bundle, and unhook the hoist as described in the erection flow diagram. In the same manner, shakeout occurs by bundle, but the bundles are assumed to be smaller, and do not require the setting of blocking, thereby taking only 1.00 minute per bundle. For example, subcrew B, which is composed of two workers who will install and tighten bolts in parallel, has a production rate of 0.50 minutes per bolt for installing, and 2.00 min per bolt for tightening. This adds to 2.50 minutes per bolt which is installed and tightened. Since two workers are working in parallel, this amounts to 5.00 minutes per bolt per worker which is equivalent to 96 bolts per person per day. Subcrew C consists of one welder who can weld nine linear inches per minute. Finally, the two workers in subcrew D can lay 120 sheets per day and weld 2000 shear studs per day.

Within this section of the spreadsheet, there is a list of nine site parameters shown in Table 4.4 that may affect the productivity. Mathematical models are currently being developed to analyze site parameters that affect productivity (Thomas and Sakaracan, 1994). The purpose of these parameters is to explicitly include project attributes which influence the duration and cost of erecting a given structure. Site conditions, project characteristics, resources, and management can affect the standard productivity. While additional research may yield more exact measures, the nine parameters used in this simulation model can provide an approximate adjustment of productivity. The influence

Table 4.4: Site parameters

FACTOR PRODUCTIVITY
Factors (-2...0...+2)

Parameter	Actual Factor	Normal Factor
Site conditions		
materials handling	2	0
presence of existing structure	2	2
Project characteristics		
regularity of topology	2	0
standardization of connections	2	2
weight of members	-1	0
Resources		
level of technology of equipment	0	0
experience of crew	0	0
erection sequence	0	0
Management		
expected organization	2	2
Score	9	6

Actual Average	1.00
Percent	0.75
Normal Average	0.67
Percent	0.67
0.89	Normalized Factor

Table 4.4: Site parameters

FACTOR PRODUCTIVITY
Factors (-2...0...+2)

Parameter	Actual Factor	Normal Factor
Site conditions		
materials handling	2	0
presence of existing structure	2	2
Project characteristics		
regularity of topology	2	0
standardization of connections	2	2
weight of members	-1	0
Resources		
level of technology of equipment	0	0
experience of crew	0	0
erection sequence	0	0
Management		
expected organization	2	2
Score	9	6

Actual Average	1.00	
Percent	0.75	
Normal Average	0.67	
Percent	0.67	
	0.89	Normalized Factor

of each parameter on the productivity on site is assumed to be approximately equal.

The first two parameters are concerned with site conditions, specifically the ease of materials handling/delivery, and the presence of existing structures or facilities on the site. The next three parameters relate to the project characteristics, the regularity of the structure, the standardization of the connections, and the weight of the members. The more regular or rectilinear the structure, the more standardized the connections, and the lighter and more maneuverable the members, the faster the erection can proceed. In the same way, the three parameters associated with resources can speed erection when using advanced or powerful equipment, having the presence of a highly experienced and skilled crew, and following a straightforward erection sequence. The on-site project management, and explicitly the organization of resources and tasks, is the final site parameter considered.

The scale for each parameter is centered on zero as the normal condition, with -2 denoting a strong adverse effect and +2 indicating a strong favorable effect. A *standard* baseline was also constructed which would be expected to exist for the estimated production rates discussed above. In the baseline, the standard project would include normal materials handling, no existing structure on the site, and a rectilinear structure with highly standardized connections and normal-weight members. The resources would include standard equipment, crew skills and sequencing. A strong project organization would be included, too. The standard project score on the site factors equals 6 as can be seen in Table 4.5.

Table 4.5: Normal Productivity factor calculated from site parameters

Parameter	Normal Factor
Materials handling	0
Presence of existing structure	2
Regularity of structure	0
Standardization of connections	2
Weight of members	0
Effective equipment	0
Experience of crew	0
Erection sequence	0
Site management and organization	2
Total score	6
Average score	0.67
Score percentage	0.67

The productivity factor can be calculated for a specific project based on an evaluation of these nine parameters. For example, if every condition was at its most favorable, the project score would be equal to +18. The average score for each parameter would be +2, when dividing by 9, the number of parameters. This average score then needs to be adjusted to the range between -2 and +2 which includes four subranges. This is accomplished by adding 2 to the average score and dividing by the four subranges. For the most favorable conditions, the percentage is 1.00, the highest value. The result of this computation for the standard case is 0.67, a percentage of the range between -2 and +2.

The actual factor for a project is defined as the ratio of the standard percentage of the range to the actual project's percentage of the range. To compute the factor of the most favorable case, the ratio of 0.67 to 1.00 results in a factor of 0.67 (note that there is a coincidence in the mathematical computations when the values 1.00 and 0.67 repeat for the percentages of the range and the productivity factors). This most favorable project productivity factor translates to the production rate for any activity occurring in 67 percent of the standard time. That is, the most favorable site conditions can increase the production rates by 33%. To avoid division by zero in the least favorable case, it is assumed that even the worst site conditions would have a total score of no less than -17, with a resulting project productivity factor on no more than 24.12.

The site conditions, the project characteristics, the resources and the management combine during the erection process to create a specific atmosphere described by the normalized factor. This atmosphere is described by delays, organization problems, reassignment of resources, availability of resources, crowded sites, and patterns of sequence of erection which may result in productivity changes. Since these latter aspects are effects of the three main factors, they do not enter in the formulation of the normalized factor.

After these computations, the actual productivity is displayed as shown in the fourth column, *min/unit*, of the table for standard production rates in the second model.

4.3.4 Total Time Estimates

From the standard productivity rates of steel erection, actual productivity estimates for the project under consideration are computed. The actual estimates are then multiplied by the quantities to obtain the time estimates. These computations are based on the following algebraic relation:

$$T=P_a \bullet N,$$

where each of the variables is defined as follows:

T =Time estimate for a given activity.

P_a=Actual productivity rate for a specified project, computed by $F \bullet P_p$.

N =Number of structural quantities to be set in the given activity.

Thus, the time estimate for a given activity can be formulated as:

$$T=(F \bullet P_p) \bullet N,$$

where the additional variables are defined as follows:

F =Productivity factor which may increase or decrease the standard rates.

P_p=Standard production rate as observed in the construction industry.

Since productivity is defined as the ratio between output and input, the *standard* production rates listed in Table 4.3 are listed for the specified subcrews, which are the input. When running the spreadsheet, the actual production rates are computed by entering the desired values in the columns labeled *No. of Units* and *Number of Crews* of the table listing the *actual* production rates.

Four different charts tabulating the duration of several activities in the productivity/resource model show time estimates by member, connection, plumbing and decking. The first two charts include unloading, shaking out, erection and permanent connections. Plumbing and decking are included in the third and fourth charts. During the unloading and shakeout stages, only the number of bundles contribute to the accumulation of time. The erection stage is composed of erecting members and installing bolts during erection. The permanent connections stage includes installing the remaining bolts, and tightening all bolts and welding every connection as needed.

4.3.5 Results

The approach used to run the spreadsheet is iterative. After estimating an initial set of resources, the results are inspected. If the cost or time to complete the project is too high, the resources can be decreased or increased on the second iteration. For projects which require the utilization of only one crane, usually subcrew A with three ironworkers and a crane operator is needed for the erection stage. However, for the plumbing and bolting, one or two subcrews of type B may be needed. An initial estimate of a total of two subcrews may be insufficient to meet a pre-established deadline. Hence on a second run of the spreadsheet, three subcrews may be specified and hopefully the deadline will be met. In general, a mid-size project can be carried out by three subcrews: A, B and E, which means there would be one supervisor, six ironworkers, and one crane operator. These eight workers would then constitute the labor crew.

The time estimates of this productivity/resource model are grouped into four categories: unloading, shakeout/erection, plumbing/bolting and decking. The critical path for standard methods of structural steel erection is assumed to be controlled by the plumbing/permanently connecting category which is defined to start halfway into the first day of the project, after the first erection unit is set. Decking generally ends one day after permanently connecting is completed. In other words, the duration of the project is calculated as the duration of the plumbing/permanently connecting category plus an approximate two days. This approximation is later validated with the third model.

In addition to project duration, other results are presented. Crane utilization time is the summation of the duration of unloading, shaking out and erection activities. The number of workers is specified in the resources section of the model. From the labor and equipment resources, the direct and indirect costs for the project are calculated. The direct cost includes the renting of the crane with the crane operator included; the wages of subcrews A, B, C and E for the duration of the project; and the wages of subcrew D for the duration of the decking activities. The indirect costs are based on the percentage premium that the erecting company must pay to an insurance company for workman's compensation benefits, which averages 52% for structural steel erection (Powers, 1994). Other indirect costs are overhead and profit costs based on 45% of payroll costs. These base costs can be easily adjusted to reflect prevailing rates in different geographic regions.

4.4 Dynamic Daily Simulation Model

The third model matches the flow diagram from the first model to the durations of activities or cycles of activities in the second model to *dynamically* simulate the erection of structural steel. Taken into account in this time-based simulation are the capacity of the resources and the length of the workday. For instance, the crane cannot be fully occupied performing two tasks at once (*e.g.* unloading and erection). At the moment, the calculations required for the third model are performed using a commercially available spreadsheet program tailored to specific building designs and erection units. Future development of the model is expected to automate this process and the transfer of information from the first two models.

The model also works within the requirement that the erected steel must be self-stabilizing or externally stabilized at the end of the workday. While most structural steel designs are assumed to be stable under erection conditions, leaving unbraced members for a long period of time may result in the collapse or failure of the members. Some erection units, such as a bay, are stable when a certain number of members have been connected. Other erection units, such as a gable frame, are not in themselves stable, and must have stabilizing guy wires attached. The stability of the frame can influence the daily progress on the erection within the context of a day. For instance, if a portion of the structure could not be stabilized by the end of the day (*e.g.* 4 columns erected), it may not be started that day but instead delayed for the following day.

Another consideration that the third model incorporates is the safety of the workers. Structural steel erection has one of the highest accident rates of the construction fields. Since steel erection involves the handling and positioning of very large and heavy members with the help of high capacity equipment, the potential for severe injury and death is significant from such causes as falls from an elevation, being struck by a member or being struck against a wall. The third model includes factors which incorporate the type and number of potential dangers for specific workers who are exposed to these dangers for different amounts of time. The direct exposure of the workers to dangers, while not currently incorporated into insurance calculations or regulations, can be an important factor when assessing the potential contributions of new techniques or designs.

The result from the third model is a daily sequence of activities with the duration for each stage related to the structural layout. From this daily sequence, the utilization of the resources can be examined more explicitly, and the relative safety of the workers can be analyzed. Daily costs for equipment and labor can be calculated and related to the percent complete of the structure. This third model provides a true *simulation.* It captures the dynamic aspects of the steel erection process, uses the repetitive cycles of certain tasks, and responds to technical constraints such as the stability of the structure.

4.4.1 Computations

The dynamic daily simulation model consists of a series of computations which are necessary for the efficient scheduling, proper resource allocation and safety requirements of a project. The duration of the project and the daily utilization of labor and equipment resources constitute the direct costs of erecting a structure. The purpose of these computations is thus to determine the duration and cost of a project.

Similar to the productivity/resource model, the dynamic daily simulation model focuses on the duration of the six stages identified for the erection of steel structures. However the third model has different categories of stages. The first category consists of the unloading and shakeout stages. The second category is the erection stage alone. In the productivity/resource model unloading was the first category and shakeout and erection were grouped in the second category. The reason for this change is that it is convenient to analyze the erection stage alone since this stage will be important in the assessment of the advanced construction technologies analyzed in Chapter 5. Moreover, the unloading and shakeout stages have a low duration which even when grouped in the same category remains low and barely affects the scheduling of the project.

Throughout the flow model, it was proposed to base all construction considerations on the erection unit. Consistent with this formulation, the dynamic daily simulation model focuses its resource allocation and scheduling of activities on the erection unit. For example, it is important to know how many erection units are expected to be erected in an eight-hour day so that the same amount of erection units are shaken out. Similarly, it is necessary to know how many erection units can be erected before another truck delivers material to the site where the unloading will take place. Considerations of this sort suppress the probability of delays which highly reduces the production rates. Delays have been considered as probabilistic and uncontrollable, but these considerations show that they can be minimized.

As an example, consider a structure in which the erection unit is a bay composed of columns and beams. The first truck that arrives at the site must contain enough columns and beams in the correct proportion so that the erection stage can be performed throughout the whole workday. This seems obvious, but many times in practice it has been observed that a truck arrives at a site with beams and no columns. In this example, it would be necessary to count how many beams and columns are needed to be delivered, to consider the maximum weight that the delivery truck can hold, to estimate the duration of the unloading, shaking out of the material and erection of the structure. All these computations are made based on the production rates that have been identified.

With this understanding that the erection unit is the focus of all computations, the assumptions made can be addressed before explaining the mechanics in which the computations are made. An assumption made is that the individual production rates are constant throughout the duration of the project. However the reallocation of resources causes the subcrew production rates to change. For instance, installing and tightening bolts has been set to 5.00 minutes per bolt per worker. Therefore, whenever a different number of workers is scheduled to connect bolts, the productivity changes. The changes are proportional and thus computed with linear algebraic relations. Nonetheless, these changes do not get rid of the deterministic nature of the model. The way around this problem is to consider the site parameters discussed in section 4.3.3. If the productivity/resource model is run with just enough members to unload, shakeout, erect, plumb and connect them so that the cumulative duration is one workday, then the normalized production factor can be computed for each day. The result would be different actual production rates since the standard production rates are being multiplied by a normalized factor that is changing with each day. The site conditions do change as the erection process develops. For instance, a site may become more congested as more trucks deliver material to the site.

Another assumption is that to obtain a stable structure at the end of the day, the eight-hour workday is sometimes exceeded by as much as one hour. These additional costs are neglected and thus constitute a limitation of the model. Indeed, overtime payroll costs are considerably higher than the basic eight-hour cost.

When performing the calculations, durations are rounded to the nearest half-workday. In the assessment of the advanced construction technologies, it will be noticed that durations for the same project vary between 7.0 days and 10.0 days, with alternatives of 7.5 days, 8.0 days and 8.5 days in between. This half-day calculation can be important during planning and analysis, even though crews are usually paid on a full day basis.

Finally, an assumption about resource reallocation is made. Whenever there is an excess of labor resources, especially towards the end of the project (when erection has ended), it is assumed that certain workers remain idle. For example, when the decking of the last erection units is taking place, erection and permanently connecting have ended. This means that all workers could potentially be decking. If this were the case, as many as eight workers could be decking and the remaining last erection units could be decked in less than an hour. However, there would not be enough equipment for all workers to work at once. The capacity of the equipment resources would control over the labor resource. With the eight workers mentioned above, four decking subcrews can be formed. However, most likely there are only enough shear stud guns for two subcrews. In actual practice, the idle workers start to clean the site, pack certain equipment and inspect the structure. The flow model addresses this as the cleanup stage.

With these assumptions in mind, the mechanics of the computations can be addressed with one example for each of the stages. With a simple programmed algorithm, a spreadsheet, or even quick manual computations, the production rates (including idle time) can be linearly expanded to cover durations of one workday to compute daily rates.

The first category of stages in the third model organizes the activities which use a crane as their primary equipment (*i.e.* unloading, shakeout and erection.) When only one crane is available, these activities cannot occur simultaneously. The second category of stages is the plumbing and permanent connection of the erection units, which can only occur after the unit has been erected but must be completed before it can be decked. Decking activities constitute the third category.

Using the production rates from Table 4.3, the production times and resources can be established as per the second model. The exact sequence of the activities is established as per the first model. The following text treats examples for each stage.

For the crane-dependent activities of unloading, shakeout and erection, the activities are linearly sequenced. On the first day, several trucks can arrive with material for the next several days. A truck can usually carry approximately 60 members weighing a total of 72,000 pounds (with 48 lbs/ft for a typical rolled I-beam of 25 feet in length). If three trucks arrive the first day, the trucks can be unloaded by bundles of 6 members, where each bundle takes approximately 4 minutes, for a total of 120 minutes or two hours. These two hours equal one fourth of the workday, shown shaded in the daily simulation progress chart in Chapter 5 for each of the advanced construction technologies. The 42 members for the first four erection units expected to be erected that day could be shaken out in bundles of two, taking 1 minute per bundle and a total of 21 minutes. The members of the first erection unit are erected, taking approximately 8 minutes per member, followed by the second, third and fourth erection units. The erection of the 42 members takes 336 minutes, and the workday is finished at a cumulative time of 8 hours. For days when no material is delivered to the site, the erection subcrew could shakeout and erect approximately 55 members as will be noted below.

The plumbing and permanent connecting activities can be performed in parallel with the crane-based activities after the first erection unit has been set. On the first day, after the first erection unit has been set, the bolting subcrew can start plumbing and installing and tightening bolts. The bolting subcrew can include workers who later will be involved in decking. Since each worker can install and tighten a bolt in 5 minutes, with four workers, four bolts can be installed and tightened in 5 minutes. If the first erection unit has 120 bolts, the four-person subcrew can complete the unit in 150 minutes or two and a half hours. For a daily production rate, this four-worker bolting crew could bolt 3.2 erection units a day. The plumbing rate is averaged at 10 minutes per erection unit, even though several erection units may be plumbed simultaneously. For example, a set of two or three bays can be plumbed at the same time, using guy wires extending from the lower vertices and crossing at midspan to form an X when connected at the top vertices of a bay.

After the first erection unit is connected and plumbed, the decking can be installed. It takes approximately 18 minutes for the two workers in the decking subcrew to lay the 8 sheets (which are each 24 feet by 3 feet) to cover the first floor, and 35 minutes to lay the sheets for both floors of the bay. For floor systems requiring shear studs welded along the beam lengths, it takes 32 minutes to weld the studs for each floor of the erection unit if each beam has 15 studs and the erection unit has 9 beams. The studs are placed every six inches for the ends of the beam, and 3 studs at 3 feet intervals in the middle. Therefore, it would take a total of 99 minutes to lay the decking and weld the shear studs for one erection unit's two floors. The daily rate for a two-person decking crew can be computed as approximately 5 bays a day.

A comparison of the general rates at which the erection units can be unloaded, shaken out, erected, plumbed, connected and decked reveals the crucial element of complexity in dynamically modelling steel erection: several activities can occur simultaneously at different rates. This complexity leads to either conflicts over resource access or activities interfering with each other. In the example problem, the end of the first day had 180 members unloaded, 42 members in 4 erection units shaken out and erected, and approximately 3 erection units plumbed and connected when the decking subcrew was reassigned to bolting. At the end of the second day, 55 members in 4 erection units could be shaken out and erected for a total of 8 erection units erected and 3 more units plumbed and connected for a total of six units connected. When the decking crew is reassigned from the bolting to the decking activity on the third day, two important results occur. First, the production rates of the remaining bolting crew is halved (2 bolts installed and tightened in 5 minutes). Second, the decking proceeds faster than connecting. The result of this interaction is that either the decking is performed as an intermittent activity with a few bays decked every other day, or the decking is done all at once when it is absolutely necessary in order to proceed to the next elevation for the erection stage.

These results point to a key aspect of the dynamic model, which is that the scheduling of activities depends not only on the production rates and quantities of structural elements but also on the availability of resources and the logical and technical constraints. The latter two elements must be treated simultaneously and iteratively.

Given the production rates for a certain set of resources, the logical relationship among the stages must be maintained. That is, the erection of a unit must be completed before it can be plumbed and connected, which in turn must occur before the unit can be decked. At the same time, the established technical constraints must be met, such as erecting adjacent units and ensuring structural stability. The dynamic simulation model explicitly includes consideration of these elements, which may be framed as a problem in time efficient allocation of resources. A set of resources (*e.g.*, a subcrew) will be assigned to a stage when the preceding stage has progressed far enough to keep the assigned resources active for a specified amount of time. For example, the decking subcrew will be assigned to the decking stage when the connecting stage has completed the equivalent of one full day of decking activities. If the two-person decking crew can complete five bays in a day, the connecting crew must have completed connections for at least five bays for the decking crew to be assigned. (The specified amount of time may include any time increment.) The resources will also be assigned to expedite the performance of the succeeding stage. Since the decking on lower levels must be complete before steel can be erected on upper levels, the decking resources will be assigned to minimize the delay for the upper elevation erection. The complex problem of resource allocation to minimize delays and disruptions is discussed in relation to related research in section 4.5.

Once the labor and equipment resources are established, the costs are computed. At $35 per hour per worker and $800 per day for crane rental (based on telephone quotes), the direct cost can be computed. A project with ten workers and a duration of ten days, of which five are used for setting steel with a crane, can have the following cost. Assume that the crane must remain idle for one day in which decking of lower floors is conducted. This means that the crane must be rented for six days. Of the ten days, the last four do not require the presence of the crane operator who is included in the crane cost. Therefore, there are nine workers during ten days, and a crane and crane operator during six days. Assuming an eight-hour workday, the labor cost is $25,200. Adding the crane cost of $4,800, the total resource direct cost is $30,000. An estimate of 45% of the direct cost covers administration, taxes, overhead and profit (Waier, 1992). Similarly, 52% of the labor cost is added for the premium to insure the workers' compensation in case of accidents (Powers, 1994). These two costs are $13,500 and $13,100, respectively. Thus the indirect costs add to $26,600. The total cost, thus yields $56,600.

This iterative procedure is based on an initial choice which is adjusted for efficiency by the reallocation of resources. It is not the optimum choice. Trying to program for the optimum choice quickly expands into thousands of possibilities which make scheduling algorithms explode (Manber, 1989). Engineering judgement and quick and simple calculations are always highly recommended. A simple procedure to guide in the scheduling of activities is as follows:

1)Determine the number of erection units that can be unloaded, shaken out, and erected in one day for a given set of resources.

2)Determine the number of erection units that can be plumbed and permanently connected in one day for a given set of resources.

3)Verify that step 2) is always logically dependant on step 1).

4)If the condition in step 3) is violated, reassign resources.

5)Identify the days in which decking can occur such that it always lags behind the permanent connection stage.

6)Verify that the safety constraint of decking lower levels to allow erection on higher levels is met.

7)If the condition in step 6) is violated, reassign resources.

4.4.2 Safety Module

Safety assessment has been addressed by several authors. The procedures proposed by these authors focus on the standard construction methods, and are based on identifying dangerous tasks in order to create awareness among construction professionals (Drewin, 1982; Parker and Oglesby, 1972; Heinrich, 1959). This research focuses the safety assessment on the operational aspects of new construction technologies. The danger index presented in this section is an innovative concept in the construction industry. It quantifies the workers' exposure to the most common injuries reported in construction. The index emphasizes its focus on the worker since the worker is the most valuable asset in the construction process. The safety module in the dynamic daily simulation model can be applied to industries other than the structural steel industry.

The safety module in the third model is based on injuries reported by the Bureau of Labor Statistics (OSHA, 1992). As the daily simulation of the project is being carried out, fulfillment of OSHA requirements and any other technical constraints, as defined in section 4.5, are taken into consideration. The safety module serves as part of the assessment of the advanced construction technologies. It consists of matching the ten causes of injury identified by Heinrich with the tasks necessary to perform the activities in which a given construction technology is used (Heinrich, 1959). At the same time the tasks are matched to the workers performing them. Therefore an evaluation of the danger to which the workers are exposed is conducted.

A letter has been assigned to each of the workers, and a number to each of the tasks as shown in Table 4.6 and Table 4.7, respectively. The supervisor and helper have not been included since they do not participate directly in the performance of the tasks despite the fact that they contribute to almost all of the tasks. The need to label the tasks and workers is just a tool to facilitate the tabulation of data in the subsequent figures and tables.

Table 4.6: Worker Type

Worker	Worker Type
Crane operator	A
Erector No. 1	B
Erector No. 2	C
Person hooking	D
Connector No. 1	E
Connector No. 2	F
Deck Layer No. 1	G
Deck Layer No. 2	H
Mighty Jack operator	I
Crane operator for Mighty Jack	J
Welding Robot operator	K

Table 4.7 also includes production times that do not include idle times since the approach used to quantify the exposure to injuries is based on the relation between tasks and injuries as presented in section 5.2.3.3. Therefore, the times at which the workers remain idle could expose the workers to additional injuries, but this is out of the scope of this safety module.

Table 4.7: Tasks and production rates for active times

Task/Activity	Task No.	Unit	Rate (min/unit)
Hooking member	1	member	0.50
Swinging in member	2	member	1.00
Handling member in air	3	member	0.50
Connecting member in air	4	member	1.00
Unhooking member in air	5	member	0.33
Swinging out member	6	member	0.67
Installing bolts	7	bolt	0.25
Tightening bolts	8	bolt	1.00
Laying sheets	9	bay	32.00
Welding studs	10	bay	17.50
Positioning Mighty Jack	11	Mighty Jack	3.00
Positioning beam/column	12	member	0.67
Remotely Unhooking	13	member	0.03
Handling member on ground	14	member	0.30
Unhooking member on ground	15	member	0.03
Plumbing bay	16	bay	5.00
Plumbing column	17	column	250.
Programmed welding	18	girder	16.00

Table 4.9 shows an example of the relationship between ten causes of injury and the tasks or activities for a stage. From Heinrich's Accident Prevention Manual, the ten causes that initiate most of the construction accidents have been incorporated in this research (Heinrich, 1959). These are the same causes used by the Bureau of Labor Statistics, from which the statistical analysis of injuries and fatalities have been obtained (OSHA, 1992). The objective of these tables is to assign a danger index to each task in each of the stages.

Once the tasks have been matched with the worker who performs them, and a production rate has been attached to them, a tabulation for the causes of injury present in each task may be made. Tables like the one that follows should be carefully reviewed because these are the basis of the indexes that will be computed. It is recommended to do so in two steps. First, for a given task, the list of ten possible causes of injury should be noted with a check for the causes of injury that may be present in performing that given task. Then, as a verification, for each cause of injury, all of the tasks should be noted with a check. In other words the checks should be made first by column, then by row as a verification.

The last row of Table 4.9 shows the summation of all the percentages of the causes of injury that have been checked for a given task. This number will become the base of the safety assessment danger index. Section 5.2.3.3 explains how this number is used.

The statistical report from the Bureau of Labor Statistics shows the percentages listed in Table 4.8 (OSHA, 1992). These percentages are the causes of injury reported for

Table 4.8: Causes of injury

Causes of Injury for the Construction Industry	Percentage
1. Struck against	8.0
2. Struck by	21.0
3. Caught in or between	4.1
4. Rubbed, abraded and penetrated	3.5
5. Fall of person (different level)	14.9
6. Fall of person (same level)	7.0
7. Bodily reaction	31.6
8. Contact, electric current	9.9
9. Contact, temperature extremes	
10. Contact, radiations, caustics, toxic and noxious substances	

Source: OSHA, 1992.

the construction industry. Similarly, causes of fatalities in the steel erection industry have been published (Bureau of National Affairs, 1992). A significant note is that being struck, falling of a person from a different level and bodily reactions are the causes of the majority of all reported injuries. Automation of the tasks which present any of these causes of injury could reduce the number of casualties. Indeed, fall prevention and overexertion are two of the aspects most widely considered by the new technologies analyzed in this research.

The ideal analysis should be based on the causes of injury in the steel erection industry, but at present the analysis is being made with the values in Table 4.8. Future research can incorporate rates of injuries per 1000 workhours, which can provide an index scaled to time-exposure dependent risks. At the moment, the danger index represents a unit-less measure of relative exposure to dangerous conditions.

The worker has been selected as the focus of attention in the assessment carried out in the safety module. In this way the concern for safety will be directed toward the person, and not as economic value. Safety indeed represents a savings in cost, but one should never forget that the one getting injured is the worker, and that all efforts to protect a life are invaluable.

The danger index for each stage, D, is obtained by summing the specific indices calculated for each worker for all tasks performed by all members in the subcrew active in that stage. These specific danger indices, d, describe the presence of all possible causes of injury. The index is computed by carrying out the following multiplication:

$$d = t \bullet n \bullet p,$$

in which the variables are defined as follows:

t = Time rate for each task,

n = number of units, and

p = Percentage summation of causes of injury. And

$$D = \Sigma\, d_i.$$

The objective of this index is to represent the danger to which each worker is exposed when performing the given activity or task. The product of time, t, and number of units, n, represents the duration of the period in which the worker is exposed to a danger. The percentage value, p, aggregates all the percentages of each cause of injury as reported by the Bureau of Labor Statistics (OSHA, 1992). Although the statistical data used shows the percentage of each cause in relation to all causes of injury which workers actually reported, the values are used with a different connotation in this research. When this percentage value, p, is in turn multiplied by the product (t•n), the result (t•n•p) represents the danger to which the worker is exposed, since the percentage value, p, explicitly describes the presence of all possible causes of injury.

Table 4.9: Cause of injury *vs.* task for Erection stage

Cause of Injury	T	A	S	K		
	1	2	3	4	5	6
1.Struck against						
2.Struck by	✓		✓			
3.Caught in or between	✓		✓	✓		
4.Rubbed, abraded and penetrated	✓		✓	✓		
5.Fall of person (different level)		✓	✓	✓	✓	✓
6.Fall of person (same level)	✓					
7.Bodily reaction	✓		✓	✓		
8.Contact, electric current		✓				✓
9.Contact, temperature extremes						
10. Contact, radiations, caustics, toxic and noxious substances						
Total Percentage	67.2	18.2	75.1	54.1	14.9	18.2

As will be seen in Chapter 5, the danger indexes for the six stages are calculated by summing the danger index for each worker by subcrew (i.e. all workers involved in the stage). This does not mean that a stage with a higher danger index is more dangerous than a stage with a lower value. The values do reflect that given the exposure time during which the stage takes place, more causes of injury are present in performing the tasks of that stage than in those of a stage of shorter duration, and it also reflects the number of workers involved. Thus, the danger index may be referred to as an *exposure-to-injury index*.

It should be noted that the time factor and the resources are characteristics of each project. The characteristics of the resources will obviously affect the exposure time for workers when advanced construction technologies are utilized. Conversely, the stages themselves are present in all projects, which is to say, they cannot be universally labeled as more or less dangerous than another stage, but their relative safety is defined by exposure durations instead..

The total index for the six stages adds to a total danger index for the project. This project value will be used to compare the safety of the different technologies. For example, consider worker A of erection of the prototype building. Task number 2 in Table 4.10 has a danger index, d=45. This value is computed by the product t•n•p (1.00• 245• 0.182).

Table 4.10: Index for Worker A

Task No.	Time,t (min/unit)	Percent, p	Units	No.of Units, n	Index, d
2	1.00	18.2	members	245	45
6	0.67	18.2	members	245	30
					75

The following procedure can be used for the safety assessment of any construction technology:

1)Determine the stages where the technology is utilized;

2)Identify the tasks necessary to operate the technology;

3)Estimate the production rates of each of the tasks identified in step 2);

4)Identify the causes of injury present in each task;

5)Identify each worker who will perform each tasks listed in step 2);

6)Compute the danger index for each worker;

7)Compute the danger index for each stage; and

8)Compare the danger index to the alternative of not using the technology.

4.5 Construction as a Manufacturing Process

In the future, it may be possible to program the flow of structural steel erection stages with a resource-based scheduling algorithm. In joint research between the Department of Civil and Environmental Engineering and the Department of Industrial Engineering at Lehigh University, the construction problem has been approached as a manufacturing problem.

A logic network of the construction activities needed to erect the prototype building was developed and used as a sample to test the algorithm developed by faculty in the Department of Industrial Engineering (Storer and Wu, 1992). This test exposed the need to define logical constraints as well as resource constraints. At present the algorithm can handle both types of constraints. However, a new type of constraint referred to as a *technical constraint* was introduced to allow for the structural and construction decisions that must be taken to properly simulate the erection process. For example, the need to assure that an erection unit is stable, or a limit on the maximum number of bays that could be plumbed together are technical constraints. These technical constraints restrict the scheduling algorithm from randomly scheduling activities. As an example, consider the erection of the first tier of columns. Since the erection unit is the column, there seems to be no constraint in erecting them in any order. However, the random moving of the crane from one end of the site to another would be a delay and a safety risk. Thus the order in which they are erected can be specified as a technical constraint. In the same way, if four columns were to be erected and then braced with four beams, then the erection unit is a bay. The next two adjacent columns would be set next, and this time three beams would be need to complete the second bay. This technical constraint could be specified if stability concerns are considered critical by the engineer. Heavy members, long spans and slender members are just a few examples of why ensuring stability may be critical.

The algorithm considers an efficient allocation of resources, and finds the critical path of the network. The results of the scheduling algorithm for four cases of the erection of the prototype building are shown in Table 4.16. Each case is defined by its resources. The project being scheduled is the same for all four cases. The network should have the internal and external decisions identified for the particular project under consideration. The output of the algorithm is the scheduling of sequential and parallel activities with respect to best allocation of resources. The results of these preliminary analyses using the resource allocation algorithm indicate that the project duration changes significantly when the number of workers is increased from six members in a crew to eight (a time reduction of 23% and 22% for one and two cranes, respectively). On the other hand, when keeping the number of workers constant, the duration is barely affected (less than 1% duration reduction for one and two cranes). However, the crane utilization drops by approximately 50% when increasing the resources from one to two cranes, emphasizing the fact that the additional crane is not worth the cost.

While the results of this ongoing research remain to be explored in greater detail, it appears to indicate that current allocation of resources is relatively efficient for existing designs and technologies. New designs and advanced construction technologies that alter the flow of the construction process or require different sets of resources show promise in increasing the efficiency of resource allocation and project scheduling.

Table 4.11: Results from industrial engineering scheduling algorithm

Observation	Case A	Case B	Case C	Case D
Cranes	1	2	1	2
Ironworkers	6	6	8	8
Days	10.8	10.7	8.8	8.8
Crane utilization	45%	23%	55%	28%
Crew Utilization	77%	78%	71%	71%

4.6 Summary

In summary, Chapter 4 presents the three models that were developed to simulate the erection process. The flow diagram is conceptually dynamic and infinitely adaptable to any project, but lacks a definite output. The productivity/resource model is accurate for specifically counting structural components, and estimating times for the different stages.

The disadvantage of this model is that it is static. In other words, it cannot overlap activities. The third model enhances the erection flow diagram with the attributes of the spreadsheet, and provides dynamic results.

These models will be used in the assessment of the nine advanced construction technologies in Chapter 5.

Chapter 5

Assessment of Advanced Construction Technologies for Structural Steel Erection

Even though structural steel erection procedures have remained virtually unchanged since welding and strength bolts replaced rivets, certain new technologies have been recently developed. Advanced construction technologies for all construction trades were identified in a recent survey of new construction innovations (Higgins and Slaughter, 1993). This chapter uses the three simulation models developed in Chapter 4 to assess several advanced construction technologies for structural steel erection. The analysis is centered around three economic aspects: duration, cost and safety.

Although the advanced construction technologies that will be analyzed in this thesis are not robots, their intention is to automate the construction process. The term *robot* has no internationally agreed definition, and requires some clarification. Europeans regard robots as autonomous machines, capable of mobility, of dealing with large forces, harsh environments, and having some cognitive skills. Many of Japan's robots would be termed advanced automation devices or telerobots by the European definition. Teleoperation, which is the remote operation by a human, is a principle likely to be adopted for construction sites where performing tasks with heavy loads in dangerous situations may be controlled by an operator situated safely away from the hazard (Wing, 1989). Some of the goals in automating construction tasks are to increase productivity, enhance quality, decrease cost and increase safety. Several approaches to automate construction combine human senses, intelligence and adaptability with machine's speed strength and repeatability. The design approach for construction robots should: 1) be task specific, 2) be rugged and reliable, 3) have a one to two year payback and, 4) take one to two years to manufacture, and have a minimum five year lifetime (Slocum *et al.*, 1987). In brief, it is believed that there are several means by which construction automation might repay the investment in advanced technologies. The eight technologies analyzed in this thesis will prove to make the erection process more safe.

In order to make an assessment of the advanced construction technologies, it is necessary to assess a baseline case to which all the technologies can be compared. The use of a prototype building has been selected for this purpose. The assessment consists of using the three simulation models of Chapter 4 to analyze the impacts of using a given technology in the erection of this building. The focus of the assessment is to identify the operational behavior of each of the technologies, and the consequences they will have in the erection process, including increases or decreases in several aspects such as duration, cost and safety. The assessment also reveals opportunities for new technologies and modifications to existing technologies.

5.1 Procedure for the Assessment

The assessment has been divided in three parts, following the simulation models. The first part identifies the activities which are performed when using the technology which is being assessed. In this part, the flow model for the standard erection process is used to identify any activities that are removed or added in the utilization of the given technology. It may also be the case that an activity must be divided into several tasks due to the operational characteristics of the given technology.

After using the first model, the productivity/resource model is used to set the production rates pertaining to the technology being analyzed. Values of production rates from Table 4.3 are assigned to each of the tasks or activities. Similarly, the resources necessary to conduct the erection activities are listed. These resources, and specifically the crews attached to each of the activities, constitute the core of the safety module assessment, which will be addressed in the third model.

The third model is used to assess the increase in productivity, decrease in costs and the safety of the technology. The safety module analysis included in this model is conducted based on the workers of each crew that perform the tasks or activities associated with the specified technology. The ten causes of injuries presented in Table 4.8, are matched to the tasks identified in the first model. In this stage of the assessment a danger index is determined for each of the tasks.

These three parts of the assessment are then summarized in a table which permits a direct comparison of the technologies with respect to the erection of the prototype building using standard methods. Duration, cost and safety are tabulated for each of the technologies.

All of the stages are analyzed in the baseline case of the prototype building. Any of the results of the baseline case which may be needed in the assessment of the advanced construction technologies will be extracted and used to complement the analysis of each of the technologies. For instance, when analyzing the ATLSS Connector, only the erection and permanent connections stages are addressed. The remaining four stages that the analysis for the ATLSS Connector does not cover are extracted from the baseline case since they do not change.

5.2 Assessment of the Prototype Building

The simulation models are applied to a prototype structure to accomplish two objectives. The first is to demonstrate the use of the models in a project. This example application provides a detailed examination on how the design details of a building are translated into the simulation models. The second objective is to provide a common baseline upon which comparisons can be made on the effectiveness of new technologies. This building is a four-story high building, two bays wide and six bays long. This building was designed in conjunction with research conducted on the ATLSS Connector (Rosa, Lu and Viscomi, 1993). The structure uses standard rolled sections, with bolted connections. Figure 5.1 shows that the structural system is a series of seven frames in the transverse direction. Figure 5.2 shows the structural connections. Partially restrained seated connections on the frames, and simple shear connections on the infill and bracing beams between frames constitute the connection design. The structural system and geometry of the building show that in the plan view, there are 12 "bays" per floor, for a total of 48 "bays" for the four floors. However, for the geometry of this structure the sequence assumed for its erection is based on defining the erection unit. A module of two floors consisting of four columns, four perimetral beams and two infill beams on the first floor, and four other perimetral beams and two other infill beams on the second floor will be defined as a *bay*. Thus the prototype building will be referred to as having a total of 24 *bays*.

The columns are specified as 56 feet, the full length of the four floors. Although erectors do not recommend columns longer than two floors, the columns of the prototype building have been assumed to be fabricated for the whole four-story height of the building (Zimmerman, 1995). The reason for this assumption is that the Mighty Jack will require relatively long columns to work efficiently. For simplification of the analyses, the same fabrication procedures have been assumed for all cases. Thus, there will be no splice bolts in any of the cases presented.

Erection of the prototype building is performed using standard procedures of erecting structural steel. That is, a boom crane and standard minor provisions like an impact wrench, a compressor, manual tools and emergency oxy-acetylene equipment are basic equipment and tools for any project. For labor resources, the crew consists of two erectors, a crane operator, a hooking person, two connectors, two deck layers, a helper and a supervisor. In the assessment of the advanced technologies, each technology will

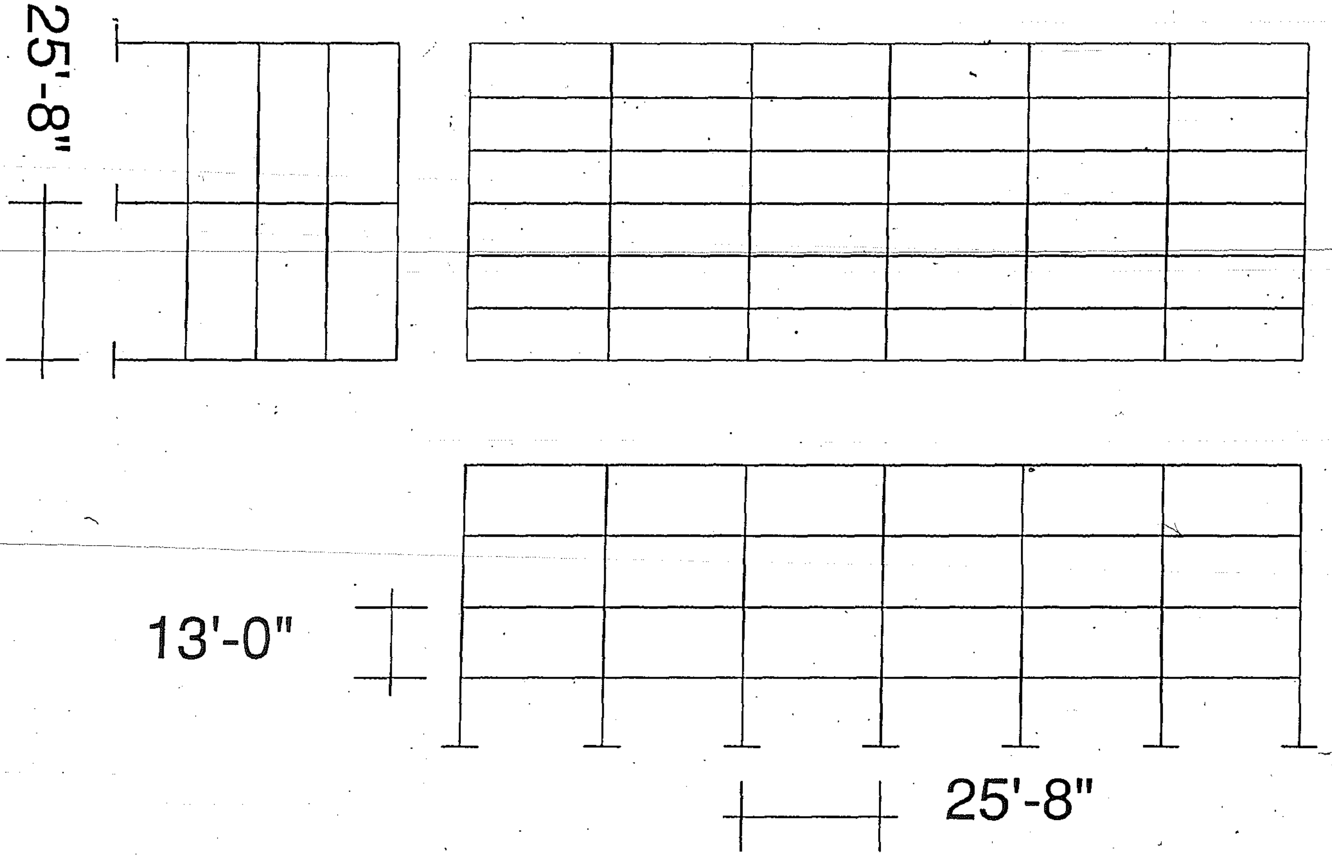
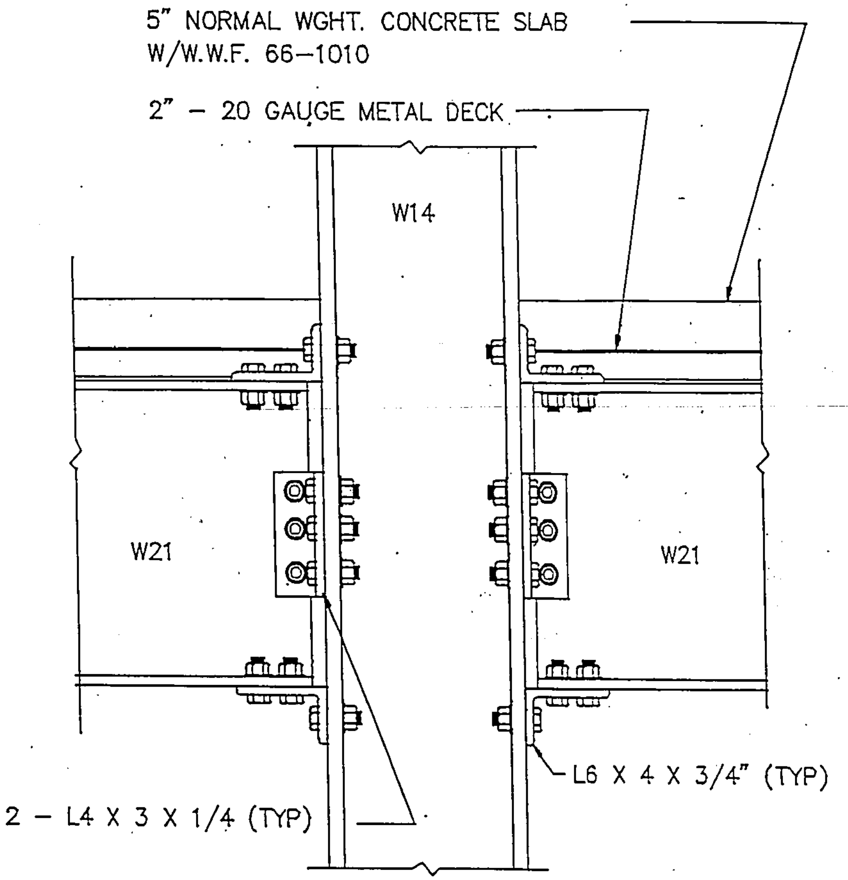


Figure 5.1 Structural System of Prototype Building



NOTE: ALL BOLTS ARE 7/8" DIA A325F (42 TOTAL PER JOINT)
STRUCTURAL STEEL – A36
CONNECTION ANGLES – 50 KSI YIELD STRENGTH

Figure 5.2 Structural Connections of Prototype Building be introduced as part of the erection process for the prototype building, thereby permitting the direct evaluation of the technology.

5.2.1 Flow Model

The erection sequence that has been selected is one of the standard procedures: the erection of one bay after another. In the first bay, four columns are set and then tied by erecting the beams. The sequence proceeds in the second bay with the erection of two columns and tying them to the previous two columns which are shared between the two adjacent bays. Some erectors prefer to erect all columns and then tie them with the beams. A combination of these two sequences is also probable, where an erector may set the columns in as many bays as are expected to be erected in one day, and then work bay by bay setting the beams. These sequences are all dependent on the experience of the erector and his/her preferred method of erection, and on the stability of the erected members when work is stopped. As will be seen in the analysis of the technologies, this will make a difference in the assessment. Certain developments in determining the most effective sequence are being studied in the Department of Industrial Engineering at Lehigh University, in a joint research with the Department of Civil and Environmental Engineering (discussed in Section 4.5).

Using the flow model and Table 4.7, the tasks and activities required for the erection of the prototype building are selected listed in Table 5.1.

Table 5.1: Tasks and activities for each of the stages for the prototype building

Stage	Task/Activity
Unloading	1, 2, 14, 15, 6
Shakeout	1, 14, 15
Erection	1, 2, 3, 4, 5, 6
Plumbing	16
Permanently Connecting	7, 8
Decking	9, 10

5.2.2 Productivity/Resource Model

The quantities in Table 5.2 show all structural elements that must be considered to analyze the prototype building. The members are divided into 224 beams and 21 columns. There are 2926 bolts which will be bolted on-site. All other bolts are shop installed. The decking requires 16 sheets per bay, with a total of 384 sheets for the whole building. Finally, with 15 shear studs per beam (spaced 6 inches apart on the end with 3 studs 3 feet apart in the middle), there are a total of 3360 shear studs.

The productivity/resource model has been run for this baseline scenario and the results are listed in Tables 5.3 to 5.6. Appendix B shows all the computations necessary to obtain these results that are incorporated into a commercially available spreadsheet. Tables 5.3 through 5.6 show the duration of the project, the direct and indirect costs, resources and the productivities associated with the erection of the building.

The standard production rates in Table 4.3 have been multiplied by the site factor

Table 5.2: Quantities of Structural elements for the prototype building

Structural Elements	Number of elements
members	245
bolts	2926
deck sheets	384
shear studs	3360
bays	24

and include different idle times as assigned in Chapter 4. The productivity factor was calculated based on a site condition of a slightly greater ease of materials handling than the one for the normal case, no existing structure to be interfering with the erection of the prototype building, regularity of structural layout (since the geometry of the prototype building is indeed perfectly regular), standardization of connections since there are only three types of connections in the whole structure (anchor bolts, double shear angles, partially restrained seated connections); normal weight of members at 45 pounds per foot; average skilled and experience crew; normal equipment; efficient erection of sequence; and normal site management organization. These values add to +9 (Appendix B, page 3). The *normal* condition is defined as +6, so these two values yield a productivity factor, F=0.89 for the prototype building.

As an example of the results, the decking time estimate can be computed. There are 384 sheets that a subcrew of two workers can install at 4 minutes per sheet. There are also 3360 studs that can be sequentially installed by the same subcrew at 0.25 minutes per stud. These two activities yield a standard time estimate of 4.95 days (2376 minutes). When multiplied by the site factor, the actual time estimate is 4.40 days as shown in

Table 5.3. For the prototype building, the factor is less than 1.00, meaning it reduces the duration for each activity.

The production rates multiplied by the quantities for different structural elements yield *static* time estimates in this second model. Thus, they do not represent the dynamic overlapping of activities which really occurs at a site. As an approximation for the total duration of the project, two days have been added to the plumbing/permanent connection stages, which at this point is assumed to be on the critical path. These two days include: one day of work of unloading, shaking out and erecting before starting the permanent connection stage, and another day at the end presuming further activities such as decking until the completion of the project. Therefore 6.76 days plus two days yield 8.76, which the model rounds to 9.00 days.

It is important to note that the costs are based on a crane utilization of five days. Since the model is not dynamic, the total cost is not showing additional costs that may be caused due to proper scheduling of the activities, as is done in model number three when the crane is utilized during six days.

Table 5.3: Static Durations of Productivity/Resource Model for the Prototype Building

Times	
Unload	0.49 days
Shakeout/Erect	3.79 days
Plumb/Perm. Conn.	6.76 days
Deck	4.40 days

Table 5.4: Costs based on Productivity/Resource Model for the Prototype Building

Cost	
Direct	$ 28,900
Indirect	$ 25,900
Total	$ 54,800

Table 5.5: Resources for Productivity/Resource Model for the Prototype Building

Resources	
No. of cranes	1 crane
Crane utilization	5 days
Labor	12 workers

Table 5.6: Productivity based on Productivity/Resource Model for the Prototype Building

Productivity	
Members/day	57
Bolts/person/day	108
Project duration	9 days

5.2.3 Daily Dynamic Model

The third model analyzes the *dynamic* aspects. The results are shown in Tables 5.7 to 5.10, which demonstrate how the safety and stability constraints have been followed to comply with OSHA regulations of Subpart R (OSHA, 1994). The logic sequencing of erecting bays mandates the stability of the structure, and is explicitly included in the analysis. Examples of these constraints are that at no point in time are the erection activities performed unless the decking stage is completed 32 feet beneath the level at which erection is being conducted. Moreover, it can be seen that at the end of each day, a bay is completed to guarantee the stability of the frames, thereby eliminating the need to perform any type of temporary guying.

Both the productivity/resource model and the daily simulation model, as explained in Chapter 4, refer to the first model of process flow. Since the second model has already identified the production times, and the first model the repetitiveness of the activities, this information merges into the third model. Stability and other technical constraints and safety issues are considered for the full simulation.

It is important to note that resources are reassigned and shared by different activities throughout the whole duration of the project. This sharing and reassigning is not possible to model using standard methods or existing commercial software packages with a time-based scope rather than a resource scope. The procedures for reassigning resources were described in section 4.4.1.

The third model is the final simulation that can be achieved with the models presented in this research. The results of models number one and two should be analyzed by an engineer to come up with this final third model according to the procedures listed in Chapter 4.

Tables 5.7 through 5.10 show some differences with respect to those of the second model due to the dynamic nature that is introduced in the third model. Two important changes cause differences. First, the crane utilization time is six days since it is necessary to skip the third day and reassign resources to comply with OSHA regulations. Specifically, decking is started on the third day to provide a floor 32 ft below the elevation at which erection is being conducted, as stated by OSHA's Subpart R on structural steel erection. Second, the efficient reassignment of resources is performed so that connecting and decking can both be achieved, with the latter depending on the prior finalization of permanently connecting the structure. Note that the results show that with two less workers and the proper overlapping of activities, the third model results in a duration of 8.5 days rather than 9.0 days computed by the second model.

Table 5.7: Durations using Daily Dynamic Model for the Prototype Building

Times	
Unload/Shake/Erect	4.60 days
Plumb/Perm. Conn.	7.50 days
Deck	4.50 days

Table 5.8: Costs based on Daily Dynamic Model for the Prototype Building

Cost	
Direct	$ 25,800
Indirect	$ 22,500
Total	$ 48,300

Table 5.9: Resources for Daily Dynamic Model for the Prototype Building

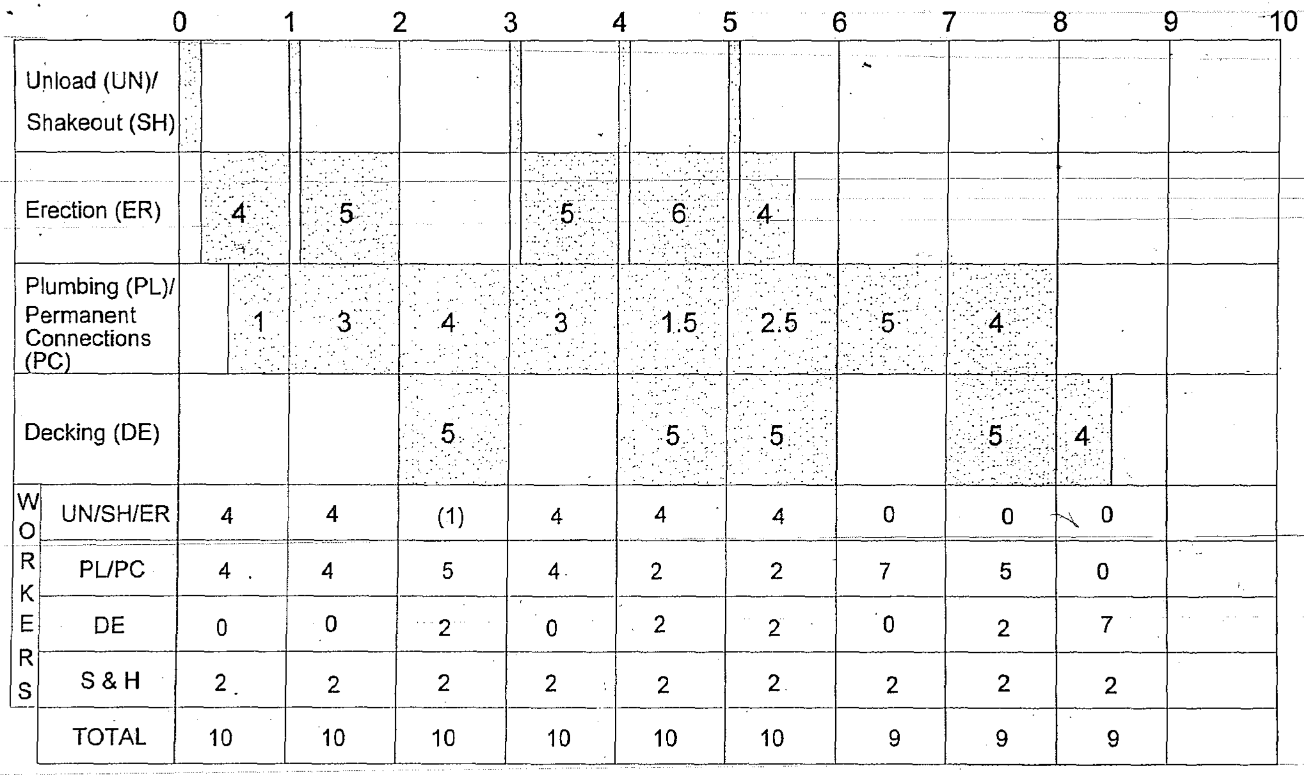
Resources	
No. of cranes	1 crane
Crane utilization	6 days
Labor	10 workers

Table 5.10: Productivity based on Daily Dynamic Model for the Prototype Building

Productivity	
Members/day	53
Bolts/person/day	92
Project duration	8.5 days

5.2.3.1 Duration

The duration of the project is computed after considering the following aspects. Two trucks arrive and are unloaded on the first day, and one on the second, fourth and fifth days (Figure 5.3). Shakeout is performed on these same days, plus on the sixth day. Erection occurs on the first six days, except that on the third day, the workers are reallocated to perform decking activities to permit the erection of members on higher levels. Plumbing and permanently connecting start as soon as the first bay is erected. Reassignment of labor resources creates different production rates for bolting every day. Finally, decking is performed on the third, fifth, sixth, eighth and last half-day using the same subcrew for each day. Thus the production rate for decking is constant from day to day. On the fifth day all stages are being performed. There are not enough labor resources for the connecting stage, so the daily production rate is low at 2.5 bays. Conversely, on the sixth day, as much as seven workers could be bolting for a high daily rate of 5 bays.



WORKERS	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10
UN/SH/ER	4	4	(1)	4	4	4	0	0	0	
PL/PC	4	4	5	4	2	2	7	5	0	
DE	0	0	2	0	2	2	0	2	7	
S & H	2	2	2	2	2	2	2	2	2	
TOTAL	10	10	10	10	10	10	9	9	9	

Notes: (1) - Crane operator is idle.
S & H - Supervisor and Helper
Shaded numbers represent # of bays completed.

Figure 5.3 Gantt Chart for the Prototype Building Using Standard Methods

5.2.3.2 Cost

Looking at the labor resource information on the bottom of Figure 5.3, there are nine workers needed for the first eight days, one crane operator needed for the first six days, and six workers on the last half-day. Since the crane operator is included in the crane rental cost, the wage, W, is computed as follows:

$$W = \Sigma R \bullet H \bullet D \bullet L,$$

where each of the variables is defined as follows:

R=Wage rate per hour,

H=Number of hours worked in a day,

D=Number of days worked,

L=Number of laborers.

Therefore, the wage for the duration of the erection of the prototype building is:

$$W = (35 \bullet 8 \bullet 8 \bullet 9) + (35 \bullet 4 \bullet 1 \bullet 6)$$

$$W = \$21{,}000.$$

All other costs in Table 5.11 are rounded to the nearest hundred. Notice that the direct cost is the summation of the crane rental cost and wages. This third model uses ten rather than the twelve workers used in the second model. The reassignment of labor resources accounts for this advantage. Even with one additional crane day in model number three, the cost of the whole project remains lower than in the second model.

Table 5.11: Erection costs of prototype building using dynamic model

Cost Aspect	Rate	Cost
Wage	$35/hour	$21,000
Workmans's Compensation	52 % of wage	$10,900
Overhead and Profit	45 % of direct cost	$11,600
Crane Rental	$800/day	$4,800
Total		$48,300

5.2.3.3 Safety

The purpose of this section is to show how the safety module in the dynamic model is applied to the prototype building. As explained in the previous chapter, thedanger index, D, is a summation of all specific danger indexes, d, for each worker. The following tables show the values of the specific danger indexes for each task or activity, and aggregates this value for a subtotal corresponding to each stage. The danger index for the whole erection process is 2290, computed from adding unloading (129), shakeout (34), erection (631), plumbing (4), permanently connecting (32) and decking (860).

Tables 5.12 and 5.13 are show how the actual times (without including idle time) are used for the assessment of safety. As an example, consider the production rate of a subcrew of two workers bolting. The rate is 2.5 minutes per bolt installed and tightened. This value includes idle time, since it is obtained from the standard production rates. When subtracting the idle time of 50 percent of the *total* time, the active time is 1.25 minutes per bolt (and 1.25 minutes per bolt for idle time). This value is separated into two tasks: install bolts (task 7) and tighten bolts (task 8) in Table 5.13.

Table 5.12 Idle percentages by stage

Stage	Idle Percentage of Total Time
Unloading	50 %
Shakeout	25 %
Erection	50 %
Plumbing	25 %
Permanently Connecting	50 %
Decking	50 %

Table 5.13:Production rates for danger exposure index

Task No.	Stage	Production Rate
1	UN, SH, ER	0.50 min/lift
2	UN, ER	1.00 min/lift
3	ER	0.50 min/member
4	ER	1.00 min/member
5	ER	0.33 min/member
6	UN,ER	0.67 min/lift
7	PC	0.25 min/bolt
8	PC	1.00 min/bolt
9	DE	32.0 min/bay
10	DE	17.5 min/bay
14	UN, SH	0.30 min/lift
15	UN, SH	0.03 min/lift
16	PL	5.0 min/bay

5.2.3.3.1 Tasks vs. Injuries

Following the procedures of Chapter 4, each of the identified tasks must be analyzed in relation to the causes of injury. Tables 5.14 to 5.19 analyze each stage separately. The check marks indicate that the injury is present, and replaces the values of the percentages listed in Table 4.8, which do not change.

Table 5.14: Cause of injury *vs.* task for Unloading stage for Prototype Building

Cause of Injury	TASK				
	1	2	14	15	6
1.Struck against					
2.Struck by	✓		✓		
3.Caught in or between	✓		✓		
4.Rubbed, abraded and penetrated	✓		✓	✓	
5.Fall of person (different level)		✓			✓
6.Fall of person (same level)	✓		✓		
7.Bodily reaction	✓		✓		
8.Contact, electric current		✓			✓
9.Contact, temperature extremes					
10. Contact, radiations, caustics, toxic and noxious substances					
Total Percentage	67.2	18.2	67.2	3.5	18.2

Table 5.15: Cause of injury *vs.* task for Shakeout stage for Prototype Building

Cause of Injury		T	A	S	K
		1	14	15	
1.Struck against					
2.Struck by		✓	✓		
3.Caught in or between		✓	✓		
4.Rubbed, abraded and penetrated		✓	✓	✓	
5.Fall of person (different level)					
6.Fall of person (same level)		✓	✓		
7.Bodily reaction		✓	✓		
8.Contact, electric current					
9.Contact, temperature extremes					
10. Contact, radiations, caustics, toxic and noxious substances					
Total Percentage		67.2	67.2	3.5	

Table 5.16: Cause of injury *vs*. task for Erection stage for Prototype Building

Cause of Injury	TASK					
	1	2	3	4	5	6
1.Struck against						
2.Struck by	✓		✓			
3.Caught in or between	✓		✓	✓		
4.Rubbed, abraded and penetrated	✓		✓	✓		
5.Fall of person (different level)		✓	✓	✓	✓	✓
6.Fall of person (same level)	✓					
7.Bodily reaction	✓		✓	✓		
8.Contact, electric current		✓				✓
9.Contact, temperature extremes						
10. Contact, radiations, caustics, toxic and noxious substances						
Total Percentage	67.2	18.2	75.1	54.1	14.9	18.2

Table 5.17: Cause of injury *vs*. task for Plumbing stage for Prototype Building

Cause of Injury	T	A	S	K
		16	17	
1.Struck against				
2.Struck by				
3.Caught in or between				
4.Rubbed, abraded and penetrated		✓	✓	
5.Fall of person (different level)				
6.Fall of person (same level)				
7.Bodily reaction				
8.Contact, electric current				
9.Contact, temperature extremes				
10. Contact, radiations, caustics, toxic and noxious substances				
Total Percentage		3.5	3.5	

Table 5.18: Cause of injury *vs*. task for Permanent Connections stage for Prototype Building

Cause of Injury	TASK			
		7	8	
1.Struck against				
2.Struck by				
3.Caught in or between				
4.Rubbed, abraded and penetrated		✓	✓	
5.Fall of person (different level)		✓	✓	
6.Fall of person (same level)				
7.Bodily reaction				
8.Contact, electric current				
9.Contact, temperature extremes				
10.Contact, radiations, caustics, toxic and noxious substances				
Total Percentage		18.4	18.4	

Table 5.19: Cause of injury *vs*. task for Decking stage for Prototype Building

Cause of Injury	T	A	S	K
		9	10	
1.Struck against				
2.Struck by				
3.Caught in or between		✓		
4.Rubbed, abraded and penetrated		✓	✓	
5.Fall of person (different level)		✓		
6.Fall of person (same level)				
7.Bodily reaction		✓		
8.Contact, electric current				
9.Contact, temperature extremes				
10.Contact, radiations, caustics, toxic and noxious substances				
Total Percentage		54.1	3.5	

5.2.3.3.2 Workers *vs.* Injuries

These tables show how to compute the specific danger indexes from the relation d = t•n•p which was explained in Chapter 4. The values for the time, t, the percent, p, and the number of units, n are obtained from the previous tables in this chapter.

For the unloading stage, five workers are present. Usually the two erectors climb on the truck and tie members in bundles. Two workers should be present during the unhooking tasks since the load of the bundles is as high as three tons and requires that one worker be reassigned to help the hooking person. This stage adds all specific indexes for the subcrew workers to 129.

Table 5.20: Specific danger indices for unloading (workers A, B, C, D and E)

Worker A

Task No.	Time, t (min/unit)	Percent, p	Units	No.of Units, n	Index
2	1.00	18.2	members	245	45
6	0.67	18.2	members	245	30
					75

Worker B

Task No.	Time, t (min/unit)	Percent, p	Units	No.of Units, n	Index
1	0.50	67.2	lifts	49	17
					17

Worker C

Task No.	Time, t (min/unit)	Percent, p	Units	No.of Units, n	Index
1	0.50	67.2	lifts	49	17
					17

Worker D

Task No.	Time, t (sec/unit)	Percent, p	Units	No.of Units, n	Index
14	0.30	67.2	lifts	49	10
15	0.03	3.5	lifts	49	0
					10

Worker E

Task No.	Time, t (min/unit)	Percent, p	Units	No.of Units, n	Index
14	0.30	67.2	lifts	49	10
15	0.03	3.5	lifts	49	0
					10

UNLOADING DANGER INDEX: 129

The shakeout stage is one of the safest, with a summation of 34 for the specific indexes for the workers in this stage. Two workers are involved in this analysis.

Table 5.21: Specific danger indices for shakeout (workers B and D)

Worker B

Task No.	Time, t (sec/unit)	Percent, p	Units	No.of Units, n	Index
14	0.50	67.2	lifts	49	17
15	0.03	3.5	lifts	49	0
					17

Worker D

Task No.	Time, t (min/unit)	Percent, p	Units	No.of Units, n	Index
1	0.50	67.2	lifts	49	17
					17

SHAKEOUT DANGER INDEX: 34

The next stage is erection. The four members of this subcrew are the crane operator, the two erectors and the person hooking. The addition of all specific indexes yields 631 for the erection subcrew.

Table 5.22: Specific danger indices for erection (workers A, B, C and D)

Worker A

Task No.	Time, t (min/unit)	Percent, p	Units	No.of Units, n	Index
2	1.00	18.2	members	245	45
6	0.67	18.2	members	245	30
					75

Worker B

Task No.	Time, t (min/unit)	Percent, p	Units	No.of Units, n	Index
3	0.50	75.1	members	245	92
4	1.00	54.1	members	245	133
5	0.33	14.9	members	245	12
					237

Worker C

Task No.	Time, t (min/unit)	Percent, p	Units	No.of Units, n	Index
3	0.50	75.1	members	245	92
4	1.00	54.1	members	245	133
5	0.33	14.9	members	245	12
					237

Worker D

Task No.	Time, t (sec/unit)	Percent, p	Units	No.of Units, n	Index
1	0.50	67.2	members	245	82
					82

ERECTION DANGER INDEX: 631

Plumbing is a stage that without assessment of any sort can be intuitively assessed as safe. One reason is that it doesn't last long. The other reason is that when the plumbing tasks of the higher bays are performed, part of the decking has been set. Thus there are no present dangers of falling or straining. Indeed the safety module shows its reliability by expressing the danger of this stage for this stage as 4.

Table 5.23: Specific danger indices for plumbing stage (worker E)

Worker E

Task No.	Time, t (min/unit)	Percent, p	Units	No.of Units, n	Index
16	5.00	3.5	bay	24	4
17	2.50	3.5	column	0	0
					4

PLUMBING DANGER INDEX: 4

The permanent connections stage aggregates a danger index of 632 for its subcrew. Notice that although there are two workers who share the activity, only one was specified. This is important to realize since in the dynamic model there is an intricate reassignment of labor resources, and it is hard to know exactly when there are only two workers bolting. The fact is that 2926 bolts need to be tightened and 2030 installed, and modelling the danger index for one worker captures the repetition of the activity for the whole building.

Table 5.24: Specific danger indices for permanently connecting stage (worker E)

Worker E

Task No.	Time, t (min/unit)	Percent, p	Units	No.of Units, n	Index
7	0.25	18.4	bolts	2030	94
8	1.00	18.4	bolts	2926	538
					632

PERMANENTLY CONNECTING DANGER INDEX: 632

The decking stage is the most dangerous. Again, the models show their reliability as in the literature, decking has been reported to be the stage that causes the most fatalities (Bureau of National Affairs, 1992). An index of 860 been calculated for this stage. Again note that the number of workers is irrelevant. The assessment could have been done for six workers, each decking four of the 24 bays, and the same result would have been obtained.

Table 5.25: Specific danger indices for decking stage (worker G)

Worker G

Task No.	Time, t (min/unit)	Percent, p	Units	No.of Units, n	Index
9	64.0	54.1	bay	24	830
10	35.0	3.5	bay	24	30
					860

DECKING DANGER INDEX: 860

Table 5.26 lists all the stages and the corresponding danger indexes.

Table 5.26: Danger Indices for each stage for the prototype building

Stage	Danger Index
Unloading	129
Shakeout	34
Erection	631
Plumbing	4
Permanent Connections	632
Decking	860
Total	2290

5.2.4 Results

Table 5.27 shows the results obtained after applying the simulation models to the prototype building. These results are the baseline case to which all other technologies will be compared.

Table 5.27: Results for the prototype building as a baseline for comparison

Economic Aspect	Prototype Building
Project Duration	8.5 days
Direct and Indirect Cost	$48,300
Safety Index	2290 units
Labor and Equipment Resources	10 workers, 1 crane

5.3 Assessment of Advanced Construction Technologies

Eight innovations in structural steel erection were selected from a previously identified set of advanced construction technologies described in ATLSS Report No. 93-15 (Higgins and Slaughter, 1993). This report includes technologies for all the construction industry, but only the ones applicable to steel erection will be analyzed in this research. The ATLSS Connector and the Stewart Platform were developed at Lehigh University, the Shear Stud Welder was developed at M.I.T., and the Mighty Jack, the Mighty Shackle Ace, the Auto-Clamp, the Auto-Claw, and a welding robot were developed in Japan. The references and producers are listed in Table 5.28. Each of these technologies employs different means of operation or locomotion control. The type of control that these technologies have is listed in Table 5.29. Other innovations, like the blind bolt for tubular members, washer-like direct tension indicators, and partially restrained composite connections, exist and could be treated with the methodology presented in this thesis (Lawrence, 1994; J & M Turner, 1992; Leon, 1992b). Construction innovations like the SMART system in Japan deal with long preparation times for its roof-crane assembly, and could be treated in further research to study its increase in productivity (Normile, 1993).

The eight technologies presented here can be grouped according to their operational characteristics. The ones which can be crane replacements are the Stewart Platform and the Mighty Jack. The technologies that serve as crane attachments are the Mighty Shackle Ace, the Auto-Claw and the Auto-Clamp. The equipments for performing connections are the Shear Stud Welder and the Welding Robot. Finally, the ATLSS connector is in a different category since it entails changes in the design, fabrication and erection of connections.

Table 5.28: Advanced construction technologies for structural steel erection

Name	Reference	Producer	Country
ATLSS Connector	Perreira, 1993	Lehigh University	U.S.A.
Stewart Platform	Perreira, 1993	NIST, Lehigh University	U.S.A.
Mighty Jack	Ueno *et al.*, 1986	Shimitzu	Japan
Auto-Claw	Sherman,1988	Ohbayashi	Japan
Auto-Clamp	Sherman, 1988	Ohbayashi	Japan
Mighty Shackle Ace	Ueno *et al.*, 1988	Shimitzu	Japan
Shear Stud Welder	Slocum *et al.*, 1987	M.I.T.	U.S.A.
Welding Robot	Wing, 1989	Fujita	Japan

Table 5.29: Control systems for advanced construction technologies

Name	Control
ATLSS Connector	not applicable
Stewart Platform	remote positioning and operation
Mighty Jack	remote operation
Auto-Claw	remote operation
Auto-Clamp	remote operation
Mighty Shackle Ace	remote operation
Shear Stud Welder	programmed operation
Welding Robot	programmed operation

5.3.1 ATLSS Connector

The ATLSS Connector is a self-aligning shear connector composed of two pieces, the mortise and the tenon (Perreira, 1993; Fleischman *et al.*, 1993). The tenon slides into the mortise, in a tongue and groove fashion. Due to the friction and close fit of both pieces, shear forces are transferred to the connected part. The connector can also transfer moment loads when properly located in the web of the beam and used in conjunction with other elements. Figure 5.4 shows a shear connection using the ATLSS Connector, where the mortise is welded to the column flange, whereas the tenon is bolted to the beam web. In other detailing cases, the mortise is welded to an end plate which is bolted to the column flange. At present the connector is being analyzed as part of a partially restrained (semi-rigid) composite connection in which reinforcing steel in the deck is used to transfer the loads.

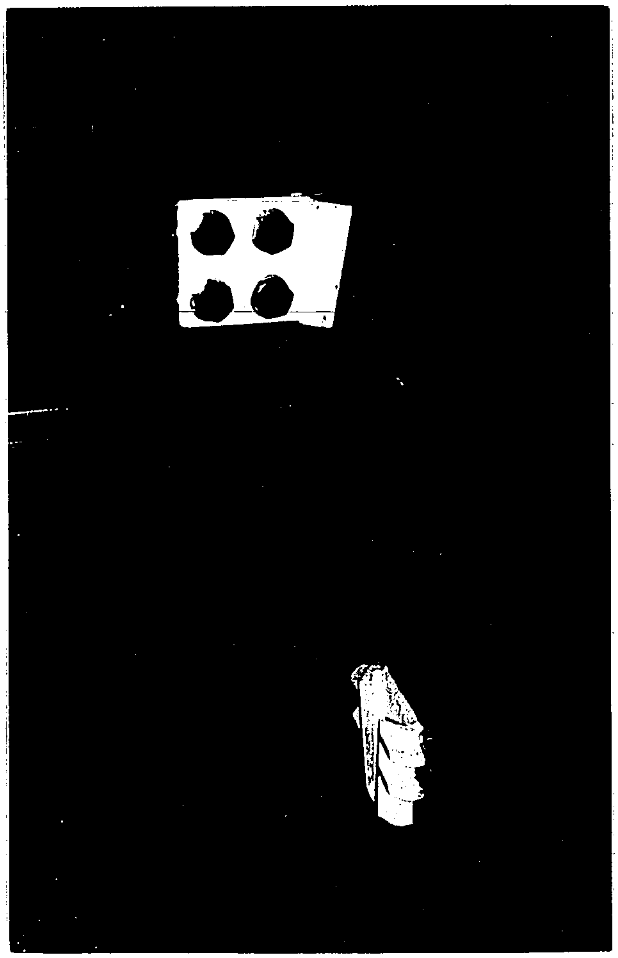


Figure 5.4 ATLSS Connector

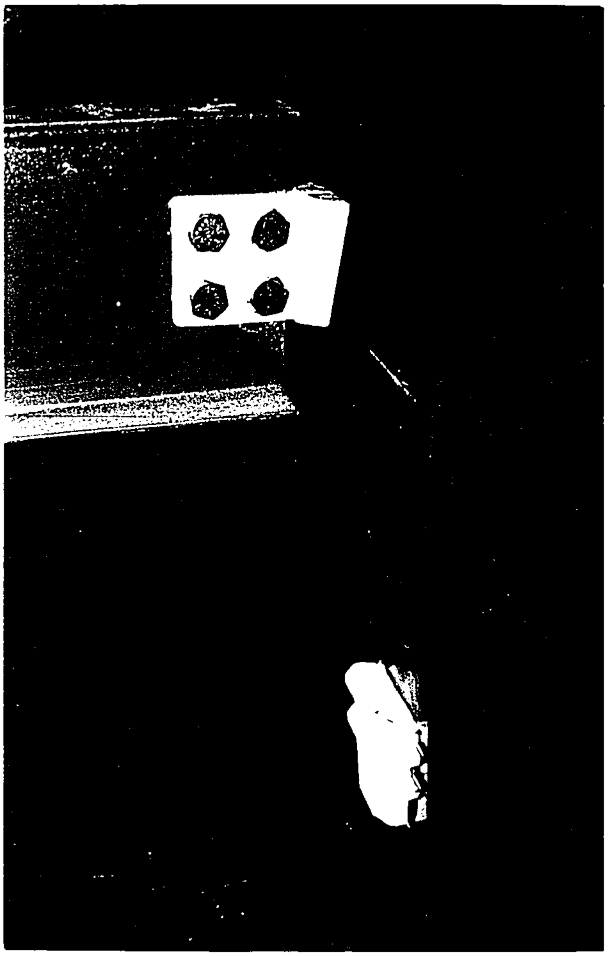


Figure 5.4 ATLSS Connector

The ATLSS Connector has been utilized in two field demonstrations on industrial facilities in Clinton, Iowa and New Johnsonville, Tennessee. The first installation was for connections on a panel which was later dismounted to extend the structure to a higher level. The second project in which the connector was utilized was in the construction of a processing facility in Du Pont's chemical plant in New Johnsonville, Tennessee. This time the connector is expected to remain for the life of the structure. Its utilization demonstrated advantages over standard connections, since it saved time in the connecting activities (Eraso, 1995). In both demonstrations the connector was used on assembled floor or roof panels which consisted of approximately 20 members. However, it can also be used at both ends of a single beam to erect beams one after another.

5.3.1.1 Simulation Models

Three assumptions were used to apply the simulation models to the assessment of the ATLSS Connector. First, one connector at each end of every beam is loosely installed with four bolts. This permits adjustment to erection and fabrication tolerances. Second, every connector has one seating bolt which prevents uplift. This bolt is installed and tightened during the permanent connection stage. And third, the connections in the structural frame of the prototype building are moment resistant, but the installation of additional elements such as reinforcement for the transfer of loads to the deck has been neglected.

The total number of bolts is decreased significantly when using the ATLSS

Connector. This is the main savings in duration that this technology provides, since bolting is on the critical path for the erection of the prototype building. Only 126 anchor bolts and 448 seating bolts have to be installed, and 2366 bolts tightened (81 percent of those needed for the standard connections). All other quantities remain the same as for the standard methods.

Tables 5.30 and 5.31 list the tasks that change with respect to the standard methods. Two of the six stages need to be modified: erection and permanently connecting. In the erection stage, tasks 3, 4, 5 in the standard method have been substituted with new tasks 12 and 13. Positioning the beams (task 12) and remotely unhooking (task 13) are new tasks necessary to replace handling (task 3), connecting (task 4) and unhooking members in the air (task 5). This shows that with the use of the ATLSS connector, safety will be improved since the number and duration of activities above ground are lessened. In addition, although the permanent connection stage's tasks and rates remain the same as for the standard baseline method, the quantities are reduced significantly.

Therefore, the flow of activities can change dramatically when a new technology is introduced. The erection sequence for the ATLSS Connector is as follows. The person hooking hooks the beam with the two tenons loosely tightened at each end, and makes sure to hang a tagline. The crane operator swings the beam to the place where it will be positioned. One erector grabs the tagline while standing on the ground or the deck of the lower level. With the help of the crane operator, he positions the beam by sliding the tenons into the mortises. The erector remotely unhooks the beam by twitching the tagline. (During the site visits of this research, some mechanisms with a lever handle have been observed to help in this unhooking task.) Finally, the crane operator swings the boom out

Table 5.30: Tasks in erection stage for the ATLSS Connector

Task No.	Worker Type	Production Rate (min/members)
1. Hooking	D	0.50
2. Swinging in	A	1.00
12. Positioning beams	A,B	0.67
13. Remotely unhooking	B	0.03
6. Swinging out	A	0.67
	Total	2.87

Table 5.31: Tasks in permanent connection stage for the ATLSS Connector

Task No.	Worker Type	Production Rate (min/bolts)
7.Installing	E,F	0.25
8.Tightening	E,F	1.00

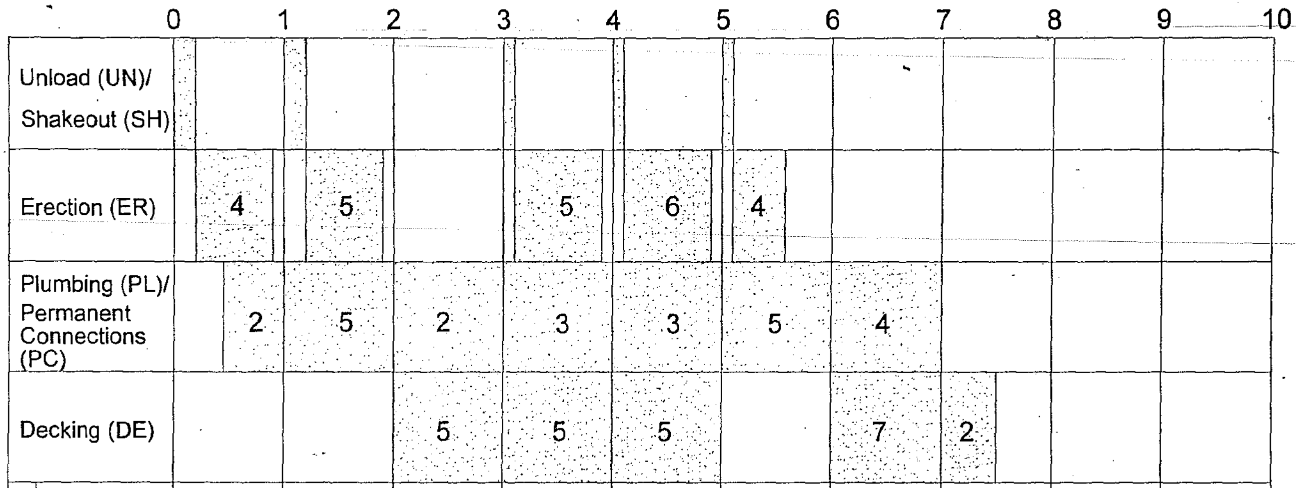
and directs it to where the hooking person is ready for the next cycle. The connectors only have to install one seating bolt at each beam end, and tighten this seating bolt and the four web bolts.

With the ATLSS Connector, it take 2.87 minutes to erect one member. With an idle percentage of 50 percent, the ATLSS Connector production rate is 5.74 minutes per member, compared to 8.00 minutes per member for the standard case. The savings due to the change of tasks is 28 percent per member. This speeds up the stabilization of each of the bays which results in an increase in safety for the workers.

The decrease in the duration of the project results from the decrease in erection time and in number of bolts (Figure 5.5). In turn, as the erection proceeds more quickly, the erector can be reassigned to the permanent connections tasks, thereby reducing the total project by 12 percent.

The calculations for the cost of this project are performed in the same way as for the standard method. The costs when using the ATLSS Connector with a crew of ten workers and a crane is $42,800, a savings of 11 percent over the standard method. More workers could be introduced to speed up the plumbing, permanently connecting and decking stages further for a lower proportional cost due to the increased safety and productivity.

For the assessment of safety, Table 5.32 relates the causes of injury to the tasks needed in the erection and permanent connecting of the prototype building using ATLSS Connectors.



WORKERS	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10
UN/SH/ER	3	3	(1)	3	3	3	0	0		
PL/PC	5	5	5	3	3	5	4	0		
DE	0	0	2	2	2	0	3	2		
S & H	2	2	2	2	2	2	2	2		
TOTAL	10	10	10	10	10	10	9	4		

Notes: (1) - Crane operator is idle.
S & H - Supervisor and Helper
Shaded numbers represent # of bays completed.

Figure 5.5 Gantt Chart for ATLSS Connector

Table 5.32: Cause of injury *vs.* task for the Erection and Permanent Connections Stages for ATLSS Connector

Cause of Injury	TASK						
	1	2	12	13	6	7	8
1.Struck against							
2.Struck by	✓						
3.Caught in or between	✓						
4.Rubbed, abraded and penetrated	✓		✓	✓		✓	✓
5.Fall of person (different level)		✓			✓	✓	✓
6.Fall of person (same level)	✓						
7.Bodily reaction	✓						
8.Contact, electric current		✓			✓		
9.Contact, temperature extremes							
10. Contact, radiations, caustics, toxic and noxious substances							
Total Percentage	67.2	18.2	3.5	3.5	18.2	18.4	18.4

The workers *vs.* injuries tables that follow are presented only for the workers involved in the tasks that have changed with respect to the baseline case (Tables 5.33 and 5.34). All other specific indexes which are unchanged will be extracted from the baseline case as shown in the computations below.

Table 5.33: Specific danger indices for erection using ATLSS Connector

Worker A

Task No.	Time, t (min/unit)	percent, p	Units	No.of Units, n	Index
2	1.00	18.2	members	245	45
6	0.67	18.2	members	245	30
					75

Worker B

Task No.	Time, t (min/unit)	percent, p	Units	No.of Units, n	Index
12	0.67	3.5	members	245	5.7
13	0.03	3.5	members	245	0.3
					6.0

Worker D

Task No.	Time, t (sec/unit)	percent, p	Units	No.of Units, n	Index
1	0.50	67.2	members	245	82
					82

ERECTION DANGER INDEX: 163

Table 5.34: Specific danger indices for permanent connections using ATLSS Connector

Worker E

Task No.	Time, t (min/unit)	percent, p	Units	No.of Units, n	Index
7	0.25	18.4	bolts	574	26
8	1.00	18.4	bolts	2366	435
					461

PERMANENT CONNECTION DANGER INDEX: 461

The danger index, D, for the whole project is computed by adding the six danger index components, D1 through D6, for each of the stages. The third component, the erection danger index, has a value of D3 = 163, and is calculated for workers A, B and D. The fifth component, the connecting danger index, is D5 = 461, calculated for worker E. These values show an increase in safety of 74 percent in erection and 27 percent in connecting with respect to the baseline case. The danger index for all other activities or tasks which will be performed in the same way as for the standard method, are extracted from the baseline case: D1 + D2 + D4 + D6 = 1027. Finally, adding all six components yields 1651 for the whole project.

Table 5.35: Danger index by stage for the ATLSS Connector

Danger index by stage	ATLSS Connector	Standard Method	Reduction
Erection	163	631	74%
Permanent connection	461	632	27%

5.3.1.2 Results

All aspects of the project show onsiderable savings, in utilizing the ATLSS Connector (Table 5.36), indicating the benefits of using the connector. Calculations of potential savings from elimination of the seating bolt and fully tightened web connectors indicate that the ATLSS Connector could potentially reduce erection times by 47% to 4.5 days, reduce costs by 62% by eliminating the connecting subcrew, and increase safety overall by eliminating the permanent connections stage.

Table 5.36: Results for the ATLSS Connector compared to the baseline case

Economic Aspect	ATLSS connector	Standard Method	Savings
Duration	7.5 days	8.5 days	12%
Cost	$42,800	$ 48,300	11%
Danger Index	1651	$\overset{5}{2}290$	28%
Resources	1 crane, 10 workers	1 crane, 10 workers	0%

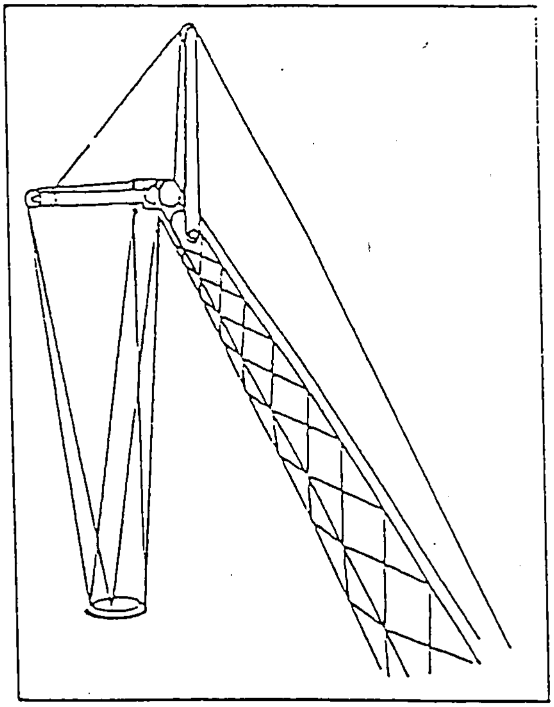
5.3.2 Stewart Platform

The Stewart Platform is a lifting device that offers increased maneuverability in the positioning of structural members. Figure 5.6 shows adaptations of boom and tower cranes to incorporate the Stewart platformm (Perreira, 1993). Manual control by the crane operator uses a specially designed joystick to maneuver the lower platform.

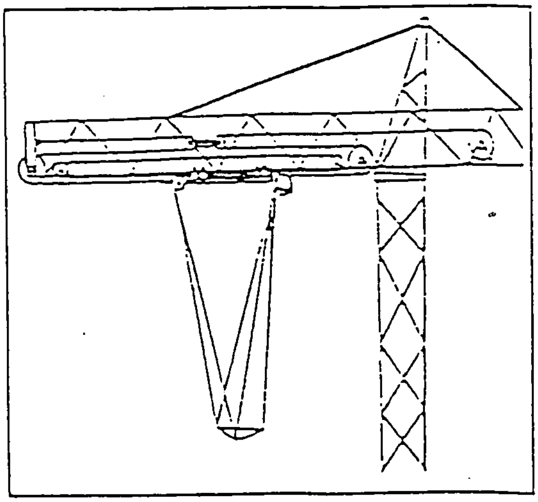
A Stewart Platform is actually two platforms connected by six individually controlled cables which make the lower platform move with six degrees of freedom. In its current configuration, the upper platform is an equilateral triangle four meters on a side. A smaller equilateral triangle two meters on the side hangs as the bottom platform. Thus a horizontal translation of the bottom platform with respect to the upper one is limited to approximately one meter in any direction. Vertical translations are limited only by the length of the cable at hand.

The Stewart Platform is a stable and stiff system. The heavier the payload, the more resistant the platform becomes in the horizontal direction. The stiffness of the platform is an important factor when considering flight speed and susceptibility to wind effects in the placement of large members.

The National Institute of Standards and Technology is currently working on developing the Stewart Platform further, including a universal gripper and the addition of a vision system that could also allow the development of an automated crane erection system.



On Boom Crane



On Tower Crane

Figure 5.6 Stewart Platform

5.3.2.1 Simulation Models

It is assumed that the Stewart Platform is used during the erection stage only. A Stewart Platform is attached to the boom of the crane and more degrees of freedom can be controlled by the crane operator, allowing slightly faster production rates for crane-assisted tasks. The connections remain the same as for the standard baseline case.

None of the structural quantities change. The number of bolts, members, deck sheets and studs is the same as for the standard case.

The use of this technology eliminates the need to handle the members in the air. The two erectors now connect the members, but the positioning and unhooking is done by the crane operator, so the erectors do not need to walk on the recently erected beam and unhook it, thereby increasing the safety of the erection stage. Table 5.37 shows the tasks that are identified by the use of the flow model.

Table 5.37: Tasks in erection stage for the Stewart Platform

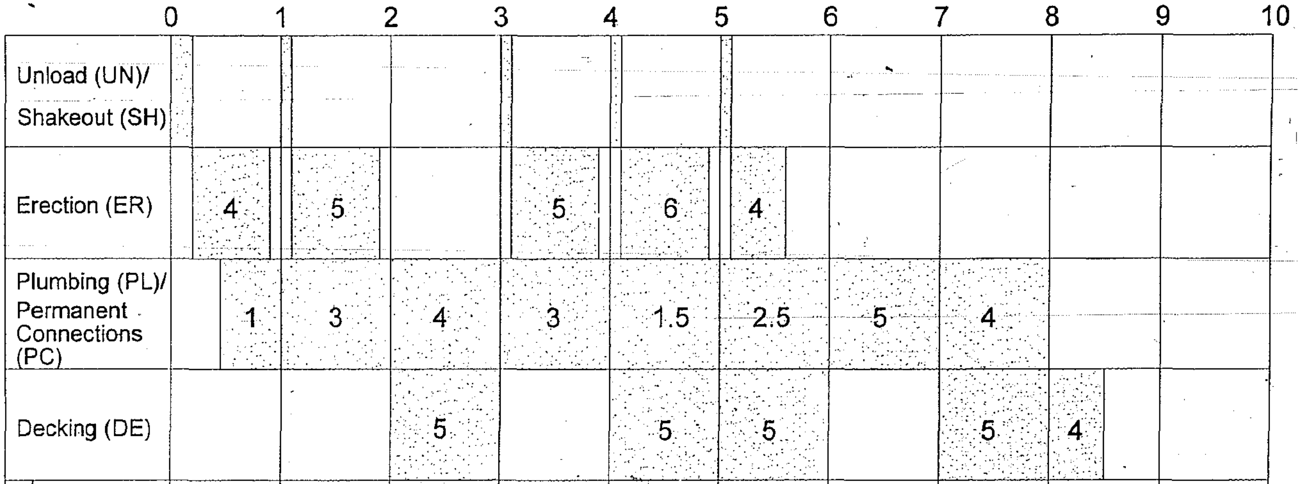
Task No.	Worker Type	Production Rate (min/members)
1. Hooking	D	0.50
2. Swinging in	A	1.00
4. Connecting member in air	B, C	1.00
12. Positioning beams	A, B, C	0.67
13. Remotely unhooking	A	0.03
6. Swinging out	A	0.67
	Total	3.87

Table 5.37 also lists the production rates. When idle time is added, the production rate equals 7.74 minutes per member, compared to the standard rate of 8.00 minutes per member.

The duration of the project remains the same as for the standard case. The decrease in erection time is not on the critical path and does not affect the duration of the project. Figure 5.7 shows the Gantt chart for the erection of the prototype building using this technology.

Since the duration and Gantt chart are the same as for the standard case, the cost of completing the project with the Stewart Platform is the same. The only difference is the potential investment for a Stewart Platform. However, safety does increase, and this may decrease costs in the long run, as seen in Table 5.38 which lists the injuries *vs.* tasks relationships.

The workers *vs.* injuries table (Table 5.39) shows that the danger index for erection is D3 = 302, compared to the standard case of 631, providing a 52 percent decrease (Table 5.40). When combined with the other six components from the baseline case, the danger index, D, for the whole project is computed as 1988.



WORKERS	UN/SH/ER	4	4	(1)	4	4	4	0	0	0	
	PL/PC	4	4	5	4	2	2	7	5	0	
	DE	0	0	2	0	2	2	0	2	7	
	S & H	2	2	2	2	2	2	2	2	2	
	TOTAL	10	10	10	10	10	10	9	9	9	

Notes: (1) - Crane operator is idle.
S & H - Supervisor and Helper
Shaded numbers represent # of bays completed.

Figure 5.7 Gantt Chart for Stewart Platform

Table 5.38: Cause of injury *vs.* task for the erection stage for the Stewart Platform

Cause of Injury	TASK					
	1	2	4	12	13	6
1.Struck against						
2.Struck by	✓					
3.Caught in or between	✓		✓			
4.Rubbed, abraded and penetrated	✓		✓	✓	✓	
5.Fall of person (different level)		✓	✓			✓
6.Fall of person (same level)	✓					
7.Bodily reaction	✓		✓			
8.Contact, electric current		✓	✓			✓
9.Contact, temperature extremes						
10. Contact, radiations, caustics, toxic and noxious substances						
Total Percentage	67.2	18.2	54.1	3.5	3.5	18.2

Table 5.39: Specific danger indices for erection using the Stewart Platform

Worker A

Task No.	Time, t (min/unit)	percent, p	Units	No.of Units, n	Index
2	1.00	18.2	members	245	45
12	0.67	3.5	members	245	6
13	0.03	3.5	members	245	0
6	0.67	18.2	members	245	30
					81

Worker B

Task No.	Time, t (min/unit)	percent, p	Units	No.of Units, n	Index
4	1.00	54.1	members	245	133
12	0.67	3.5	members	245	6
					139

Worker D

Task No.	Time, t (min/unit)	percent, p	Units	No.of Units, n	Index
1	0.50	67.2	members	245	82

ERECTION DANGER INDEX: 302

Table 5.40: Danger index by stage for the Stewart Platform

Danger index by stage	Stewart Platform	Standard Method	Reduction
Erection	302	631	52%

5.3.2.2 Results

Table 5.41 shows that, with the use of the Stewart Platform, safety increases. The maneuverability of this technology may offer additional benefits than are measured in this analysis.

Table 5.41: Results for the Stewart Platform compared to the baseline

Economic Aspect	Stewart Platform	Standard Method	Savings
Duration	8.5 days	8.5 days	0%
Cost	$ 48,300	$ 48,300	0%
Danger Index	1988	2290	13%
Resources	1 crane, 10 workers	1 crane, 10 workers	N/A

5.3.3 Mighty Jack

This technology is a rigid lifting device for placing two or three steel beams between columns (Ueno *et al.*, 1986). The Mighty Jack itself is carried by a crane and installed on two column tops. A griping system allows the Mighty Jack to adjust to different column separations. Once it is set on the column tops, it can be released by the crane, allowing the crane to continue its hoisting tasks in other parts of the site. The Mighty Jack then lowers the beams into position by teleoperation. This technology is currently used commercially for structural steel erection by Shimizu (Figure 5.8).

The main attributes of the Mighty Jack include greater safety, more rapid assembly, and noise reduction due to the jigging and tapping that goes on in standard erection methods during connecting. The positioning and assembly work of the beams is carried out by the manipulator as follows: 1) Set grippers at suitable position for column separation; 2) Hook steel beams with cables from manipulator; 3) Lift the manipulator with beams using a crane; 4) Place the manipulator on the top of two columns; 5) Manually release crane cable from the manipulator; 6) Adjust distance between columns so that beams can be lowered; 7) Set beams in the correct position one by one; 8) Manually connect beams to columns; and 9) Lift the manipulator to perform next cycle (Ueno *et al.*, 1986).

A potentially important function performed by the Mighty Jack is realigning the positions of the columns (step 6) to their correct position. This function could prevent problems in tolerance and fitting.

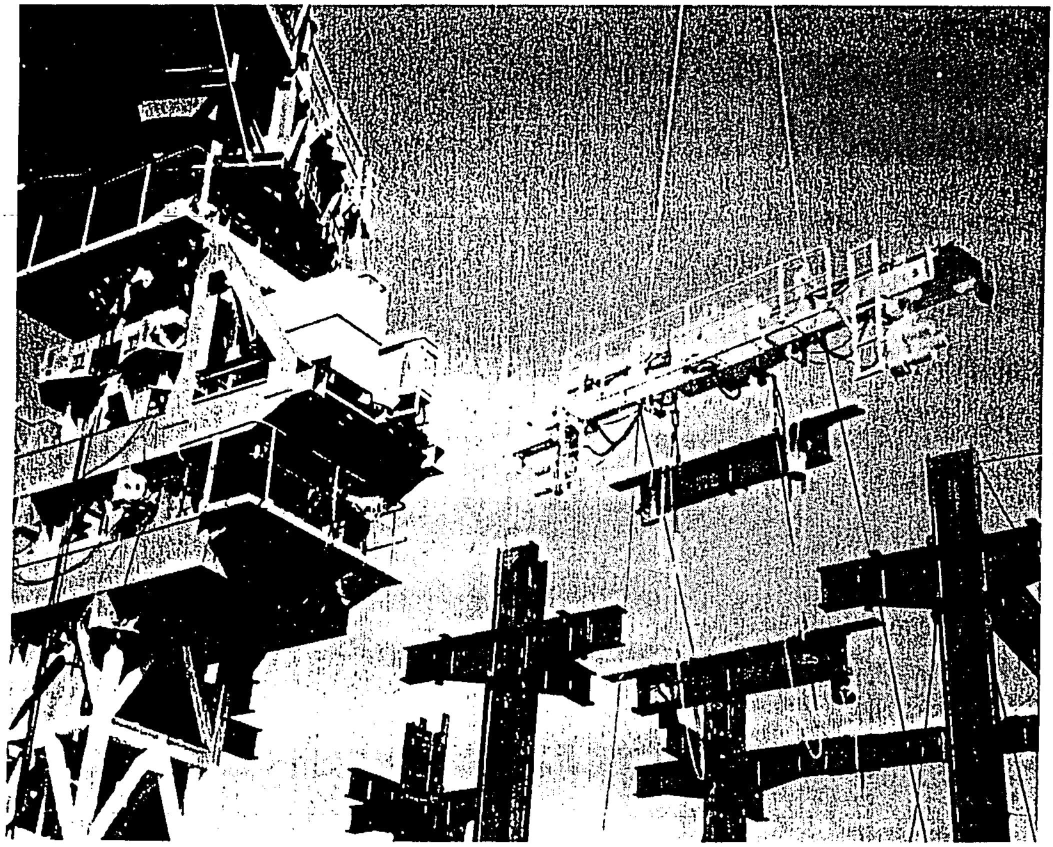


Figure 5.8 Mighty Jack

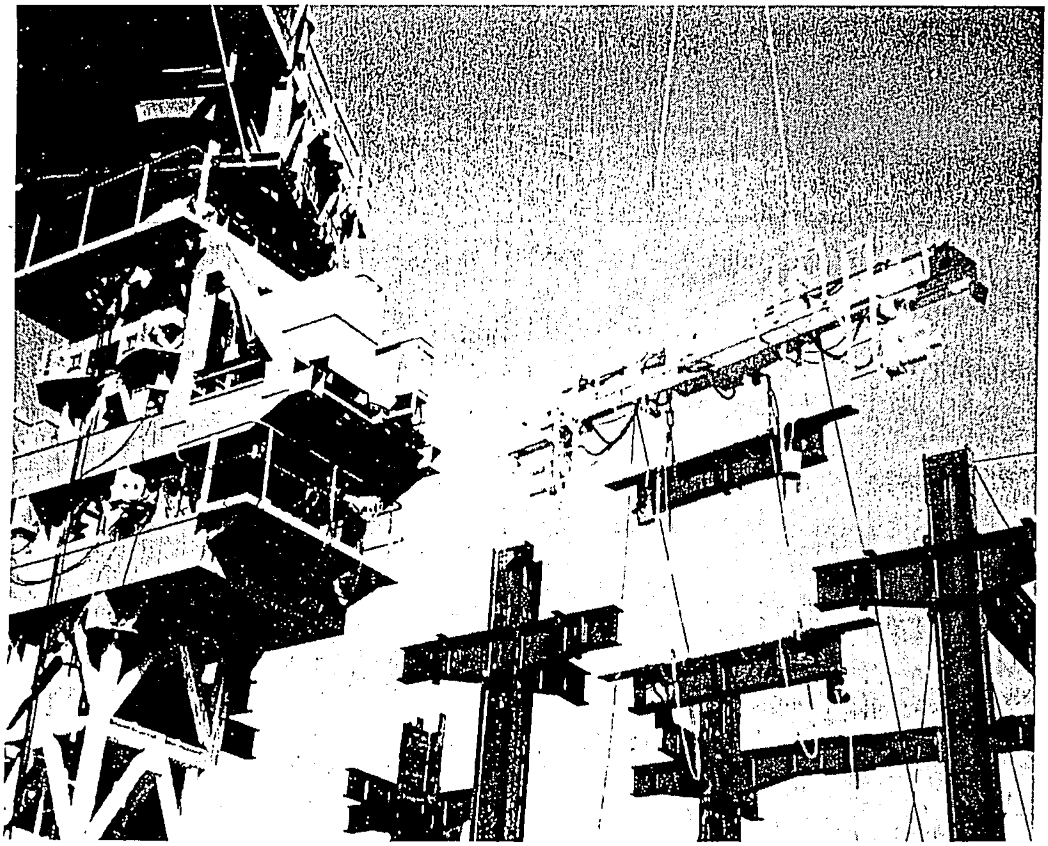


Figure 5.8 Mighty Jack

5.3.3.1 Simulation Models

Three assumptions were made to apply the simulation models to the assessment of the Mighty Jack. First, only the beams spanning from column to column on the first three floors are erected using the Mighty Jack. Those on the fourth floor cannot be erected with the Mighty Jack since that is the level at which the Mighty Jack is positioned. Second, the Mighty Jack lowers three beams in one erection cycle. Third, although no workers will be erecting members while more than 32 feet of height are undecked, connectors do climb up as high as the third floor to install the bolts to secure the beams. This assumption violates OSHA's Subpart R safety requirements for the connecting stage, but not for the erecting stage. Finally, although the type of connections would be different for the positioning of the beams with the Mighty Jack (using the welded beam stub extending from the column as shown in Figure 5.8), the number of bolts has been assumed to remain unchanged.

There are 96 beams that can be erected with the Mighty Jack, whereas the remaining 149 members will be erected using the standard methods. As noted in the assumptions, the number of bolts remain the same.

Table 5.42 shows that the Mighty Jack changes the flow of activities. First, three beams are hooked to the Mighty Jack before the Mighty Jack is hooked to the crane. Second, the positioning of the Mighty Jack is a new task. Third, the Mighty Jack has to be removed and brought back to the ground for additional members. Changes in tasks and cycles should become apparent when using the models, and safety precautions can then

Table 5.42: Tasks in the erection stage for the Mighty Jack

Task No.	Worker Type	Production Rate (min/ 3 members)
1. Hooking	I	1.50
2. Swinging in	J	1.00
11. Positioning Mighty Jack	I, J	3.00
12. Positioning beams	I	2.00
7. Installing bolts	I	3.00
13. Remotely unhooking	I	0.10
6. Swinging out	J	0.67
	Total	11.27

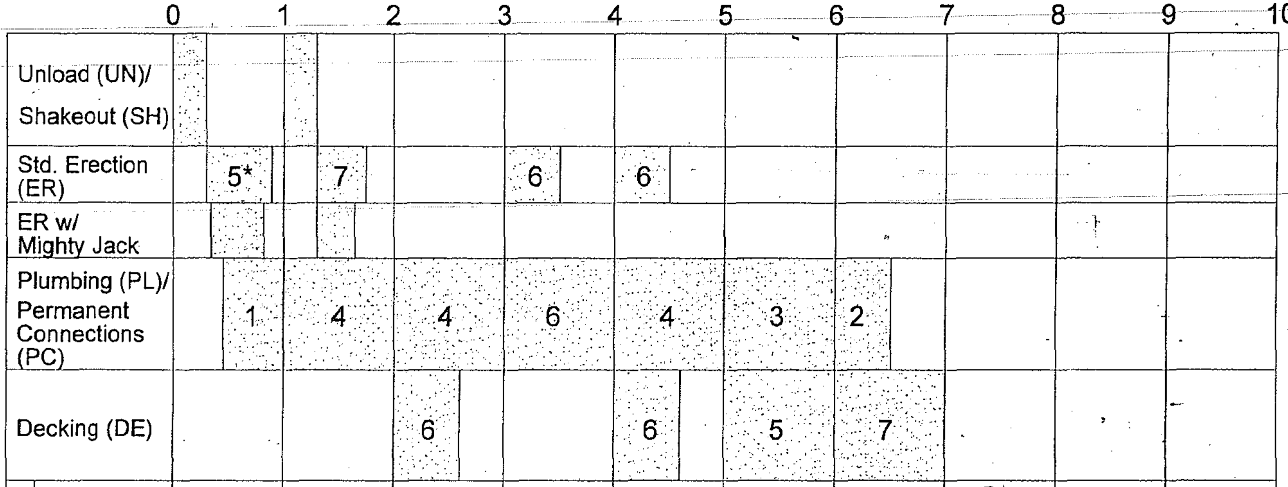
be identified when new technologies are introduced to the site.

Notice that in table 5.42 the rates add to 11.27 minutes per cycle which is equivalent to 3.76 minutes per member. When considering the idle time, due to the more repetitive flow of tasks, the idle percent of the total time can be estimated at 25 percent. Observations at some of the visited sites, where several beams at different levels were hooked from the same hoist line, suggest that this reduction in the idle time is possible. Computations for total time, thus yield 5.01 minutes per member.

At this point, it is important to recall the values obtained from the previous analyses for the ATLSS Connector and the Stewart Platform. While the rate for the standard method is 8.00 minutes per member, for the ATLSS Connector, the Stewart Platform and the Mighty Jack, the rates are 5.74 minutes per member, 7.74 minutes per member and 5.01 minutes per member, respectively. This is the strength of the Mighty Jack as will be noticed in the analysis of the duration of activities of erecting the prototype building with the aid of the Mighty Jack. However, the Mighty Jack needs to be analyzed in two steps since the standard methods are used for 149 of the members at 8.00 minutes per member. After appropriate calculations, a weighted average of 6.83 minutes per member results for the process in which erection is conducted with the Mighty Jack and the standard methods of erection.

To improve the utilization of the Mighty Jack, an additional crane is introduced so that the primary crane's activities are not interrupted. Although a smaller crane may be used, the analysis considers two of the same capacity and rental cost. Therefore, two cranes and two crane operators are needed, as well as the addition of an operator for the Mighty Jack. Workers I (Mighty Jack operator) and J (second crane operator) represent this variation in labor resources. The Mighty Jack operator performs all tasks: hooks members to Mighty Jack, positions the beams by teleoperation and then installs the erection bolts for each of the three beams. Obviously this worker would have to be experienced, trained and effective, but the combination of tasks required is not beyond the skill levels of ironworkers.

The Gantt chart in Figure 5.9 shows that the flow of activities is highly affected by the use of the Mighty Jack. The unloading stage is done on the first two days to ensure that material is available. This *external* decision is made since with two cranes setting the steel, the rate of erection will increase significantly and the members need to be available at all times. Appropriate planning for the delivery of the material, and



WORKERS	Standard UN/SH/ER	4	4	(1)	4	(1)	4	0			
	ER w/ Mighty Jack	2	2	0	0	0	0	0			
	PL/PC	4	4	4	5	4	3	5			
	DE	0	0	4	0	4	2	3			
	S & H	2	2	2	2	2	2	2			
	TOTAL	12	12	11	11	11	11	10			

Notes: (1) - Crane operator is idle.
S & H - Supervisor and Helper
Shaded numbers represent # of bays completed.
* Five bays plus ten columns

Figure 5.9 Gantt Chart for Mighty Jack

fabrication scheduling are critical. Cases such as this one show that the scheduling of activities does not start and end at the site, but must be explicitly considered during design and planning. The systems approach is emphasized once again.

The numbers indicating the bays completed in the Gantt chart are equivalent to erecting on the first day 51 members with the Mighty Jack and 41 with the conventional crane. On the second day, 45 members are set with the Mighty Jack and 28 using standard methods.

Erection must stop on the third day as occurred with the standard methods, so that connecting and decking could catch up. When erection resumes on the fourth and sixth days, only the standard crane is used because all appropriate members have already been set by the Mighty Jack in the first two days. Overall, the duration is decreased to 7.0 days, a reduction of 18 percent with respect to the standard methods.

Even though more workers and an additional crane are used when utilizing the Mighty Jack, there is a very small (1 percent) decrease in cost since the duration of the whole project is shorter. In addition, the Mighty Jack and its crane are on-site only for two days. Even with a utilization rate of approximately 50 percent on each of the two days, the Mighty Jack remains economically efficient.

In the assessment of safety, Table 5.43 lists the tasks *vs.* injuries relationships as has been done for all other technologies.

Table 5.43: Cause of injury *vs.* task for the Mighty Jack

Cause of Injury	TASK						
	1	2	11	12	7	13	6
1.Struck against							
2.Struck by	✓						
3.Caught in or between	✓						
4.Rubbed, abraded and penetrated	✓			✓	✓	✓	
5.Fall of person (different level)		✓	✓		✓		✓
6.Fall of person (same level)	✓						
7.Bodily reaction	✓						
8.Contact, electric current		✓	✓				✓
9.Contact, temperature extremes							
10. Contact, radiations, caustics, toxic and noxious substances							
Total Percentage	67.2	18.2	18.2	3.5	18.4	3.5	18.2

For the workers *vs.* injuries relationships, workers I and J are listed. They constitute part of the erection subcrew assigned to the Mighty Jack for the 96 members.

Table 5.44: Specific danger indices for erection using the Mighty Jack
Worker I

Task No.	Time, t (min/unit)	%	Units	No. of Units	Index
1	1.50	67.2	3 beams	32	32.0
11	3.00	18.2	cycles	32	17.5
12	2.00	3.5	3 beams	32	2.2
7	4.00	18.4	12 bolts	32	23.4
13	0.10	3.5	3 beams	32	0.1
					75

Worker J

Task No.	Time, t (min/unit)	%	Units	No. of Units	Index
2	1.00	18.2	lifts	32	5.8
6	0.67	18.2	lifts	32	5.8
					12

ERECTION DANGER INDEX: 87

The danger index erection component for the Mighty Jack, $D3_m$, is obtained by adding the danger specific indexes for workers I and J. Therefore, $D3_m = 87$. The danger index erection component for the remaining 149 members erected with the standard method has a value $D3_s = 384$, calculated as shown in section 5.3.1. The erection danger index component, D3, is then found by adding $D3_m$ and $D3_s$, thus, D3 = 471, a 25 percent decrease in danger relative to the standard method. From the baseline case, all other components: D1, D2, D4, D5 and D6 add to 1659 units. Finally, by adding all six components for each of the stages, D = 471 + 1659 = 2130, providing an overall decrease in the danger index of 7 percent.

Table 5.45: Danger index by stage for the Mighty Jack

Danger index by stage	Mighty Jack	Standard Method	Reduction
Erection	471	631	25%

5.3.3.2 Results

The conclusion of this analysis is that the Mighty Jack is economically efficient even with additional resources. At practically no change in cost, savings in safety and productivity are achieved. Table 5.46 shows the results of utilizing the Mighty Jack. The design changes (i.e. four-story high columns) improved the effectiveness of the Mighty Jack and demonstrated how use of new technologies may require changes in project phases such as design, planning and on-site processes.

Table 5.46: Results for the Mighty Jack Compared to the Baseline

Economic Aspect	Mighty Jack	Standard Method	Savings
Duration	7 days	8.5 days	18 %
Cost	$ 47,900	$ 48,300	1%
Danger Index	2119	2290	7%
Resources	2 cranes, 12 workers	1 crane, 10 workers	N/A

5.3.4 Auto-Clamp, Auto-Claw and Mighty Shackle Ace

These three technologies can be analyzed together since they are all devices to enable teleoperated unhookings. The Auto-Clamp is used for steel column erection on construction sites. It was developed in 1986, and has been used on three commercial projects (Sherman, 1988). This technology has the objectives of speeding up erection time and minimizing the risks incurred by steel workers. It uses a special electro-steel cylinder tube to secure and erect columns, so a steel appendage plate with a hole in the center must be welded to the top end of the column. The steel cylinder is then electrically inserted and locked by remote control. After each columns is erected, the appendage plates must be removed. The Auto-Clamp has a fail-safe system which prevents the cylinder from retracting from the hole. The capacity of the Auto-Clamp is 15 tons.

Auto-Claw is used for steel beam erection on construction sites. It was developed in 1987 and has been used on one project (Sherman, 1988). Similar to the Auto-Clamp, this technology has the objectives of speeding up erection time and minimizing the risks incurred by steel workers. The Auto-Claw consists of a steel encased unit containing a DC battery pack, an electrical panel, a microprocessor unit, and two steel clamps that extend from the encased unit. The Auto-Claw hangs from a standard crane, and has a capacity of two tons for each clamp. The gripping system of the clamps can be adjusted to fit beam flange widths of 8 to 12 inches. Once the beam is safely in place, the clamps release the beam by a remote radio control. An electronic circuit prevents the accidental release of the clamps during erection.

The Mighty Shackle Ace also permits unmanned release of structural steel members, both beams and columns (Ueno *et al.*, 1988). It was developed in the mid 1980s, and appears to be available for commercial use (Figure 5.10). It shares the same objectives of reducing erection time and improving safety. The Mighty Shackle Ace consists of a controlling unit, lifting cables, operating cables and clamps. The special clamps are attached to the steel member on the ground. The Mighty Shackle Ace hangs from a standard crane and, when the member is lifted into place, an operator remotely controls the Mighty Shackle Ace to release the clamps.

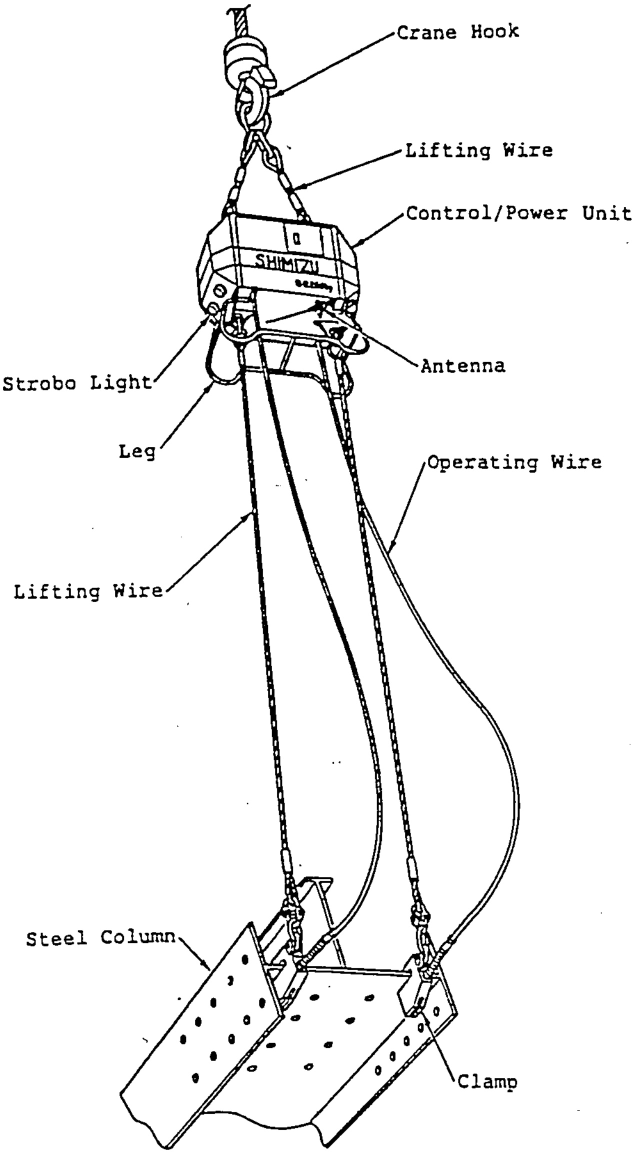


Figure 5.10 Mighty Shackle Ace

5.3.4.1 Simulation Models

The assumption made for the simulation in this case is that all members are unhooked by remote control during erection stage only. Since the Mighty Shackle Ace can be used for both columns and beams, the simulation is actually made for this technology. The assessment would then encompass the performance of both the Auto-Claw and the Auto-Clamp.

None of the structural quantities change when using this technology. The unhooking task is independent of the quantities

The only change in tasks is that instead of performing tasks 1 through 6 as described for the prototype building, task 5 is replaced by task 13 (remotely unhooking), so that the erectors do not have to walk along the member at high elevations to unhook the members. Table 5.47 shows that task 13 (remotely unhooking) is controlled by the crane operator, and takes a couple of seconds.

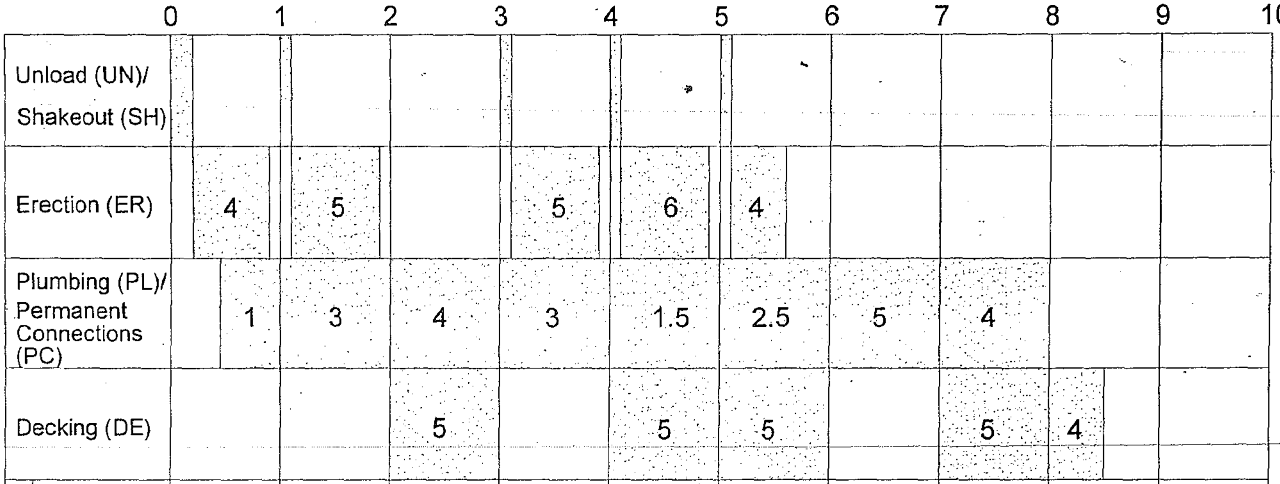
Although the resources do not change with respect to the baseline case, the summation of rates changes when considering task 13. The usual treatment of idle time causes the 3.70 minutes per member to increase to 7.40 minutes per member, compared to 8.00 minutes per member for the standard case. Again, it is interesting to compare at this point the previous rates that were calculated. Note that this change in production rate is similar to that calculated for the Stewart Platform (7.74 minutes per member), and much greater than the rates calculated for the ATLSS Connector (5.74 minutes per member) and the Mighty Jack (6.83 minutes per member).

Table 5.47: Tasks in the Erection Stage for Mighty Shackle Ace, Auto-Clamp and Auto-Claw

Task No.	Worker Type	Production Rate (min/member)
1	D	0.50
2	A	1.00
3	B, C	0.50
4	B, C	1.00
13	A	0.03
6	A	0.67
	Total	3.70

The duration and cost are exactly the same as for the baseline case, since the unhooking devices reduce time, but by a negligible amount (Figure 5.11).

The tasks *vs*. injuries chart is completed as for all the previous technologies. Table 5.48 shows that task 13 includes fewer causes of injury. Indeed the workers vs. injuries relationships in Table 5.49 show that the specific danger index for erection for these unhooking technologies is 607, a decrease of 4 percent from the standard method, since task 5 was eliminated. The overall danger index for the Mighty Shackle Ace is 2266, only a 1 percent reduction.



WORKERS	UN/SH/ER	4	4	(1)	4	4	4	0	0	0	
	PL/PC	4	4	5	4	2	2	7	5	0	
	DE	0	0	2	0	2	2	0	2	7	
	S & H	2	2	2	2	2	2	2	2	2	
	TOTAL	10	10	10	10	10	10	9	9	9	

Notes: (1) - Crane operator is idle.
S & H - Supervisor and Helper
Shaded numbers represent # of bays completed.

Figure 5.11 Gantt Chart for Auto-Clamp, Auto-Claw and Mighty Shackle Ace

Table 5.48: Cause of Injury *vs.* task for the Erection Stage for Mighty Shackle Ace, Auto-Clamp and Auto-Claw

Cause of Injury	TASK					
	1	2	3	4	13	6
1.Struck against						
2.Struck by	✓					
3.Caught in or between	✓					
4.Rubbed, abraded and penetrated	✓			✓	✓	
5.Fall of person (different level)		✓	✓			✓
6.Fall of person (same level)	✓					
7.Bodily reaction	✓					
8.Contact, electric current		✓	✓			✓
9.Contact, temperature extremes						
10. Contact, radiations, caustics, toxic and noxious substances						
Total Percentage	67.2	18.2	18.2	3.5	3.5	18.2

Table 5.49: Specific Danger Indices for Erection Using the Mighty Shackle Ace, Auto-Clamp and Auto-Claw

Worker A

Task No.	Time, t (min/unit)	percent, p	Units	No.of Units, n	Index
2	1.00	18.2	members	245	45
13	0.03	3.5	members	245	0
6	0.67	18.2	members	245	30
					75

Worker B

Task No.	Time, t (min/unit)	Percent, p	Units	No.of Units, n	Index
3	0.50	75.1	members	245	92
4	1.00	54.1	members	245	133
					225

Worker C

Task No.	Time, t (min/unit)	Percent, p	Units	No.of Units, n	Index
3	0.50	75.1	members	245	92
4	1.00	54.1	members	245	133
					225

Worker D

Task No.	Time, t (sec/unit)	Percent, p	Units	No.of Units, n	Index
1	0.50	67.2	members	245	82
					82

ERECTION DANGER INDEX: 607

Table 5.50: Danger index by stage for the Mighty Shackle Ace, Auto-Clamp and Auto-Claw

Danger index by stage	Mighty Shacke Ace, Auto-Clamp and Auto-Claw	Standard Method	Reduction
Erection	607	631	4%

5.3.4.2 Results

Since erection is not on the critical path, the savings shown in Table 5.51 are negligible. However, the Mighty Shackle Ace, Auto-Clamp and Auto-Claw could also be used for unloading and shakeout if the grip were adjusted to handle bundles.

Table 5.51: Results for the Mighty Shackle Ace, Auto-Clamp and Auto-Claw Compared to the Baseline

Economic Aspect	Auto-Clamp, Auto-Claw, Mighty Shackle Ace	Standard Method	Savings
Duration	8.5 days	8.5 days	0%
Cost	$ 48,300	$ 48,300	0%
Danger Index	2266	2290	1%
Resources	1 crane, 10 workers	1 crane, 10 workers	N/A

5.3.5 Shear Stud Welder

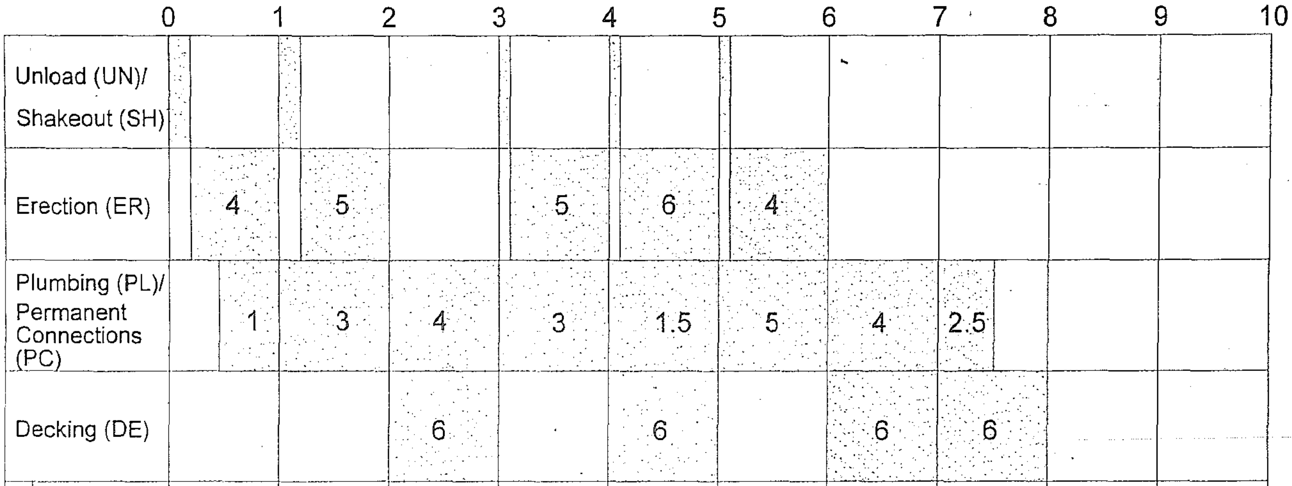
The Shear Stud Welder is a wheeled robot that welds shear studs to the flooring surface automatically (Slocum *et al.*, 1987). The carriage is moved and positioned by a human operator. Welding of the shear studs is conducted automatically. No external sensors are required as the operator performs all navigation and positioning functions. While it is not currently available for commercial use, this technology is meant to replace the shear stud welding gun and to increase the production rate. The introduction of the stud welding gun has improved the common use of shear connectors in composite steel/concrete construction. Typically two workers can place 2000 studs per day. The workers will lay out the studs with their ceramic ferrules (devices to shield the welding gases), and then weld one by one through the decking into the beams' top flange. The Shear Stud Welder could eliminate the layout step and reduce the strenuousness of the task.

5.3.5.1 Simulation Models

The tasks, activities and cycle units are unchanged by the Shear Stud Welder. Similarly, none of the structural quantities change. The number of bolts, members, deck sheets and studs is the same as for the standard case.

The tasks in Table 5.52 are unchanged from the standard case, but the production rates do change significantly. The production rate for the Shear Stud Welder is assumed to be 50 percent of the standard method, requiring only 8.8 minutes per bay to weld the shear studs instead of 17.5 minutes per bay for the standard case.

The decking stage as shown in the Gantt chart in Figure 5.12 can be performed in four days, decking 6 bays every day. Notice that during the fourth and sixth days there are no decking activities, whereas in the standard case, decking had stopped for the fourth and seventh days. Since decking is being performed faster, the sixth day must be skipped in order for decking not to catch up with bolting. In other words, at the end of day five, there are 12 bays decked and 12.5 connected. Decking, thus, must be stopped and resources shifted to increase the rate at which connection tasks are being performed. This shortens the duration of connecting, which combined with the shortening of decking



WORKERS										
UN/SH/ER	4	4	(1)	4	4	4	0	0		
PL/PC	4	4	5	4	2	4	5	5		
DE	0	0	2	0	2	0	2	2		
S & H	2	2	2	2	2	2	2	2		
TOTAL	10	10	10	10	10	10	9	9		

Notes: (1) - Crane operator is idle.
S & H - Supervisor and Helper
Shaded numbers represent # of bays completed.

Figure 5.12 Gantt Chart for Shear Stud Welder caused by the use of the Shear Stud Welder, reduces the whole duration of the project by 6 percent in relation to the standard method.

The cost of the project when using the shear stud welder is computed in the same way as for the standard case. The only difference is that on the last day the standard method uses six workers for half a day, leading to cost savings of 3 percent.

Since the tasks during the decking stage do not change (Table 5.52), the table for injuries *vs.* tasks does not change (Table 5.53), but the decrease in duration does affect the workers *vs.* injuries calculations (Table 5.54). The danger index for decking is 844, a 2 percent decrease from the standard method (Table 5.55) while the overall danger index is 2274, a 1 percent reduction.

Table 5.53: Cause of injury vs. task for the decking stage for shear stud welder

Cause of Injury	T	A	S	K
		9	10	
1.Struck against				
2.Struck by				
3.Caught in or between		✓		
4.Rubbed, abraded and penetrated		✓	✓	
5.Fall of person (different level)		✓		
6.Fall of person (same level)				
7.Bodily reaction		✓		
8.Contact, electric current				
9.Contact, temperature extremes				
10. Contact, radiations, caustics, toxic and noxious substances				
Total Percentage		54.1	3.5	

Table 5.52: Tasks in the Decking Stage for Shear Stud Welder

Task No.	Worker Type	Production Rate (min/bay)
9.Laying sheets	G, H	32.00
10.Welding studs	G, H	17.50

Table 5.54: Danger indices for decking stage using Shear Stud Welder

Worker G

Task No.	Time, t (min/unit)	%	Units	No. of Units	Index
9	32.0	54.1	bay	24	415
10	8.8	3.5	bay	24	7
					422

Worker H

Task No.	Time, t (min/unit)	%	Units	No. of Units	Index
9	32.0	54.1	bay	24	415
10	8.8	3.5	bay	24	7
					422

DECKING DANGER INDEX: 844

Table 5.55: Danger index by stage for Shear Stud Welder

Danger index by stage	Shear Stud Welder	Standard Method	Reduction
Decking	844	860	2%

5.3.5.2 Results

The Shear Stud Welder does not appear to offer significant savings. The duration savings noted in Table 5.56 are due to the assumed production rate. If this rate could be further increased, more significant savings could possibly be obtained.

Table 5.56: Results for the Shear Stud Welder Compared to the Baseline

Economic Aspect	Shear Stud Welder	Standard Method	Savings
Duration	8.0 days	8.5 days	6%
Cost	\$ 46,700	\$ 48,300	3%
Danger Index	2274	2290	1%
Resources	1 crane, 10 workers	1 crane, 10 workers	N/A

5.3.6 Welding Robot

The Welding Robot is an industrial robot modified for on-site welding of beam flanges to column flanges. This robot uses a rotary jig to permit welding of both sides of the beam flange (Wing, 1989). It has been used commercially, primarily for the preassembly of structural members which are then erected in one lift. A similar robot is used commercially for welding column splices (Powers, 1994).

5.3.6.1 Simulation Models

Several assumptions were made to apply the simulation models to the Welding

Robot. First, the robot is assumed to be small enough to be positioned on erected beams and columns. Second, it is assumed that two robots are positioned, monitored and repositioned by one operator. Third, it is assumed that welding the beam flanges to the column flanges requires seven passes of welding per flange with a 3/16 inch electrode.

The number of bolts installed and tightened is reduced since the welded connections replace the bolted flange connections on the frames. The number of bolts tightened is 2254 rather than 2926 for the prototype building erected with standard methods, and 1358 bolts are installed rather than 2030 bolts. Each of the seven frames in the prototype building has eight beams, for a total of 56 beams that can be welded with the robots. The top and lower flanges at each end implies that there are four welds per beam. Since the width of each beam flange is 8 1/4 inch, then 12936 linear inches of weld are needed.

The tasks of the whole erection process do not change considerably. The beams are erected in the standard method, connecting two of the shear bolts in the web of the beams. Then the robot operator positions the two robots at each end of the beam that needs to be welded. Table 5.57 shows that only task 18 is needed for the analysis.

Table 5.57: Tasks in permanent connection stage for the Welding Robot

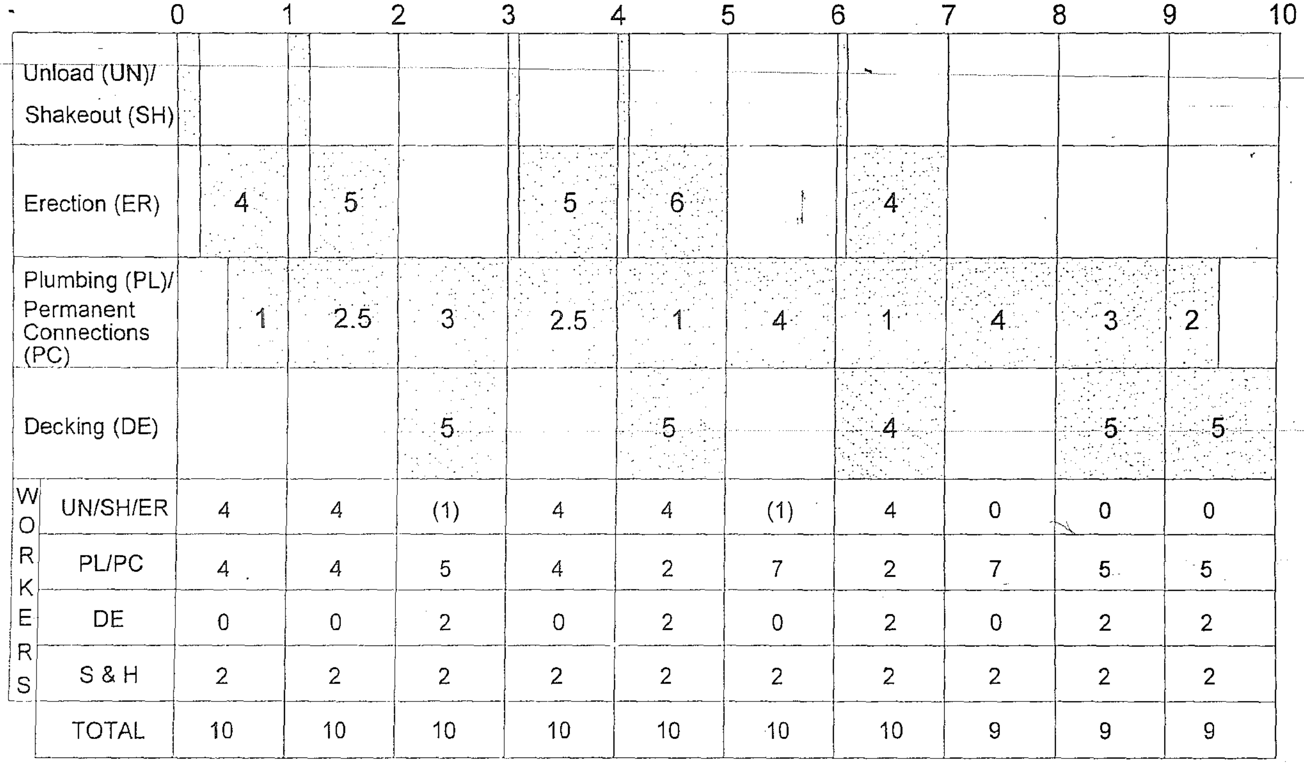
Task No.	Worker Type	Production Rate (min/members)
18. Welding	K	8.00

The rate for a person welding at a shop has been estimated at 7 inches per minute. For the welding robot, twice the rate is assumed for one robot. Since the two robots weld simultaneously under the guidance of the operator, the rate for the two robots is 28 inches per minute, four times the rate of a person welding at a shop. At this rate, the 12936 inches can be welded in 462 minutes of active time. Idle time due to spot welding backing bars, setting the robots and moving the robots to the next beam is estimated at 67% of the total time. This implies 1386 minutes with the two robots welding simultaneously.

Since these connecting activities are on the critical path, the slowing of the permanent connections stage affects the decking stage production rate. The decking activities must then stop during one day as shown in the Gantt chart (Figure 5.13), which in turn affects the erection stage because of the safety for the safety measures mentioned before where the floor 32 feet below the erection activities must be decked. The result is that all stages stretch to a total project duration of ten days, an 18 percent increase in duration.

By the same procedures of calculating cost for the other technologies, the final cost is computed for this technology, revealing that the slower connecting rate translates to a 20 percent increase in cost.

The usual analysis for the tasks *vs.* injuries relationships is shown in Table 5.58. Similarly, the same analysis for the workers vs. injuries relationship is performed. This analysis reveals that the additional robot operator has a danger index of 82 (Table 5.59).



		0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10
Unload (UN)/ Shakeout (SH)											
Erection (ER)		4	5		5	6		4			
Plumbing (PL)/ Permanent Connections (PC)		1	2.5	3	2.5	1	4	1	4	3	2
Decking (DE)				5		5		4		5	5
WORKERS	UN/SH/ER	4	4	(1)	4	4	(1)	4	0	0	0
	PL/PC	4	4	5	4	2	7	2	7	5	5
	DE	0	0	2	0	2	0	2	0	2	2
	S & H	2	2	2	2	2	2	2	2	2	2
	TOTAL	10	10	10	10	10	10	10	9	9	9

Notes: (1) - Crane operator is idle.
S & H - Supervisor and Helper
Shaded numbers represent # of bays completed.

Figure 5.13 Gantt Chart for Welding Robot

Table 5.58: Cause of Injury *vs.* task for erection stage for welding robot

Cause of Injury	TASK
	18
1.Struck against	
2.Struck by	
3.Caught in or between	
4.Rubbed, abraded and penetrated	✓
5.Fall of person (different level)	✓
6.Fall of person (same level)	
7.Bodily reaction	
8.Contact, electric current	
9.Contact, temperature extremes	
10. Contact, radiations, caustics, toxic and noxious substances	
Total Percentage	18.4

Table 5.59: Specific danger indices for permanent connections using the Welding Robot

Worker K

Task No.	Time, t (min/unit)	%	Units	No. of Units	Index
18	8.00	18.4	girder	56	82

PERMANENT CONNECTIONS DANGER INDEX: 559

The decrease in number of bolts installed and tightened offsets the added danger index for the robot operator. This yields a danger index for permanent connections of 559, an 12 percent decrease (Table 5.60).

Table 5.60: Danger index by stage for the Welding Robot

Danger index by stage	Welding Robot	Standard Method	Reduction
Permanent Connection	559	632	12%

5.3.6.2 Results

The results in Table 5.61 show that the Welding Robot is safe even though the duration of the project extends for longer, thereby generally increasing the exposure to injuries for the workers. The increased duration also leads to higher costs. The quality of welds achieved by the utilization of this technology is not assessed in the models, but is assumed to be better than the welds performed manually. Additional research could investigate the consequences of using more robots and thicker electrodes to reduce the number of passes per weld. These factors could result in final savings, as well as improved safety.

Table 5.61: Results for the Welding Robot Compared to the Baseline

Economic Aspect	Welding Robot	Standard Method	Savings
Duration	10.0 days	8.5 days	-18%
Cost	$ 57,800	$ 48,300	-20%
Danger Index	2217	2290	3%
Resources	1 crane, 10 workers	1 crane, 10 workers	N/A

5.4 Summary of Results

The prototype building has characteristics which show the applicability of all the advanced construction technologies, except the Welding Robot. The results are dependent on the structural layout and the site conditions. Therefore, when a technology is assessed as inefficient economically, it does not mean that the technology would not be beneficial for a different project.

The following ranges can be observed from Table 5.62 which presents the results from all eight technologies assessed in this research. The duration range varies from 7.0 days to 10.0 days. The Mighty Jack performs best in this category, decreasing duration by 18 percent. Conversely, the Welding Robot increases the duration by 18 percent. For cost, the range varies from $42,800 to $57,800, with the ATLSS Connector being the best, saving 11 percent. The Welding Robot, however, increases cost by 20 percent. Finally, for the danger index, the range varies from 1651 to 2290, showing that all technologies improve safety. Once again the ATLSS Connector yields the greatest savings at 28 percent.

Table 5.62: Comparison of all technologies

Technology	Duration (days)	Cost	Index	Resources (cranes, workers)
Standard Methods	8.5	$48,300	2290	1, 10
ATLSS Connector	7.5 (12%)	$42,800 (11%)	1651 (28%)	1, 10
Stewart Platform	8.5 (0%)	$48,300 (0%)	1988 (13%)	1, 10
Mighty Jack	7.0 (18%)	$47,900 (1%)	2130 (7%)	2, 12
Unhooking Technologies	8.5 (0%)	$48,300 (0%)	2266 (1%)	1, 10
Shear Stud Welder	8.0 (6%)	$46,700 (3%)	2274 (1%)	1, 10
Welding Robot	10.0 (-18%)	$57,800 (-20%)	2217 (3%)	1, 10

Note: Percentages in parentheses represent the reduction with respect to the baseline case.

5.5 Research and Development Opportunities

The assessment of each of these technologies has shown that by using the models, it is possible to reveal the benefits and problems of each technology. It is also possible to identify the opportunities for automation existing in other erection activities. The plumbing stage, for instance, still needs to be automated. Other minor tasks which the helper performs could also provide opportunities for automation.

Several operational aspects of two of the technologies analyzed in this research can be improved. For example, although the Mighty Jack performed well in the analysis, it could be modified to increase its effectiveness. If the Mighty Jack had a self-positioning mechanism the crane costs for the second crane would be eliminated. The repositioning could be thought of as a 90-degree horizontal swing from one set of two columns, pivoting around one of the columns, to a third free column to which the Mighty Jack could attach. The Mighty Jack could also be set on top of two column stubs above the last floor, permitting the installation of the beams of the last floor.

Moreover, certain technologies can be used together on the same project. The ATLSS Connector could be used in conjunction with the Mighty Jack. The beams would be positioned by remote control and no connecting tasks would be required, reducing the danger and improving the production rate. The field tolerance problems would be reduced since the Mighty Jack would force the columns to be plumbed, enabling a swift sliding of the tenon into the mortise in the ATLSS Connector.

The AIBS project in the ATLSS Engineering Research Center at Lehigh University tries to integrate the use of the Stewart Platform with the ATLSS Connector. The ideal concept that is being targeted is to be able to lift members with the Stewart Platform, having ATLSS Connectors on each end of the members. Again safety and speed would increase.

Future research should focus on major savings which are achieved by changing the flow of activities in the structural steel erection process rather than incremental changes in production rates.

Chapter 6

Conclusions

This research has addressed the problem of how to assess the expected impacts from using new construction technologies. A systematic methodology based on three simulation models was developed to economically assess these innovative techniques. The models presented in this thesis assess eight technologies for structural steel erection. This research also identifies opportunities to further improve the cost, speed and safety of structural steel erection.

6.1 Summary

This thesis uses a practical methodology of gathering information related to construction activities, and presents three models that simulate the dynamic process of construction activities. The economic assessment of eight structural steel erection innovations is carried out by comparing their operational performance to a baseline case in which a prototype building's erection is simulated.

The research methodology included interviewing industry experts and visiting structural steel erection sites under construction. The feedback obtained by using this approach was invaluable, and was used to modify and refine the simulation models as they were being developed. It also improved the models' reliability and applicability.

The models relate in such a way that the first two merge to create the basis of the dynamic daily model. The flow model identifies tasks, activities and stages, and how they relate to each other for the given construction process. The static productivity/resource model determines the duration of tasks, activities and stages by analyzing production rates and resources for a specific building design. The third model dynamically simulates a project considering logical, technical and safety constraints to obtain the duration, safety and cost of the given project.

The safety module included in the dynamic daily simulation model is based on the worker's exposure to the most common injuries during actual worktime (excluding idle time). This approach can be used for any construction activity. The procedure to estimate the danger index is based on three stages: identifying the tasks, production rates and workers performing those tasks; linking the tasks to the most common causes of injuries; and computing the danger index which is essentially a measure of the relative exposure to dangerous conditions.

The erection of a prototype building is simulated using standard methods of erection. This simulation serves as a baseline for comparing the modifications introduced by the use of each of the eight technologies presented in this thesis. The results of the economic assessment are summarized in duration, cost and safety. Production rates and specified resources, such as crews and cranes, determine the duration of the project. The cost is divided into direct and indirect costs such as overhead and profit and workman's compensation. The safety assessment is based on the safety module included in the third simulation model.

6.2 Discussion

All the technologies analyzed in this research have demonstrated an increase in safety. The results of the economic analyses are dependent on the structural layout and site conditions. Therefore, a given technology is assessed on whether it is appropriate for the erection of a particular project.

Table 6.1 shows the sensitivity of the cost results when the cost parameters are varied for three of the cases analyzed in this research. The percentages in parentheses reflect the percentage change with respect to each of the variations of the standard case. The largest percentage change is seen when labor wage rates are increased. These percentages imply that the technologies with small cost savings would provide greater benefits in countries where the wage rates are high.

If a given company maintains satisfactory safety records, improvements in safety might in the future cause a reduction of workman's compensation rates. This lowering of the rates can offer some savings, but improvements in production rates are more significant since they cause shorter project durations. The duration of a project and high wage rates are the main cause of cost increases. Therefore new technologies that improve safety should also pay attention to increasing production rates overall to decrease total project duration. Attention to the dynamics in the project is of paramount importance.

Improving decking rate, for instance, does not provide the savings obtained by increasing the connecting stage rates, which fall on the critical path of most structural steel erection projects

Table 6.1: Cost sensitivity

Cost Parameters	Standard Method	ATLSS Connector	Mighty Jack
Thesis results for cost analysis ($35/hr wage rate, 45% O&P, 52% workman's compensation)	$48,300	$42,800 (11%)	$47,900 (1%)
Vary wage rate to $60/hr	$77,900	$68,000 (13%)	$75,500 (3%)
Vary O & P to 20%	$41,900	$36,800 (12%)	$41,400 (1%)
Vary workman's compensation to 20%	$41,600	$36,800 (12%)	$41,600 (0%)

6.3 Conclusions

The significance of this research is that by assessing construction innovations with the methodology presented, it is possible to reveal the benefits and foreseeable operational problems that a technology may have at the site. It is also possible to identify opportunities for automation.

Construction professionals could benefit in using these models to maintain their competitiveness by innovating at the site and not hesitating in performing a detailed analysis of new construction techniques. The integration of engineering phases such as design, fabrication, erection and management of structural steel was used in this research to provide awareness of the implications that the systems approach can have.

It is concluded that major savings are achieved by changing the flow of activities rather than providing incremental savings in production rates. As an illustration, conceiving the ATLSS Connector with less bolts to decrease the connecting time is a marginal change in the flow of activities. Removing the bolts completely, and focusing on the self-aligning attributes of this connector would dramatically decrease costs in the erection of steel structures.

For future research, the elements presented in this research should be used to create a computer-integrated system for office use to integrate fabrication, construction and managerial procedures.

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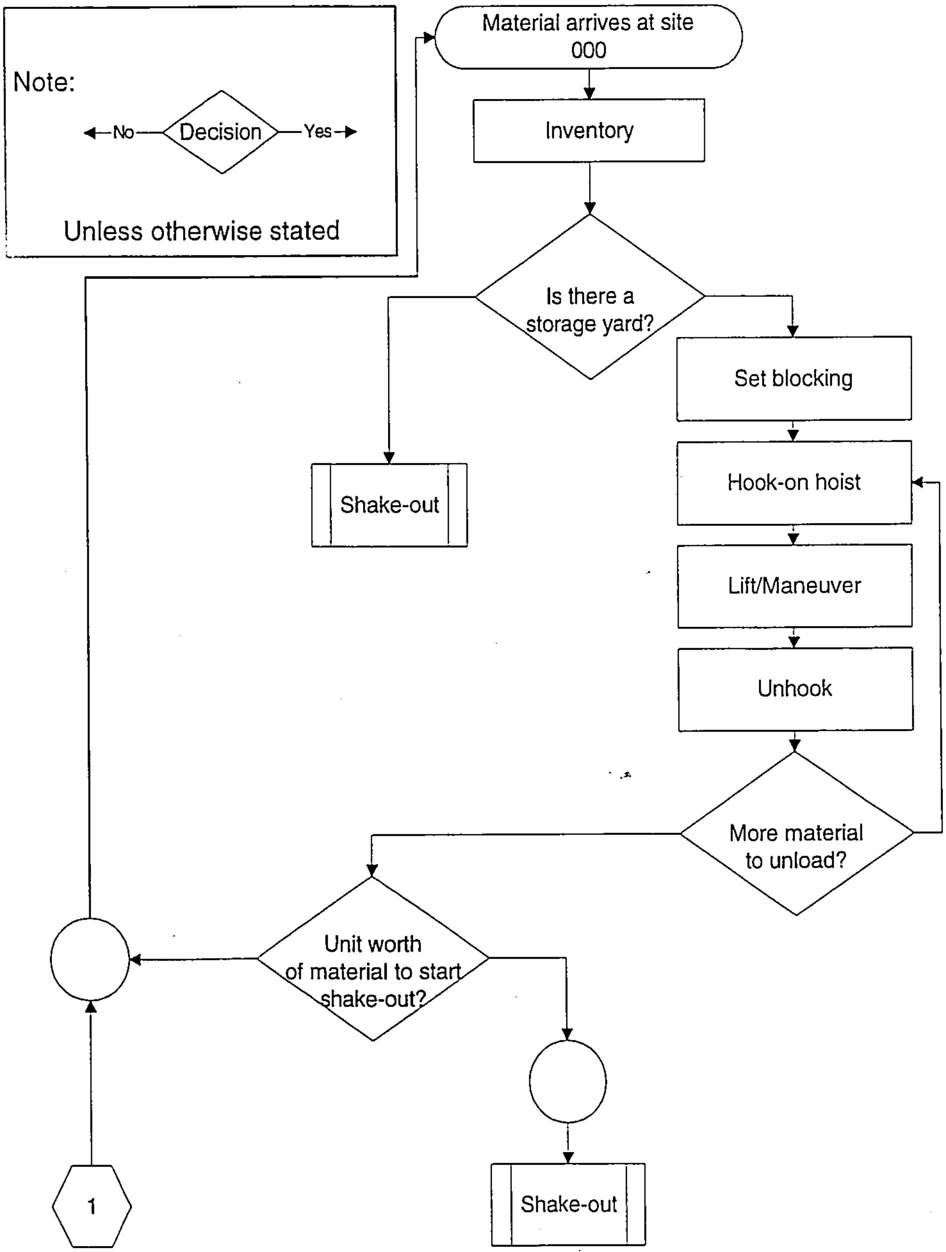
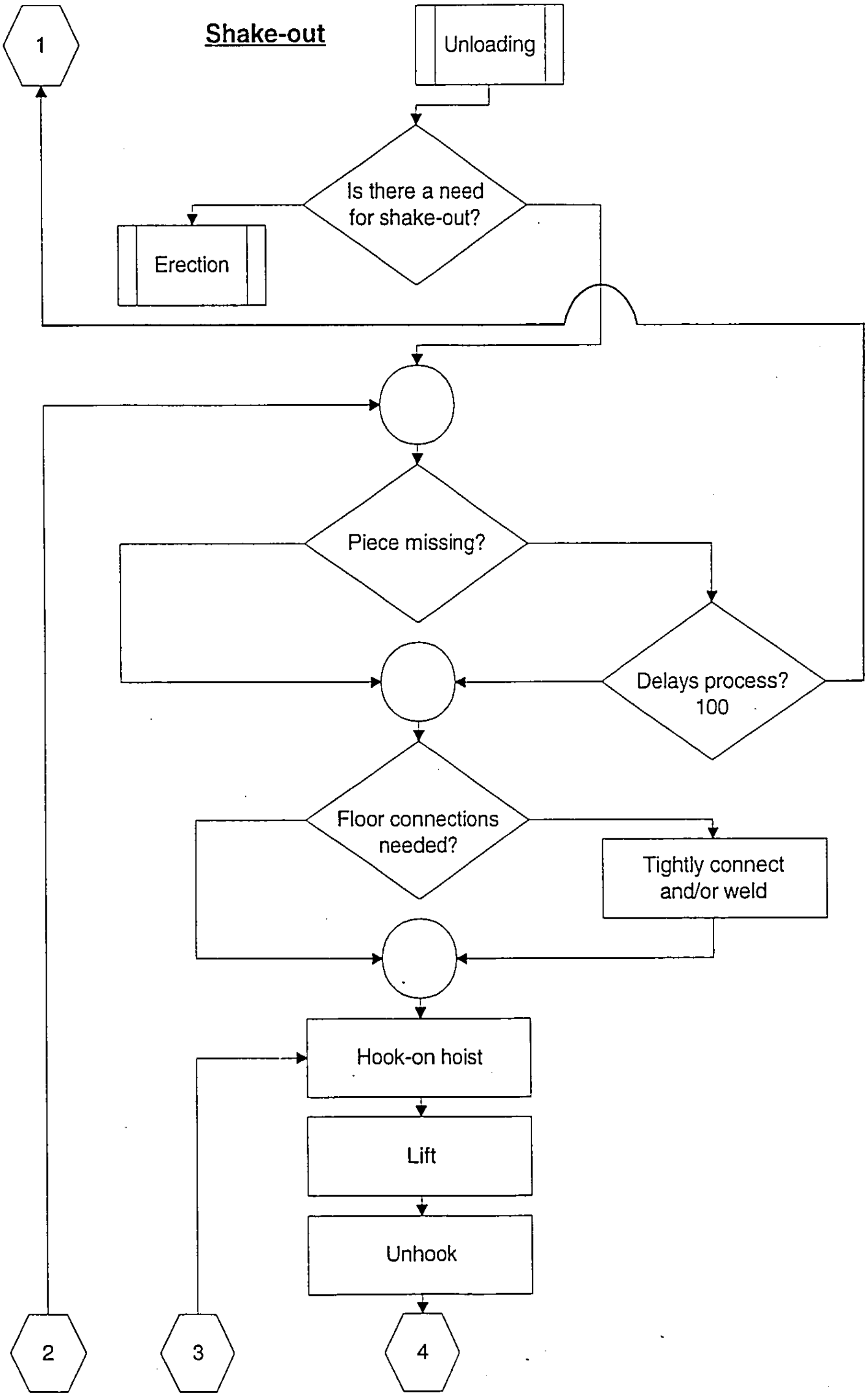
Appendix A

Flow Diagram Model

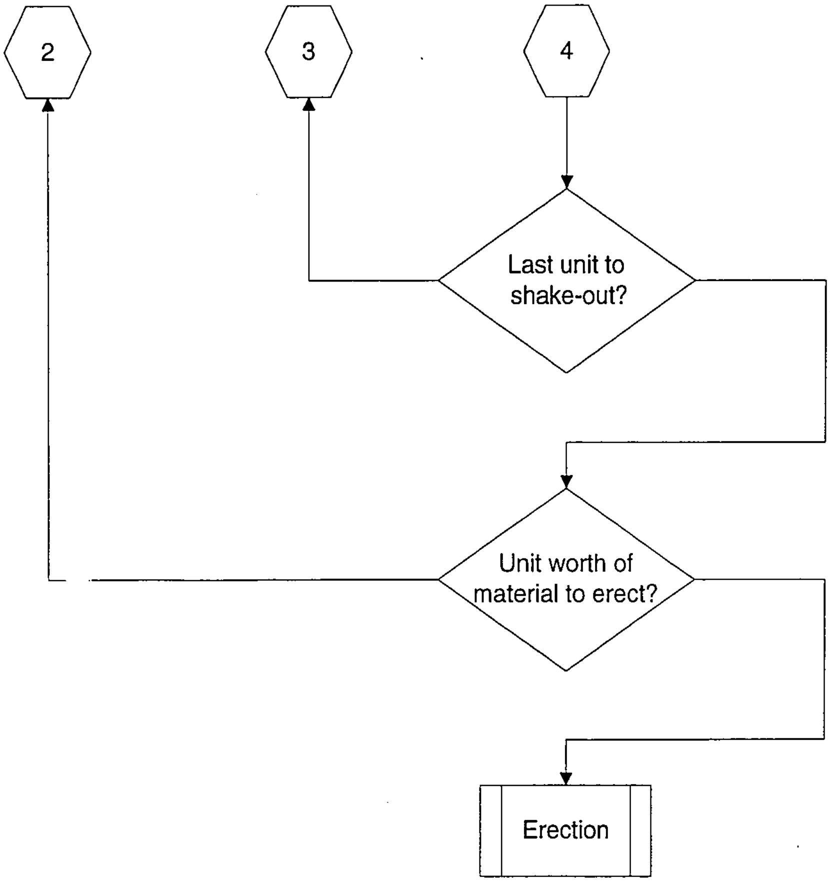
FLOW DIAGRAM IN THE ERECTION OF A STEEL STRUCTURE

Unloading

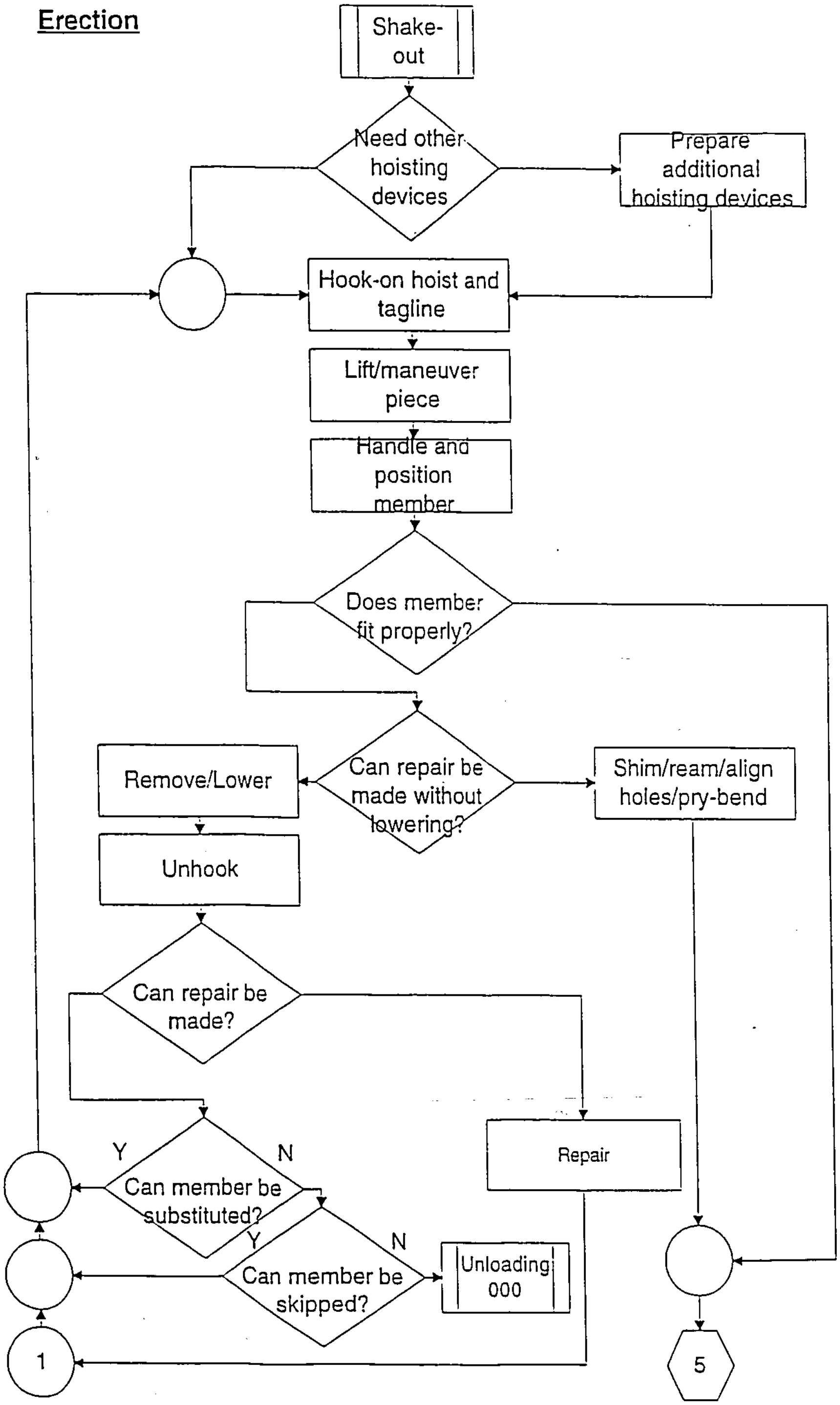



1
Shake-out
Unloading
Is there a need for shake-out?
Erection
Piece missing?
Delays process? 100
Floor connections needed?
Tightly connect and/or weld
Hook-on hoist
Lift
Unhook
2
3
4

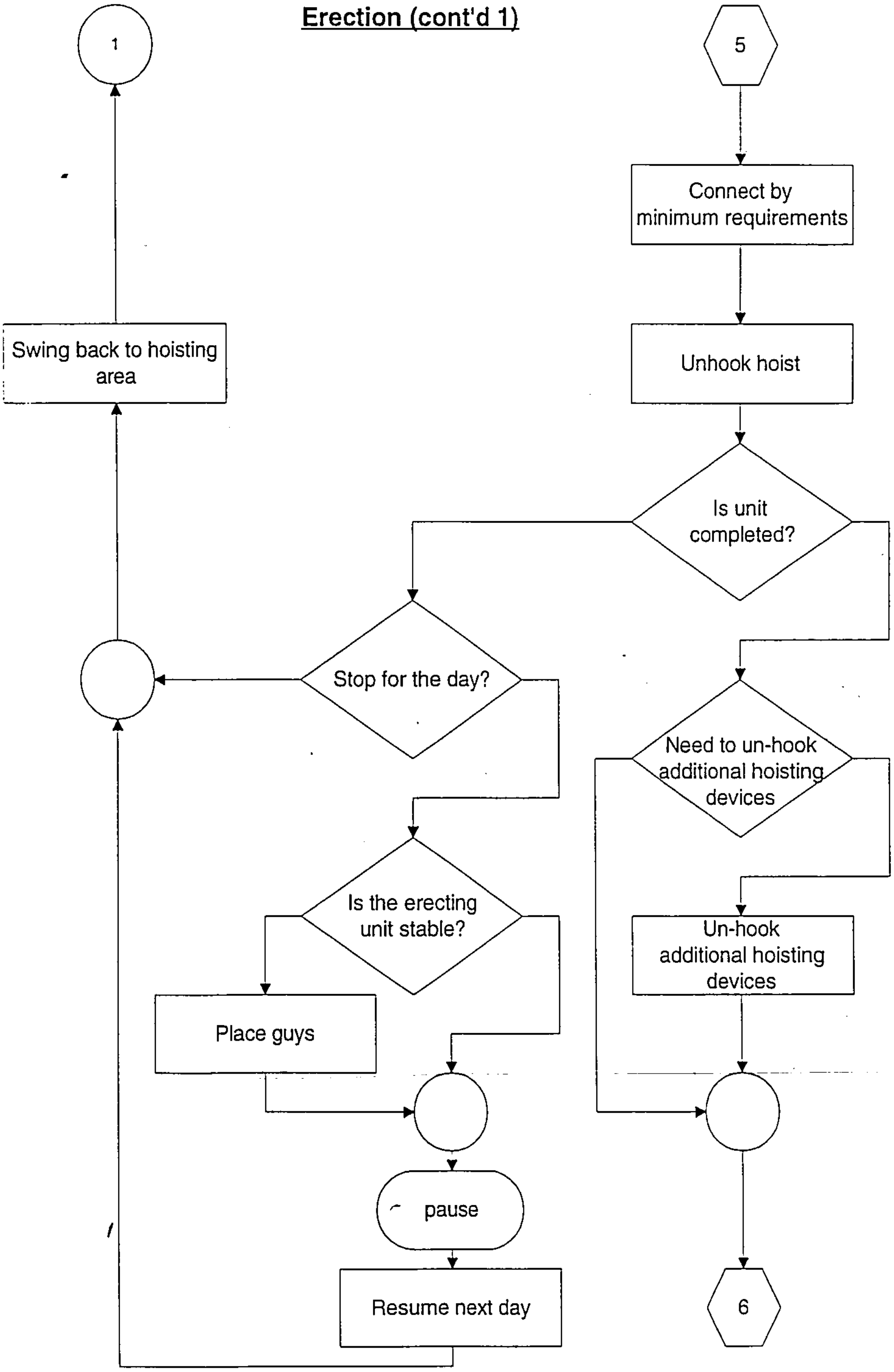
Shake-out (cont'd 1)



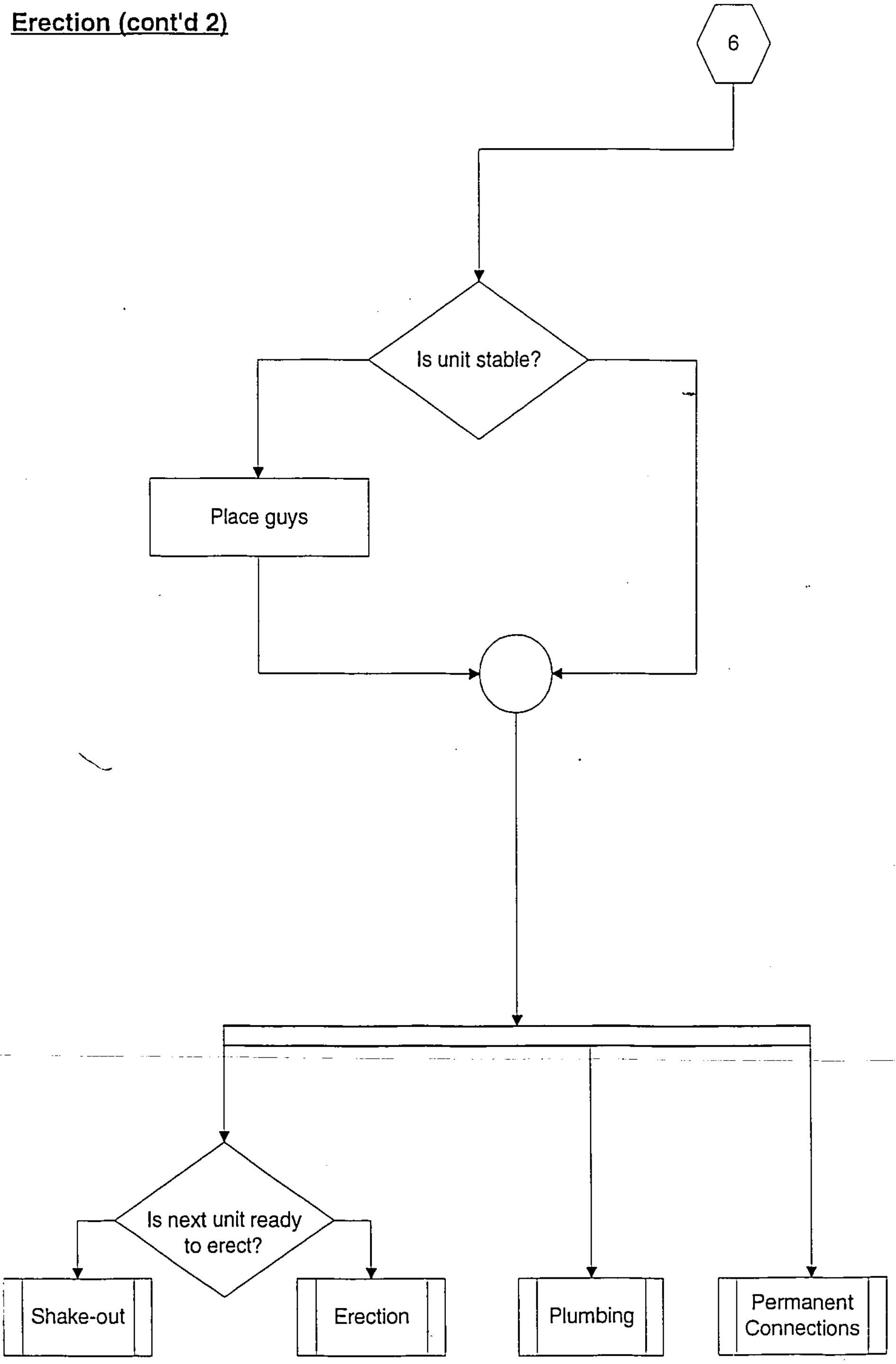
Erection


Shake-out
Need other hoisting devices
Prepare additional hoisting devices
Hook-on hoist and tagline
Lift/maneuver piece
Handle and position member
Does member fit properly?
Can repair be made without lowering?
Remove/Lower
Shim/ream/align holes/pry-bend
Unhook
Can repair be made?
Repair
Y
N
Can member be substituted?
Y
N
Can member be skipped?
Unloading 000
1
5

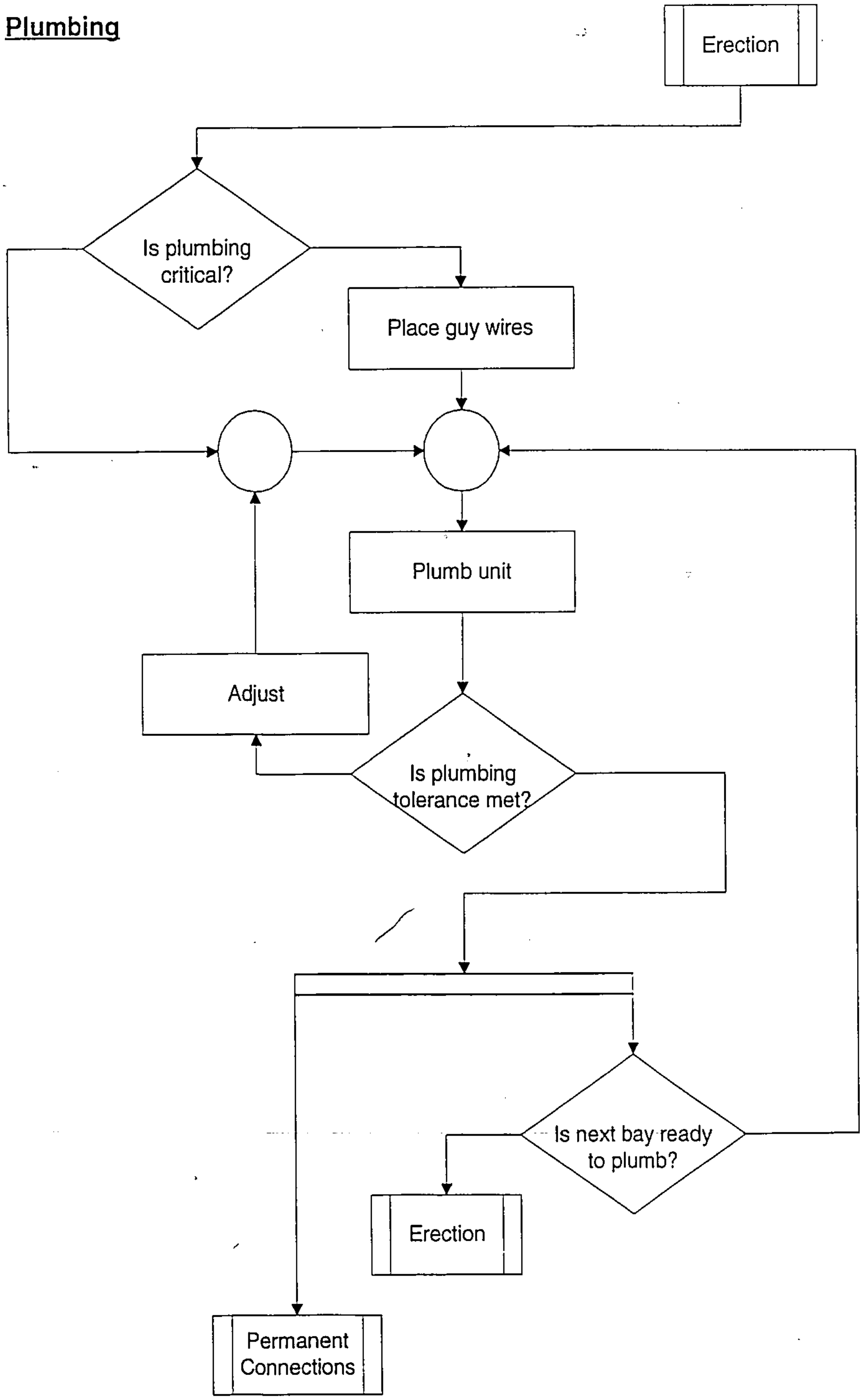
Erection (cont'd 1)



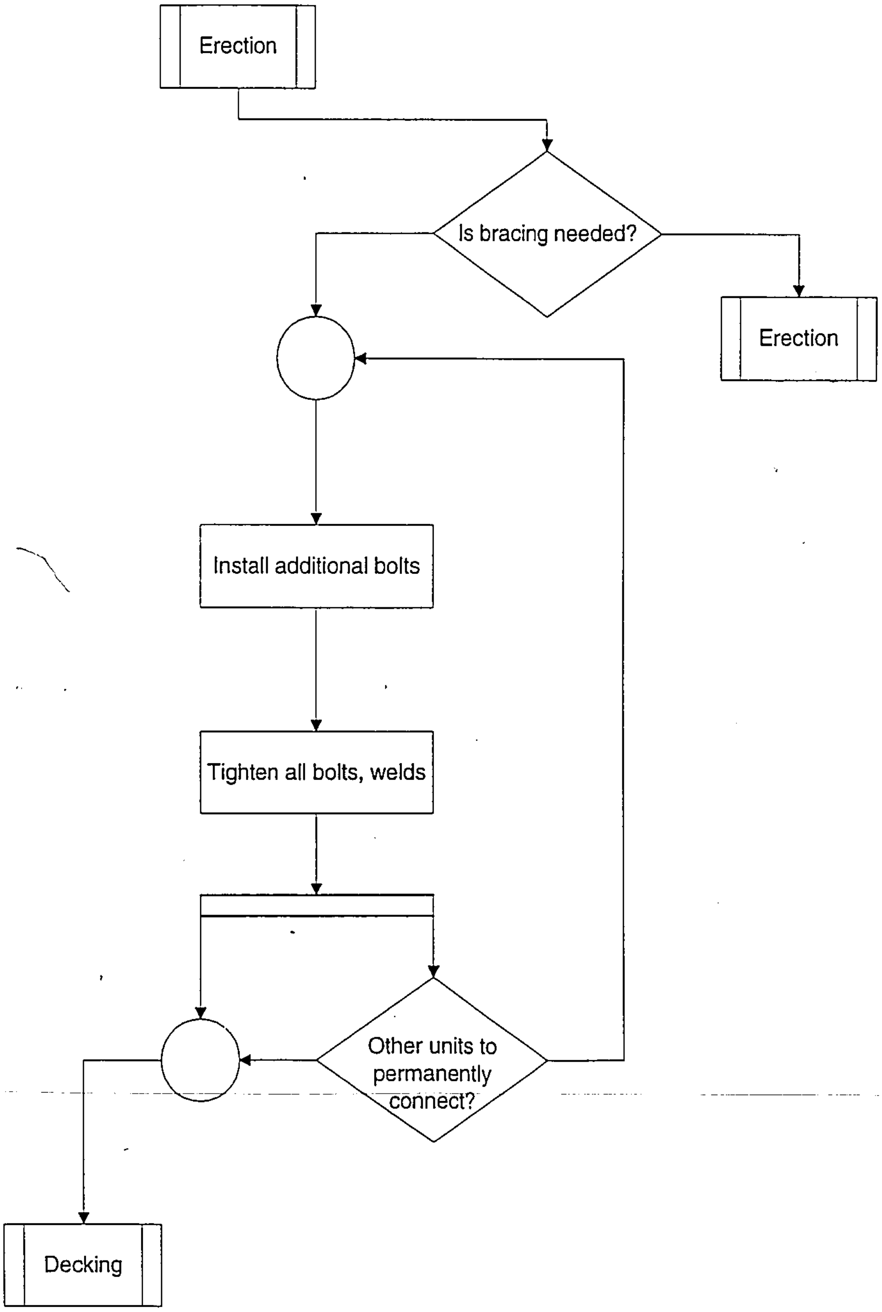
Erection (cont'd 2)



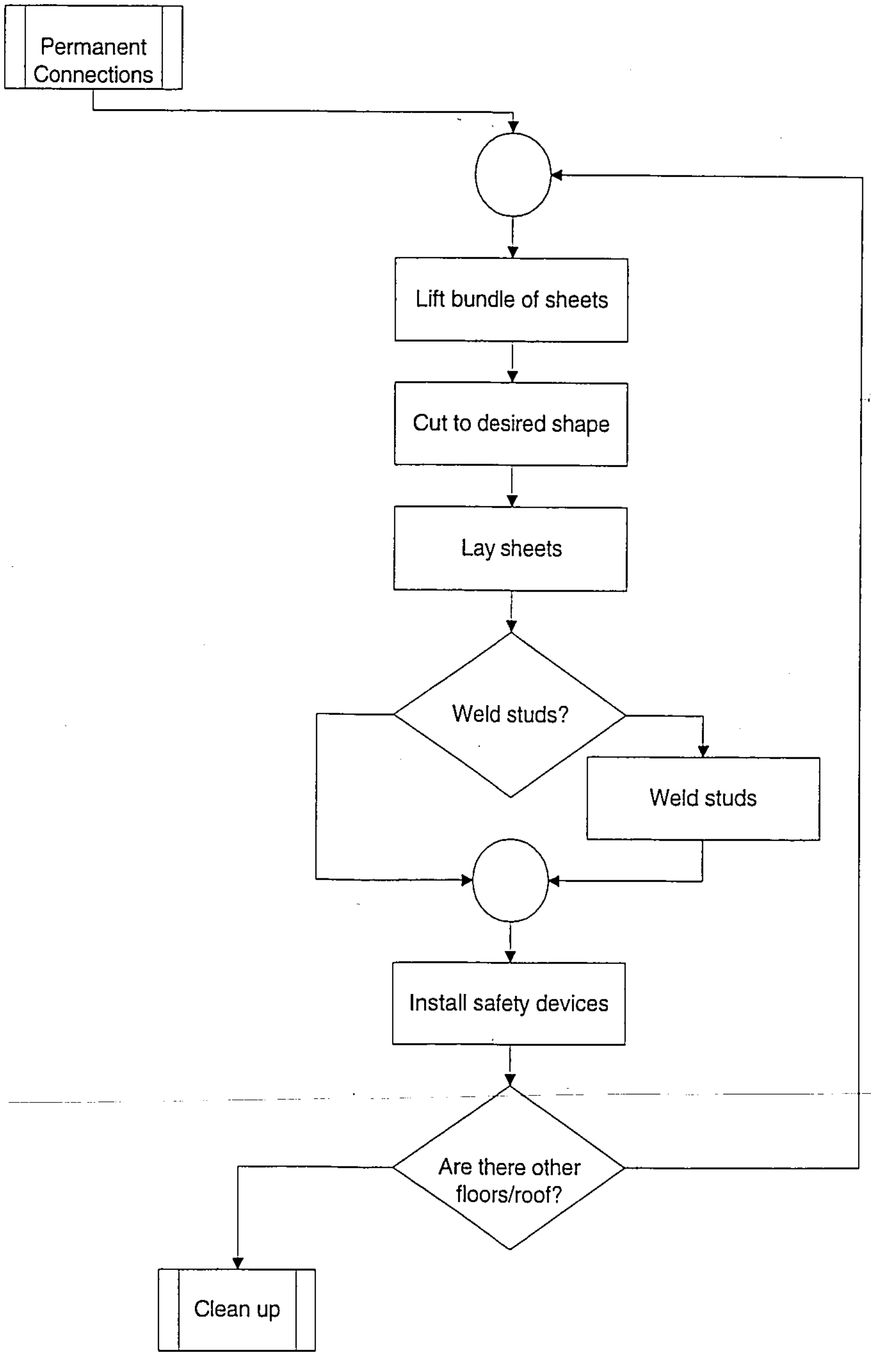
Plumbing


Erection
Is plumbing critical?
Place guy wires
Plumb unit
Adjust
Is plumbing tolerance met?
Is next bay ready to plumb?
Erection
Permanent Connections

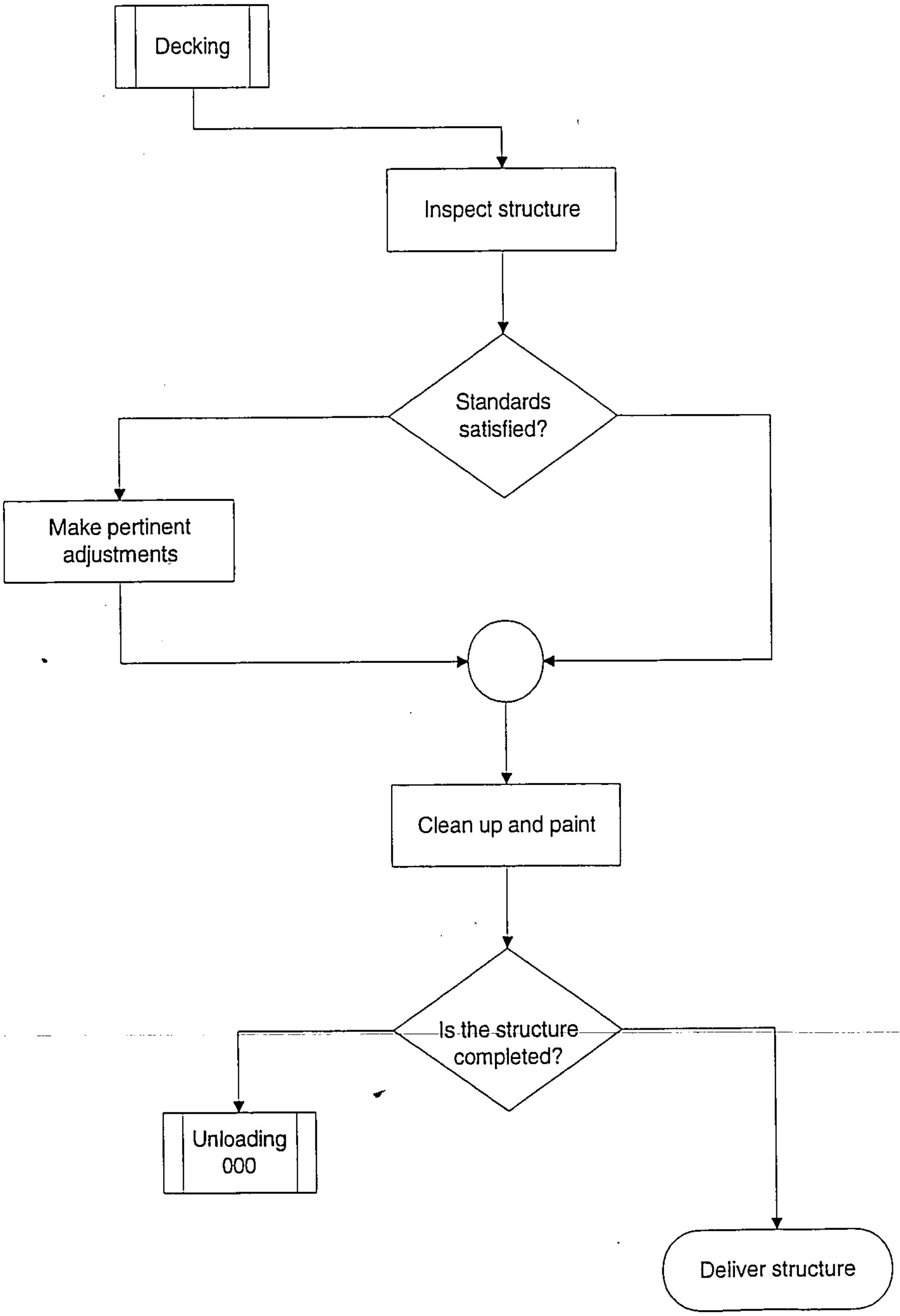
Permanent Connections



Decking


Permanent Connections
Lift bundle of sheets
Cut to desired shape
Lay sheets
Weld studs?
Weld studs
Install safety devices
Are there other floors/roof?
Clean up

Clean-up


Decking
Inspect structure
Standards satisfied?
Make pertinent adjustments
Clean up and paint
Is the structure completed?
Unloading 000
Deliver structure

Appendix B

Productivity/Resource Model Spreadsheet

TIME ESTIMATES
-for activities in the steel construction process

DATE: 04/03/95

PROJECT: Prototype Building
WEIGHT: 150 Tons

STRUCTURAL SYSTEM:

A series of rigid frames connected by bracing beams.
four-floor column tiers.
Filler beams in composite action.

Members

Member	Unit	Unit quantity	members/unit	total No. of members	imput No. of members(*)
Columns	tier	1	21	21	21
Girders/supporting beams	floor	4	14	56	56
Bracing beams	floor	4	12	48	48
Filler beams	floor	4	30	120	120
Diagonal braces				0	1
Steel joists				0	1
Purlins				0	1
Trusses				0	1

245 Total

*---Zeros must be replaced by ones to avoid division by zero in subsequent tables.

TIME ESTIMATES
-for activities in the steel construction process

DATE: 04/03/95

PROJECT: Prototype Building
WEIGHT: 150 Tons

STRUCTURAL SYSTEM:

A series of rigid frames connected by bracing beams.
four-floor column tiers.
Filler beams in composite action.

Members

Member	Unit	Unit quantity	members/unit	total No. of members	imput No. of members(*)
Columns	tier	1	21	21	21
Girders/supporting beams	floor	4	14	56	56
Bracing beams	floor	4	12	48	48
Filler beams	floor	4	30	120	120
Diagonal braces				0	1
Steel joists				0	1
Purlins				0	1
Trusses				0	1
				245	Total

*---Zeros must be replaced by ones to avoid division by zero in subsequent tables.

Connections

Bolts per connection

Connection	Unit	Unit quantity	total bolts/unit	shop bolted/unit	field bolted/unit
Anchor bolts	column	21	6	0	6
Column splice	column	0	0	0	0
Beam/girder/truss/joist to column flange	girder	56	42	18	24
Beam/girder/truss/joist to column web					
Shared bolts	beam-col-beam	60	12	4	8
Unshared bolts	column-beam	24	8	2	6
Beam/girder/truss/joist to Beam/girder/truss/joist					
Shared bolts	filler-girder-filler	80	12	4	8
Unshared bolts	girder-filler	32	8	2	6
Diagonal brace to beam/column					0

Connections

Bolts per connection

Connection	Unit	Unit quantity	total bolts/unit	shop bolted/unit	field bolted/unit
Anchor bolts	column	21	6	0	6
Column splice	column	0	0	0	0
Beam/girder/truss/joist to column flange	girder	56	42	18	24
Beam/girder/truss/joist to column web					
Shared bolts	beam-col-beam	60	12	4	8
Unshared bolts	column-beam	24	8	2	6
Beam/girder/truss/joist to Beam/girder/truss/joist					
Shared bolts	filler-girder-filler	80	12	4	8
Unshared bolts	girder-filler	32	8	2	6
Diagonal brace to beam/column					0

Total bolts

Connection	ER ins (*)	PC ins (**)	total No. of bolts	total No. of shop bolts(***)	total No. of field bolts
Anchor bolts	126	0	126	0	126
Column splice	0	0	0	0	0
Beam/girder/truss/joist to column flange	224	1120	2352	1008	1344
Beam/girder/truss/joist to column web					
Shared bolts	240	240	720	240	480
Unshared bolts	48	96	192	48	144
Beam/girder/truss/joist to Beam/girder/truss/joist					
Shared bolts	320	320	960	320	640
Unshared bolts	64	128	256	64	192
Diagonal brace to beam/column	0	0	0	0	0
		TOTAL	4606	1680	2926

*---Two bolts at each end (OSHA regulation), 50% of splice bolts, 100% of anchor bolts
**--Remaining bolts
***-Installed and tightened

Other quantities

Plumbing bays	24
Plumbing columns	0
linear inches of welding	0
truss sections	0
studs	3360
deck sheets	384

Total bolts

Connection	ER ins (*)	PC ins (**)	total No. of bolts	total No. of shop bolts(***)	total No. of field bolts
Anchor bolts	126	0	126	0	126
Column splice	0	0	0	0	0
Beam/girder/truss/joist to column flange	224	1120	2352	1008	1344
Beam/girder/truss/joist to column web					
Shared bolts	240	240	720	240	480
Unshared bolts	48	96	192	48	144
Beam/girder/truss/joist to Beam/girder/truss/joist					
Shared bolts	320	320	960	320	640
Unshared bolts	64	128	256	64	192
Diagonal brace to beam/column	0	0	0	0	0
		TOTAL	4606	1680	2926

*---Two bolts at each end (OSHA regulation), 50% of splice bolts, 100% of anchor bolts
**--Remaining bolts
***-Installed and tightened

Other quantities

Plumbing bays	24
Plumbing columns	0
linear inches of welding	0
truss sections	0
studs	3360
deck sheets	384

PRODUCTIVITY AND RESOURCES

Productivity, $p = \dfrac{\text{output}}{\text{input}}$

CREWS	STAGE	RESOURCES	
A	UN/SH/ER	2	erectors
		1	hookers
		1	crane operators
B	PL/PC	2	connectors
C	PC(weld)	1	welders
D	DE	2	deck layers
E	ALL	1	helpers
		1	supervisors

Production Rates
-including idle time

	Output			Input (crew)	
	Unit	Unit Quantity	(min/unit)	Crew	No. of crews
UNLOAD					
Beam	bundle	1	4.00	A	1
Joist/Purlin	bundle	1	4.00	A	1
Column	bundle	1	4.00	A	1
Truss section	bundle	1	4.00	A	1
Diagonal brace	bundle	1	4.00	A	1
SHAKEOUT					
Beam	bundle	1	1.00	A	1
Joist/Purlin	bundle	1	1.00	A	1
Column		1	1.00	A	1
Truss section	bundle	1	1.00	A	1
Diagonal brace	bundle	1	1.00	A	1
ERECT					
Beam	member	1	6.00	A	1
Joist/Purlin	member	1	6.00	A	1
Column	member	1	6.00	A	1
Truss	member	1	6.00	A	1
Diagonal brace	member	1	6.00	A	1
Install bolt	bolt	1	0.50	A	1

	Output			Input (crew)	
	Unit	Unit Quantity	(min/unit)	Crew	No. of crews
PLUMB					
Bay	bay	1	20.00	B	1
Column	column	1	5.00	B	1
PERMCON					
Install bolt on floor	bolt	1	0.25	B	1
Tighten bolt on floor	bolt	1	1.00	B	1
Install bolt at height	bolt	1	0.50	B	1
Tighten bolt at height	bolt	1	2.00	B	1
Install anchor bolt	bolt	1	0.50	A	1
Tighten anchor bolt	bolt	1	2.00	A	1
weld	inch	1	1.50	C	1
DECK					
stud	stud	1	0.25	D	1
deck sheets	sheet	1	4.00	D	1

FACTOR PRODUCTIVITY
Factors (-2...0...+2)

Parameter	Actual Factor	Normal Factor
Site conditions		
materials handling	2	0
presence of existing structure	2	2
Project characteristics		
regularity of topology	2	0
standardization of connections	2	2
weight of members	1	0
Resources		
level of technology of equipment	0	0
experience of crew	0	0
erection sequence	0	0
Management		
expected organization	2	2
Score	9	6

Actual Average	1.00
Percent	0.75
Normal Average	0.67
Percent	0.67

0.89	Normalized Factor

FACTOR PRODUCTIVITY
Factors (-2...0...+2)

Parameter	Actual Factor	Normal Factor
Site conditions		
materials handling	2	0
presence of existing structure	2	2
Project characteristics		
regularity of topology	2	0
standardization of connections	2	2
weight of members	-1	0
Resources		
level of technology of equipment	0	0
experience of crew	0	0
erection sequence	0	0
Management		
expected organization	2	2
Score	9	6

Actual Average	1.00	
Percent	0.75	
Normal Average	0.67	
Percent	0.67	
	0.89	Normalized Factor

Actual Production Rates

	Output			Input (crew)	
	Unit	Unit Quantity (*)	(min/unit)	Crew	No. of crews (*)
UNLOAD					
Beam	bundle	4	0.89	A	1
Joist/Purlin	bundle	1	3.56	A	1
Column	bundle	2	1.78	A	1
Truss section	bundle	1	3.56	A	1
Diagonal brace	bundle	1	3.56	A	1
SHAKEOUT					
Beam	bundle	4	0.22	A	1
Joist/Purlin	bundle	1	0.89	A	1
Column	bundle	2	0.45	A	1
Truss section	bundle	1	0.89	A	1
Diagonal brace	bundle	1	0.89	A	1
ERECT					
Beam	member	1	5.34	A	1
Joist/Purlin	member	1	5.34	A	1
Column	member	1	5.34	A	1
Truss	member	1	5.34	A	1
Diagonal brace	member	1	5.34	A	1
Install bolt	bolt	1	0.45	A	1

Actual Production Rates

	Output			Input (crew)	
	Unit	Unit Quantity (*)	(min/unit)	Crew	No. of crews (*)
UNLOAD					
Beam	bundle	4	0.89	A	1
Joist/Purlin	bundle	1	3.56	A	1
Column	bundle	2	1.78	A	1
Truss section	bundle	1	3.56	A	1
Diagonal brace	bundle	1	3.56	A	1
SHAKEOUT					
Beam	bundle	4	0.22	A	1
Joist/Purlin	bundle	1	0.89	A	1
Column	bundle	2	0.45	A	1
Truss section	bundle	1	0.89	A	1
Diagonal brace	bundle	1	0.89	A	1
ERECT					
Beam	member	1	5.34	A	1
Joist/Purlin	member	1	5.34	A	1
Column	member	1	5.34	A	1
Truss	member	1	5.34	A	1
Diagonal brace	member	1	5.34	A	1
Install bolt	bolt	1	0.45	A	1

	Output			Input (crew)	
	Unit	Unit Quantity (*)	(min/unit)	Crew	No. of crews (*)
PLUMB					
Bay	bay	2	4.45	B	2
Column	column	1	2.23	B	2
PERMCON					
Install bolt on floor	bolt	1	0.11	B	2
Tighten bolt on floor	bolt	1	0.45	B	2
Install bolt at height	bolt	1	0.22	B	2
Tighten bolt at height	bolt	1	0.89	B	2
Install anchor bolt	bolt	1	0.45	A	1
Tighten anchor bolt	bolt	1	1.78	A	1
weld	inch	1	1.34	C	1
DECK					
stud	stud	1	0.22	D	1
deck sheets	sheet	1	3.56	D	1

*---Enter a one (1) in items that will not be used to avoid division by zero.

SUMMARY

Crew Type	No. of workers
Crew A	4
Crew B	4
Crew C	0
Crew D	2
Crew E	2
Total	12

Remember crews can be relocated.

	Output			Input (crew)	
	Unit	Unit Quantity (*)	(min/unit)	Crew	No. of crews (*)
PLUMB					
Bay	bay	2	4.45	B	2
Column	column	1	2.23	B	2
PERMCON					
Install bolt on floor	bolt	1	0.11	B	2
Tighten bolt on floor	bolt	1	0.45	B	2
Install bolt at height	bolt	1	0.22	B	2
Tighten bolt at height	bolt	1	0.89	B	2
Install anchor bolt	bolt	1	0.45	A	1
Tighten anchor bolt	bolt	1	1.78	A	1
weld	inch	1	1.34	C	1
DECK					
stud	stud	1	0.22	D	1
deck sheets	sheet	1	3.56	D	1

*---Enter a one (1) in items that will not be used to avoid division by zero.

SUMMARY

Crew Type	No. of workers
Crew A	4
Crew B	4
Crew C	0
Crew D	2
Crew E	2
Total	12

Remember crews can be relocated.

TOTAL TIMES (min) relocated.

Members	quantity		UN	SH	ER	
Columns	21	21	37.4	9.3	112.1	
Girders/supp.beams	56	56	49.8	12.5	299.0	
Bracing beams	48	48	42.7	10.7	256.3	
Filler beams	120	120	106.8	26.7	640.8	
Diagonal braces	1	0	0.0	0.0	0.0	
Steel joists	1	0	0.0	0.0	0.0	
Purlins	1	0	0.0	0.0	0.0	
Truss parts	1	0	0.0	0.0	0.0	
		245	236.7	59.2	1308.3	Total min
			3.9	1.0	21.8	Total hrs
			0.5	0.1	2.7	Total days

TOTAL TIMES (min)

relocated.

Members	quantity		UN	SH	ER	
Columns	21	21	37.4	9.3	112.1	
Girders/supp.beams	56	56	49.8	12.5	299.0	
Bracing beams	48	48	42.7	10.7	256.3	
Filler beams	120	120	106.8	26.7	640.8	
Diagonal braces	1	0	0.0	0.0	0.0	
Steel joists	1	0	0.0	0.0	0.0	
Purlins	1	0	0.0	0.0	0.0	
Truss parts	1	0	0.0	0.0	0.0	
		245	236.7	59.2	1308.3	Total min
			3.9	1.0	21.8	Total hrs
			0.5	0.1	2.7	Total days

Connections	quantity				ER ins	PC ins	PC tight	
	ER ins	ER ins	PC ins	PC ins				
Anchor bolts	126	126	0	0	56.1	0.0	224.3	
Column splice	0	0	0	0	0.0	0.0	0.0	
Beam/girder/truss/joist to column flange	224	224	1120	1120	99.7	249.2	1196.2	
Beam/girder/truss/joist to column web								
Shared bolts	240	240	240	240	106.8	53.4	427.2	
Unshared bolts	48	48	96	96	21.4	21.4	128.2	
Beam/girder/truss/joist to Beam/girder/truss/joist								
Shared bolts	320	320	320	320	142.4	71.2	569.6	
Unshared bolts	64	64	128	128	28.5	28.5	170.9	
Diagonal brace to column/beam					0.0	0.0	0.0	
		1022		1904	454.8	423.6	2716.3	Total min
			2926		7.6	7.1	45.3	Total hrs
			Field bolts		0.9	0.9	5.7	Total days

Plumbing	quantity		PL	
Bay	24	24	106.8	
Column	0	0	0.0	
			106.8	Total min
			1.8	Total hrs
			0.2	Total days

Decking	quantity		DE	
Studs	3360	3360	747.6	
Sheets	384	384	1367.0	
			2114.6	Total min
			35.2	Total hrs
			4.4	Total days

Connections	quantity				ER ins	PC ins	PC tight	
	ER ins	ER ins	PC ins	PC ins				
Anchor bolts	126	126	0	0	56.1	0.0	224.3	
Column splice	0	0	0	0	0.0	0.0	0.0	
Beam/girder/truss/joist to column flange	224	224	1120	1120	99.7	249.2	1196.2	
Beam/girder/truss/joist to column web								
Shared bolts	240	240	240	240	106.8	53.4	427.2	
Unshared bolts	48	48	96	96	21.4	21.4	128.2	
Beam/girder/truss/joist to Beam/girder/truss/joist								
Shared bolts	320	320	320	320	142.4	71.2	569.6	
Unshared bolts	64	64	128	128	28.5	28.5	170.9	
Diagonal brace to column/beam					0.0	0.0	0.0	
		1022		1904	454.8	423.6	2716.3	Total min
			2926		7.6	7.1	45.3	Total hrs
			Field bolts		0.9	0.9	5.7	Total days

Plumbing	quantity		PL	
Bay	24	24	106.8	
Column	0	0	0.0	
			106.8	Total min
			1.8	Total hrs
			0.2	Total days

Decking	quantity		DE	
Studs	3360	3360	747.6	
Sheets	384	384	1367.0	
			2114.6	Total min
			35.2	Total hrs
			4.4	Total days

SUMMARY OF RESULTS

Time Estimates

Stage	Time		
UN	0.49	days	
SH/ER	3.80	days	
PL/PC	6.76	days	
DE	4.41	days	
Considering overlap	8.76	days	1 + PL/PC + 1

Note: if higher than x.5, correct cell D387.
UN + SH/ER = 4.3

ANALYSIS

Cost

	Rates
supervisor	45 $/hr
ironworker	35 $/hr
helper	25 $/hr
crane	800 $/day
Overhead and Profit	45 %
Compensation Premium	52 %
Equipment cost	$4,000
Labor cost	$24,900
Compensation Premium	$12,900
Overhead and Profit	$13,000
Total	$54,800

Resources

Crane Utilization:	5 days
Number of cranes:	1 cranes
Number of workers including supervisor:	12 workers

Productivity

Members:	57 per day
Bolts :	108 per person per day
Project duration:	9 days

Appendix C

Dynamic Model Spreadsheet

PRODUCTION TIMES:	
UNLOAD	2.67
SHAKEOUT	0.80
ERECT	6.40
INSTALL	0.67
TIGHTEN	2.67
DECK	2.67
STUD	0.20
PLUMB	6.67

IDLE PERCENT	
UNLOAD	0.50
SHAKEOL	0.25
ERECT	0.25
IN,TI,PL	0.50
DECK	0.50
STUD	0.25

NUM.PEOPLE	
UN,SH,EF	4
BOLT	4
DE,ST	2
supr+help	2
total	12

DYNAMIC SIMULATION: DAILY PROGRESS ON PROTOTYPE BUILDING

ACTIVITY	UNITS	No.	TIME/UNI	TOT. TIMI	IDLE TIMI	ELPSD TI	CUM.TIMI	DAYS
UNLOAD	BUNDLE	20	2.67	53.40	26.70	80.10	80.10	0.17
		100						
SHAKEOUT	BUNDLE	20	0.80	16.00	4.00	20.00	100.10	0.21
		100						
ERECTION								
BAY 1	COLUMNS	4	6.40	25.60	6.40	32.00	132.10	0.28
	GIRDERS	4	6.40	25.60	6.40	32.00	164.10	0.34
	BEAMS	2	6.40	12.80	3.20	16.00	180.10	0.38
	INFILL	6	6.40	38.40	9.60	48.00	228.10	0.48
		16						
BAY2	COLUMNS	2	6.40	12.80	3.20	16.00	244.10	0.51
	GIRDERS	4	6.40	25.60	6.40	32.00	276.10	0.58
	BEAMS	2	6.40	12.80	3.20	16.00	292.10	0.61
	INFILL	4	6.40	25.60	6.40	32.00	324.10	0.68
		28						
BAY3	COLUMNS	2	6.40	12.80	3.20	16.00	340.10	0.71
	GIRDERS	2	6.40	12.80	3.20	16.00	356.10	0.74
	BEAMS	2	6.40	12.80	3.20	16.00	372.10	0.78
	INFILL	6	6.40	38.40	9.60	48.00	420.10	0.88
		40						
UNLOAD	BUNDLE	10	2.67	26.70	13.35	40.05	460.15	0.96
		50						
SHAKEOUT	BUNDLE	10	0.80	8.00	2.00	10.00	470.15	0.98
		50						0.00
CUM.AVAIL.		**150**						
BAY4	COLUMNS	1	6.40	6.40	1.60	8.00	478.15	1.00
	GIRDERS	2	6.40	12.80	3.20	16.00	494.15	1.03
	BEAMS	2	6.40	12.80	3.20	16.00	510.15	1.06
	INFILL	4	6.40	25.60	6.40	32.00	542.15	1.13
		49						

BAY5	COLUMNS	2	6.40	12.80	3.20	16.00	558.15	1.16
	GIRDERS	2	6.40	12.80	3.20	16.00	574.15	1.20
	BEAMS	2	6.40	12.80	3.20	16.00	590.15	1.23
	INFILL	6	6.40	38.40	9.60	48.00	638.15	1.33
		61						
BAY6	COLUMNS	1	6.40	6.40	1.60	8.00	646.15	1.35
	GIRDERS	2	6.40	12.80	3.20	16.00	662.15	1.38
	BEAMS	2	6.40	12.80	3.20	16.00	678.15	1.41
	INFILL	4	6.40	25.60	6.40	32.00	710.15	1.48
		70						
BAY7	COLUMNS	2	6.40	12.80	3.20	16.00	726.15	1.51
	GIRDERS	2	6.40	12.80	3.20	16.00	742.15	1.55
	BEAMS	2	6.40	12.80	3.20	16.00	758.15	1.58
	INFILL	6	6.40	38.40	9.60	48.00	806.15	1.68
		82						
BAY8	COLUMNS	1	6.40	6.40	1.60	8.00	814.15	1.70
	GIRDERS	2	6.40	12.80	3.20	16.00	830.15	1.73
	BEAMS	2	6.40	12.80	3.20	16.00	846.15	1.76
	INFILL	4	6.40	25.60	6.40	32.00	878.15	1.83
		91						
UNLOAD	BUNDLE	10	2.67	26.70	13.35	40.05	918.20	1.91
		50						
SHAKEOUT	BUNDLE	10	0.80	8.00	2.00	10.00	928.20	1.93
		50						0.00
CUM.AVAIL.		**200**						
BAY9	COLUMNS	2	6.40	12.80	3.20	16.00	944.20	1.97
	GIRDERS	2	6.40	12.80	3.20	16.00	960.20	2.00
	BEAMS	2	6.40	12.80	3.20	16.00	976.20	2.03
	INFILL	6	6.40	38.40	9.60	48.00	1024.20	2.13
		103						
BAY10	COLUMNS	1	6.40	6.40	1.60	8.00	1032.20	2.15
	GIRDERS	2	6.40	12.80	3.20	16.00	1048.20	2.18
	BEAMS	2	6.40	12.80	3.20	16.00	1064.20	2.22
	INFILL	4	6.40	25.60	6.40	32.00	1096.20	2.28
		112						
BAY11	COLUMNS	2	6.40	12.80	3.20	16.00	1112.20	2.32
	GIRDERS	2	6.40	12.80	3.20	16.00	1128.20	2.35
	BEAMS	2	6.40	12.80	3.20	16.00	1144.20	2.38
	INFILL	6	6.40	38.40	9.60	48.00	1192.20	2.48
		124						
UNLOAD	BUNDLE	9	2.67	24.03	12.02	36.05	1228.25	2.56
		45						
SHAKEOUT	BUNDLE	9	0.80	7.20	1.80	9.00	1237.25	2.58
		45						0.00
CUM.AVAIL.		**245**						
BAY12	COLUMNS	1	6.40	6.40	1.60	8.00	1245.25	2.59
	GIRDERS	2	6.40	12.80	3.20	16.00	1261.25	2.63
	BEAMS	2	6.40	12.80	3.20	16.00	1277.25	2.66
	INFILL	4	6.40	25.60	6.40	32.00	1309.25	2.73
		133						

TIER 2***

BAY13	COLUMNS	0	6.40	0.00	0.00	0.00	1309.25	2.73
	GIRDERS	4	6.40	25.60	6.40	32.00	1341.25	2.79
	BEAMS	2	6.40	12.80	3.20	16.00	1357.25	2.83
	INFILL	6	6.40	38.40	9.60	48.00	1405.25	2.93
		145						
BAY14	COLUMNS	0	6.40	0.00	0.00	0.00	1405.25	2.93
	GIRDERS	4	6.40	25.60	6.40	32.00	1437.25	2.99
	BEAMS	2	6.40	12.80	3.20	16.00	1453.25	3.03
	INFILL	4	6.40	25.60	6.40	32.00	1485.25	3.09
		155						
BAY15	COLUMNS	0	6.40	0.00	0.00	0.00	1485.25	3.09
	GIRDERS	2	6.40	12.80	3.20	16.00	1501.25	3.13
	BEAMS	2	6.40	12.80	3.20	16.00	1517.25	3.16
	INFILL	6	6.40	38.40	9.60	48.00	1565.25	3.26
		165						
BAY16	COLUMNS	0	6.40	0.00	0.00	0.00	1565.25	3.26
	GIRDERS	2	6.40	12.80	3.20	16.00	1581.25	3.29
	BEAMS	2	6.40	12.80	3.20	16.00	1597.25	3.33
	INFILL	4	6.40	25.60	6.40	32.00	1629.25	3.39
		173						
BAY17	COLUMNS	0	6.40	0.00	0.00	0.00	1629.25	3.39
	GIRDERS	2	6.40	12.80	3.20	16.00	1645.25	3.43
	BEAMS	2	6.40	12.80	3.20	16.00	1661.25	3.46
	INFILL	6	6.40	38.40	9.60	48.00	1709.25	3.56
		183						
BAY18	COLUMNS	0	6.40	0.00	0.00	0.00	1709.25	3.56
	GIRDERS	2	6.40	12.80	3.20	16.00	1725.25	3.59
	BEAMS	2	6.40	12.80	3.20	16.00	1741.25	3.63
	INFILL	4	6.40	25.60	6.40	32.00	1773.25	3.69
		191						
BAY19	COLUMNS	0	6.40	0.00	0.00	0.00	1773.25	3.69
	GIRDERS	2	6.40	12.80	3.20	16.00	1789.25	3.73
	BEAMS	2	6.40	12.80	3.20	16.00	1805.25	3.76
	INFILL	6	6.40	38.40	9.60	48.00	1853.25	3.86
		201						
BAY20	COLUMNS	0	6.40	0.00	0.00	0.00	1853.25	3.86
	GIRDERS	2	6.40	12.80	3.20	16.00	1869.25	3.89
	BEAMS	2	6.40	12.80	3.20	16.00	1885.25	3.93
	INFILL	4	6.40	25.60	6.40	32.00	1917.25	3.99
		209						

BAY21	COLUMNS	0	6.40	0.00	0.00	0.00	1917.25	3.99
	GIRDERS	2	6.40	12.80	3.20	16.00	1933.25	4.03
	BEAMS	2	6.40	12.80	3.20	16.00	1949.25	4.06
	INFILL	6	6.40	38.40	9.60	48.00	1997.25	4.16
		219						
BAY22	COLUMNS	0	6.40	0.00	0.00	0.00	1997.25	4.16
	GIRDERS	2	6.40	12.80	3.20	16.00	2013.25	4.19
	BEAMS	2	6.40	12.80	3.20	16.00	2029.25	4.23
	INFILL	4	6.40	25.60	6.40	32.00	2061.25	4.29
		227						
BAY23	COLUMNS	0	6.40	0.00	0.00	0.00	2061.25	4.29
	GIRDERS	2	6.40	12.80	3.20	16.00	2077.25	4.33
	BEAMS	2	6.40	12.80	3.20	16.00	2093.25	4.36
	INFILL	6	6.40	38.40	9.60	48.00	2141.25	4.46
		237						
BAY24	COLUMNS	0	6.40	0.00	0.00	0.00	2141.25	4.46
	GIRDERS	2	6.40	12.80	3.20	16.00	2157.25	4.49
	BEAMS	2	6.40	12.80	3.20	16.00	2173.25	4.53
	INFILL	4	6.40	25.60	6.40	32.00	2205.25	4.59
		245						

0.89
4.09

ACTIVITY	UNITS	NO.UNITS	NO.BOLT		TIME/UNI	TOT.TIME	IDLE	ELPSD TI	CUM.TIME	DAYS
			INSTALI	TIGHT				228.10		0.48
PLUMB	BAY1	1			6.67	6.67	3.34	10.01	238.11	0.50
BOLTING UP										
BAY1	COLUMN	4	6	6	20.04	20.04	10.02	30.06	268.17	0.56
	GIRDERS	4	8	12	37.40	37.40	18.70	56.10	324.27	0.68
	BEAMS	2	4	14	40.06	20.03	10.02	30.05	354.31	0.74
	INFILL	6	4	14	40.06	60.09	30.05	90.14	444.45	0.93
PLUMB	BAY2	1			6.67	6.67	3.34	10.01	454.45	0.95
BAY2	COLUMN	2	6	6	20.04	10.02	5.01	15.03	469.48	0.98
	GIRDERS	4	8	12	37.40	37.40	18.70	56.10	525.58	1.09
	BEAMS	2	4	14	40.06	20.03	10.02	30.05	555.63	1.16
	INFILL	4	4	14	40.06	40.06	20.03	60.09	615.72	1.28
PLUMB	BAY3	1			6.67	6.67	3.34	10.01	625.72	1.30
BAY3	COLUMN	2	6	6	20.04	10.02	5.01	15.03	640.75	1.33
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	668.80	1.39
	BEAMS	2	4	8	24.04	12.02	6.01	18.03	686.83	1.43
	INFILL	6	4	8	24.04	36.06	18.03	54.09	740.92	1.54
PLUMB	BAY4	1			6.67	6.67	3.34	10.01	750.93	1.56
BAY4	COLUMN	1	6	6	20.04	5.01	2.51	7.52	758.44	1.58
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	786.49	1.64
	BEAMS	2	4	8	24.04	12.02	6.01	18.03	804.52	1.68
	INFILL	4	4	8	24.04	24.04	12.02	36.06	840.58	1.75
PLUMB	BAY5	1			6.67	6.67	3.34	10.01	850.59	1.77
BAY5	COLUMN	2	6	6	20.04	10.02	5.01	15.03	865.62	1.80
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	893.67	1.86
	BEAMS	2	4	8	24.04	12.02	6.01	18.03	911.70	1.90
	INFILL	6	4	8	24.04	36.06	18.03	54.09	965.79	2.01
PLUMB	BAY6	1			6.67	6.67	3.34	10.01	975.79	2.03
BAY6	COLUMN	1	6	6	20.04	5.01	2.51	7.52	983.31	2.05
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	1011.36	2.11
	BEAMS	2	4	8	24.04	12.02	6.01	18.03	1029.39	2.14
	INFILL	4	4	8	24.04	24.04	12.02	36.06	1065.45	2.22
PLUMB	BAY7	1			6.67	6.67	3.34	10.01	1075.45	2.24
BAY7	COLUMN	2	6	6	20.04	10.02	5.01	15.03	1090.48	2.27
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	1118.53	2.33
	BEAMS	2	4	8	24.04	12.02	6.01	18.03	1136.56	2.37
	INFILL	6	4	8	24.04	36.06	18.03	54.09	1190.65	2.48
PLUMB	BAY8	1			6.67	6.67	3.34	10.01	1200.66	2.50
BAY8	COLUMN	1	6	6	20.04	5.01	2.51	7.52	1208.17	2.52
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	1236.22	2.58
	BEAMS	2	4	8	24.04	12.02	6.01	18.03	1254.25	2.61
	INFILL	4	4	8	24.04	24.04	12.02	36.06	1290.31	2.69
PLUMB	BAY9	1			6.67	6.67	3.34	10.01	1300.32	2.71
BAY9	COLUMN	2	6	6	20.04	10.02	5.01	15.03	1315.35	2.74
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	1343.40	2.80
	BEAMS	2	4	8	24.04	12.02	6.01	18.03	1361.43	2.84
	INFILL	6	4	8	24.04	36.06	18.03	54.09	1415.52	2.95
PLUMB	BAY10	1			6.67	6.67	3.34	10.01	1425.52	2.97
BAY10	COLUMN	1	6	6	20.04	5.01	2.51	7.52	1433.04	2.99
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	1461.09	3.04
	BEAMS	2	4	8	24.04	12.02	6.01	18.03	1479.12	3.08
	INFILL	4	4	8	24.04	24.04	12.02	36.06	1515.18	3.16

PLUMB	BAY11	1			6.67	6.67	3.34	10.01	1525.18	3.18
BAY11	COLUMN	2	6	6	20.04	10.02	5.01	15.03	1540.21	3.21
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	1568.26	3.27
	BEAMS	2	8	6	21.38	10.69	5.35	16.04	1584.30	3.30
	INFILL	6	8	6	21.38	32.07	16.04	48.11	1632.40	3.40
PLUMB	BAY12	1			6.67	6.67	3.34	10.01	1642.41	3.42
BAY12	COLUMN	1	6	6	20.04	5.01	2.51	7.52	1649.92	3.44
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	1677.97	3.50
	BEAMS	2	8	6	21.38	10.69	5.35	16.04	1694.01	3.53
	INFILL	4	8	6	21.38	21.38	10.69	32.07	1726.08	3.60
PLUMB	BAY13	1			6.67	6.67	3.34	10.01	1736.08	3.62
BAY13	COLUMN	0	0	0	0.00	0.00	0.00	0.00	1736.08	3.62
	GIRDERS	4	8	12	37.40	37.40	18.70	56.10	1792.18	3.73
	BEAMS	2	4	14	40.06	20.03	10.02	30.05	1822.23	3.80
	INFILL	6	4	14	40.06	60.09	30.05	90.14	1912.36	3.98
PLUMB	BAY14	1			6.67	6.67	3.34	10.01	1922.37	4.00
BAY14	COLUMN	0	0	0	0.00	0.00	0.00	0.00	1922.37	4.00
	GIRDERS	4	8	12	37.40	37.40	18.70	56.10	1978.47	4.12
	BEAMS	2	4	14	40.06	20.03	10.02	30.05	2008.51	4.18
	INFILL	4	4	14	40.06	40.06	20.03	60.09	2068.60	4.31
PLUMB	BAY15	1			6.67	6.67	3.34	10.01	2078.61	4.33
BAY15	COLUMN	0	0	0	0.00	0.00	0.00	0.00	2078.61	4.33
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	2106.66	4.39
	BEAMS	2	4	8	24.04	12.02	6.01	18.03	2124.69	4.43
	INFILL	6	4	8	24.04	36.06	18.03	54.09	2178.78	4.54
PLUMB	BAY16	1			6.67	6.67	3.34	10.01	2188.78	4.56
BAY16	COLUMN	0	0	0	0.00	0.00	0.00	0.00	2188.78	4.56
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	2216.83	4.62
	BEAMS	2	4	8	24.04	12.02	6.01	18.03	2234.86	4.66
	INFILL	4	4	8	24.04	24.04	12.02	36.06	2270.92	4.73
PLUMB	BAY17	1			6.67	6.67	3.34	10.01	2280.93	4.75
BAY17	COLUMN	0	0	0	0.00	0.00	0.00	0.00	2280.93	4.75
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	2308.98	4.81
	BEAMS	2	4	8	24.04	12.02	6.01	18.03	2327.01	4.85
	INFILL	6	4	8	24.04	36.06	18.03	54.09	2381.10	4.96
PLUMB	BAY18	1			6.67	6.67	3.34	10.01	2391.10	4.98
BAY18	COLUMN	0	0	0	0.00	0.00	0.00	0.00	2391.10	4.98
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	2419.15	5.04
	BEAMS	2	4	8	24.04	12.02	6.01	18.03	2437.18	5.08
	INFILL	4	4	8	24.04	24.04	12.02	36.06	2473.24	5.15
PLUMB	BAY19	1			6.67	6.67	3.34	10.01	2483.25	5.17
BAY19	COLUMN	0	0	0	0.00	0.00	0.00	0.00	2483.25	5.17
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	2511.30	5.23
	BEAMS	2	4	8	24.04	12.02	6.01	18.03	2529.33	5.27
	INFILL	6	4	8	24.04	36.06	18.03	54.09	2583.42	5.38
PLUMB	BAY20	1			6.67	6.67	3.34	10.01	2593.42	5.40
BAY20	COLUMN	0	0	0	0.00	0.00	0.00	0.00	2593.42	5.40
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	2621.47	5.46
	BEAMS	2	4	8	24.04	12.02	6.01	18.03	2639.50	5.50
	INFILL	4	4	8	24.04	24.04	12.02	36.06	2675.56	5.57

PLUMB	BAY21	1			6.67	6.67	3.34	10.01	2685.57	5.59
BAY21	COLUMN	0	0	0	0.00	0.00	0.00	0.00	2685.57	5.59
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	2713.62	5.65
	BEAMS	2	4	8	24.04	12.02	6.01	18.03	2731.65	5.69
	INFILL	6	4	8	24.04	36.06	18.03	54.09	2785.74	5.80
PLUMB	BAY22	1			6.67	6.67	3.34	10.01	2795.74	5.82
BAY22	COLUMN	0	0	0	0.00	0.00	0.00	0.00	2795.74	5.82
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	2823.79	5.88
	BEAMS	2	4	8	24.04	12.02	6.01	18.03	2841.82	5.92
	INFILL	4	4	8	24.04	24.04	12.02	36.06	2877.88	6.00
PLUMB	BAY23	1			6.67	6.67	3.34	10.01	2887.89	6.02
BAY23	COLUMN	0	0	0	0.00	0.00	0.00	0.00	2887.89	6.02
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	2915.94	6.07
	BEAMS	2	8	6	21.38	10.69	5.35	16.04	2931.97	6.11
	INFILL	6	8	6	21.38	32.07	16.04	48.11	2980.08	6.21
PLUMB	BAY24	1			6.67	6.67	3.34	10.01	2990.08	6.23
BAY24	COLUMN	0	0	0	0.00	0.00	0.00	0.00	2990.08	6.23
	GIRDERS	2	8	12	37.40	18.70	9.35	28.05	3018.13	6.29
	BEAMS	2	8	6	21.38	10.69	5.35	16.04	3034.17	6.32
	INFILL	4	8	6	21.38	21.38	10.69	32.07	3066.24	6.39

-0.48

2254

5.91

0.89

5.26

ACTIVITY	UNITS	NO.UNITS	TIME/UNI	TOTAL TIME	IDLE	ELAPSED	CUM.TIM	DAYS
DECKING		(2 PEOPLE)					960.00	2.00
BAY1	SHEETS	16	2.67	42.72	21.36	64.08	1024.08	2.13
	STUDS	140	0.20	28.00	7.00	35.00	1059.08	2.21
BAY2	SHEETS	16	2.67	42.72	21.36	64.08	1123.16	2.34
	STUDS	140	0.20	28.00	7.00	35.00	1158.16	2.41
BAY3	SHEETS	16	2.67	42.72	21.36	64.08	1222.24	2.55
	STUDS	140	0.20	28.00	7.00	35.00	1257.24	2.62
BAY4	SHEETS	16	2.67	42.72	21.36	64.08	1321.32	2.75
	STUDS	140	0.20	28.00	7.00	35.00	1356.32	2.83
BAY5	SHEETS	16	2.67	42.72	21.36	64.08	1420.40	2.96
	STUDS	140	0.20	28.00	7.00	35.00	1455.40	3.03
BAY6	SHEETS	16	2.67	42.72	21.36	64.08	1519.48	3.17
	STUDS	140	0.20	28.00	7.00	35.00	1554.48	3.24
BAY7	SHEETS	16	2.67	42.72	21.36	64.08	1618.56	3.37
	STUDS	140	0.20	28.00	7.00	35.00	1653.56	3.44
BAY8	SHEETS	16	2.67	42.72	21.36	64.08	1717.64	3.58
	STUDS	140	0.20	28.00	7.00	35.00	1752.64	3.65
BAY9	SHEETS	16	2.67	42.72	21.36	64.08	1816.72	3.78
	STUDS	140	0.20	28.00	7.00	35.00	1851.72	3.86
BAY10	SHEETS	16	2.67	42.72	21.36	64.08	1915.80	3.99
	STUDS	140	0.20	28.00	7.00	35.00	1950.80	4.06
BAY11	SHEETS	16	2.67	42.72	21.36	64.08	2014.88	4.20
	STUDS	140	0.20	28.00	7.00	35.00	2049.88	4.27
BAY12	SHEETS	16	2.67	42.72	21.36	64.08	2113.96	4.40
	STUDS	140	0.20	28.00	7.00	35.00	2148.96	4.48
BAY13	SHEETS	16	2.67	42.72	21.36	64.08	2213.04	4.61
	STUDS	140	0.20	28.00	7.00	35.00	2248.04	4.68
BAY14	SHEETS	16	2.67	42.72	21.36	64.08	2312.12	4.82
	STUDS	140	0.20	28.00	7.00	35.00	2347.12	4.89
BAY15	SHEETS	16	2.67	42.72	21.36	64.08	2411.20	5.02
	STUDS	140	0.20	28.00	7.00	35.00	2446.20	5.10
BAY16	SHEETS	16	2.67	42.72	21.36	64.08	2510.28	5.23
	STUDS	140	0.20	28.00	7.00	35.00	2545.28	5.30
BAY17	SHEETS	16	2.67	42.72	21.36	64.08	2609.36	5.44
	STUDS	140	0.20	28.00	7.00	35.00	2644.36	5.51
BAY18	SHEETS	16	2.67	42.72	21.36	64.08	2708.44	5.64
	STUDS	140	0.20	28.00	7.00	35.00	2743.44	5.72
BAY19	SHEETS	16	2.67	42.72	21.36	64.08	2807.52	5.85
	STUDS	140	0.20	28.00	7.00	35.00	2842.52	5.92
BAY20	SHEETS	16	2.67	42.72	21.36	64.08	2906.60	6.06
	STUDS	140	0.20	28.00	7.00	35.00	2941.60	6.13
BAY21	SHEETS	16	2.67	42.72	21.36	64.08	3005.68	6.26
	STUDS	140	0.20	28.00	7.00	35.00	3040.68	6.33
BAY22	SHEETS	16	2.67	42.72	21.36	64.08	3104.76	6.47
	STUDS	140	0.20	28.00	7.00	35.00	3139.76	6.54
BAY23	SHEETS	16	2.67	42.72	21.36	64.08	3203.84	6.67
	STUDS	140	0.20	28.00	7.00	35.00	3238.84	6.75
BAY24	SHEETS	16	2.67	42.72	21.36	64.08	3302.92	6.88
	STUDS	140	0.20	28.00	7.00	35.00	3337.92	6.95

Appendix D

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Vita

Mario Eraso was born in Cali, Colombia on November 3, 1965. He is the third of five children to Servio Tulio Eraso and Elisa Monzón de Eraso.

He attended Lehigh University from 1984 to 1988, where he obtained a Bachelor of Science degree in Civil Engineering. After graduation, he worked in SAC Estructuras Metalicas, a company in Bogota, Colombia which specializes in the design, fabrication and erection of steel structures. In 1993, he returned to Lehigh University to pursue a Master of Science degree in Civil Engineering.

END

OF

TITLE