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Preliminary Simulation Models of the Fabrication and Erection of Steel Structures

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ADVANCED TECHNOLOGY FOR
LARGE
STRUCTURAL SYSTEMS

Lehigh University

PRELIMINARY SIMULATION MODELS
OF THE
FABRICATION AND ERECTION
OF
STEEL STRUCTURES

by

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ABSTRACT

This report presents the results of the second and third phases of ATLSS project ADC-11, "Economic Assessment of an Integrated Building System." The objective of this research is to develop a methodology to systematically assess the economic impacts of new designs and advanced construction technologies on the fabrication and construction of large structural systems. The focus of this stage has been on steel structures, and the methodology is based on the commonalities in the fabrication and erection stages. Three preliminary simulation models of the fabrication and erection sequences for steel structures describe the steel construction process. The first model is the flow diagrams which describe the activities in fabricating and erecting structural steel. The second model is a computer-based spreadsheet which estimates the duration of a project by keeping track of specific members, bolts, welds and other structural quantities. It is also possible in this second model to mix resource and productivity alternatives by use of specified crew types and site parameters. The third model merges the first two models to provide the daily status of a project. This last model provides the opportunity to examine the detailed changes that new designs and technologies might bring, such as decreasing costs and improving safety. In addition, this third model provides the framework for future developments in a fully computer-based simulation model. Future research will use these models to assess the economic impacts of selected advanced construction technologies for the erection of steel structures.

CHAPTER 1

INTRODUCTION

Many opportunities exist to improve the design, fabrication, construction and operation of large structural systems. The National Science Foundation Engineering Research Center for Advanced Technology for Large Structural Systems has addressed these opportunities through many research activities. In particular, several projects have focused on developing the components needed for an "integrated building system." The objective of this set of projects is to develop a family of structural systems with enhanced fabrication and erection characteristics. Among the specific developments are a new type of connection, the ATLSS Connector (AC), which is self-aligning and requires no bolting during erection, and a modified prototype of a computer-assisted positioning crane, the Stewart Platform.

1.1 Research Objectives

The objective of this project, "Economic Assessment of an Integrated Building System," is to develop a methodology to systematically assess the economic impacts of new designs and advanced construction technologies on the fabrication and construction of large structural systems. This research seeks to assess the potential benefits, opportunities and costs of an integrated building system with respect to two bases: best available current practice, and new or emerging technologies. The research program consists of four phases: 1) assess the state-of-the-art in construction automation, robotics and other related technologies; 2) develop a methodology for the systematic comparison and evaluation of different building systems; 3) develop and conduct computer-based simulations that include critical influence factors and can aid the economic assessment of new construction technologies; and 4) evaluate the opportunities and potential net benefits of integrated building systems, including the use of the ATLSS Connector and other applicable technologies.

The results from the first phase of the research are presented in an ATLSS Report (Higgins and Slaughter, 1993). This analysis of the state-of-the-art identified specific existing or emerging construction technologies (in the U.S. and internationally) that used automatic or robotic systems to control process and navigation activities. This set of advanced construction technologies was analyzed to determine apparent trends in the selection of tasks to be automated and the sophistication of process and navigation controls employed.

This report represents the results from the second and third phases of the project. The methodology of the research to compare building systems has built upon the physical processes of fabrication and erection. While building designs may differ in an infinitely large number of ways, nonetheless they are fabricated and erected using the same basic activities. This methodology provides a framework to analyze the effectiveness of new designs and construction technologies. The simulation models presented here reconstruct the fabrication and erection processes to provide the basis for analyzing the changes that the use of new designs or advanced technologies might entail. For example, to fully assess the impact that a new connection, such as the ATLSS Connector, might have on the erection process, it is necessary to examine the minute activities (e.g. temporary erection bolts for shared web connections) that will be changed if the new connection is used. The simulation models have been constructed to provide that level of detail.

During the fourth phase of the project, the simulation models will be used to assess the economic impacts of specific new designs and automated and robotic technologies for the erection of steel structures. These technologies will include the ATLSS Connector, and some selection of the seven automatic or robotic construction technologies that can be used during structural steel erection that were identified during phase one. This methodology can provide the capability to systematically evaluate the impact that the application of the new technologies will have on the job flow, resources, activity and project durations, cost, and other factors (such as safety).

1.2 Research Significance

The development of this methodology has several areas of potential application. These methodologies can compare design alternatives to each other, and can evaluate the applicability of new technologies as compared to the current best methods and to other new technologies. The specific tools developed are preliminary simulation models of the fabrication and erection of a steel structure coupled with an analysis of the economic implications of the use of new technologies. These tools go several steps beyond the current computer-aided design and engineering packages since they focus on the assemblage of the components rather than on their idealized final location. It is hoped, however, that future research could develop the simulation models further and eventually join them with CAD/CAE systems to provide a multi-faceted and richer understanding of the completed facility.

The research can have significant implications in improving the efficiency of the construction of facilities and the performance of the completed assets. In particular, the applications of the methodologies developed in this research can improve the robustness of facility design and technology selections. In addition, by providing a systematic means of evaluating new technologies, the existing barriers to the application of new technologies can be lowered. The methodologies can approximate field conditions and experiential information while avoiding the risk naturally associated with full-scale field experimentation. This process will allow designers, builders, and owners to evaluate design alternatives with greater ease and to assess the impacts of incorporating new technologies into fabrication and erection processes. This assessment of new technologies can have a longer term effect in aiding the development of new technologies by revealing opportunities for future technical development that could increase efficiency or reduce costs.

1.3 Summary of Approach

This report describes the three models developed to approximate the detailed activities involved in the fabrication and erection of a steel structure. The first model is flow diagrams that describe the specific activities and decision points associated with the fabrication of structural steel materials and the erection of a steel structure. The second model is a spreadsheet-based program that calculates the total time and cost for the erection of the steel structure based on detailed member counts (e.g. number of beams, number of bolts installed during erection) and productivity rates. The third model is a manual combination of the flow diagram and spreadsheet calculations to approximate the daily flow of the project, and to incorporate other concerns, such as the structural stability of the erected frame.

The development of these models was significantly enriched from the strong involvement of professionals in the construction industry. This research received help through several means, from cost and productivity estimates to detailed interviews. In addition, site visits to ten (10) steel erection sites provided the opportunity to collect data directly (See Chapter 3). Steel fabrication and erection professionals provided valuable feedback and detailed statistics which were crucial to developing these models. Many experts in professional organizations generously provided us with their insight and expertise (Table 1.1).

This report is structured around the preliminary simulation models. A later report will include a detailed description of the methodology developed to compare different building types, and to provide the results of the economic assessment of the use of advanced construction technologies in the erection of steel structures.

The background literature described in Chapter 2 concentrates primarily on simulation methods developed for construction applications, and on the fabrication and erection processes themselves. Chapter 3 explains the methodology for the research, including the data collection activities and the use of the data in developing and testing the models. This chapter also contains information concerning the validity and reliability of the models. The models themselves are described in detail in Chapter 4, and in Chapter 5 they are applied to a prototype building to demonstrate their use. This example application will also become the baseline case to assess several new technologies during the next phase of the research. The final chapter presents the conclusions on the potential of these models for both economic assessment activities and for assessing the use of new designs and new technologies.

The appendices include important supplementary information. Appendices A, B and C contain the detailed flow diagrams and the spreadsheet-based program, while Appendix D contains examples of the manual computations. Appendix E is the data collected at the ten sites visited. All people to whom the draft erection flow diagram and productivity estimates were sent are listed in Appendix F. Some suggestions for designing safe connections to avoid shared bolts are included in Appendix G. Finally, Appendix H shows some sensitivity analyses of the spreadsheet.

TABLE 1.1: RESEARCH CONTRIBUTORS FROM THE STEEL FABRICATION AND ERECTION INDUSTRY

Robert G. Abramson Interstate Iron Works Corporation	Jay Larson Bethlehem Steel Corporation
Arthur Aubin Yonkers Contracting Company	Terry Malta Interstate Iron Works Corporation
Edward Becker Lehigh University	John McMahon Institute of the Ironworking Industry
Milt Gore DuPont	John O'Brien Falcon Steel Company
Geerhard Haaijer AISC	Brett Paddock Falcon Steel Company
Richard Hendricks Dupont	Robert Potocko Bechtel Corporation
Tim Horst Bechtel Corporation	Abraham Rokach AISC
Nestor Iwankiw AISC	John Schlecht Institute of the Ironworking Industry
Don L. Johnson Butler Manufacturing Company	Roger Wildt Bethlehem Steel Corporation

CHAPTER 2

BACKGROUND

The need for a systematic methodology for comparing alternatives has prompted developments in several fields. Methods from several fields seeks to mimic the dynamic use of technologies to examine their impact on production processes and flows. Experimenting with these models can provide understanding which may not be available in field conditions or in real-time operations. For the simulation of construction activities, the models have taken several distinctly different paths which often provide complementary insights into the construction process.

The primary background required for this phase of the research was the understanding of the standard procedures, tools, equipment and methods for fabricating and erecting structures, specifically those made of steel. Several texts proved invaluable in the initial formulation of the flow diagram and the early productivity estimates.

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 construction, where many repetitive actions (e.g. 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.

Research on computer-based simulation models for construction processes has developed along several themes. The first is characterized by the cyclic activities in construction (e.g. filling a dump truck with excavated earth). These cyclic activities are modelled through subroutines or "modules." 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). Through defining the task and process and the associated resources, this simulation model allows analysis of alternative construction procedures with time as the dynamic element, and the efficiency of the resource use as the 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.

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 (a problem which no doubt will be corrected over time). In addition, the simulation assumes a certain set of resources (e.g. a certain crane) and uses a pre-established general sequence, and 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). 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. In addition, not all design implications are linked to resource utilization.

While many of these simulation model 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 Fabrication and Erection

The primary sources of information on structural fabrication and 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 fabrication and erection of steel structures. The second category provided both data and analysis methods of construction productivity.

The references for steel fabrication and 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 fabrication and 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, such as "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 affecting change on the erection site, stating that "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 Section 4.6). 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 fabrication and erection processes for steel structures are complex activities that make 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 fabrication and erection.

CHAPTER 3

RESEARCH METHODOLOGY

The purpose of the models presented in this report is to portray the patterns of activities present in the fabrication and erection sequences of any steel building. It is very common in the construction industry to characterize every project as unique. However, the thrust of this research is to identify the similarities present in different projects. Specific sequences on how to erect a steel structure depends on the project under consideration, which entails the uniqueness referred to above. Nonetheless, different projects have similar sequences which the models try to convey. The three models were gradually modified to capture the decisions, sequences, and use of resources inherent in any project. In their final version, they provide guidance to understand the nature of the fabrication and erection processes.

3.1 Necessary Data

In general, any interaction between design, fabrication, erection and management was considered as a source of information relevant to the creation of the models. The information needed to fully analyze the fabrication and erection processes may be categorized into three major areas: the sequences of activities, the rate at which the activities are performed, and the overall utilization of the resources. This information was gathered through several means, which were related to the type of information needed.

First, the sequence in which activities occur is the essence of the problem this research tries to analyze. The steel erection process is a practical phenomenon that can only be fully understood by taking part in it. However, describing and understanding the sequences of its activities constitutes one of the essential aspects of closely simulating any process. Rates of productivity are equally important, but more elusive. A qualitative description of the parameters which may affect productivity is currently being accepted by some companies instead of the classical time-independent productivity analyses. Finally, the cranes and crews most widely utilized are needed to describe the erection process.

3.2 Data Collection

To begin to calculate the cost aspects of steel fabrication and erection, designs of a prototype structure with four variations were sent to selected steel fabrication and erection companies to determine the relative fabrication and erection costs. The prototype structure is a two-tier, four-story building, two bays wide and six bays long (as described in Chapter 5). This structure was designed by a graduate student at Lehigh University in the Department of Civil and Environmental Engineering, Alan Rosa, in conjunction with his research on the behavior of the ATLSS Connector as a semi-rigid composite connection (Rosa, Lu and Viscomi, 1993; Rosa, 1994). Several specific research projects are referenced in this prototype design, focusing on the development and full-scale tests of semi-rigid composite connections at the University of Minnesota (Leon, 1990; Leon et al., 1987; Leon, 1992a; Leon, 1992b; Laughlin, 1988; Forcier, 1991). The prototype structure variations sent to the companies were: 1) standard bolted connections, with seated connections on the frame members and simple double-angle connections for the bracing and infill beams; 2) semi-rigid composite connections based upon the University of Minnesota research; 3) ATLSS Connectors in conjunction with a composite deck to create a semi-rigid composite connection; and 4) ATLSS Connectors in conjunction with the use of the Stewart Platform, a semi-automated construction crane. Four companies responded with cost or time estimates. The detailed fabrication and erection cost estimates were within 10 percent of each other for all four variations. However, the range of costs for the composite system, ATLSS Connector, and ATLSS Connector with Stewart Platform compared to the standard connections varied more widely, with estimates ranging from adding 6 percent to costs, to saving over 20 percent.

To explore the rationale behind the variations, interviews with members of the companies that responded indicated that different assumptions were made for the estimates. For example, some companies included the cost of the material while others did not include total material costs. In addition, the companies needed additional information about the new connection types and their influence on the erection process.

To improve the comparability of the cost estimates, the plans for the prototype building for **only** the standard connections (not the semi-rigid composite, ATLSS Connectors, or ATLSS Connectors with Stewart Platform) were sent to a larger sample of fabrication and erection companies, who were then asked for the determinants of their estimates, such as the way in which they decide erection sequences and their productivity goals. Using these materials applied **for the standard connections only** for the prototype building, the estimates were recalculated. These time and cost estimates are included in Chapter 5. A list of productivity rates was included with the plans, and were revised. The productivity rates are listed in the spreadsheet model, and include idle time.

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. Valuable information related to the process of steel erection was collected, such as assigning different crews to different activities, having the erection stage always ahead of the permanent connections stage, 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.

The cyclic, sequential and parallel nature of the process became more apparent as the research progressed. Realizing the importance of a systems analysis approach which integrates design, fabrication and erection, the erection decisions and sequences were noted to depend on the fabrication criteria. At this moment, the need to create a fabrication model became critical. The fabrication model remains as a coarse model to be refined in future research, but it provides insight into foreseeing problems in the erection process. With a quite robust model, the next stage was to arrange for several site visits (Table 3.1). Specific data collected at each site is included in Appendix E.

TABLE 3.1: VISITED SITES AND LOCATION

SITE	LOCATION
MBNA	Wilmington, DE
Mutual of America Bank	Manhattan, NY
Chanel Store	Manhattan, NY
Church	Bethlehem, PA
Indoor Tennis Courts, Lehigh University	Bethlehem, PA
Addition to Sacred Heart Hospital	Allentown, PA
Watchtower Parking Garage	Brooklyn, NY
Store	Quakertown, PA
Home Depot	Whitehall, PA
Breathalizer Plant	Bethlehem, PA

3.3 Use of Data

The collected data was used in four different stages: 1) development of models; 2) modification of models; 3) estimation of productivity; and 4) testing of the models for validity and reliability.

3.3.1 Development of the Models

Two books that deal with the phases of structural steel erection (Oppenheimer, 1960; Rapp, 1968) were studied to gather the initial information needed to create the erection flow diagram. The sequences followed at the site today are essentially the same as those discussed in these references over 30 years ago. A preliminary model consisting of the stages such as unloading, shaking out, erecting, plumbing and connecting was developed in a flow diagram fashion. Several activities within each stage were developed at this time.

While the data was being collected, it was simultaneously being incorporated into the research. The data that was obtained from industry sources was invaluable in creating the models, and then in modifying them to incorporate the richness and variety in actual projects. The data also provided a basis to evaluate the validity and reliability of the resultant models.

3.3.2 Modification of the Models

The following section describes the way in which each site and the interviews helped to modify the models. The specific data collected at each site is included in Appendix E.

The MBNA building is currently under construction in Wilmington, Delaware. The structural system is composed of rigid frames and a composite deck. A system of transfer girders on the first floor made this project different from the others visited since the weight of each one of these girders impacts the sequencing of activities. Usually one ironworker receives a beam at each end and connects it to a column. For a transfer girder of approximately 650 pound per linear foot as several girders were in this project, two ironworkers must position themselves at each end. For this site, one tower crane was the main equipment resource utilized for the erection of structural steel components. Seven light header beams were connected in the first 23 minutes of the afternoon. This was a high productivity, but it must be noted that a bundle of three beams were raised in a single lift. This experience suggested that the spreadsheet should include the unit by which the production rate is specified. That is, erecting a single member may take the same time as erecting a bundle of three members.

The Mutual of America project was the rehabilitation of an existing multi-story building in Manhattan. Again the system was a series of rigid steel frames. A tower crane attached to the existing structure was critical in the proper sequencing of activities. Two fronts were contemplated: one dealt with the addition of new rigid frames, the other with the dismantling of the old structure on the roof. Being in downtown Manhattan, OSHA regulations were carefully complied with by the general contractor. Vertical and horizontal nets, wooden barricades, wires and railing were positioned in every area presenting potential danger. After visiting this site, it was decided to add an activity of installing safety devices during the decking stage. Welding and flame cutting were major activities, too, in this project. The models however do not reflect these types of activities since the models describe a project starting from its original concept.

The Chanel building was also located in Manhattan. This site presented major delays in the erection scheme. Two columns were set in two hours. The traffic continuously interrupted the unloading of the truck, and it was decided to unload and erect one column at a time. The traffic would be stopped, the truck would back up to position, and then the crane unloaded the column onto the sidewalk. The truck would move out of the traffic way while the column was properly hooked and plate components loosely connected to it. Finally, the crane would lift the column into position. This final step was probably the most complicated as the column had to be "threaded" through a series of horizontal triangular braces positioned at different elevations. The column was inserted in the upper most triangular brace, guided downward through about four other braces until it reached the ground. The braces were the end supports of a series of girders supporting the lateral pressures exerted by the walls of the two neighboring buildings. The erection model was modified after visiting this site, as it became apparent that the availability of a storage area was critical for some sites. In the model, this is presented as an external decision which must be confronted at the very beginning of the flow. Also the erection diagram was modified to allow for the possibility of erecting directly from the truck, skipping the unloading and shakeout stages.

The church project visited in Bethlehem, Pennsylvania had a more explicit architectural design than the MBNA and Chanel sites, seeking to satisfy aesthetics requirements rather than optimize commercial space. The joints where members met were complicated since the members met at skewed angles, forming different planes in space. The elegant but simple design of the connections shows the interaction between design, fabrication and erection. The project consisted of several structural systems: trusses, steel joists, and a series of simple frames composed of rolled shapes braced with double angle members. A small telescopic crane was utilized since the members were light and the structure consisted of one level. The lack of rectangularity and the combination of structural systems does not permit the full usage of the spreadsheet model which is based on counting structural members by the repetition units. However, the rows and columns in the spreadsheet may be ignored; and the total number of structural members could be entered by overwriting the cell formulas.

The indoor tennis courts project consisted of a series of gabled rigid frames. The site had ample space, storage area and accessibility. The project itself presented a totally repetitive topology. All columns were erected first, noting that the design structural system is not always the erection unit. An erector may choose to erect each frame, guy it, and proceed to the next frame. This is a flexibility which the erection model now modified permits since the cycles are repetitions based on the selected erection unit. A telescopic crane was also utilized for this project.

The Breathilizer plant project consisted of built-up frames having tubular square columns and joist girders to support a series of lighter joists perpendicular to the plane of the frame. The ends of one series of joists were seated on the surface of a masonry wall. Bundles of about five joists were lifted and unloaded on the girders. The idea of unloading, erecting or shaking out by bundles, was first observed at this site. Plumbing was done by column and not by bay. Usually for one-story buildings of this type, plumbing is not critical so there is no need to use turnbuckles and guy wires, as the model shows. In addition, after visiting this site, it was decided to combine lifting and maneuvering a member into the same activity.

The hospital, the parking garage and the two stores were similar projects which validated the observations noted on other projects. All of these four projects consisted of rigid frames of rolled sections, erected by bay after setting the columns. Note that the erection units are the columns during the first days, while the following days the erection units are the bays. In each case, there was a telescopic crane being used.

From the five in-depth interviews, it became apparent the need for two decision diamonds for checking the stability of the structure during erection. Both are located in the erection stage. The first one assures that at the end of the day all erection units must be checked for stability. The structure may collapse due to wind or earthquake loadings if left unstabilized. In addition the respondents emphasized the importance of three specific OSHA regulations. For example, shared bolts and slip bolts are dangerous for the ironworkers, especially if they are unexperienced. 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 spreadsheet model. Also in the scheduling of activities, it should be considered that the deck must be present at most two levels under the floor on which erection is going on. 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 productivity.

It is important to mention that the original spreadsheet was changed to make it a more flexible environment, allowing the users to change productivity estimates according to their own experience and expertise. The version of the spreadsheet in this report also provides greater flexibility in its application to different structural designs.

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 models at present show the current procedures in erecting structural steel, but the use of the ATLSS Connector, for instance, may induce changes in the flow. For example, it is very attractive to assemble a complete floor of 25 ft by 25 ft with four or six perimetral ATLSS Connectors, and then raise the assemblage into position. Bolting would occur on the floor, increasing the productivity. As a matter of fact, this solution was used once and will be used again by one of the companies aiding in the research conducted at Lehigh University. Erection of a steel structure using ATLSS Connectors is several locations of the structure is scheduled to start during November, 1994.

3.3.3 Estimation of productivity

From the interviews with industry members, it was concluded that the industry standard is approximately 60 structural members erected in one day by a type A crew (1 crane, 1 crane operator, 3 ironworkers). Type B crews (2 ironworkers) are estimated to connect 100 bolts per person per day. Similarly, Type D crews (2 ironworkers) can install the decking, welding 500 studs per person per day and laying 30 sheets per person per day. Although productivity obviously changes with different phases of the project, these productivity rates are very useful in estimating the duration of the project.

While visiting the sites, the measurements in Table 3.2 were recorded. These productivity rates include idle time. Most measurements show similar results to the industry standard estimates when converted to appropriate units. For example, the average of 7.0 min/member is equivalent to 69 members/day.

Having the industry standard productivity estimates and the site verification measurements, the spreadsheet standard productivity table was developed. To account for the parameters (described in Section 4.4), the concept of factoring the estimates was introduced. These factors may decrease productivity rates by about a factor of 2.00 as noted in the Chanel site. A maximum increase of 1.07 can be expected in projects with favorable parameters. The prototype building was assumed to be built under conditions providing a factor of 1.02.

Idle time in construction is hard to measure. Research has shown that as much as 20-30% of the time is spent in preparation for carrying out each activity (Tucker et al., 1990). In this report the idle time is embedded in the productivity rates.

TABLE 3.2: ON-SITE OBSERVATIONS OF PRODUCTIVITY RATES

No. of members	Member type	Activity	Time	Rate (min/member min/bolt)
7	header beam	erect	23 min	3.3
2	column	erect	2 hrs	60.0
200	member	erect	4 days	9.6
1	purlin	erect/perm. connect	10.1 min	10.1
273	member	erect	4 days	7.0
1	column	erect	4.7 min	4.7
1	column	erect	3.1 min	3.1
83	member	erect	2 days	10.1
1	filler beam	erect/perm. connect	8.3 min	8.3
4	bolts	perm. connect	8.2 min	2.1
4	bolts	perm. connect	5.1 min	1.3
4	bolts	perm. connect	7.4 min	1.9

Notes: Average rate for members (neglecting second row) is 7.0 min.
Average rate for bolts is 1.8 min.
Source in Appendix E.

3.3.4 Testing of the Models

The duration of the activities needed to erect the prototype building was approximated by using the models. Chapter 5 discusses this application in greater detail. As discussed in Section 3.3.2, each of the visited sites was compared to the models. The models were continually modified to guarantee that if each of the visited projects were to be run, the models would be able to capture the characteristics of each project. This shows the validity of the models. The topology of the indoor tennis court project was used in the spreadsheet model, and model performed well, demonstrating the flexibility of the model to adapt to real structures.

Moreover, sensitivity analyses on the prototype building were conducted to observe the reliability of the models. In a previous version of the current spreadsheet model, a full sensitivity analysis was 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 (Appendix H). The current spreadsheet 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% in the total duration of the project. This shows the importance of the bolting stage has, and preliminarily identifies the feasibility of using the ATLSS Connector.

As mentioned in Section 3.4.3 the productivity factor was tested to observe its sensitivity. It was noted that the factor responds as expected, having a range from decreasing productivity by a factor of 2.00 to increasing it to a maximum of 1.07. Future research on factor productivity will continue, as it is desired to change the current formulation to incorporate current research (Thomas and Sakarcan, 1994).

CHAPTER 4

DESCRIPTION OF PRELIMINARY SIMULATION MODELS

The fabrication and erection of steel structures is a complex process. Each member must be cut, shaped, and prepared through a number of stages, with concurrent work on the connection fittings, while always conforming to the performance criteria for the completed structure. Once the shop work is completed, the members must be shipped to the construction site, where another series of 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 resources on the site (for example, crane and crews). And finally, they must respond dynamically to different conditions on the site (for instance, bad weather or the misalignment of bolt holes).

Several techniques exist for planning the fabrication and erection stages, and for providing control mechanisms for activities in progress. These techniques include cost estimation, project scheduling, progress tracking, cost control accounts, as well as several other methods. The models in this section do not seek to replace those techniques but rather to add a new set of capabilities. These preliminary simulation models are the basis upon which the research can build an interactive simulation system that will allow designers, fabricators and erectors to model the stages for specific projects.

Because the sequence of activities follows a general pattern, the fabrication and erection may be approximated through a diagram that charts the flow of those activities. This flow diagram can also include specific points where decisions must be made. The usefulness of the flow diagram is that it reveals the repeated sets of activities by certain units (for example, unloading a truck by bundle) and also provides insight in where disruptions can occur, and how these disruptions can alter the flow of the activities. Two flow diagrams are included in this report. The first is a very simple diagram that captures only the major activities in the fabrication of elements (members and connection fittings) for a steel structure (this diagram will be refined in subsequent research). The more detailed flow diagram is for structural steel erection.

The second model is a spreadsheet-based model that provides time estimates for specific building designs, aggregated by the major activities identified in the flow diagram. Using the design details, this model can provide counts for each component of the structure (e.g. members, bolts, splice plates), and matches those component counts to productivity rates for each activity. The result is a total time and cost estimate for a specific structural steel erection project.

At the moment, the third model is assembled through manual computations, to match the flow diagram for each activity to the number of elements and related productivity rates. The product of these manual calculations is a daily flow of the project, including the number of pieces erected and bolted, as well as direct consideration of such elements at resource utilization and the stability of the frame during erection. It is hoped that eventually these manual computations can be replaced with a computer-based full simulation model. 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 (Chapter 3).

4.1 Fabrication Flow Diagram

Although the primary focus of this research was on the erection of steel structures, consideration of the fabrication processes is essential to incorporate the full set of conditions that constitute an erection project. The degree of preparation of the pieces, including the shop installation of connection fittings, sets the baseline conditions for what must be done on the site. The fabrication activities also affect other dimensions of the flow of the erection activities, such as the tolerance of the members, the correct details for erection and connection, and the schedule of delivery from the shop to the site.

The fabrication flow diagram presented in this report is a general approximation of these activities. The objective of this flow diagram was to capture the repetitive actions performed on each structural member or connection fitting. Disruption points were not explored in this flow diagram.

The general activities identified that occur during the fabrication stage are cutting, punching, drilling, welding, bending or straightening, lathing, assembling fittings to members or members to members, and preparing (Figure 4.1 or Appendix A). These activities are modeled as occurring in a linear sequence, to represent how a specific member would progress through a fabrication shop. For example, a specific member, such as a column, would be selected from the storage yard and brought into the shop. The first decision would be whether to cut the material, which would cycle through the cutting activity until all cuts are made. Likewise, the column could move through the other stages, being processed or manipulated as appropriate to meet the design and performance specifications. It must be noted materials for connection fittings could be processed through the same series of activities, though those activities may actually occur in real time parallel to the processing of the members.

The prepared members and connection fittings are assembled through a series of steps, including bolting and welding. The completed members (as far as fabrication activities are concerned) are then finished, using such methods as sandblasting, painting, erection marking, and loading. This flow diagram represents the series of activities which are acted upon a material as it passes through the fabrication shop. However, unlike the erection flow diagram, this fabrication flow diagram does not include many of the decision points that improve the explanatory power of the diagram. This diagram, and the relating metrics for fabrication activities, will be developed further in other research.

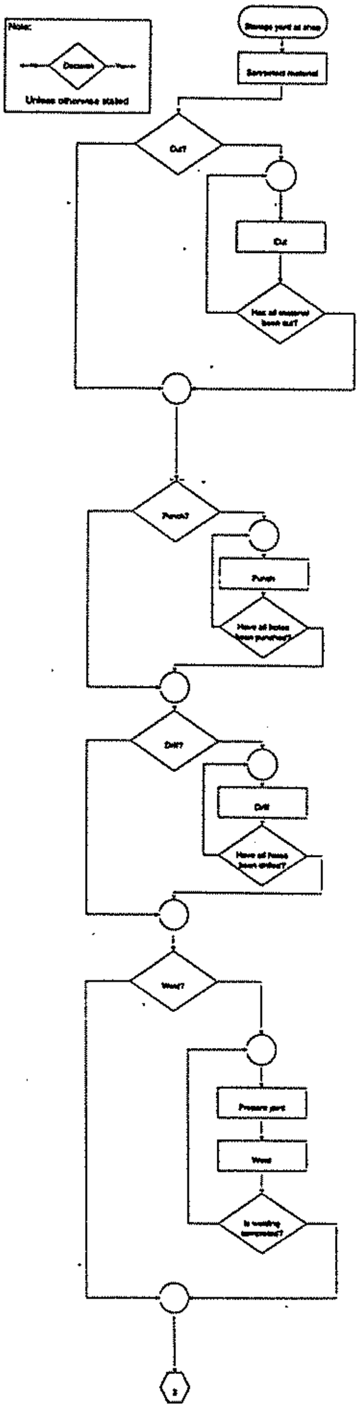

FIGURE 4.1: FABRICATION FLOW DIAGRAM

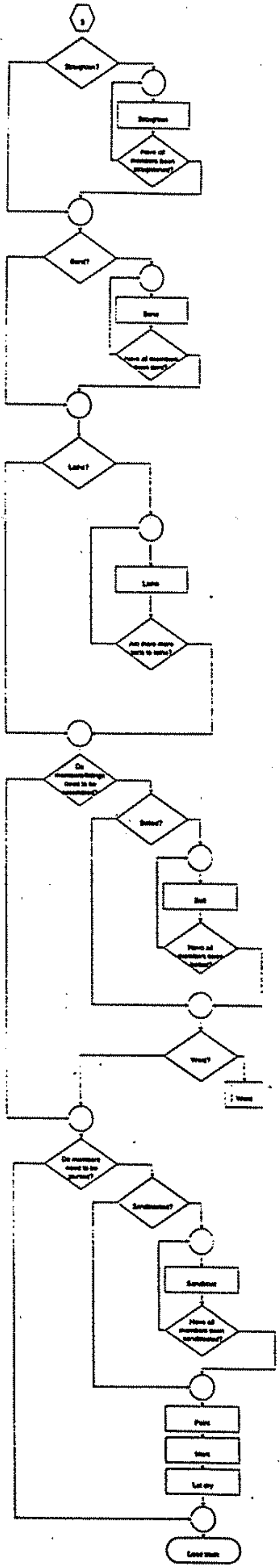

FIGURE 4.1: FABRICATION FLOW DIAGRAM

4.2 Erection Flow Diagram

The structure of the erection model is based on a specified erection unit. An erection unit is defined as the smallest assemblage of structural members by which the erection process will flow swiftly. 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 is thus the gable frame. Other structures similar to the prototype building presented in this report consist of a rigid frame of two spans and four 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 perimetral floor beams at one level and four other perimetral floor beams at a higher elevation. 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.

For a given erection unit, six stages have been identified: unloading, shaking out, erecting, plumbing, permanently connecting, and decking. The logical network of these stages has start-to-finish relationships and also contains stages occurring in parallel (Figure 4.2). These stages are characteristic of each erection unit, and will 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 unloaded in another part of the site.

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 identifiable movement in the erection process is represented in the flow diagram (Taylor, 1967). It is at this level of detail that the cyclic nature of steel construction becomes apparent. For example, in the erection stage, "hook-on hoist," "lift/maneuver," "connect" and "unhook" are start-to-finish activities that repeat member after member. This repetition requires the use of counters. If the erection sequence proceeds member by member, an internal counter in the model should keep track of the total number of members that have been erected and the total number of members that will be erected during the whole project. An alternative observed in several of the visited sites was hooking and lifting two or 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 two or three, respectively. As each activity has a specified standard productivity, defining the same problem with different counters will lead to different times.

The model has decision diamonds in each stage. These decisions can be based upon the structural design details (for example, the number of columns on the first tier), internal counting mechanisms that keep track of the sequence of activities, or based on estimates that an event will occur (for instance, the chance that a piece does not fit). 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

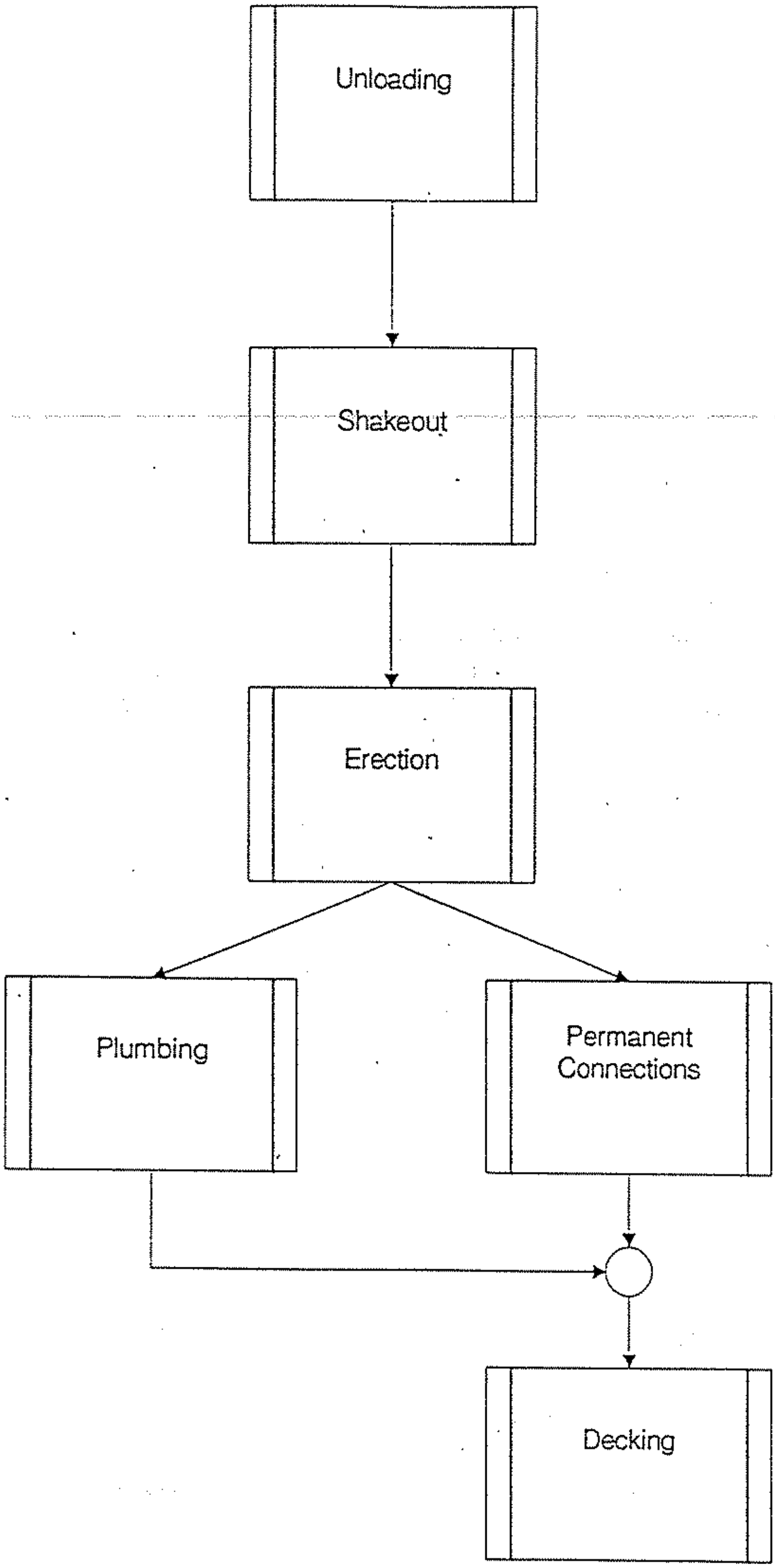

FIGURE 4.2: LOGICAL NETWORK OF STAGES

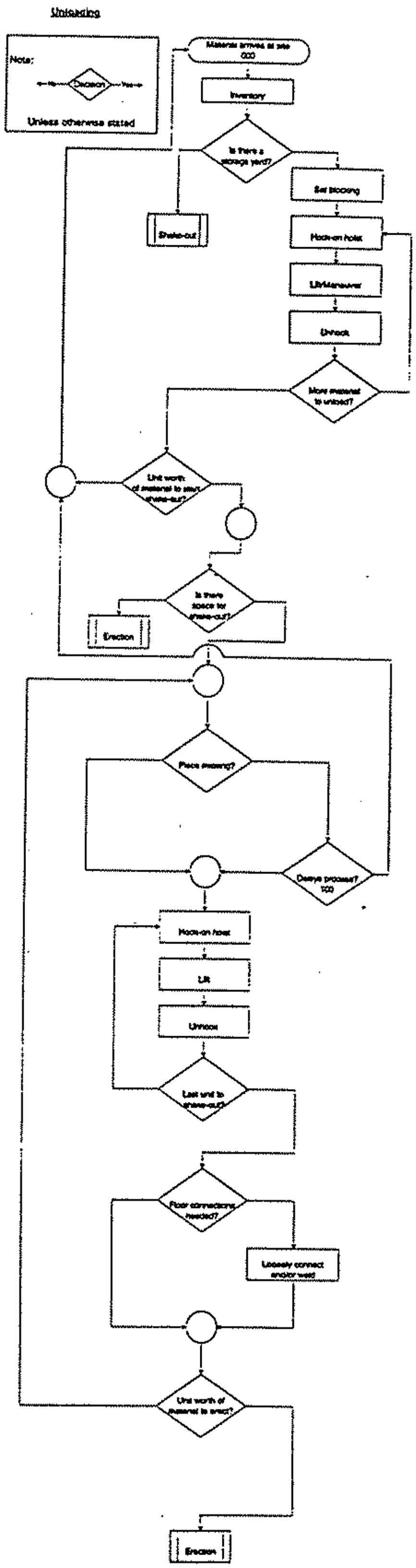

FIGURE 4.3: ERECTION FLOW DIAGRAM

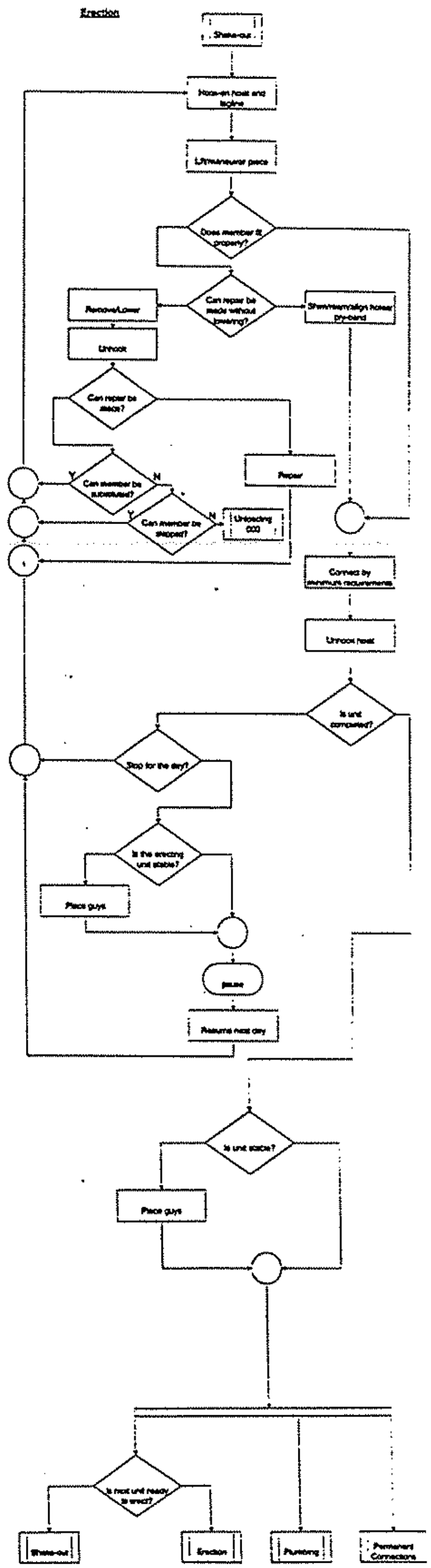

FIGURE 4.3: ERECTION FLOW DIAGRAM

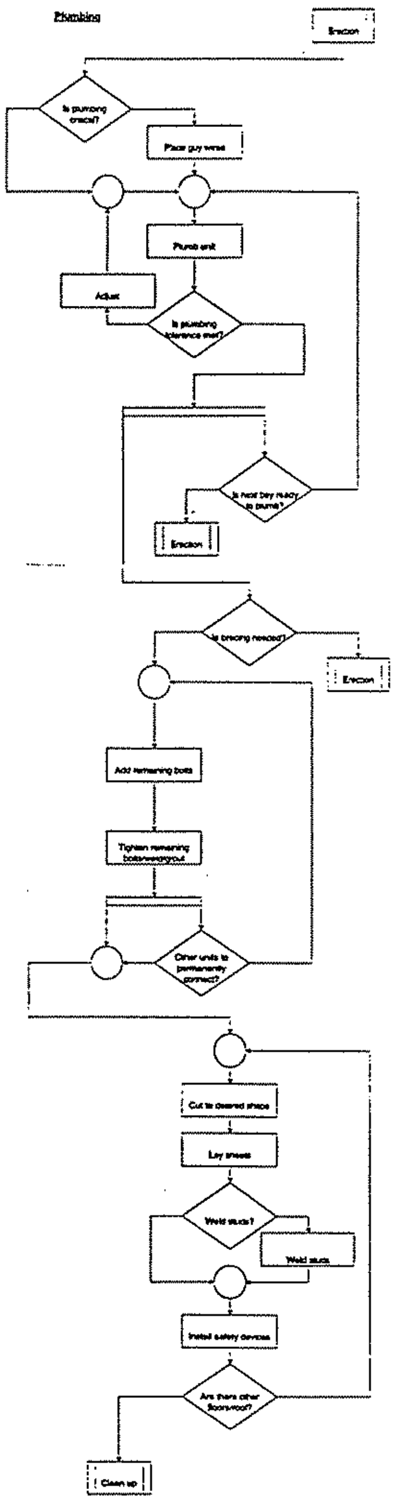

FIGURE 4.3: ERECTION FLOW DIAGRAM

checks appear in decision diamonds labeled as internal decisions. By internal it is meant that the decisions are made according to the specific project under consideration. That is, it depends on the erection unit and the number of members, bolts, welds, sheets, and studs of the given project.

The model also contains external diamonds. These are decisions made at the office prior to the erection, and most of the time depend on the site factors. For example, a site in a big city may not have space for storage, or shaking out. These decisions also depend on the selected process of erection and the scheduling of activities made at the office. Whether floor connections may be made to lift a whole panel of members, and whether plumbing is critical or not are external decisions.

Similarly, the model contains probability-based decisions. These depend on the random nature of erection and fabrication. For example, a piece may have not been delivered, the holes of a gusset plate may not align with the holes of the connecting member or repairs may or may not be made at the site. These decisions are taken as the erection unfolds, but could be predicted if enough data is collected to include a probabilistic distribution in the model.

The erection model is thus infinitely adaptable. Any project could be described by its erection unit and specified with certain counters. The model shows the unavoidable patterns reflected in any construction 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 spreadsheet-based model has been developed.

In the future, it may be possible to program this flow with a resource-based scheduling algorithm. In related research, a liaison between the Department of Civil and Environmental Engineering and the Department of Industrial Engineering at Lehigh University has approached the construction problem as a manufacturing problem. A logic network of the construction activities needed to erect the prototype building was developed from this research and used as a sample to test the algorithm developed by the Department of Industrial Engineering (Storer and Wu, 1993). This program considers an efficient allocation of resources, and finds the critical path of the network. The results of the scheduling algorithm for four cases are shown in Table 4.1. Each case is defined by its resources. The project being scheduled is the same for all four cases. When programmed, the erection model should have the internal and external decisions identified for the particular project under consideration. The output would be 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 is not changed dramatically when the number of workers is increased from 6 members of a crew to 8 crew members. On the other hand, the duration is reduced by two days when an additional crane is added; however, the crane utilization drops by approximately 50 percent, even when the number of workers is increased. 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 significantly alter the flow of the construction process or require different sets of resources show great promise in increasing the efficiency of resource allocation and project scheduling.

TABLE 4.1: RESULTS FROM INDUSTRIAL ENGINEERING SCHEDULING ALGORITHM

Case	A	B	C	D
Cranes	2	1	1	2
Ironworkers	6	8	6	8
Minutes	5134	4223	5177	4222
Days	10.7	8.8	10.8	8.8
Crane utilization	23%	55%	45%	28%
Crew Utilization	78%	71%	77%	71%

4.3 Spreadsheet

As mentioned above, the spreadsheet was developed to complement the erection model by keeping track of the projects' counts, resources, and resulting time estimates. 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 three ironworkers are needed for the erection stage (as stated by crew A). However, for the plumbing and bolting, two or three crews of type B may be needed. An initial estimate of two crews may turn to be insufficient to meet a pre-established deadline. Hence on a second run of the spreadsheet, three crews must be specified and hopefully the deadline will be met.

The spreadsheet is 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 productivity rates of steel erection, and computes actual productivity estimates for the project under consideration. The next section displays the total time estimates for each of the six stages. Finally, a summary which groups the six stages into four major phases is presented as the final results.

4.3.1 Design Characteristics

For the data entry of the first section (Table 4.2), it is assumed that a preliminary layout of the design is available. Having the layout which contains the structural quantities permits the transferring of these quantities into the spreadsheet. The more repetitive the structural system, the better it will adapt to the spreadsheet. This is evident, as the spreadsheet charts were developed such that if a repeating unit is identified, just one unit is entered along with the number of times it repeats. This may be a general sketch or a detailed blue print which shows all structural quantities. That is, the design must be completed to be able to evaluate its effectiveness.

Alternate designs with different structural systems and thus different structural quantities are highly desirable to make a comparison, and finally choose the most convenient with respect to time and cost. The next phase of this research will show the benefits of different designs or technology alternatives at this point to evaluate their economic efficiency.

TABLE 4.2: DESIGN SPECIFICATIONS

Member	Unit	Unit quant	members/	total No. o	input No. (*)
Columns	tier	2	21	42	42
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
				266	Total

4.3.2 Resources

From the site visits, interviews, and pertinent literature, it was observed that an average of sixty members can be erected by a type A crew in one day (Table 4.3). Also, about one hundred bolts can be connected per person per day, as indicated by crew B. A total of four crews have been listed in this section. Crew C consists of one welder, and crew D is made up of two ironworkers for the decking.

TABLE 4.3: RESOURCES

Crew A	2 Ironworkers, 1 Helper, 1 Crane operator
Crew B	2 Ironworkers
Crew C	1 Ironworkers
Crew D	2 Ironworkers

The size of an erection gang varies in the industry from 6 to twelve ironworkers. For the purposes of this research, the total number of workers was set at eleven, divided among the crews as follows (Table 4.4). It is possible to reassign members of a crew to another crew 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. To accomplish this reassignment, however, the total number of available ironworkers must be maintained, and the stages by day by assignment must be calculated separately.

TABLE 4.4: NUMBER OF CREWS AND IRONWORKERS FOR PROTOTYPE BUILDING

CREW TYPE	TASK	NUMBER OF CREWS	NUMBER OF IRONWORKERS
Supervisor		1	1
Crew A	Erection	1	3
Crew B	Bolt/Plumb	2	4
Crew C	Weld	1	1
subtotal			9 ironworkers
Crew D*	Deck	1	2
Total		5	11 ironworkers*

*Crew D can be composed of additional workers, or those reassigned from Crews A, B, or C.

4.3.3 Productivity Rates

The production rates were calculated from on-site observations, corrected by the observed resources (e.g. number of members in a crew). The unloading stage was assumed to occur by bundle, taking 4 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 occurred by bundle, but the bundles are assumed to be smaller, and do not require the setting of blocking, thereby taking only 1 minute per bundle. Any floor connections take additional time, with 1/4 of a minute to install a bolt, and 1 minute to tighten it to specifications.

For each specific task, production rates were estimated by individual bundle, member, or bolt (Table 4.5). These production rates are also tied to the composition of the specific crews. The objective of arranging this table by individual element was to allow specific calculations that reflect the design and connection specifications. The aggregated cost estimation techniques used in industry are extremely effective for known techniques and methods; for unfamiliar or new techniques, however, the aggregate estimation techniques rely heavily upon general assumptions, such as an overall increase or decrease in production rates for the building as a whole. By breaking down the times to individual units, assumptions can be tested and validated in a more systematic way.

TABLE 4.5: PRODUCTION RATES

	Output			Input	
	Unit	Unit Quan	(min/unit)	Crew	Number o
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	bundle	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	1.00	A	1
PLUMB					
Bay	bay	1	20.00	B	1
Column	column	1	5.00	B	1
PERMCON					
Install bolt on flo	bolt	1	0.25	B	1
Tighten bolt on fl	bolt	1	1.00	B	1
Install bolt at hei	bolt	1	0.50	B	1
Tighten bolt at he	bolt	1	2.00	B	1
Install anchor bol	bolt	1	0.50	B	1
Tighten anchor b	bolt	1	2.00	B	1
weld	inch	1	1.50	C	1
DECK					
stud	stud	1	0.25	D	1
deck sheets	sheet	1	4.00	D	1

Within this section of the spreadsheet, there is a list of site parameters that may affect the productivity (Table 4.6). Site conditions, project characteristics, resources, and their effect at the site may also affect the standard productivity. Four parameters chosen to describe the site conditions are accessibility to the site, easiness of handling material at the site, size of the site, and presence of an existing structure that may affect the erection process. A site in the middle of a congested city may cause delays since unloading of the material may be interrupted, for example, by traffic. Conversely, a site on an isolated field is easily accessed and permits the normal unfolding of the erection sequences. Adequate materials handling is achieved if a proper storage area is present at the site. A lack of a storage area, generally causes mismanagement of the inventory of each delivery (Thomas, Sanvido and Sanders, 1989). The size of a site may affect the productivity if it is too small, since ironworkers may get in each other's way. An ample site, however, permits the normal flow of activities. Existing structures at the site under erection are always an obstacle which affects the productivity. Starting a project from its original erection is always preferred to rehabilitating an existing structure. As far as project characteristics, the topology may induce changes in productivity. Some structural systems are inherently harder to erect than others. Erecting a transfer girder, for example, demands more care than erecting a header beam. Trusses and other systems of longer span require more precision than I-beam reticular frames. Connections may be standard and highly repetitive, making the productivity increase as the project progresses. Member weight is another factor that affects the ease with which a structure is erected. Moreover, the higher a structure, the more time is lost in delivering materials (e.g. bolts and tools) from the ground to the erection floor. Only two factors have been considered in the evaluation of resources: the experience of the crew, which provides higher rates of productivity with higher level of expertise; and the level or capability of equipment. The same project could be erected using a derrick or a tower crane.

TABLE 4.6: PRODUCTIVITY FACTORS

Parameter	Factor
Site conditions	
accessibility	5
easiness of materials handli	5
size of site	4
none-presence of existing st	5
Project characteristics	
regularity of topology	5
standardization of connectio	5
low weight of members	4
height of finished structure	4
Resources	
experience of ironworkers	0
level of technology of equip	0
Effect	
simplicity of erection seque	5
none-proneness to delays	5
expected organization	5
possibility to reassign resou	5
availability of resources	5

The site conditions, the project characteristics, and the resources combine during erection to create a specific atmosphere described by the effect factors. These are expected delays, organization, reassignment of resources, availability of resources, a crowded site, and pattern or sequence of erection. Rankings from -5 to +5, with zero denoting normal conditions, are assigned to each parameter. For example, while the prototype building is assumed to be erected at a site with ample space, so the parameter materials handling has been assigned a factor of +5, the Chanel project visited in midtown Manhattan had many problems due to availability of space. A factor of -5 would be assigned for such conditions. After assigning the factors, a normalized factor is computed by dividing the factor percentages of the actual project by the factor percentage of the previously defined normal condition. The respective percentage factors are computed by dividing the average factor by ten, which is the range from -5 to +5. The resulting normalized factor is finally used to modify the standard productivity rates. The factors were calibrated by running two worst scenarios. The Chanel site denotes the worst conditions for a productivity decrease by a factor 2.00, whereas the tennis court site denotes the best conditions for a productivity increase of 1.07. This means that the average factor cannot be less than 0.3. After these computations, the actual productivity is displayed (Table 4.7).

4.3.4 Total Time Estimates

The third section displays the time estimates computed by multiplying the actual productivities by the structural quantities (Table 4.8). Four different charts group the time estimates by member, connection, plumbing and decking. The first two charts include unloading, shaking out, erection and permanent connections (bolting up). Plumbing and decking are included in the third and fourth charts. During the unloading and shake out stages, only the members 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 and welding every connection as needed.

4.3.5 Results

Finally, the fourth section groups the total times into four categories: unloading, shakeout/erection, plumbing/bolting and decking (Table 4.9). In addition, the last section presents the crane utilization time, number of workers, resource cost, members per day erected, and number of bolts per day connected.

The data put into the spreadsheet constitutes the structural quantities, the rankings for each parameter, the unit quantity of each stage, and the number of crews. The output as discussed above is a summary with the time estimates for four categories which include the six stages and the cost.

TABLE 4.7: ADJUSTED PRODUCTION RATES

	Output			Input	
	Unit	Unit Quan	(min/unit)	Crew	Number o
UNLOAD					
Beam	bundle	4	1.02	A	1
Joist/Purlin	bundle	1	4.09	A	1
Column	bundle	2	2.04	A	1
Truss section	bundle	1	4.09	A	1
Diagonal brace	bundle	1	4.09	A	1
SHAKEOUT					
Beam	bundle	4	0.26	A	1
Joist/Purlin	bundle	1	1.02	A	1
Column	bundle	2	0.51	A	1
Truss section	bundle	1	1.02	A	1
Diagonal brace	bundle	1	1.02	A	1
ERECT					
Beam	member	1	6.13	A	1
Joist/Purlin	member	1	6.13	A	1
Column	member	1	6.13	A	1
Truss	member	1	6.13	A	1
Diagonal brace	member	1	6.13	A	1
Install bolt	bolt	1	1.02	A	1
PLUMB					
Bay	bay	2	5.11	B	2
Column	column	1	2.55	B	2
PERMCON					
Install bolt on flo	bolt	1	0.13	B	2
Tighten bolt on fl	bolt	1	0.51	B	2
Install bolt at hei	bolt	1	0.26	B	2
Tighten bolt at he	bolt	1	1.02	B	2
Install anchor bol	bolt	1	0.26	B	2
Tighten anchor b	bolt	1	1.02	B	2
weld	inch	1	1.53	C	1
DECK					
stud	stud	1	0.26	D	1
deck sheets	sheet	1	4.09	D	1

TABLE 4.8: ESTIMATED TOTAL TIME FOR EACH STAGE

Members	quantity		UN	SH	ER	
Columns	42	42	85.8	21.5	257.4	
Girders/su	56	56	57.2	14.3	343.2	
Bracing b	48	48	49.0	12.3	294.2	
Filler bea	120	120	122.6	30.6	735.5	
Diagonal	1	0	0.0	0.0	0.0	
Steel joist	1	0	0.0	0.0	0.0	
Purlins	1	0	0.0	0.0	0.0	
Truss part	1	0	0.0	0.0	0.0	
			314.6	78.7	1630.4	Total min
			5.2	1.3	27.2	Total hrs
			0.7	0.2	3.4	Total days

Connectio	quantity		ER ins	PC ins	PC tight	
	ER ins	PC ins				
Anchor bo	126	0	32.2	0.0	128.7	
Column s	126	126	32.2	32.2	257.4	
Beam/gird to co	224	1120	57.2	286.0	1372.9	
Beam/gird to co						
Shared	240	240	61.3	61.3	490.3	
Unshar	48	96	12.3	24.5	147.1	
Beam/gird to B						
Shared	320	320	81.7	81.7	653.8	
Unshar	64	128	16.3	32.7	196.1	
Diagonal			0.0	0.0	0.0	
			293.2	518.4	3246.4	Total min
			4.9	8.6	54.1	Total hrs
			0.6	1.1	6.8	Total days

Plumbing	quantity		PL	
Bay	24	24	122.6	
Column	0	0	0.0	
			122.6	Total min
			2.0	Total hrs
			0.3	Total days

Decking	quantity		DE	
Studs	3200	3200	817.2	
Sheets	384	384	1569.1	
			2386.3	Total min
			39.8	Total hrs
			5.0	Total days

TABLE 4.9: TOTAL TIMES FOR EACH CATEGORY AND ENTIRE PROJECT

Time Estimates

Stage	Time	
UN	0.66	days
SH/ER	4.17	days
PL/PC	8.10	days
DE	4.97	days
Considering o	10.00	days

Resources

Crane Utilization:	5	days
Number of cranes:	1	cranes
Number of workers plus supervi	10	workers

Cost

	Rates	
supervisor	45	$/hr
ironworker	35	$/hr
helper	25	$/hr
crane	800	$/day
Project Direct Cost:	$32,000	

Productivity

Members:	53	per day
Bolts :	98	per perso

4.4 Merging Spreadsheet Results with Erection Flow Diagram

In order to make real use of the models, it is required to carry out certain manual computations which provide the dynamic aspect that the flow diagrams convey. Although very versatile in the numerical variations that the user may impose, the sole use of the spreadsheet renders static results. In other words, the spreadsheet lacks the ability to overlap activities, whereas the flow chart is conceptually dynamic. By performing the manual computations, the sequences followed at a site can be approximated in a more precise way. Only then, the project under consideration can be said to have been simulated. These manual computations have the purpose of exploring what type of programming will be required to fully simulate the erection process. It has been noted that the most appropriate direction to follow is to use object-oriented programming.

The collaboration with the Industrial Engineering Department at Lehigh University to combine the simulated steel erection with resource-based scheduling 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 process. For example, OSHA regulation may be included here, or the need to assure that an erection unit is stable at all times, or a limit on the maximum number of bays that could be plumbed together.

The general assumptions in the manual computations are an eight-hour workday, a linear relation between time and productivity, availability of material at all times, and parallel scheduling within resource and technical constraints. Appendix D has some examples of the detailed computations. Chapter 5 presents the scheduling of the first three days in the erection of the prototype building.

4.5 Summary

In summary, Chapter 4 presents three models that approach fabrication and erection from different directions. The flow diagrams are conceptually dynamic and infinitely adaptable to any project. However, this model lacks a definite output and at present is not intended to keep track of structural counts. The spreadsheet is accurate for specifically counting structural components, and estimating times for the different stages. The disadvantage of the spreadsheet is that it is static (it cannot overlap activities). The manual calculations which are preliminary calculations for the computer-based simulation enhances the erection flow diagram with the attributes of the spreadsheet.

CHAPTER 5

APPLICATION OF THE MODELS TO A PROTOTYPE STRUCTURE

The preliminary simulation models are applied to a prototype structure to accomplish two objectives. The first is to demonstrate the use of the models in an actual project. This example application provides a detailed examination of how the design details of a building are translated into the flow diagrams, the spreadsheet-based model, and the manual calculations. The second objective of this example application is to provide a common baseline upon which comparisons can be made on the effectiveness of new technologies. This second objective will be pursued in greater detail during the next phase of the research.

The prototype structure is a two-tier, four-story building, two bays wide and six bays long. This structure was designed in conjunction with research conducted on the ATLSS Connector (Rosa, Lu and Viscomi, 1993; Rosa, 1994). The structure uses standard rolled sections, with bolted connections, with seated connections on the frame members and simple double-angle connections for the infill beams. The plan of the building is rectilinear and repetitive (Figure 5.1), making the structure extremely straightforward to fabricate and erect.

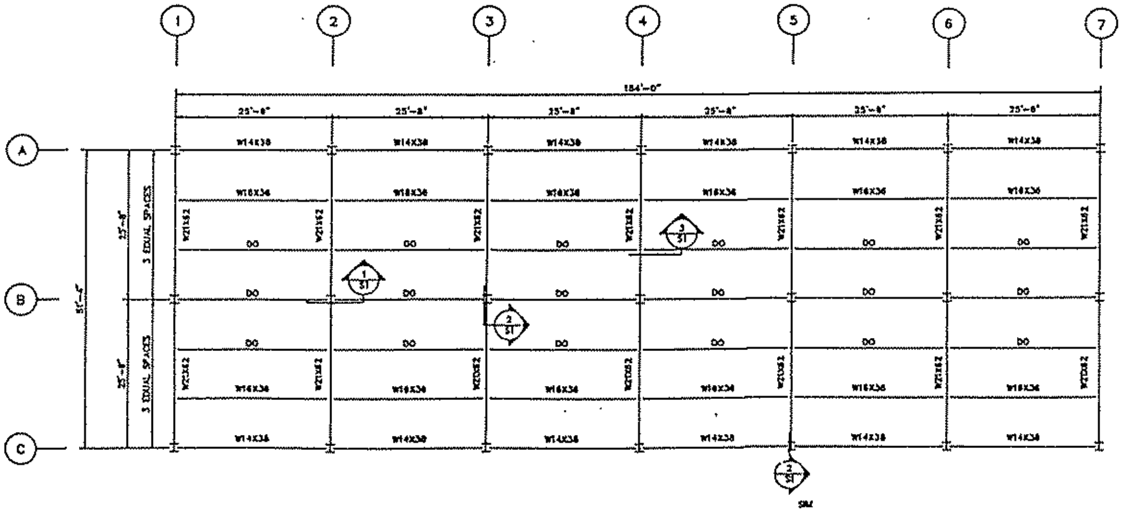

FIGURE 5.1 PLAN OF THE PROTOTYPE BUILDING

5.1 Fabrication Flow Diagram

The fabrication flow diagram is briefly applied in this example application, focusing primarily on the preparation of the members for erection, and the installation of certain connections in the shop (Appendix A).

For the prototype building, standard activities (cutting, punching, and drilling) must be performed on the members. Because the prototype building is fairly simple, consisting of rectilinear and regular bays, no special members must be fabricated. A few preparations are needed, such as coping the in-fill beams for the bays.

For the purposes of the erection simulation, certain connections were assumed to be installed in the shop. First, for the seated connections (Figure 5.2), the top flange angle and the two shear angles are assumed to be assembled on the beam in the shop. Specifically, the all bolts are installed and fully torqued. Second, the lower flange angle should be attached (bolts installed and torqued) to the column. These lower flange angles can also provide a "seat" for the beam during erection. Third, both splice plates are connected to the top of each column in the shop, with the bolts installed but not torqued (to provide clearance during erection). Fourth, the base plates for each first tier columns should be welded in the shop. Finally, the simple connections are also assumed to be bolted to the beam prior to erection, with the bolts installed and hand-tightened. (These bolts will need to be tightened further after erection.)

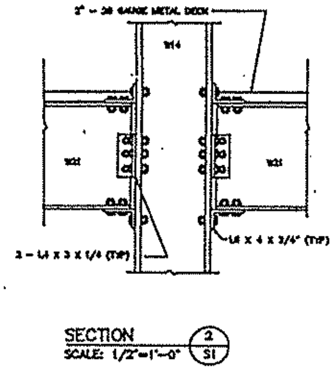

FIGURE 5.2: DETAIL OF SEATED CONNECTION FOR PROTOTYPE BUILDING

These connections are assumed to be made in the fabrication shop, as represented in the spreadsheet (Table 5.1, 5th column). They can also occur on the ground before lift, depending upon the preferences of the fabricator and erector. In that case, these connections would be made during the shakeout stage of erection.

5.2 Erection Flow Diagram

The prototype building uses 266 members, assembled in 12 bays per tier (with each tier having 2 floors). Using the maximum allowable weight for a load of steel on a standard truck (with no special permits), the members would be delivered in 9 trucks. (Appendix B shows the erection flow diagram.)

The first stage of the flow diagram, unloading, would occur with the arrival of the first truck. Since the prototype building is assumed to have space for a storage yard, unloading is not a critical stage. The members are lifted by bundle off the truck until all the members are unloaded. It is assumed that three trucks arrive on each of the first two days. On the fourth day the last three trucks would arrive.

Shakeout, the second stage, occurs right after the first truck is unloaded on the first day and each member on that truck is placed in position (though it may not follow so directly with subsequent trucks). The objective of this immediate shakeout is to progress through the erection process expeditiously on the first day. Since the crane is the limiting factor for unloading, shaking out and erecting, the crane must be utilized effectively to keep the activities progressing. For the prototype building, it is assumed that space is available for shakeout. It is also assumed that no pieces were previously substituted or skipped throughout this project. As noted previously, all connections made before erection are assumed to occur in the fabrication shop, though they could be accommodated in the shakeout stage prior to erection.

The erection stage occurs by member. For the prototype building, the members can be easily interchanged since they are identical. This condition may not hold for other projects, however. The erection is assumed to proceed by bay, with the columns erected first, followed by the perimeter beams for the first floor, then the infill beams for the first floor, with the sequence repeated for the second floor. After all members of the bay are erected, the members of the adjacent bay are then erected. A bay is considered to be stable when all of the members of the bay are erected. If the bay is not stable, and erection ceases for the day, the bay must be stabilized by placing guy wires. (These guy wires, though technically different from the plumbing guys, may on many construction sites be the same equipment.) The erection stage repeats by bay until all members that were unloaded and shaken out on that day are erected or until the end of the workday (approximately 8 hours, though overtime is possible), whichever comes first.

The plumbing and permanent connection stages can occur concurrently with each other, as well in parallel with the erection of subsequent bays. The plumbing is considered to be critical for the prototype building since it is more than 1 story tall. The prototype building can be plumbed either by each bay individually, across the 2 bays' depth of the building, or along the length of the building in sets of up to 4 bays. During the permanent connections stage, the additional bolts for each connection are installed and all of the bolts (shop, erection, and permanently installed) are tightened, either fully torqued or otherwise tightened to meet specifications. The prototype building requires no extra bracing, and the base plates for the columns do not need to be grouted since it was assumed that levelling plates were in place before erection. No other welded or grouted connections are needed for the prototype building.

The decking stage for the prototype building consists of corrugated steel sheets with shear studs along the beam lines. The topping concrete slab for the floor is not included in this erection flow. The safety devices installed on each floor include perimeter wires and welded holders for the wires on each column. The floors must be installed so that erection is never more than two stories above the installed decking.

The closeout stage is to ensure compliance with local building codes and the erection contract. The subsequent construction activities, include fireproofing of the structural steel, concrete floor slabs, and exterior enclosure, are not included in this flow diagram.

5.3 Erection Spreadsheet-Based Program

The spreadsheet-based program for the erection phase takes the design specifics for the prototype building, and matched with the expected productivity factors, calculates the total time and cost for the erection of the prototype structure by stage.

5.3.1 Design Characteristics

As mentioned previously, the prototype building is a two-tier structure, with two floors in each tier. The building has 12 bays (2 deep and 6 wide) on each floor. The translation of the general design into the calculation of the specific number of members in each category takes advantage of the unit of repetition in the design. For instance, the two bays across the building are identical to each other as well as to every other bay in the building. In addition, the second tier is identical to the first tier (Table 5.1). Other designs may have other units of design repetition.

TABLE 5.1: DESIGN SPECIFICATIONS AND NUMBER OF MEMBERS FOR PROTOTYPE BUILDING

Member	Unit	Unit quant	members/	total No. o	Input No. (*)
Columns	tier	2	21	42	42
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
				266	Total

Likewise, the specific connections can be detailed by the type of connections, with the number of bolts (installed in the shop, on the floor, or during erection) specified (Table 5.2). In the prototype building, the beams in the frames have seated connections, while the bracing and infill beams have simple connections. Installing the anchor bolts for the prototype building is assumed not to take place during erection since it is common practice to have them in position before the columns are erected. The prototype building, as detailed, includes a significant number of shared web connections for the beams. Even though these shared connections reduce the total number of bolts required, the Institute of the Ironworking Industry suggests several alternative designs to reduce the danger of shared-bolt beams becoming disconnected during erection (see Appendix G for the suggested connections).

TABLE 5.2: TYPES OF CONNECTIONS AND NUMBER OF BOLTS IN PROTOTYPE BUILDING

Bolts per connection

Connection	Unit	Unit quant	total bolts/	shop bolts	field bolts
Anchor bolts	column	21	6	0	6
Column splice	column	21	24	12	12
Beam/girder/truss/joist to colum	girder	56	42	18	24
Beam/girder/truss/joist to colum					
Shared bolts	beam-colu	60	12	4	8
Unshared bolts	column-be	24	8	2	6
Beam/girder/truss/joist to Beam/girder/truss/joist					
Shared bolts	filler-girde	80	12	4	8
Unshared bolts	girder-fille	32	8	2	6
Diagonal brace to beam/column					0

Total bolts

Connection	ER ins (*)	PC ins (**)	total No. of	total No. of	total No. of
Anchor bolts	126	0	126	0	126
Column splice	126	126	504	252	252
Beam/girder/truss/joist to colum	224	1120	2352	1008	1344
Beam/girder/truss/joist to colum					
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	5110	1932	3178

*—Two bolts at each end (OSHA regulation), 50% of spli

**—Remaining bolts

***-installed and tightened

In all, the prototype building has 42 columns, 56 supporting beams (with seated connections), 48 bracing beams (with simple connections), 120 filler beams (with simple connections), 384 deck sheets, 5110 bolts (including 126 anchor bolts, of which 1932 are installed in the shop and 1932 at the site), and 3200 shear studs.

These calculations are used throughout the rest of the program to estimate total time and cost for each stage. If the design is not easily reduced to a repetitive element (such as frame), the number of members in each category can be directly entered, as can the number of bolts for each type of connection.

5.3.2 Resources

The available resources can be set in Table 5.3. For the prototype building, three crew types are established. The first (Crew A) performs tasks in unloading, shakeout and erection. These tasks are based around the utilization of a crane, and so are usefully grouped together. For the prototype building, it is assumed that three ironworkers will work with the crane operator (and crane) for those tasks. In addition, four ironworkers perform the stages of plumbing and permanent connection (Crew B), and 2 ironworkers install the decking and weld the studs (Crew D).

TABLE 5.3: RESOURCES FOR THE PROTOTYPE BUILDING

CREWS	STAGE	RESOURCES	
A	UN/SH/ER	2	Ironworkers
		1	helper
		1	crane and operator
B	PL/PC	2	Ironworkers
C	PC(weld)	1	Ironworkers
D	DE	2	Ironworkers

While the composition of each crew can be easily altered, the production rates (Table 5.5) are based upon the established crew composition as described for the prototype building (Table 5.3). These production rates were estimated by observation on several construction sites, with corrections for the number of members in the crew (see Chapter 3).

For the prototype building, the size of the erection gang was eight ironworkers, divided among the crews as follows (Table 5.4). It is possible to reassign members of a crew (for instance, Crew A) to another crew (e.g. Crew B) if the maintenance of a schedule requires it.

TABLE 5.4: NUMBER OF CREWS AND IRONWORKERS FOR PROTOTYPE BUILDING

CREW TYPE	NUMBER OF CREWS	NUMBER OF IRONWORKERS
Supervisor	1	1
Crew A	1	3
Crew B	2	4
Crew C	0	0
subtotal		8 ironworkers
Crew D*	1	2
Total	5	10 ironworkers*

*Crew D can be composed of additional workers, or those reassigned from Crews A, B, or C.

5.3.3 Productivity Rates

For each specific task, production rates were estimated by individual bundle, member, or bolt (Table 5.5). These production rates are also tied to the composition of the specific crews.

The erection of the members includes all of the activities in the flow diagram. The estimated time of 6 minutes per member is the complete cycle time for one member, that is, from the initial hooking of the hoist on the member to the hooking of the hoist onto the next member. Additional preparations or maneuvering of the pieces would have to be accounted for separately. Installing each bolt during erection is calculated to take one minute.

Plumbing the unit can take up to 20 minutes for an assembled structure (e.g. a bay) and 5 minutes for a single member (e.g. column). The plumbing stage also incorporates all of the activities in the flow diagram, from placing the guy wires to meeting the plumbing tolerances through adjustments. Several erection units may be plumbed at the same time depending upon the geometry of the structure, the rigidity of the frame, and the requirements.

Permanent connection of the structure includes installing the additional bolts for each connections (at 1/2 a minute per bolt) and tightening the bolts (2 minutes per bolt). Any welded connections take 1 1/2 minutes per inch. The production rates also include the options for installing and tightening the bolts before erection on the floor, and for installing and tightening the anchor bolts. (The tightening of the anchor bolts does not include any placing of grout for the prototype structure, since levelling plates were assumed to be in place before erection of the first tier columns.)

Finally, the installation of the deck (including cutting to fit and laying the sheets) is calculated to take 4 minutes per sheet, and the welding of each shear studs takes 1/4 minute.

While in theory every building should use comparable production rates, in reality the rate at which the work proceeds depends on many different factors. Certainly factors beyond the control of project managers, such as weather, war or material shortages, can disrupt activities and make any time and cost estimate worthless. Other factors may, however, be more apparent during the planning stages and in force during erection, and therefore can be usefully incorporated into the design and estimation stages.

TABLE 5.5: PRODUCTION RATES FOR PROTOTYPE BUILDING

	Output			Input (cr	
	Unit	Unit Quanti	(min/unit)	Crew	Number of
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	bundle	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	1.00	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 floo	bolt	1	1.00	B	1
Install bolt at heigh	bolt	1	0.50	B	1
Tighten bolt at heig	bolt	1	2.00	B	1
Install anchor bolt	bolt	1	0.50	B	1
Tighten anchor bolt	bolt	1	2.00	B	1
weld	inch	1	1.50	C	1
DECK					
stud	stud	1	0.25	D	1
deck sheets	sheet	1	4.00	D	1

These factors are generally grouped under site conditions, project characteristics, resources, and effects (Table 5.6). For the prototype building, the project was assumed to occur under almost ideal conditions, in an unpopulated region with good access to major transportation modes and an unlimited number of highly skilled craftsmen. In particular, the site was assumed to have easy access around all sides of the building under construction (5), to be easy for deliveries (5), to have a moderately large site for the unloading, storage, and shakeout of materials (4), and to have no existing structures on the site (5). The topology of the site is assumed to be flat (5), the connections among members is of a familiar type and uncomplicated (5), the members themselves are only moderately heavily (4), and the height of the building is only 4 stories (4).

TABLE 5.6: PRODUCTIVITY FACTORS FOR THE PROTOTYPE BUILDING

Parameter	Factor
Site conditions	
accessibility	5
easiness of materials handli	5
size of site	4
none-presence of existing st	5
Project characteristics	
regularity of topology	5
standardization of connectio	5
low weight of members	4
height of finished structure	4
Resources	
experience of ironworkers	0
level of technology of equip	0
Effect	
simplicity of erection seque	5
none-proneness to delays	5
expected organization	5
possibility to reassign resou	5
availability of resources	5
TOTAL	62

Actual Av	4.13
Percent	0.91
Normal Av	4.33
Percent	0.93
1.02	Normalized factor

The overall effects that the site conditions, project characteristics and resources have on the project are all 5, to denote the best possible conditions. The prototype structure has a repetitive pattern, no delays are expected from the surrounding conditions, the site is not expected to be crowded (since it is a reasonable size) and it is expected to be well organized, while the resources can be easily reassigned and are readily available.

Recent research has focused on developing detailed estimates of productivity factors (Thomas, Sanvido, and Sanders, 1989; Thomas and Sakarcan, 1994; Halligan et al., 1994). Future developments of these simulation models will incorporate these results and approaches. For example, productivity may change over time (Thomas and Sakarcan, 1994), and different factors will modify the standard productivity times for different phases of the project.

However, this version of the model uses a simple analysis based on the average rating of site factors at a specified elapsed period of the total duration of the project. The results of this average are normalized, to create a single productivity factor. For the prototype building, this factor equals 1.02. This productivity factor is applied to all of the production rates (Table 5.7), resulting in an overall improvement in the production rates of 2%.

TABLE 5.7: ADJUSTED PRODUCTION RATES FOR PROTOTYPE BUILDING

	Output			Input (cr	
	Unit	Unit Quanti	(min/unit)	Crew	Number of
UNLOAD					
Beam	bundle	4	1.02	A	1
Joist/Purlin	bundle	1	4.09	A	1
Column	bundle	2	2.04	A	1
Truss section	bundle	1	4.09	A	1
Diagonal brace	bundle	1	4.09	A	1
SHAKEOUT					
Beam	bundle	4	0.26	A	1
Joist/Purlin	bundle	1	1.02	A	1
Column	bundle	2	0.51	A	1
Truss section	bundle	1	1.02	A	1
Diagonal brace	bundle	1	1.02	A	1
ERECT					
Beam	member	1	6.13	A	1
Joist/Purlin	member	1	6.13	A	1
Column	member	1	6.13	A	1
Truss	member	1	6.13	A	1
Diagonal brace	member	1	6.13	A	1
Install bolt	bolt	1	1.02	A	1
PLUMB					
Bay	bay	2	5.11	B	2
Column	column	1	2.55	B	2
PERMCON					
Install bolt on floor	bolt	1	0.13	B	2
Tighten bolt on floor	bolt	1	0.51	B	2
Install bolt at height	bolt	1	0.26	B	2
Tighten bolt at heig	bolt	1	1.02	B	2
Install anchor bolt	bolt	1	0.26	B	2
Tighten anchor bolt	bolt	1	1.02	B	2
weld	inch	1	1.53	C	1
DECK					
stud	stud	1	0.26	D	1
deck sheets	sheet	1	4.09	D	1

5.3.4 Total Time Estimates

Using all of the information provided through the design and connection specifications, and the estimates of the productivity factors to correct the production rates, the time for each member and bolt can be estimated, and the total times for each stage (i.e. unloading, shakeout, erection, plumbing, permanent connection, and decking) can be calculated (Table 5.8).

TABLE 5.8: ESTIMATED TOTAL TIME FOR EACH STAGE FOR THE PROTOTYPE BUILDING

Members	quantity		UN	SH	ER	
Columns	42	42	85.8	21.5	257.4	
Girders/su	56	56	57.2	14.3	343.2	
Bracing be	48	48	49.0	12.3	294.2	
Filler beam	120	120	122.6	30.6	735.5	
Diagonal b	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	
			314.6	78.7	1630.4	Total min
			5.2	1.3	27.2	Total hrs
			0.7	0.2	3.4	Total days

Plumbing	quantity		PL	
Bay	24	24	122.6	
Column	0	0	0.0	
			122.6	Total min
			2.0	Total hrs
			0.3	Total days

Decking	quantity		DE	
Studs	3200	3200	817.2	
Sheets	384	384	1569.1	
			2386.3	Total min
			39.8	Total hrs
			5.0	Total days

Connectio	quantity		ER ins	PC ins	PC tight	
	ER ins	PC ins				
Anchor bol	126	0	32.2	0.0	128.7	
Column sp	126	126	32.2	32.2	257.4	
Beam/gird to co	224	1120	57.2	286.0	1372.9	
Beam/gird to co						
Shared	240	240	61.3	61.3	490.3	
Unshar	48	96	12.3	24.5	147.1	
Beam/gird to Be						
Shared	320	320	81.7	81.7	653.8	
Unshar	64	128	16.3	32.7	196.1	
Diagonal b			0.0	0.0	0.0	
			293.2	518.4	3246.4	Total min
			4.9	8.6	54.1	Total hrs
			0.6	1.1	6.8	Total days

The total times for each stage are summations for all of the units (i.e. members and bolts). The use of these aggregated calculations requires attention, however, since they do not automatically incorporate the time dimension. That is, these numbers are the result of the number of members (or bolts) times the production rates. Obviously all of the 266 members in the prototype structure will not be unloaded all at once, taking 5.2 hours, but rather will be spread across each day of erection. Likewise the shakeout may take 1.3 hours in total, but will also occur across several days. The actual duration of the erection is the 3.4 days for lifting and positioning the members plus the 4.9 hours for the installation of erection bolts, but these activities but happen in direct succession for each and every member. The total erection time (unloading, shakeout, anderection) is then 4.9 days, but the erection may be spread across a greater number of days to allow for the unloading of the trucks and the shakeout of the members during each day, thereby reducing the availability of the crane for erection activities. However, the total duration of the unloading, shakeout and erection activities is likely to be less than the sum of their individual times due to the overlapping of activities and the possibility for workdays of greater than 8 hours.

In the same way, the time for plumbing the bays two at a time, with two crews, is calculated to be two hours total, and the time for installing the remaining bolts and tightening all of the bolts required during the permanent connection stage, also using two crews, is 7.9 days. The decking takes 2.5 days if 2 crews performing the work and 5 days with only one crew. Of course, the bays may be plumbed soon after they are erected, and the bolting up may proceed at the same time the bays are being plumbed, so the total elapsed time is one again different than the sum of the times for the different stages.

5.3.5 Results

The sums for each stage can be used to evaluate the total labor hours, and can be adjusted to calculate the duration of the project and the duration of the use of the crane (Table 5.9).

TABLE 5.9: TOTAL TIMES FOR THE PROTOTYPE BUILDING

STAGE	TOTAL TIME
Unloading	0.7 days
Shakeout/Erection	4.2 days
Plumbing/Permanent Connections	8.1 days
Decking	5.0 days
TOTAL TIME	18 DAYS
TOTAL DURATION (with overlap)	10 DAYS
Total Crane Utilization (1 crane)	5 days

5.4 Manual Calculations

The following computations illustrate the first three days of the erection of the prototype building. The objective of these manual computations is to combine the elements of the flow diagram with the details of the spreadsheet. (Appendix D contains examples of the manual computations.)

Since the project uses 150 tons of structural steel, nine trucks could possibly deliver the structure to the site. Since each truck is limited to 40,000 lbs (without special permits), the 9 trucks would not be totally loaded and additional space would be available for transporting the equipment needed. To conform with standard industry procedure, it is assumed that the building members will be delivered in three batches of three trucks each. On the first day, 3 trucks arrive and unload approximately 90 members (266/9 * 3), on the second day another 90 members are delivered, and finally on the fourth day 86 members are delivered. There is no delivery on the third day, which may be convenient for the fabricator and allows the erector to complete enough of the erection, permanent connections and decking needed to proceed to the second tier.

From the spreadsheet model, 0.66 days were computed to unload 266 members, so unloading 90 members will take 0.22 days by a linear relation. To fully utilize the eight-hour day, a remaining 0.78 days are available. Forty-nine members can be shaken-out and erected in 0.77 days, since 266 can be handled for these same stages in 4.17 days according to the spreadsheet results. (It is important to note here that no overlap has been considered because only one crane will be utilized.)

Activities can be overlapped, as shown in the erection flow diagram, when permanently connecting the bolts. After the erection of the members, bolting could possibly start with a lag of two erected bays, which means that six of the eight bays can be connected towards the end of the day. The time allowed for connecting is thus (6/8)*0.77=0.58 days. Again by a linear computation, 228 bolts could possibly be connected in this amount of time (8.10 days/3178 bolts results in 228 bolts in 0.58 days). The eight bays contain approximately 530 bolts, so approximately four of the eight bays could be connected.

At the end of the first day (0.22+0.77=0.99 days with 8 hours in a day), 90 members would have been unloaded from three trucks, 49 members would have been shaken-out and erected forming 8 bays, and four of the erected bays would have been connected.

No decking occurs on the first day, but if desired it could start on the second day since 4 bays have been permanently connected. The decking can proceed in parallel with the continued erection of members, bolting, and plumbing.

Figure 5.3 shows a diagram of the progress of the structural erection, expressing the results of the manual computations for the first three days. Note that the structure is stable at the end of each day, that the erection unit is the bay, and that OSHA regulations have been considered by maintaining the maximum of two unfloored levels.

In Figure 5.4, the relative duration of each major phase is presented. The advantage of this approach to the presentation of project activities is that it effectively conveys the nature of activities expected to occur on each day. For instance, the unloading of the trucks which occurs every day is clearly represented, and delays in the arrival of the trucks or their unloading can be directly assessed. Liekwise, the lag between the permanent connections and the decking is clearly evident, allowing immediate response (such as allocation of resources) to meet OSHA regulations and maintain the job flow.

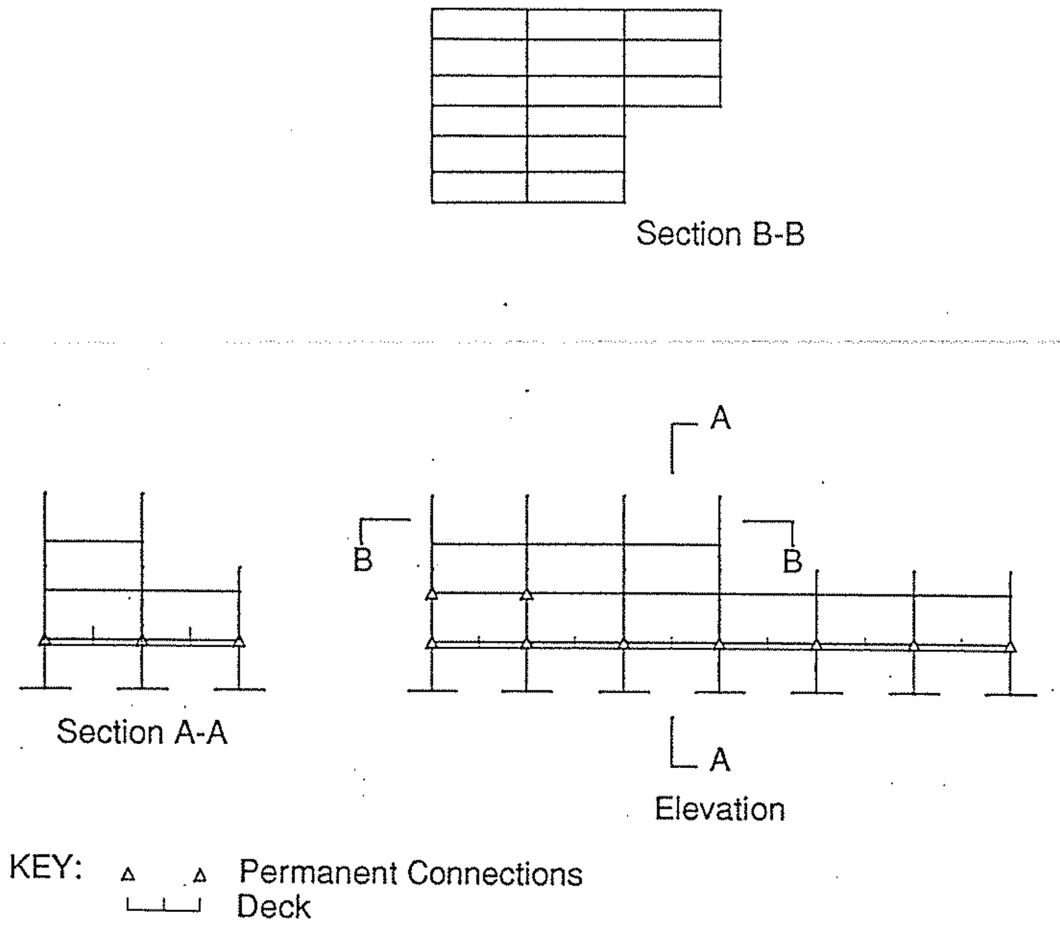

FIGURE 5.3: PROGRESS OF STRUCTURAL ERECTION OF PROTOTYPE BUILDING, DAY 3

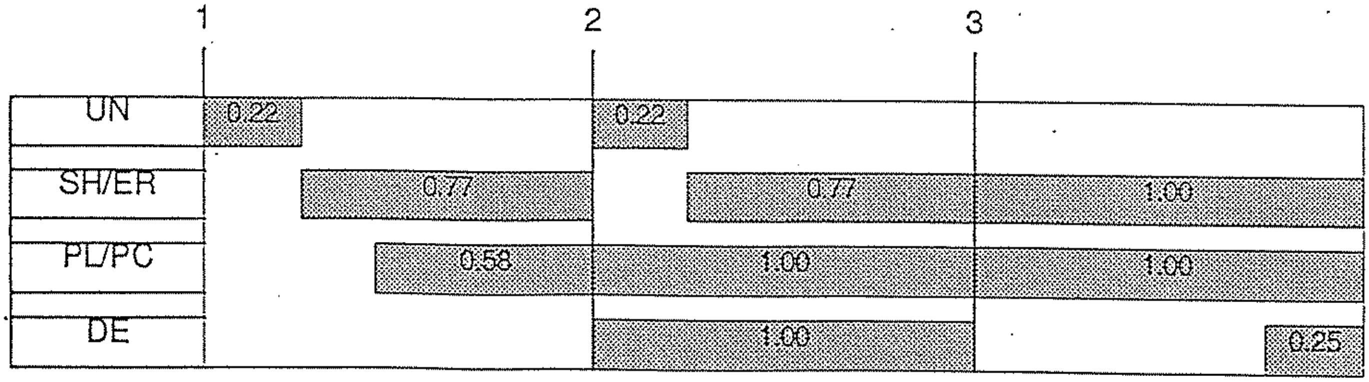

FIGURE 5.4: PROJECT DURATIONS BY PHASE FOR PROTOTYPE BUILDING

5.5 Summary

The prototype building provides an opportunity to demonstrate the application of the simulation models. It will also provide a common baseline for the comparison of new techniques and technologies used in steel erection, during the next phase of the research.

In their application to the prototype building, the preliminary simulation models performed very strongly. The flow diagrams demonstrated their infinitely adaptability, and effectively captured the dynamic aspects of the project. Indeed, the flow diagrams were particularly useful for the manual computations, since they provided an effective system for keeping track of the flow of the activities, and the cycle of repetitions. The spreadsheet captured the specific of the prototype building design, down to the last bolt, and proved useful for general estimates and logic checks. For the daily computations, the spreadsheet was modified to calculate the durations with respect to the specific number of members for each day, but the process proved time-consuming and cumbersome. The manual calculations captured the dynamic aspects of the daily activities with the specific counts and durations of activities. The process of these hand calculations, though, is laborious, and needs to be supplemented or replaced by computer-based capabilities.

The example application of the prototype structure, as captured in the preliminary simulation models, did indeed indicate possibilities for significant changes. The stability of the frame at the end of each day was an explicit criteria incorporated into this model, though its adherence on construction sites may be less rigidly observed. Alterations in the flow of erection could easily ensure the stability of the frame at the close of each workday, thereby increasing the safety of the site. Analyses of the variances of erection time when design specifications were changed (for instance, adding the shear studs along the beam line for the decking) provided insight into the erection activities which either took a significant amount of time to complete or set the pace for the rest of the erection process.

These observations will be extended in the next phase of research on the use of new designs and construction technologies in steel erection.

CHAPTER 6

CONCLUSION

The design, fabrication, and erection of large structural systems are complex processes using the expertise in many diverse areas. In the current condition of the industry, the design of the structure is often accomplished without explicit consideration of the resulting activities needed during fabrication and erection. Likewise, the fabrication and erection processes can often be performed without detailed coordination and optimization. While these divided realms have produced significant structures, room for improvement does exist. Specifically, designs can be evaluated with respect to their fabrication and erection requirements, and new technologies can be considered for fabrication and erection.

6.1 Summary of the Research

The three preliminary simulation models presented in this report provide an opportunity to systematically study the steel erection process. Each model examines the fabrication and erection processes in a different way; and the combination of these complementary models is a powerful tool to improve the robustness of facility design and lower the barriers to the use of new technologies.

The fabrication and erection flow diagrams reveal the cyclicity of these processes and highlight the points at which internal or external factors prompt shifts out of the cycles. The development of these models represents a new approach. While inherently repetitive activities have been modelled in other simulation research, most other construction processes have been viewed as too susceptible to change to be analyzed in this way. The simulation models themselves then can provide insight into these processes. In particular, the erection flow diagram provides critical criteria to analyze factors which could delay or expedite the construction process.

The spreadsheet-based model is also unique, since it combines a detailed productivity estimates with the specifics of a design to calculate total project duration. The spreadsheet model presents an innovative approach of using a site factors to affect the productivity of different activities given any combination of specified crew types. In addition, the detailed member counts (e.g. number of beams, number of each connection type) provide the opportunity to experiment with functionally equivalent designs to determine relative erection times.

The third model, currently approximated through manual calculations, explicitly links the flow diagrams to the spreadsheet-based model to create a realistic and time-based analysis of the erection process. With proper use of the models, a daily Gantt chart can be generated to describe the construction process in a more detailed way than is actually being done in industry, for example, specifically separating erection from permanent connections. This separation of the activities allows the designer or erector to consider such factors as the stability of the structure at the end of each day and the relative safety of the site.

These preliminary simulation models approximate the best available approaches and knowledge in the construction industry. They can be used by the members of industry to analyze and plan erection activities, and they may provide capabilities in design and fabrication planning as well.

6.2 Future Research

The next phase in ATLSS project ADC-11 will use these models to economically assess new construction technologies for steel erection. The example application of the prototype building will be used as the baseline on which to compare certain technologies, such as the ATLSS Connector and other advanced construction technologies. The assessment will include not only total costs, but also changes in the flow of the project, resource use, activity and overall duration, and other factors such as safety.

It is hoped that additional data acquisition activities will proceed in the future to aid the development of the probabilistic functions within the models. The randomness of the construction process could be somewhat treated in a deterministic way if enough data is gathered. Also, it is desired to increase the number of probabilistic decision diamonds in the fabrication and erection models, to more closely represent the nature of construction.

The fabrication model itself will be developed more fully in other research. The expansion of the consideration of fabrication activities can further enrich the erection simulation models by directly comparing the benefits, opportunities and costs associated with off-site and on-site activities.

Finally, the erection simulation model currently approximated through manual calculations should be incorporated into a fully computer-based model. This model may well employ current software developments and techniques, such as object-oriented languages and visual representations. The computer-based model could be as flexible as the spreadsheet-based model in accommodating different design specifications, and as generalizable as the flow diagrams, while adding the truly dynamic aspect of daily flow and all other factors relevant to structural erection.

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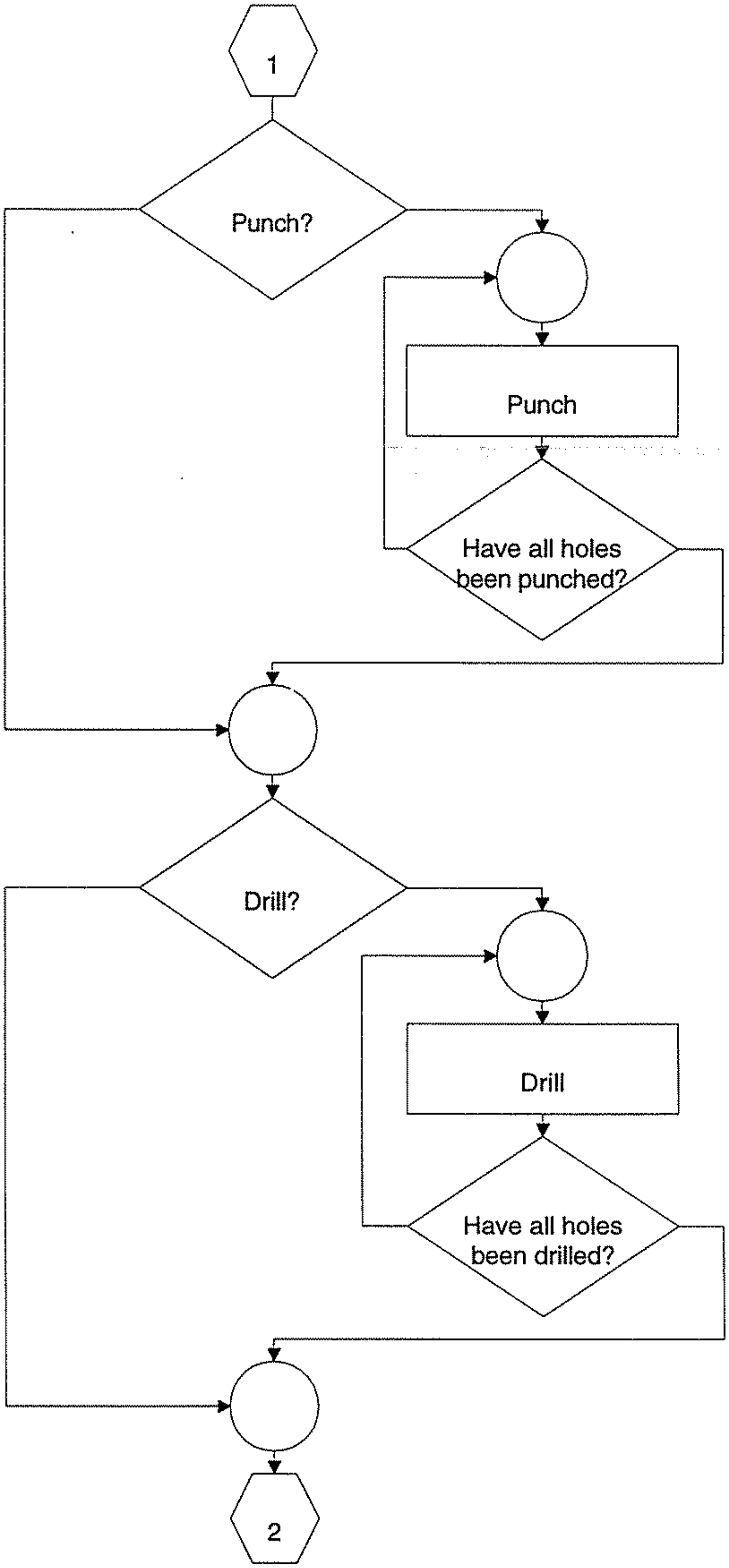
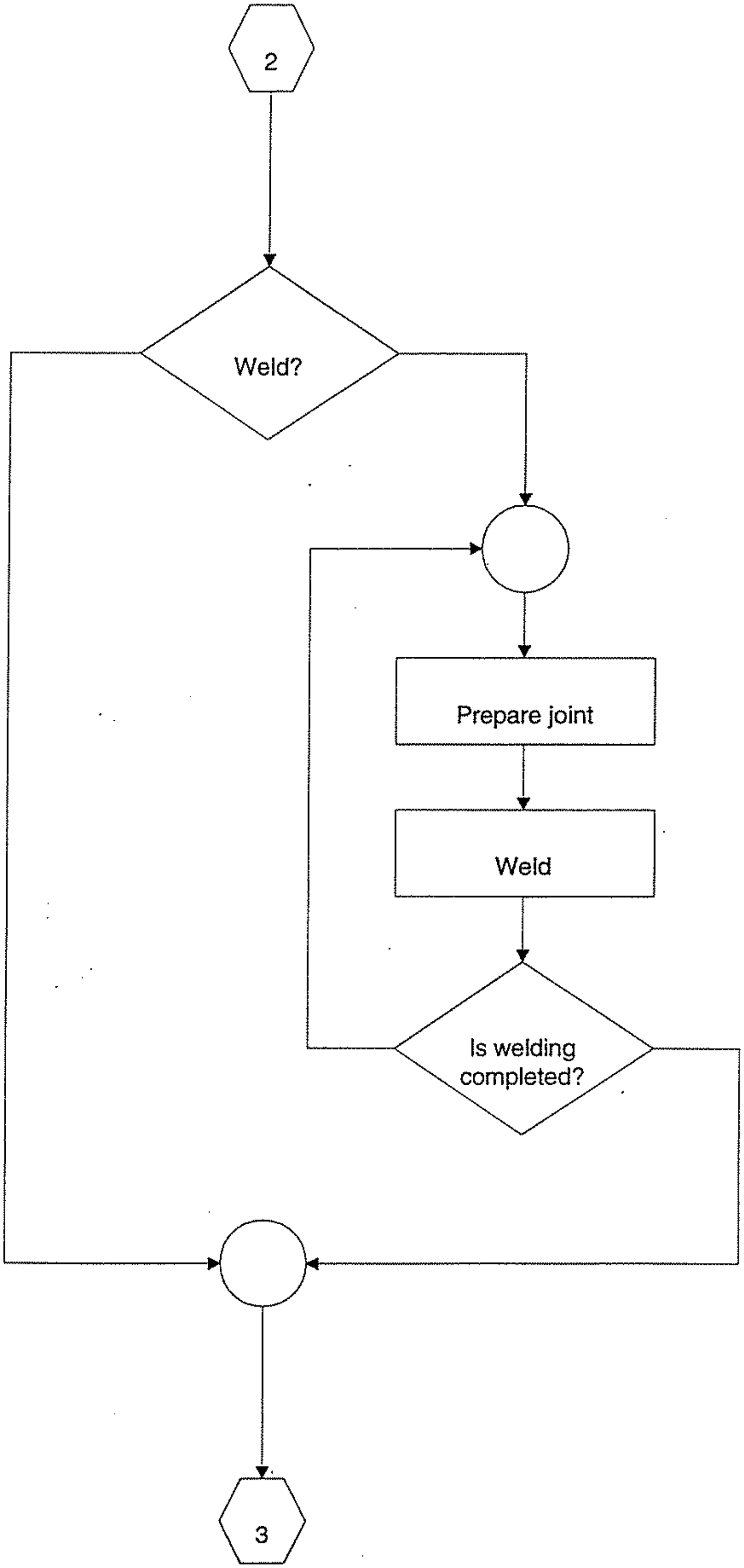
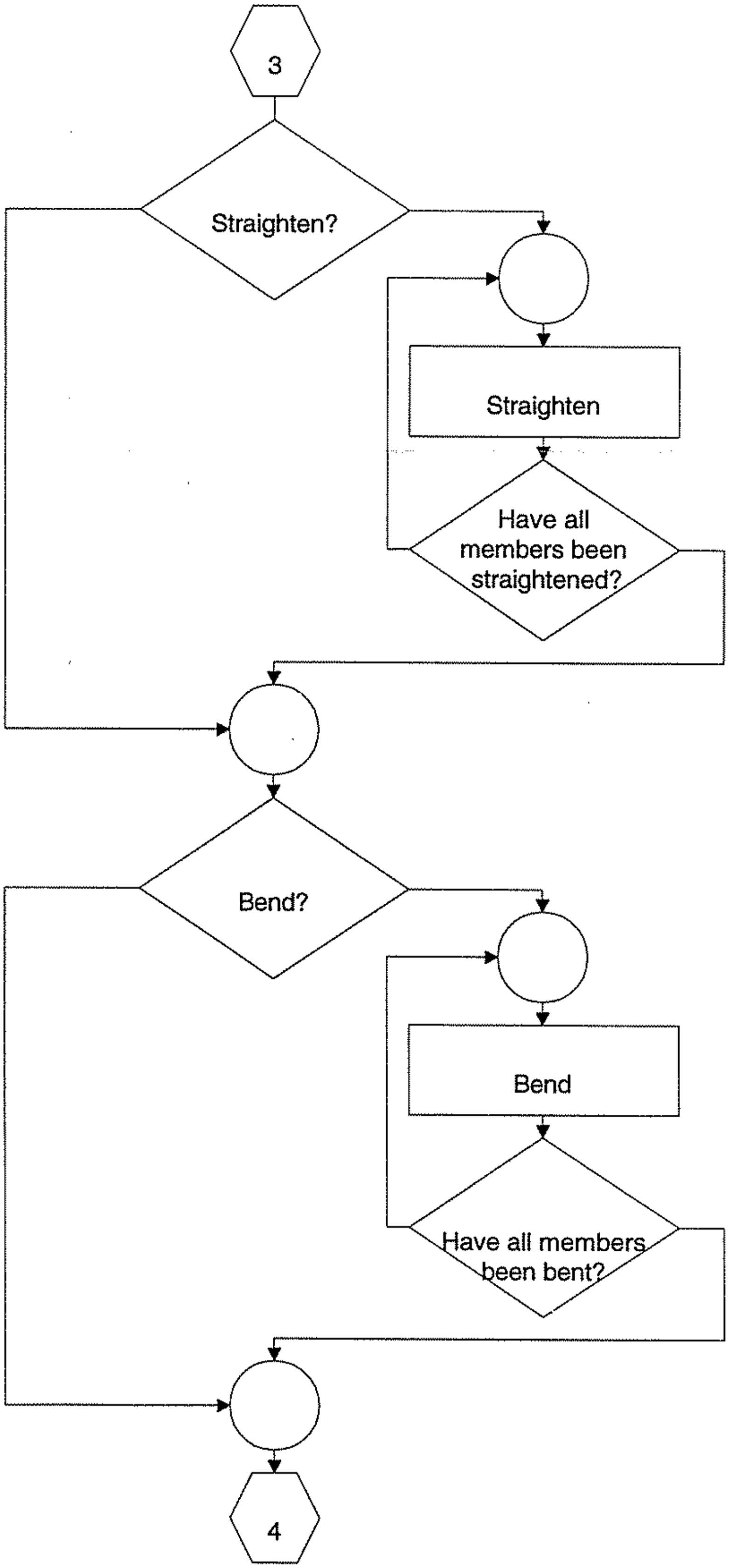
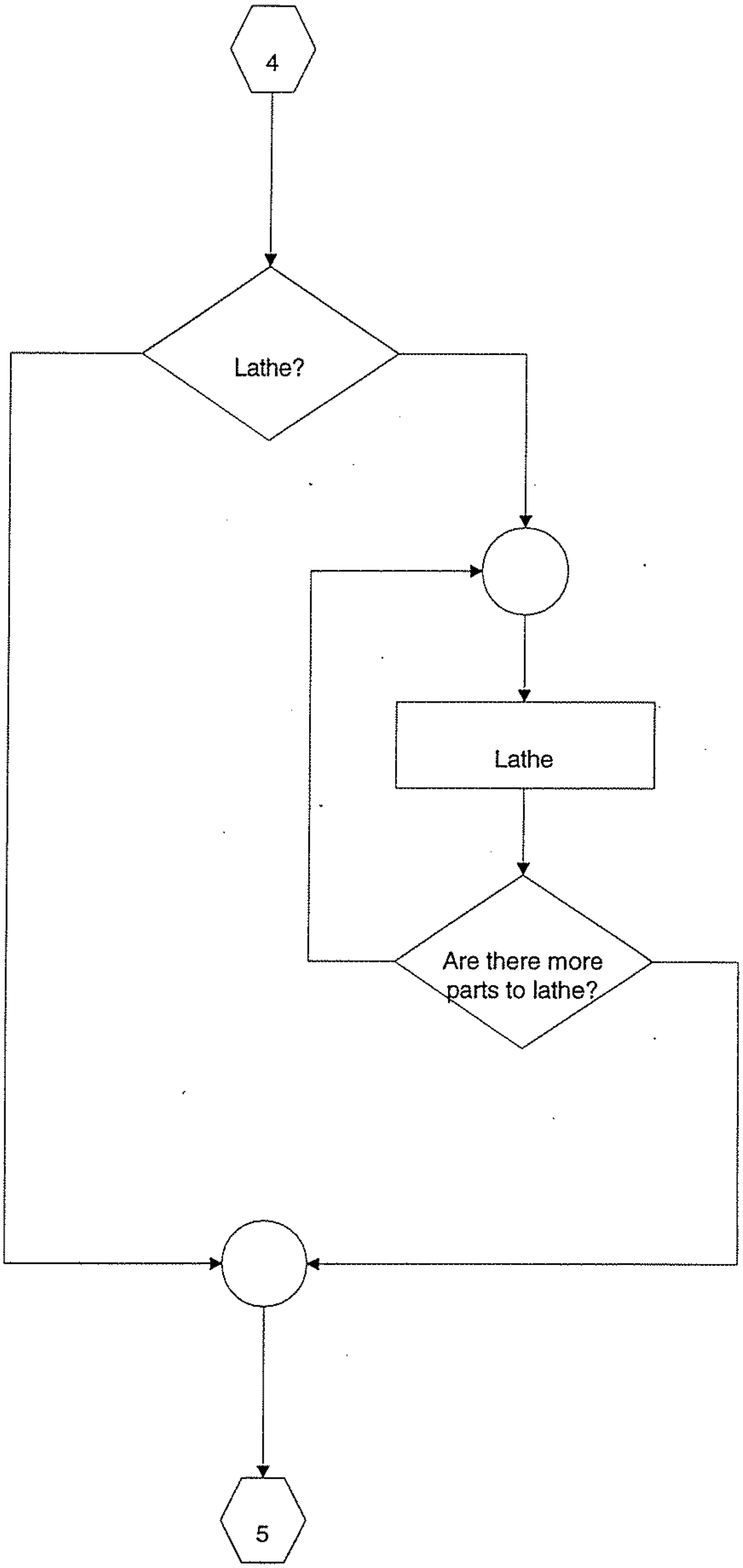
APPENDIX A

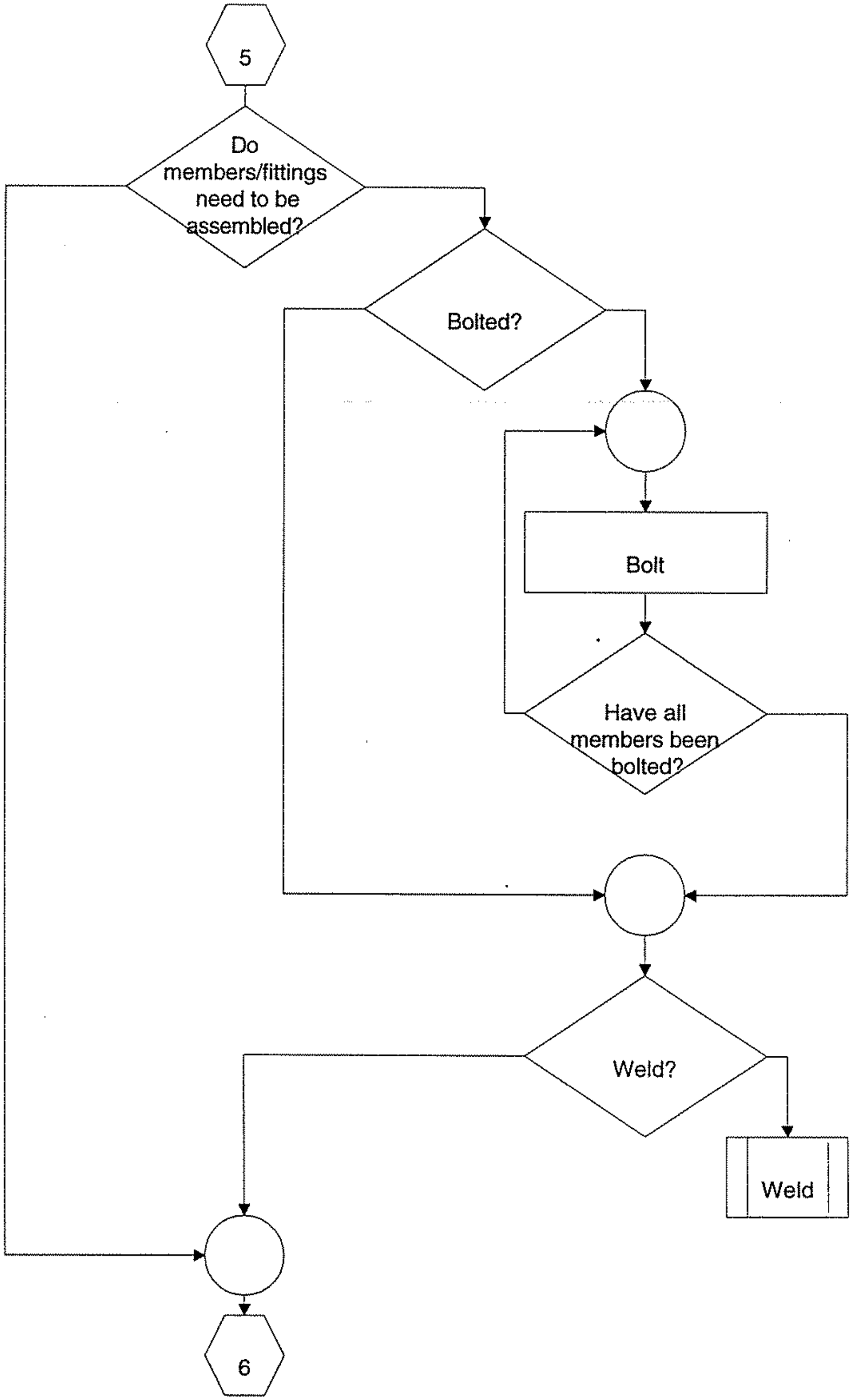
FABRICATION FLOW DIAGRAM

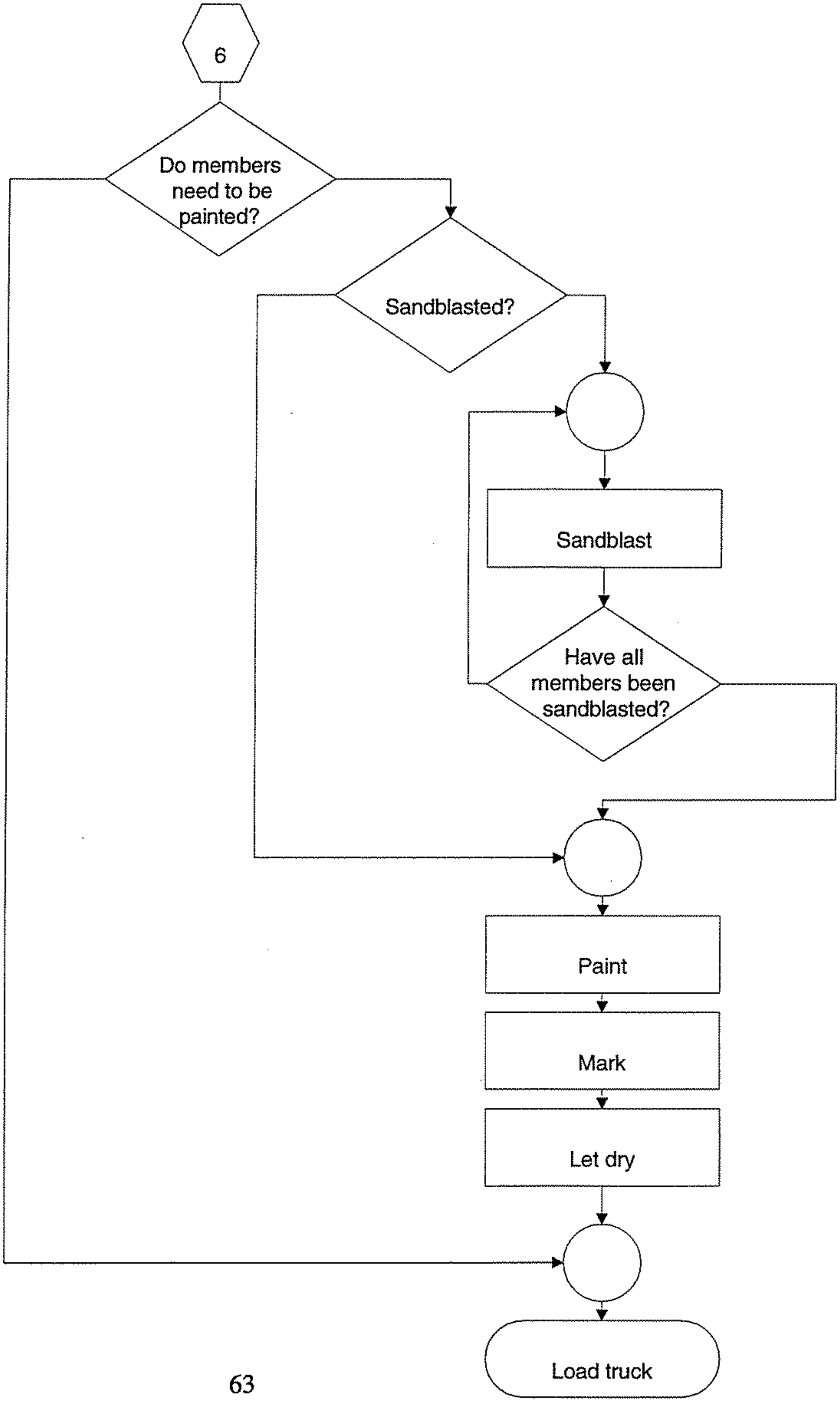

1
Punch?
Punch
Have all holes been punched?
Drill?
Drill
Have all holes been drilled?
2


2
Weld?
Prepare joint
Weld
Is welding completed?
3


3
Straighten?
Straighten
Have all members been straightened?
Bend?
Bend
Have all members been bent?
4


4
Lathe?
Lathe
Are there more parts to lathe?
5


5
Do members/fittings need to be assembled?
Bolted?
Bolt
Have all members been bolted?
Weld?
Weld
6

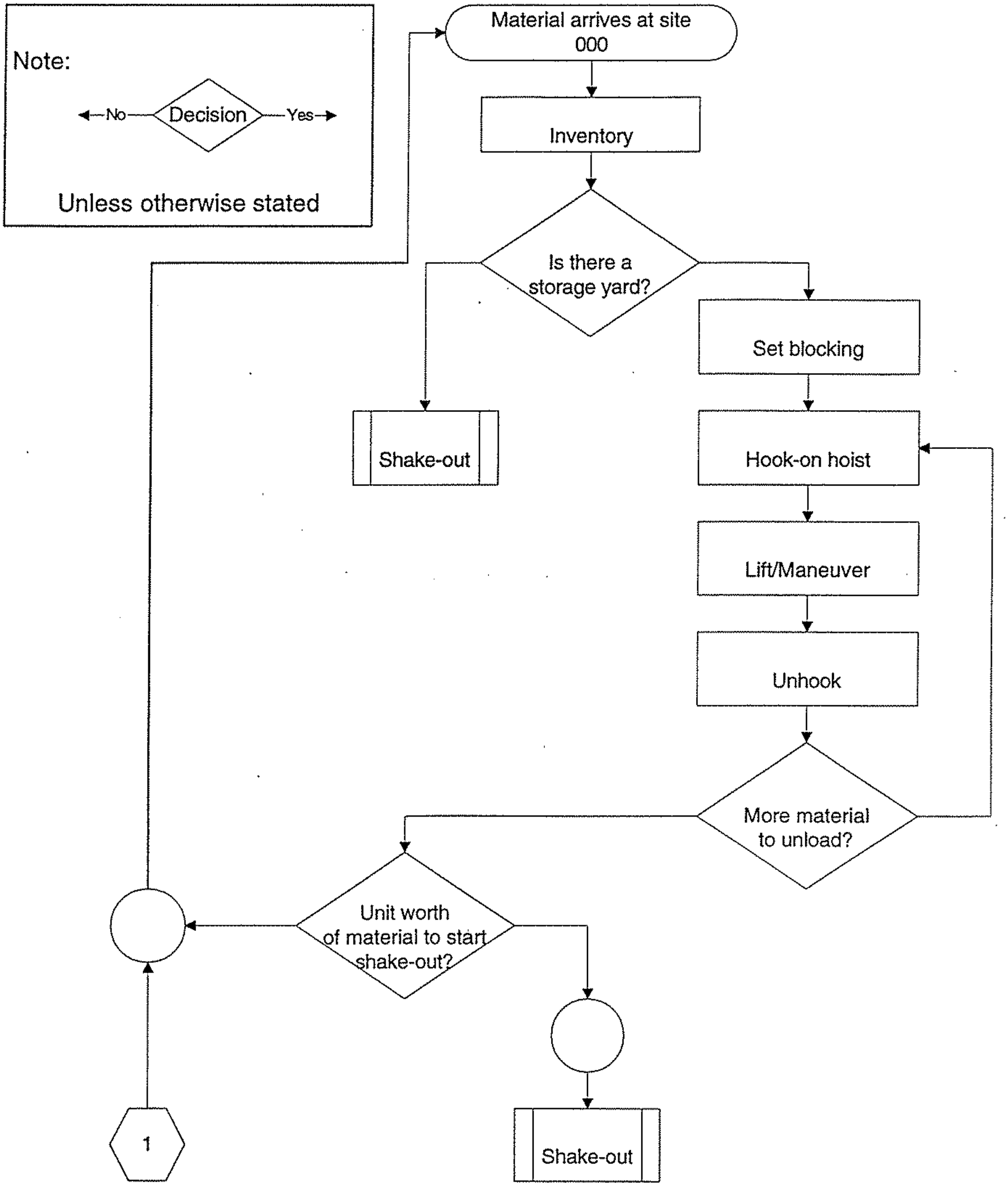

6
Do members need to be painted?
Sandblasted?
Sandblast
Have all members been sandblasted?
Paint
Mark
Let dry
Load truck

APPENDIX B

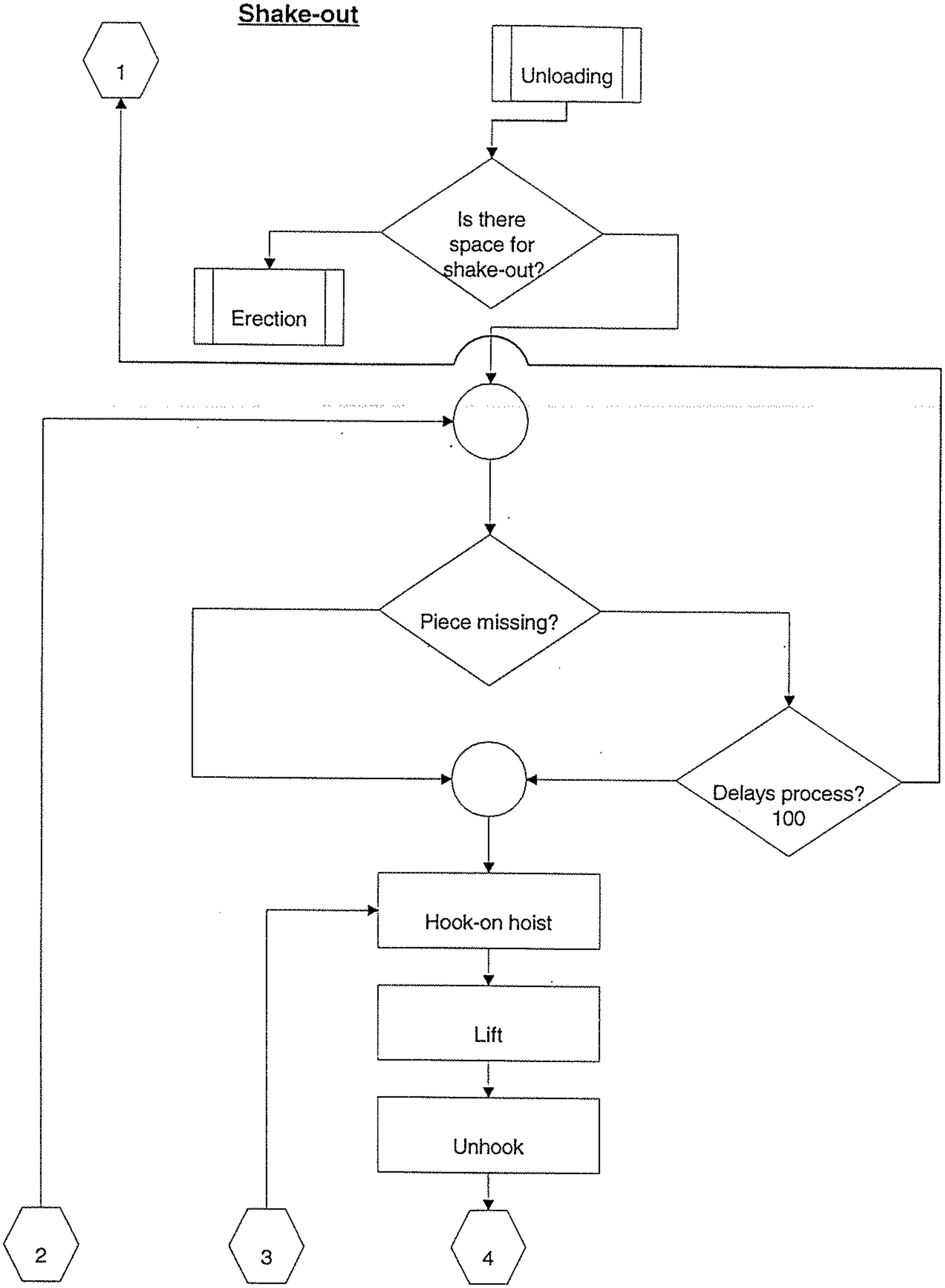
ERECTION FLOW DIAGRAM

FLOW DIAGRAM
IN THE ERECTION OF
A STEEL STRUCTURE

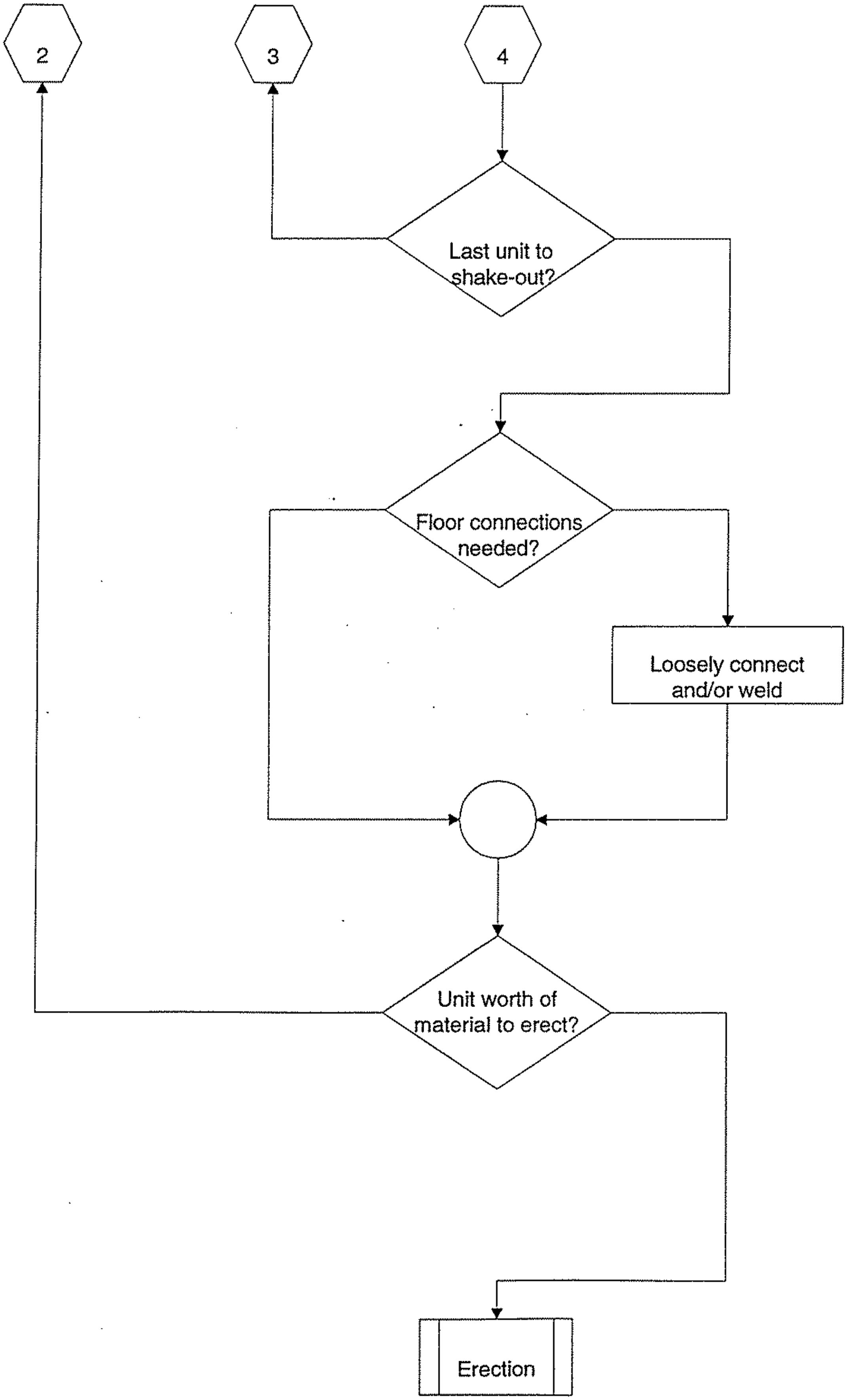
Unloading



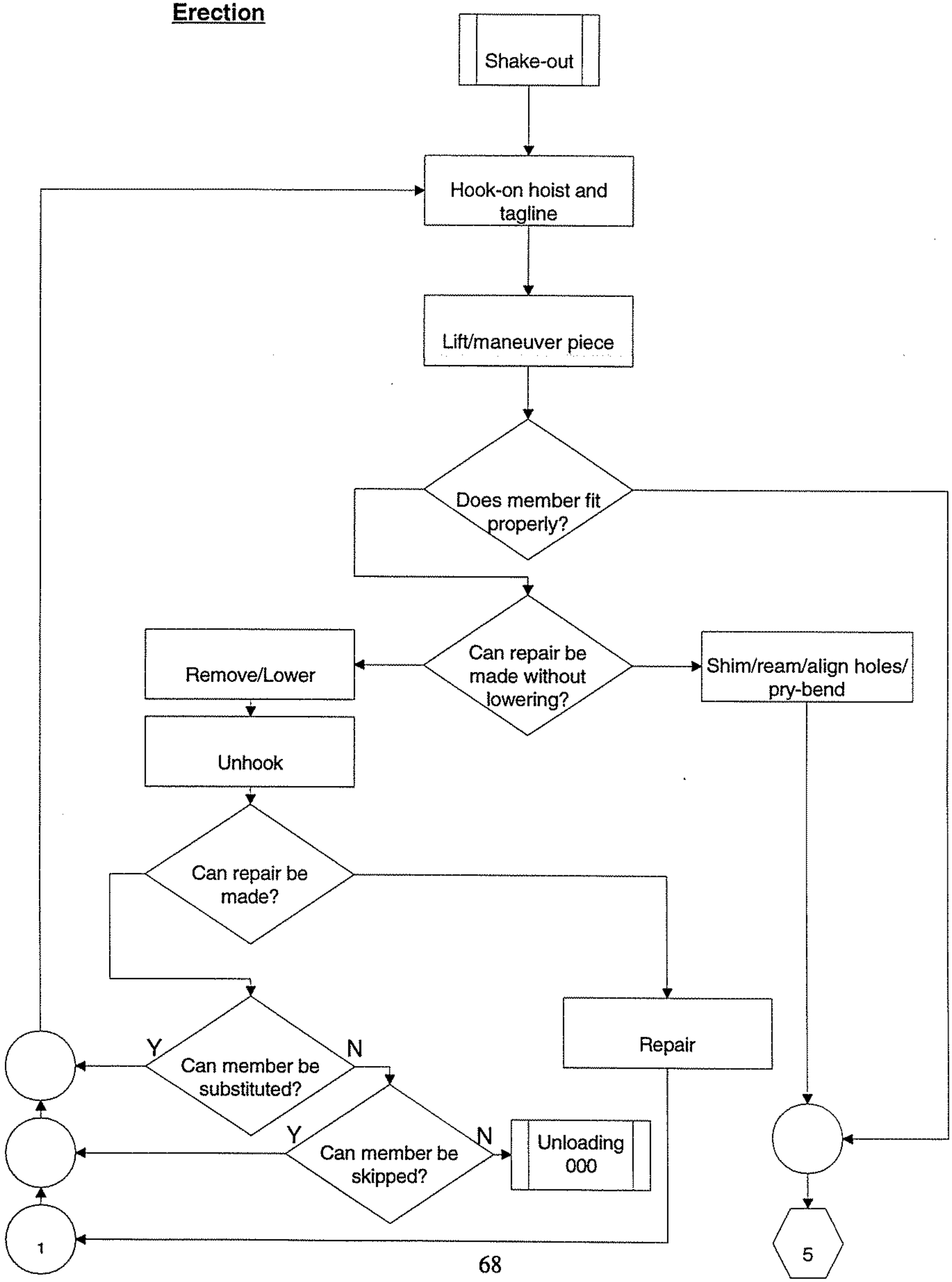
Shake-out


1
Unloading
Is there space for shake-out?
Erection
Piece missing?
Delays process? 100
Hook-on hoist
Lift
Unhook
2
3
4

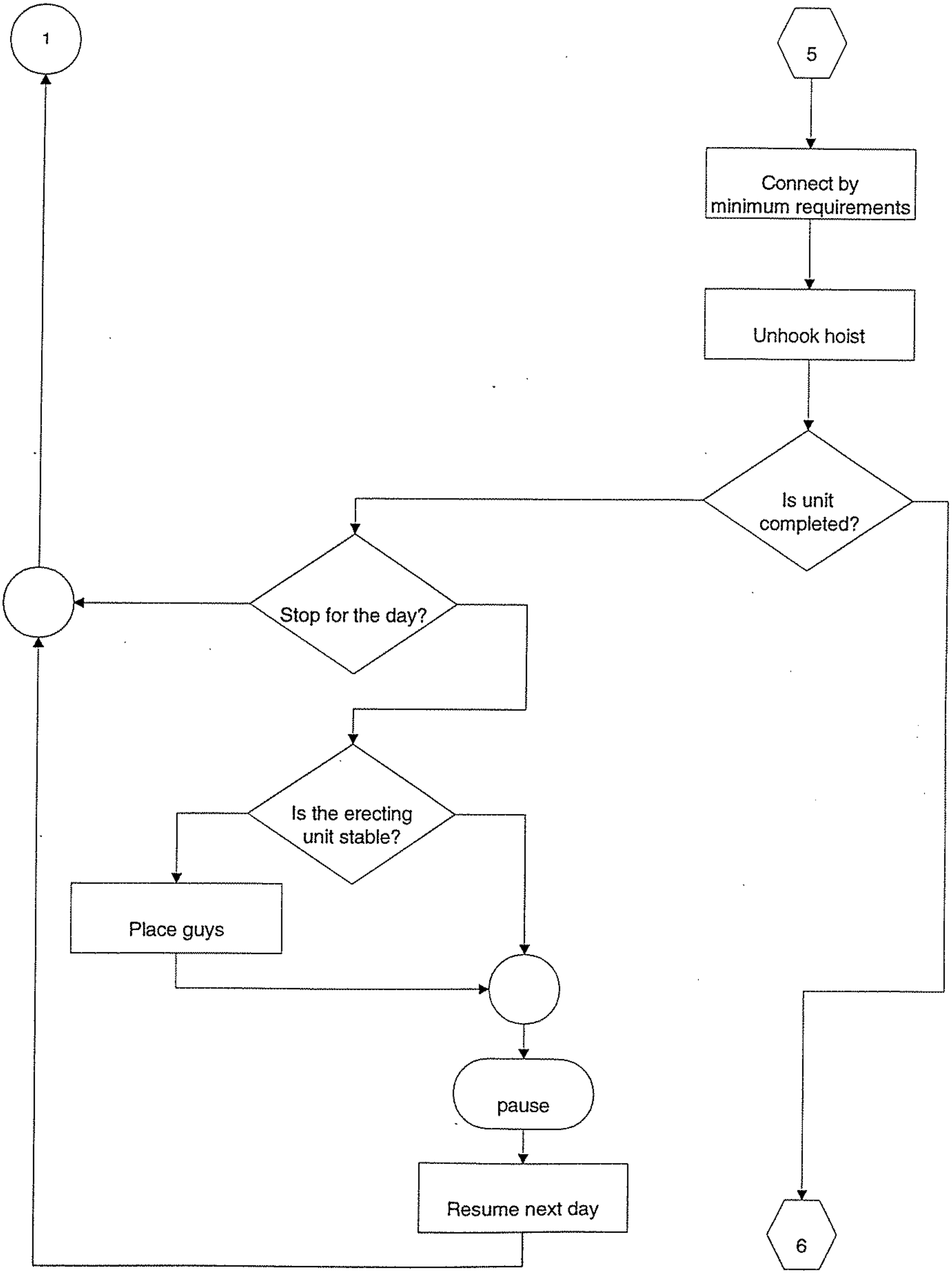
Shake-out (cont'd 1)



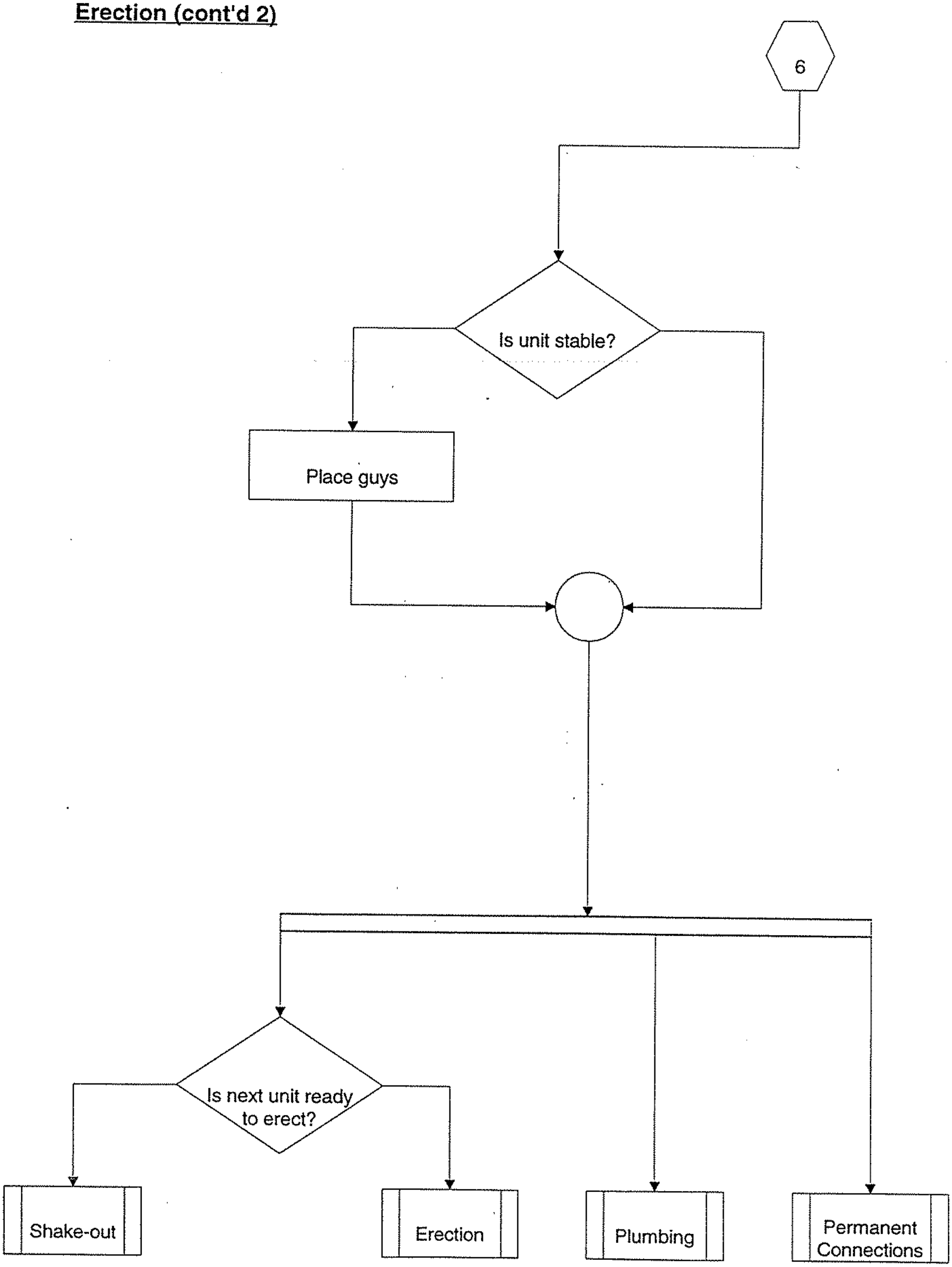
Erection


Shake-out
Hook-on hoist and tagline
Lift/maneuver piece
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

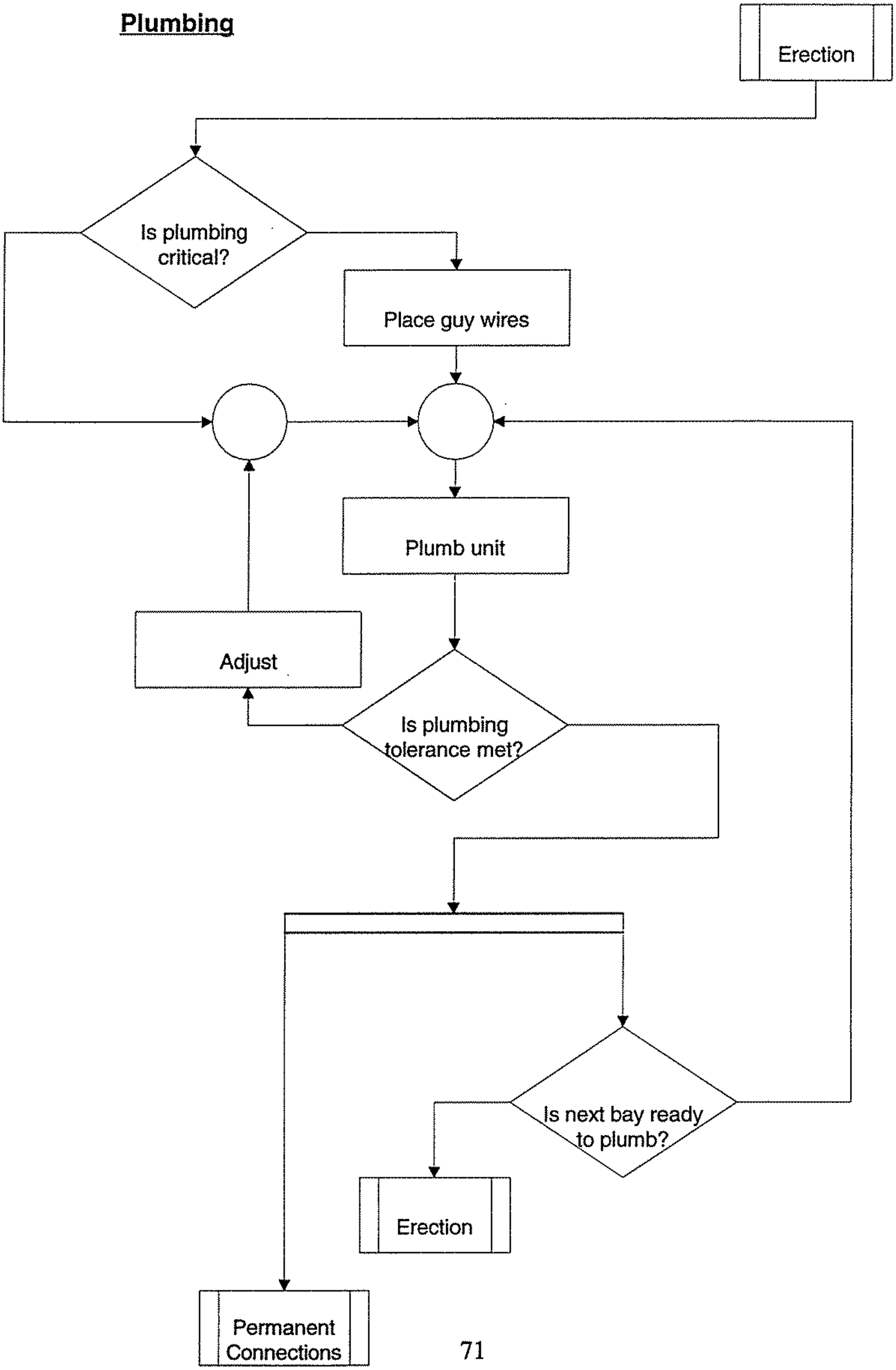
Erection (cont'd 1)



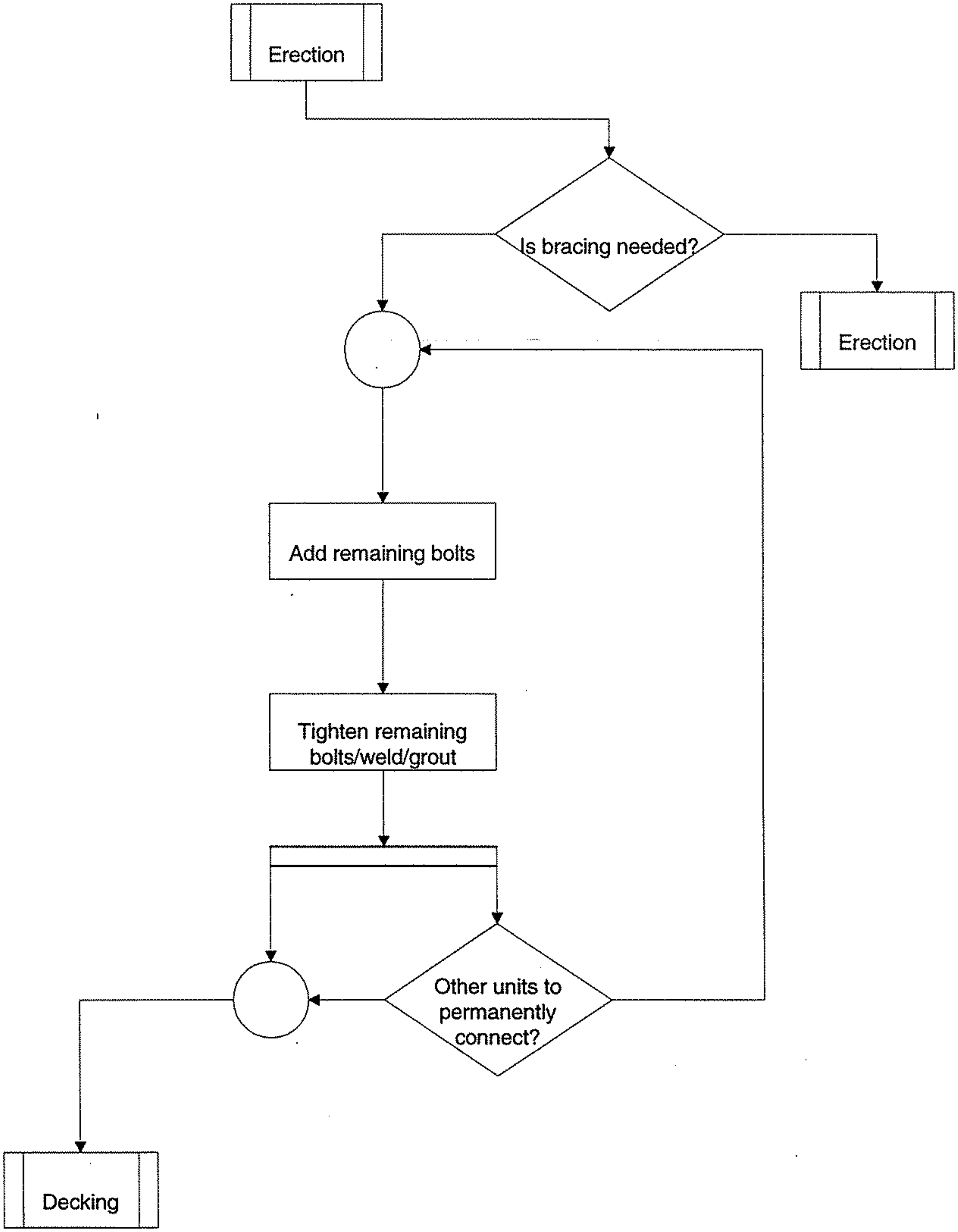
Erection (cont'd 2)



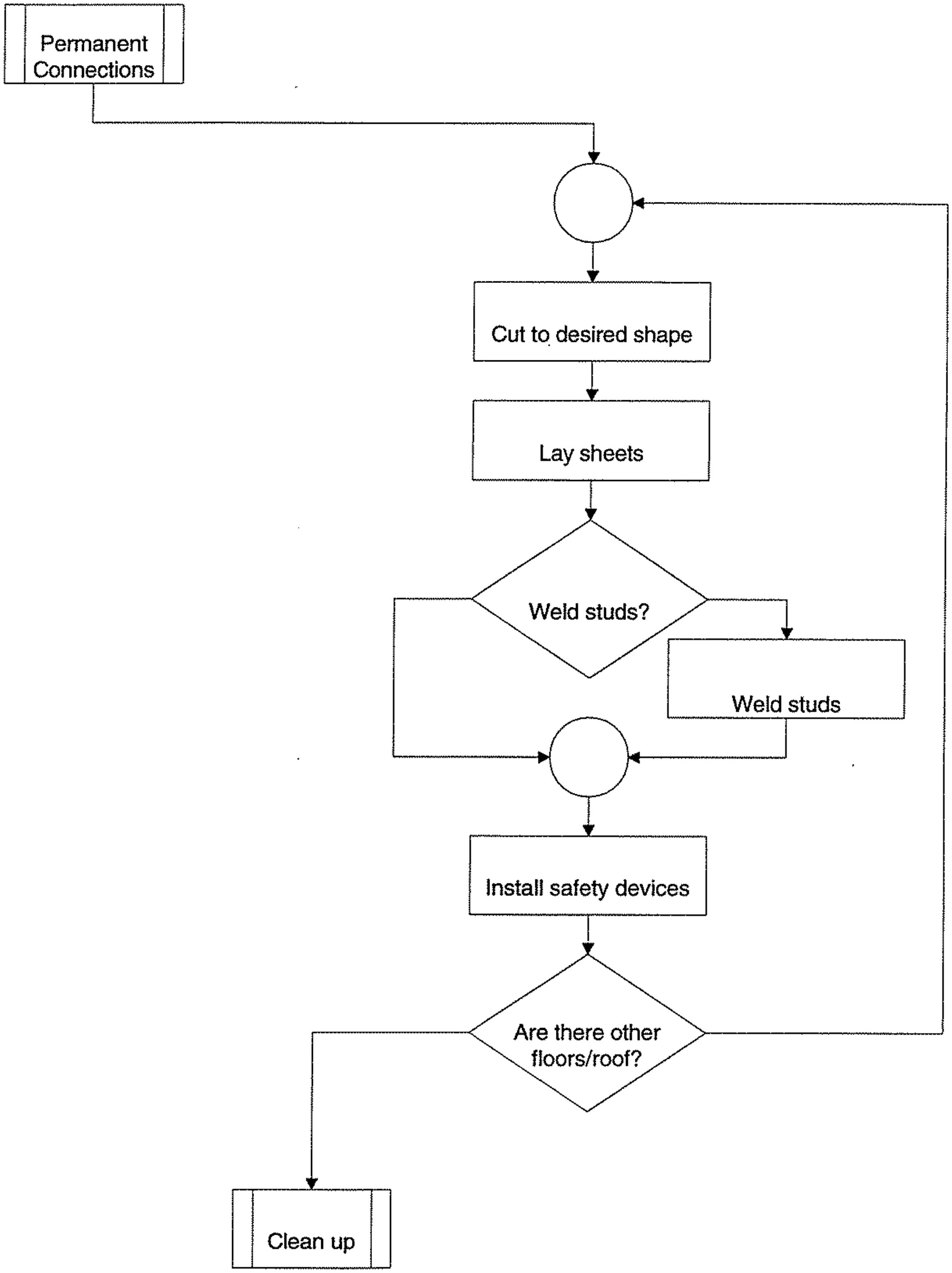
Plumbing


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

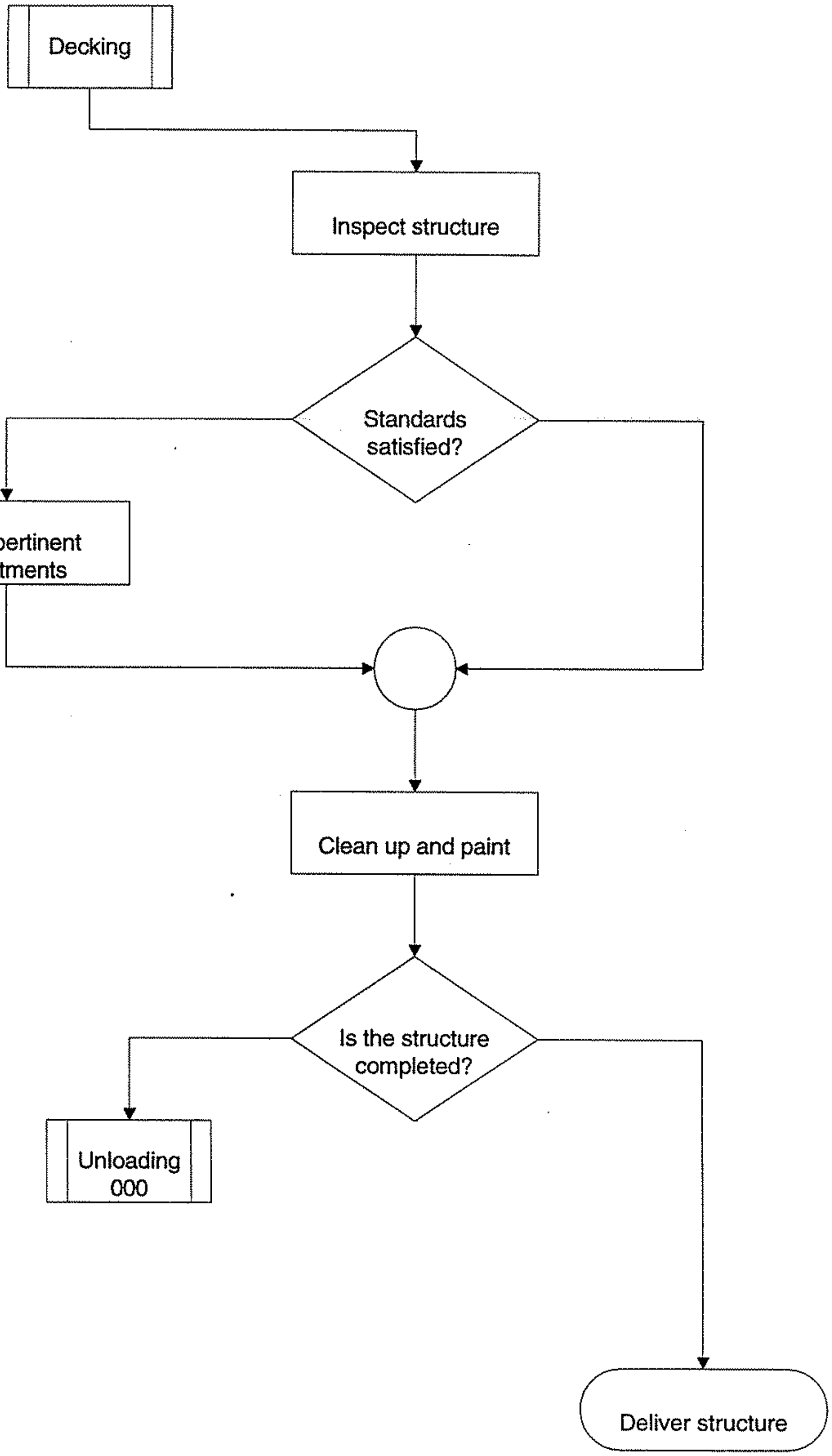
Permanent Connections



Decking


Permanent Connections
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 C

SPREADSHEET-BASED PROGRAM

TIME ESTIMATES

-for activities in the steel construction process

DATE: 10/27/94

PROJECT: Prototype Building
WEIGHT: 150 Tons

STRUCTURAL SYSTEM: A series of rigid frames connected by bracing beams.
Two-floor column tiers.
Filler beams.

Members

Member	Unit	Unit quant	members/	total No. o	input No. (*)
Columns	tier	2	21	42	42
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
				266	Total

*—Numbers in the last column must be inputed in this column. Zeros should be replaced by ones to avoid division by zero.

Connections

Bolts per connection

Connection	Unit	Unit quant	total bolts/	shop bolts	field bolts
Anchor bolts	column	21	6	0	6
Column splice	column	21	24	12	12
Beam/girder/truss/joist to colum	girder	56	42	18	24
Beam/girder/truss/joist to colum					
Shared bolts	beam-colu	60	12	4	8
Unshared bolts	column-be	24	8	2	6
Beam/girder/truss/joist to Beam/girder/truss/joist					
Shared bolts	filler-girde	80	12	4	8
Unshared bolts	girder-fille	32	8	2	6
Diagonal brace to beam/column					0

Total bolts

Connection	ER ins (*)	PC ins (**)	total No. of	total No. of	total No. of
Anchor bolts	126	0	126	0	126
Column splice	126	126	504	252	252
Beam/girder/truss/joist to colum	224	1120	2352	1008	1344
Beam/girder/truss/joist to colum					
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 5110 1932 3178

*—Two bolts at each end (OSHA regulation), 50% of spli

**—Remaining bolts

***-Installed and tightened

Other quantities

Plumbing bays	24
Plumbing columns	0
linear inches of weld	0
truss sections	0
studs	3200
deck sheets	384

PRODUCTIVITY

$$\text{Productivity}, \quad p = \frac{\text{output}}{\text{input}}$$

CREWS	STAGE	RESOURCES	
A	UN/SH/ER	2	Ironworkers
		1	helper
		1	crane and operator
B	PL/PC	2	Ironworkers
C	PC(weld)	1	Ironworkers
D	DE	2	Ironworkers

PRODUCTION RATE

Including idle time

	Output			Input (cr	
	Unit	Unit Quanti	(min/unit)	Crew	Number of
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	bundle	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	1.00	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 floo	bolt	1	1.00	B	1
Install bolt at heigh	bolt	1	0.50	B	1
Tighten bolt at heig	bolt	1	2.00	B	1
Install anchor bolt	bolt	1	0.50	B	1
Tighten anchor bolt	bolt	1	2.00	B	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 (-5...0...+5)

Parameter	Factor
Site conditions	
accessibility	5
easiness of materials handli	5
size of site	4
non -presence of existing st	5
Project characteristics	
regularity of topology	5
standardization of connectio	5
low weight of members	4
height of finished structure	4
Resources	
experience of ironworkers	0
level of technology of equip	0
Effect	
simplicity of erection seque	5
non -proneness to delays	5
expected organization	5
possibility to reassign resou	5
availability of resources	5

TOTAL	62
Actual Av	4.13
Percent	0.91
Normal Av	4.33
Percent	0.93

1.02	Normalized factor

ACTUAL PRODUCTIVITY

	Output			Input (cr	
	Unit	Unit Quanti	(min/unit)	Crew	Number of
UNLOAD					
Beam	bundle	4	1.02	A	1
Joist/Purlin	bundle	1	4.09	A	1
Column	bundle	2	2.04	A	1
Truss section	bundle	1	4.09	A	1
Diagonal brace	bundle	1	4.09	A	1
SHAKEOUT					
Beam	bundle	4	0.26	A	1
Joist/Purlin	bundle	1	1.02	A	1
Column	bundle	2	0.51	A	1
Truss section	bundle	1	1.02	A	1
Diagonal brace	bundle	1	1.02	A	1
ERECT					
Beam	member	1	6.13	A	1
Joist/Purlin	member	1	6.13	A	1
Column	member	1	6.13	A	1
Truss	member	1	6.13	A	1
Diagonal brace	member	1	6.13	A	1
Install bolt	bolt	1	1.02	A	1
PLUMB					
Bay	bay	2	5.11	B	2
Column	column	1	2.55	B	2
PERMCON					
Install bolt on floor	bolt	1	0.13	B	2
Tighten bolt on floor	bolt	1	0.51	B	2
Install bolt at height	bolt	1	0.26	B	2
Tighten bolt at heig	bolt	1	1.02	B	2
Install anchor bolt	bolt	1	0.26	B	2
Tighten anchor bolt	bolt	1	1.02	B	2
weld	inch	1	1.53	C	1
DECK					
stud	stud	1	0.26	D	1
deck sheets	sheet	1	4.09	D	1

*---Enter a one (1) in items that will n
to avoid division by zero.

	SUMMAR
Crew A	1
Crew B	2
Crew C	0
Crew D	1
Total ironw	9

TOTAL TIMES (min)

TOTAL TIMES (min)

Total Ironw	9

Members	quantity		UN	SH	ER	
Columns	42	42	85.8	21.5	257.4	
Girders/su	56	56	57.2	14.3	343.2	
Bracing be	48	48	49.0	12.3	294.2	
Filler beam	120	120	122.6	30.6	735.5	
Diagonal b	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	
			314.6	78.7	1630.4	Total min
			5.2	1.3	27.2	Total hrs
			0.7	0.2	3.4	Total days

Connectio	quantity		ER ins	PC ins	PC tight	
	ER ins	PC ins				
Anchor bol	126	0	32.2	0.0	128.7	
Column sp	126	126	32.2	32.2	257.4	
Beam/gird to co	224	1120	57.2	286.0	1372.9	
Beam/gird to co						
Shared	240	240	61.3	61.3	490.3	
Unshar	48	96	12.3	24.5	147.1	
Beam/gird to Be						
Shared	320	320	81.7	81.7	653.8	
Unshar	64	128	16.3	32.7	196.1	
Diagonal b			0.0	0.0	0.0	
			293.2	518.4	3246.4	Total min
			4.9	8.6	54.1	Total hrs
			0.6	1.1	6.8	Total days

Plumbing	quantity		PL	
Bay	24	24	122.6	
Column	0	0	0.0	
			122.6	Total min
			2.0	Total hrs
			0.3	Total days

Decking	quantity		DE	
Studs	3200	3200	817.2	
Sheets	384	384	1569.1	
			2386.3	Total min
			39.8	Total hrs
			5.0	Total days

SUMMARY OF RESULTS

Time Estimates

Stage	Time	
UN	0.66	days
SH/ER	4.17	days
PL/PC	8.10	days
DE	4.97	days
Considering ov	10.00	days

ANALYSIS

Cost

Rates		
supervisor	45	$/hr
ironworker	35	$/hr
helper	25	$/hr
crane	800	$/day
Project Direct Cost:	$32,000	

Resources

Crane Utilization:	5	days
Number of cranes:	1	cranes
Number of workers plus supervis	10	workers

Productivity

Members:	53	per day
Bolts :	98	per person

APPENDIX D

MANUAL COMPUTATIONS

MANUAL COMPUTATIONS

Definitions

T = tons of steel in project
n = number of trucks
M = number of members in project
N = number of field bolts in project
m = number of members in a truck
un = days to unload M (obtained from spreadsheet)
sh/er = days to shakeout and erect M (obtained form spreadsheet)
pl/pc = days to plumb and permanently connect M (obtained from spreadsheet)
de = days to complete decking (obtained from spreadsheet)
x = quantity variable in a linear relation
t = time variable in a linear relation

Note: x and t may both appear in a linear relation, which pressumes one has been previously computed.

Assumptions

1 day = 8 hrs

Determine resource limitations (for example, using only one crane for unloading, shaking out and erecting).

Formulas

$n = (T * 2{,}000 * 1.10) / (40{,}000)$. Add 10% to provide space for equipment.

$m = M / n$

Linear relations:

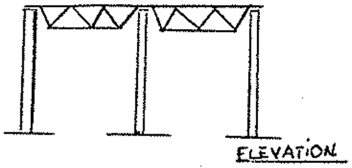
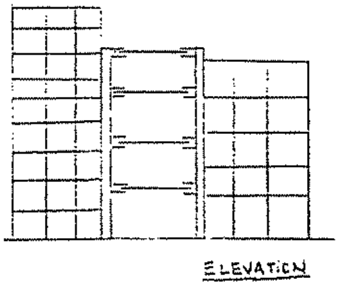
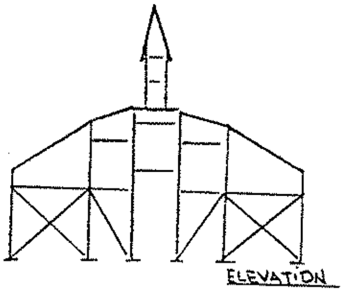
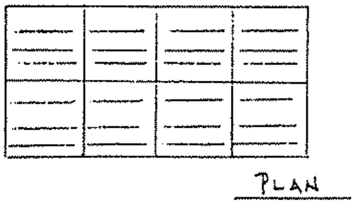
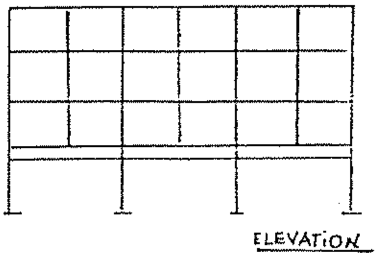
$(un / t) = (M / m)$
$((sh/er) / (t)) = (M / x)$
$((pl/pc) / (N)) = (t / x)$
$(de / M) = (t / x)$

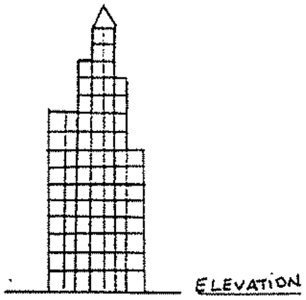
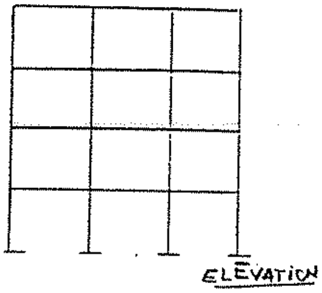
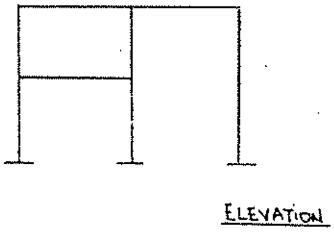
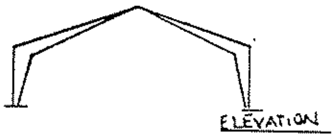
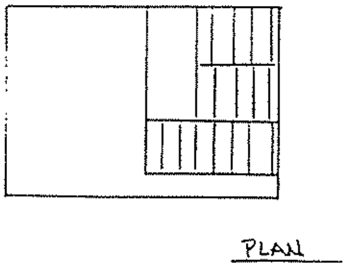
APPENDIX E

VISITED SITES

(DATA SHEETS FOR ON-SITE OBSERVATIONS)

SITE VISITS

1. Breathilizer Plant	Bethlehem, PA	
2. Chanel Building	Manhattan, NY	
3. Church	Bethlehem, PA	
4. Home Depot	Whitehall, PA	
5. MBNA	Wilmington, DE	

6. Mutual of America Building	Manhattan, NY	
7. Sacred Heart Hospital	Allentown, PA	
8. Store	Quakertown, PA	
9. Tennis Courts	Bethlehem, PA	
10. Watchtower Parking Garage	Brooklyn, NY	

INFORMATION

Site visit dates

Project Breathilizer Plant
Owner —
General contractor Boyles Associates
Erecting contractor —
Address 745 Eaton Ave., Bethlehem

Day 1) 06/23/94
Day 2) —
Day 3) —

DESCRIPTION

Square Column - Joist Frame with infill joists.
Area = $\sim 1900 yd^2$

PRODUCTIVITY

Bolts/day/person
Day 1)
Day 2) —
Day 3) —

Members/day
Day 1)
Day 2) —
Day 3) —

Lift, maneuver, position, install and tighten bolts of an infill beam : 8 min 16 sec
Lift, maneuver, position infill beam : 2 min 30 sec
Same as above : 2 min 34 sec

REPAIRS/DELAYS

One ironworker was enlarging holes w/ oxy/acet. torch.

SAFETY

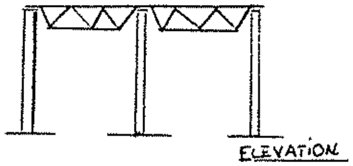
SEQUENCE OF ERECTION

Erect Column-Joist Frames → Plumb → Erect infill joists.

RESOURCES

1-telescopic crane
3-ironworkers
1- supervisor

DRAWING



INFORMATION

Site visit dates

Day 1) 08/16/94
Day 2) —
Day 3) —

Project Chanel Building
Owner —
General contractor Pavarini Construction Managers
Erecting contractor Falcon Steel
Address 57th St and Madison Ave., New York City

DESCRIPTION

Existing structure demolished as new structure was being erected. Rolled shape columns.

PRODUCTIVITY

Bolts/day/person
Day 1) —
Day 2) —
Day 3) —

Members/day
Day 1) 2 columns in two hours
Day 2) —
Day 3) —

REPAIRS/DELAYS

The temporary bracing of the walls of the adjacent buildings was an obstruction for the erection of the columns.

SAFETY

Vertical Safety nets, Wooden barricades

SEQUENCE OF ERECTION

RESOURCES

1-crane (tower)

Crew: 1- supervisor

1- crane operator

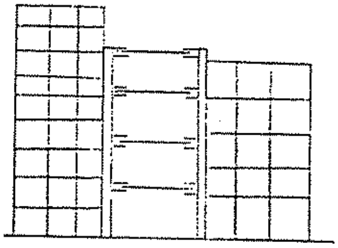
2- ironworkers unloading

1- ironworker directing

2- iron workers (idle)

others- welding, flame cutting, demolishing

DRAWING



ELEVATION

INFORMATION

Site visit dates

Project Church

Owner —

General contractor Berks Ridge Corporation, Inc.

Erecting contractor Pasco Steel Erectors

Address Center St and Dewberry St. Bethlehem, PA

Day 1) 08/18/94

Day 2) 08/19/94

Day 3) —

DESCRIPTION

Braced framing, simple framing, steel joists, rolled shapes, metal deck.

PRODUCTIVITY

Bolts/day/person

Day 1) —

Day 2) —

Day 3) —

Members/day

Day 1) —

Day 2) Approx. 200 members in 4 days

Day 3) —

REPAIRS/DELAYS

Additional connecting plates had to be ordered and welded on site.

SAFETY

Guy wires to stabilize structure when only two bolts had been installed at each end of a beam to column connection.

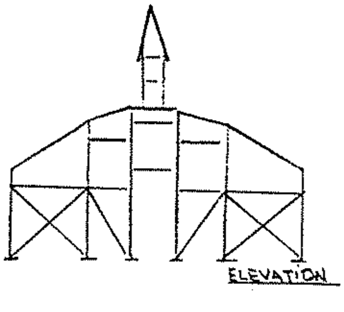
SEQUENCE OF ERECTION

Columns-beams first, Then roof joists

RESOURCES

1- crane (telescopic)
5 - ironworkers (3 ER, 2 PC)
1 - Supervisor

DRAWING



INFORMATION

Site visit dates

Project: Home Depot Department Store
Owner: —
General contractor: —
Erecting contractor: Craig Sidleg
Address: Mc Arthur Rd. and US22, Whitehall, PA

Day 1) 07/07/94
Day 2) —
Day 3) —

DESCRIPTION

One-Story building. Plan: 8×7 bays. Rigid frame. Fillet Welds. Not many bolts. Beams spot welded to girders.

PRODUCTIVITY

Bolts/day/person
Day 1) —
Day 2) —
Day 3) —

Members/day
Day 1) —
Day 2) —
Day 3) —

REPAIRS/DELAYS

—

SAFETY

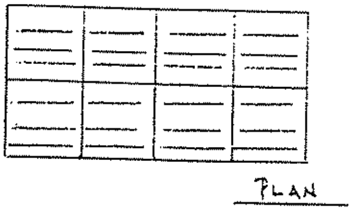
SEQUENCE OF ERECTION

Columns first, then girders. Next, use guy wires. Plumb, and bolt or weld.

RESOURCES

1- crane (telescopic)
1- helper
6- ironworkers
1- supervisor

DRAWING



INFORMATION

Site visit dates

Project: MBNA
Owner: —
General contractor: —
Erecting contractor: Falcon Steel
Address: 11th and King St., Wilmington, DE

Day 1) 10/04/94
Day 2) —
Day 3) —

DESCRIPTION

Moment steel frame with composite deck floor system. Also, transfer girders.

PRODUCTIVITY

Bolts/day/person
Day 1) —
Day 2) —
Day 3) —

Members/day
Day 1)

SH:
4 beams in 15 min
(beams shaken out from pile)
ER:
1 beam — 2 min 40 sec
" " — 2 " 20 "
" " — 2 " 00 "
" " — 1 " 30 "
Note: These beams were erected 1 by 1. Time is measured from moment beam was lifted to moment hook was released.
3 beams — 2 min 30 sec
Note: 3 beams lifted together.

Day 2) —
Day 3) —

REPAIRS/DELAYS

—

SAFETY

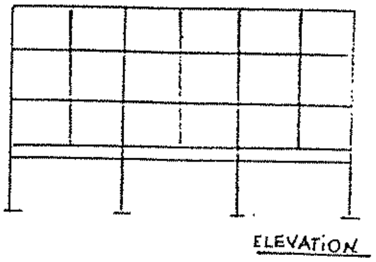
Perimetral wires were set on the floor on which erection was going on.

SEQUENCE OF ERECTION

RESOURCES

- One tower crane
- Erection Crew:
  - 2-IW erecting
  - 3-IW hooking/preparing
  - 1-Supervisor
- Plumbing/Decking/Bolting up --- Many other IW

DRAWING



INFORMATION

Site visit dates

Project Rehab of Mutual of America Building
Owner Mutual of America
General contractor Turner Co.
Erecting contractor Falcon Steel
Address 320 Park Ave. Manhattan

Day 1) 07/20/94
Day 2) 07/22/94
Day 3) —

DESCRIPTION

Multistory Steel frame rehabilitation.

PRODUCTIVITY

Bolts/day/person
Day 1) —
Day 2) → wouldn't provide info. One measurement was 2bolts/min/person
Day 3) —

Members/day
Day 1) —
Day 2) —
Day 3) —

REPAIRS/DELAYS

Permanent Connection Crew: One ironworker was using the flame cutter to enlarge holes.

SAFETY

Vertical, perimetral, orange nets set by Turner Co. on all floors About waist level. When Falcon finished erecting a floor, they had to move the net to the edge of the building, otherwise they could be fined by Turner. Horizontal, perimetral, black nets on ~15th floor only. Wooden barricades around open spaces were installed by Turner. Decking every 32′ max ⇒ every other floor.

SEQUENCE OF ERECTION

Unload/Shakeout → Erect (and "connect" two bolts @ ea. end) all bays → PLumb/"Bolt-up" → Continue Bolting-up → Floor.

Plumbing as shown on page 5/5.

Floor: Infill beams → Deck → studs → Pour concrete

RESOURCES

1-Crane (tower)

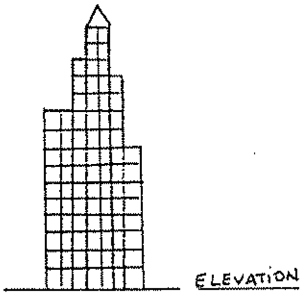
9-Ironworkers (1 welder and 1 helper, 2 erectors and 1 helper, 2 shakers and 1 helper, 1 flamer) --- all were demolishing 36th floor (Area = ~40′ × 60′), and erecting.

5-Ironworkers (5 permanent connectors) --- on 24th Floor.

2-Ironworkers (2 plumbers) --- on 23rd floor - Had a level and rod.

Note: 9+5+2 ≠ 16 since shared resources. Couldn't tell whether 16 or 14 ironworkers

DRAWING



INFORMATION

Site visit dates

Day 1) 08/19/94

Day 2) —

Day 3) —

Project: Addition to Sacred Heart Hospital

Owner: —

General contractor: —

Erecting contractor: L & L Erectors

Address: 5th St. and Chew St., Allentown, PA

DESCRIPTION

Rigid frames with infill beams. Metal deck for floor.

PRODUCTIVITY

Bolts/day/person

Day 1) —

Day 2) —

Day 3) —

Members/day

Day 1) Erection Completed in 4 days (w/o permanently connecting) (approx. 300 members) (First day: 23 columns + all of first floor)

Day 2) —

Day 3) —

REPAIRS/DELAYS

Rained during two days.

SAFETY

SEQUENCE OF ERECTION

All 28 columns first. Then erect by bay: perimetral beams and infill beams. Floor by floor.

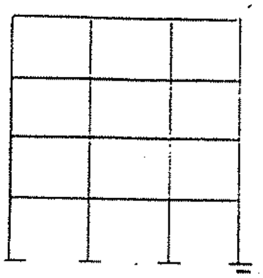
RESOURCES

1- Telescopic crane 1st week : ER, SH, UN

5- Ironworkers first week: ER

3- Ironworkers second week: PC, PL, DE

DRAWING



INFORMATION

Site visit dates

Project Store
Owner —
General contractor —
Erecting contractor —
Address Rt. 309, North of Quakertown

Day 1) 07/25/94
Day 2) —
Day 3) —

DESCRIPTION

Rigid frame with infill beams. One-story building. Approximately 120 yds × 100 yds. Concrete Floor. Tubular Columns.

PRODUCTIVITY

Bolts/day/person
Day 1) —
Day 2) —
Day 3) —

Members/day
Day 1) 20 min for two members. Entire structure in 4 days.
Day 2) —
Day 3) —

REPAIRS/DELAYS

—

SAFETY

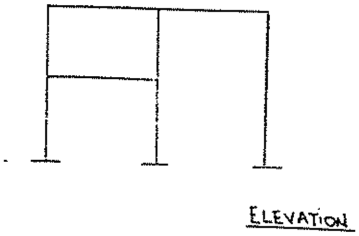
SEQUENCE OF ERECTION

Placement of all columns first. Then beams.
Plumbing - Erect as much as you can in one
day's worth of work, then plumb
and bolt simultaneously

RESOURCES

1-crane (telescopic)
7- ironworkers

DRAWING



INFORMATION

Project: Indoor-tennis courts
Owner: Lehigh University
General contractor: —
Erecting contractor: —
Address: Lehigh Univ. - Goodman Campus

Site visit dates
Day 1) 03/22/94
Day 2) —
Day 3) —

DESCRIPTION

Rigid frame and purlins

PRODUCTIVITY

Bolts/day/person
Day 1) —
Day 2) —
Day 3) —

Members/day
Day 1) —
Day 2) —
Day 3) —

Purlins
ER:
- Hook-on hoist
  1 min 06 sec
- Lift/Maneuver
  0 min 47sec

PC:
4 bolts – 8 min 10sec
4 " – 5 " 07 "
4 " – 7 " 23 "

REPAIRS/DELAYS

—

SAFETY

SEQUENCE OF ERECTION

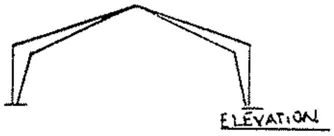
Erect frames → Stabilize frame w/ guy wires → erect purlins → PC purlins

In the erection of the frames, columns were erected first; then girders.

RESOURCES

1- telescopic crane
6- ironworkers

DRAWING



INFORMATION

Site visit dates

Project Watchtower Parking Garage
Owner —
General contractor —
Erecting contractor Falcon Steel
Address 69 Adam St, Brooklyn, NY

Day 1) 08/16/94
Day 2) —
Day 3) —

DESCRIPTION

Steel frames with infill beams to support metal deck.

PRODUCTIVITY

Bolts/day/person
Day 1) —
Day 2) —
Day 3) —

Members/day
Day 1) 80 members on first two days.
Day 2) —
Day 3) —

REPAIRS/DELAYS

—

SAFETY

Wooden barricade along retaining wall (around perimeter of site)

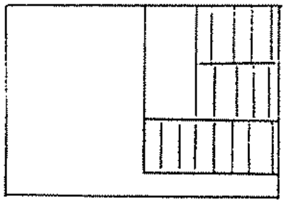
SEQUENCE OF ERECTION

RESOURCES

1-Crane (telescopic)

Crew: 1- Supervisor
1- crane operator
4- Ironworkers (2 on floor helping + 2 receiving members)-ER
1- Ironworker - PC

DRAWING



PLAN

APPENDIX F

INDUSTRY MEMBERS

(RECEIVED ERECTION FLOW DIAGRAM AND PRODUCTIVITY ESTIMATES PACKAGE)

INDUSTRY MEMBERS

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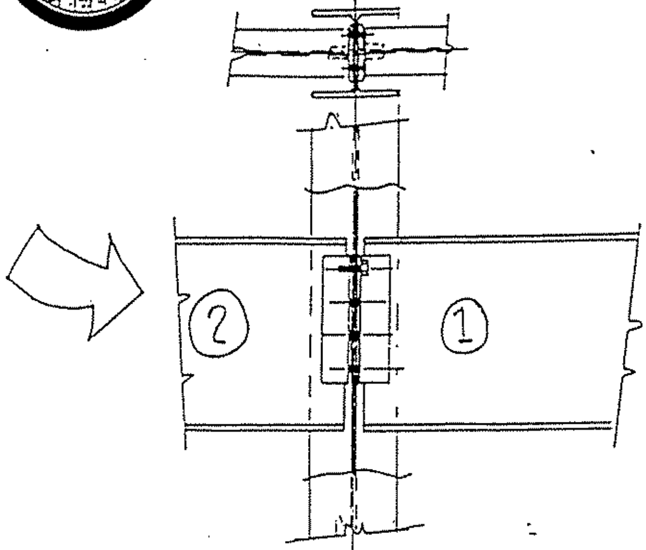
APPENDIX G

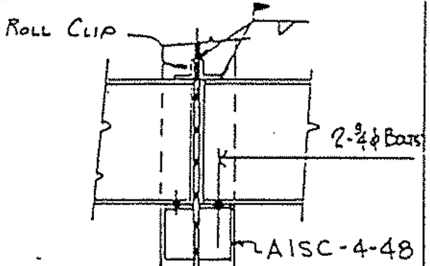
SUGGESTED CONNECTIONS



COMMON BOLTS IN COLUMN WEBS KILLS ERECTORS

THE ERECTOR SITS ON ONE BEAM WITH THE BOLTS STICKING OUT. THE SECOND BEAM CAN KNOCK FIELD BOLTS OUT CAUSING, THE BEAM AND ERECTOR TO FALL.

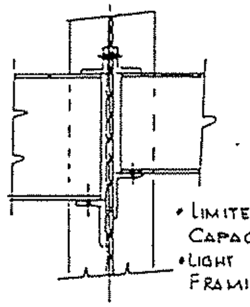
UNSAFE BEAM TO COLUMN WEB CONNECTION.



①

.SAFE

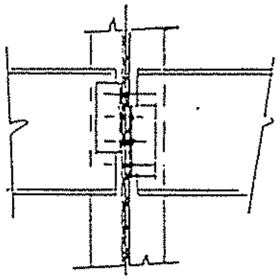
STIFFENED SEAT.



• LIMITED CAPACITIES.
• LIGHT FRAMING.

②

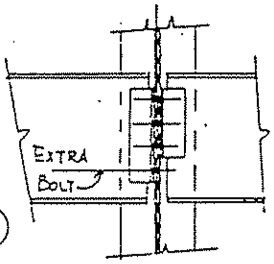
UNSTIFFENED SEATS.



③

ALLOWS FOR ERECTION IN EITHER DIRECTION

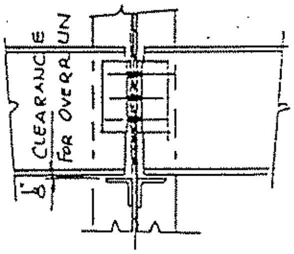
STAGGERED CLIPS



④

CAN ONLY BE ERECTED IN ONE DIRECTION.

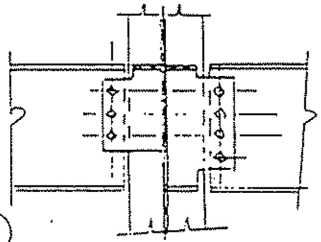
CLIPS W/ EXTRA BOLTS.



⑤

ADDED COST.

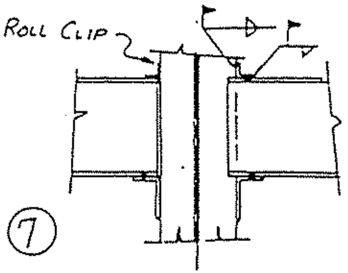
CLIPS W/ ERECTION SEATS



⑥

WEST COAST DETAIL / EXPENSIVE TO FABRICATE

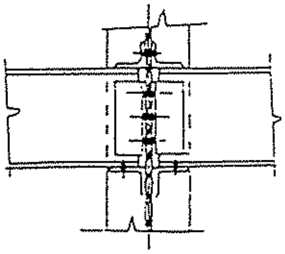
ONE SIDED SHEAR PLATE.



⑦

GOOD FOR LIGHT FRAMING. BEAMS DON'T TRAP IN COL. WEB.

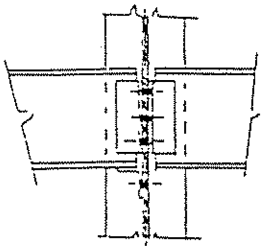
UNSTIFFENED SEAT ON COL. FLGS.



⑧

DIFFICULT TO FABRICATE AND EXPENSIVE

HEAVY FRAMING.

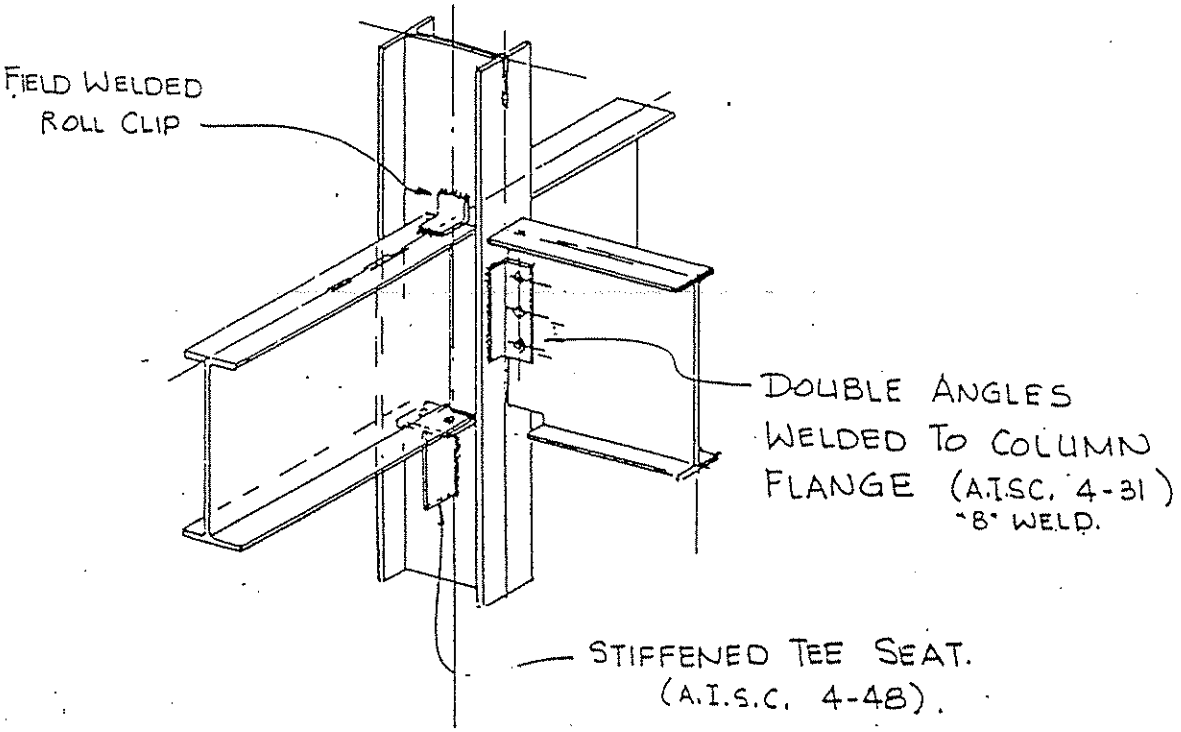


⑨

ERECTS IN ONE DIRECTION ONLY

SINGLE BOTTOM CLIP.

SAFE BEAM TO COLUMN WEB CONNECTIONS



RECOMMENDED BEAM TO COLUMN CONNECTIONS

1. SAFETY
2. ERECTS WITH ONE BOLT
3. ELIMINATES BUILDING PACKING OUT OR IN.
4. AVOIDS CONFLICTS BETWEEN WEB & FLANGE BOLTS.
5. CAN RESULT IN COLUMNS ALL WELDED & PUNCHED BEAMS.
6. FASTER HOOK TIME DURING ERECTION.

APPENDIX H

SENSITIVITY ANALYSIS

	CONECTION TIME				TOTAL ERECTION TIME		
	STANDARD	ATLSS	PERCENT		STANDARD	ATLSS	PERCENT
BASE CASE	2965.20	1792.00	39.57		6424.08	5250.88	18.26
VARY UNLOAD							
0.33 min	2965.20	1792.00	39.57		6424.08	5250.88	18.26
0.5 min	2965.20	1792.00	39.57		6468.50	5295.30	18.14
0.75 min	2965.20	1792.00	39.57		6535.00	5361.80	17.95
1.00 min	2965.20	1792.00	39.57		6601.50	5428.30	17.77
VARY SHAKE-OUT							
0.5 min	2965.20	1792.00	39.57		6291.08	5117.88	18.65
1.0 min	2965.20	1792.00	39.57		6424.08	5250.88	18.26
1.5 min	2965.20	1792.00	39.57		6557.08	5383.88	17.89
2.0 min	2965.20	1792.00	39.57		6690.08	5516.88	17.54
2.5 min	2965.20	1792.00	39.57		6823.08	5649.88	17.19
3.0 min	2965.20	1792.00	39.57		6956.08	5782.88	16.87
VARY ERECTION BOLT							
0.25 min	2825.20	1792.00	36.57		6231.58	5198.38	16.58
0.5 min	2965.20	1792.00	39.57		6424.08	5250.88	18.26
0.75 min	3105.20	1792.00	42.29		6616.58	5303.38	19.85
1.0 MIN	3245.20	1792.00	44.78		6809.08	5355.88	21.34
VARY ERECTION MEMB							
5.0 min	2965.20	1792.00	39.57		5892.08	4718.88	19.91
7.5 min	2965.20	1792.00	39.57		6557.08	5383.88	17.89
10.0 min	2965.20	1792.00	39.57		7222.08	6048.88	16.24
VARY PLUMBING INSTA							
10.0 min	2965.20	1792.00	39.57		6424.08	5250.88	18.26
12.5	2965.20	1792.00	39.57		6439.70	5266.50	18.22
15.0 min	2965.20	1792.00	39.57		6455.33	5282.13	18.17
VARY PLUMB MEMBERS							
10.0 min	2965.20	1792.00	39.57		5799.08	4625.88	20.23
25.0 min	2965.20	1792.00	39.57		5892.83	4719.63	19.91
50.0 min	2965.20	1792.00	39.57		6049.08	4875.88	19.39
75.0 min	2965.20	1792.00	39.57		6205.33	5032.13	18.91
100.0 min	2965.20	1792.00	39.57		6361.58	5188.38	18.44
120.0 min	2965.20	1792.00	39.57		6486.58	5313.38	18.09
VARY P C INSTALL							
0.25 min	2461.20	1680.00	31.74		5888.58	5107.38	13.27
0.5 min	2965.20	1792.00	39.57		6424.08	5250.88	18.26
0.75 min	3469.20	1904.00	45.12		6959.58	5394.38	22.49
1.0 min	3973.20	2016.00	49.26		7495.08	5537.88	26.11
VARY P C TIGHTEN							
0.5 min	2506.00	1344.00	46.37		5872.48	4710.48	19.79
1.0 min	3654.00	2464.00	32.57		7251.48	6061.48	16.41
1.5 min	4802.00	3584.00	25.36		8630.48	7412.48	14.11
2.0 min	5950.00	4704.00	20.94		10009.48	8763.48	12.45
VARY P C KNOCK-OUT							
0.25 min	2965.20	1792.00	39.57		6424.08	5250.88	18.26
0.5 min	3035.20	1792.00	40.96		6494.08	5250.88	19.14
0.75 min	3105.20	1792.00	42.29		6564.08	5250.88	20.01
1.0 min	3175.20	1792.00	43.56		6634.08	5250.88	20.85