Simulation to Assess Cast-In-Place Concrete Construction Innovations

by

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B.Sc. in Civil Engineering, University of Alberta, 1996

Submitted to the Department of Civil and Environmental Engineering in partial fulfillment of the requirements for the degree of

Master of Science in Civil and Environmental Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1998

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Abstract

A computer-based model for simulating cast-in-place (CIP) concrete construction is developed and used to assess the impacts of innovations on the CIP concrete construction process. Three alternative simulation approaches were considered: the queuing approach, the graphical approach, and the dynamic process approach. The dynamic process approach is selected as the basis for the simulation model. In order to develop a dynamic process model, detailed information had to be gathered on the CIP concrete construction process and on all the specific attributes affecting it. Literature, construction site visits, and interviews with industry professionals were used as data sources. A general process flow describing the CIP concrete construction process was established and it was subsequently used to develop a computer-based dynamic process model of the CIP concrete construction process. SIMPROCESS® is the environment in which the dynamic process model operates. A prototype building was designed and project specific information associated with its construction was incorporated within the model in order to verify the model's reliability. It is then used to evaluate the anticipated impact of three CIP concrete construction innovations on the CIP concrete construction process: the Talon ²360 Rebar Crosstie System, High-Performance Self-Compacting Concrete, and Precast Concrete Stay-In-Place Forms.

Thesis Supervisor: E. Sarah Slaughter
Title: Assistant Professor

Acknowledgments

I would like to express my gratitude to: my parents Larry and Sandy, my brothers David, Steven and Christopher, and my fiancee Michelle for their love, encouragement and support; Professor Sarah Slaughter for her inspiration and guidance; everyone with whom I spoke in the construction industry for having taken the time to help me with this research; CACI Products Inc. for having provide the SIMPROCESS® software; and the National Science Foundation for their funding of this research.

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Chapter 1 : Introduction

1.1 Background

The construction industry is often perceived as being rather slow when it comes to adopting new innovations. This does not mean that innovation within construction does not occur; however, it does indicate that the barriers to adopting new innovations in construction are substantial. One such barrier is the risk associated with the uncertainty of trying something new and different in construction, risk that in many instances outweighs any perceived rewards. Because construction is such a complicated process, it is often very difficult to determine with any reasonable level of certainty how an innovation might impact the construction process without actually putting it to the test in the field. Therein lies the problem. Innovations are adopted when their perceived benefits outweigh their perceived risks, but often this adoption only occurs in construction once an innovation has been tested in the field. Good innovations often do not get adopted simply because it is difficult to distinguish them from the bad ones prior to their use in the field. If there was some way of being able to gauge the impacts of innovations on construction prior to their use in the field, perhaps more innovations would be adopted.

Suppose for a moment that the construction process could be simulated with reasonable accuracy on a computer. It follows that an innovation could be placed within the simulation environment and many of its impacts on the construction process could be anticipated prior to its use in the field. Its performance in the simulation model would be an indication of how it would perform in the field, and, suddenly, the perceived benefits of a good innovation would make it a little more appealing and a little less risky, despite the fact that it has never been tested in the field. Now, imagine how the very same construction simulation model could be used to help anticipate the impact of alternate designs on the construction process, or be used to find those aspects of the construction process where the greatest potential savings in time, cost, and worker safety could be achieved. Clearly, the benefits of such a tool would be far reaching. One question remains. Can such a simulation model be created?

Ideally, this kind of simulation model would have to be responsive to the very same factors that affect the construction process (e.g., design, site management strategies, resource availability). It would have to map the construction process right down to the smallest level of detail and include within it the alternative courses of action that exist within actual construction. It would have to account for varying activity processing times and the variables of which these times are a function. It would have to consider that required resources are shared among different activities and that this resource sharing is often not cyclical in nature. It would have to track the flow of construction activity deliverables (i.e., the pieces and elements created through construction) and account for their transformation and assembly as they advance through the construction process. Finally, it would have to be simple to use and easy to modify. This thesis describes the research involved in developing one such model for simulating cast-in-place (CIP) concrete construction.

1.2 Research Objective

The purpose of this research was to develop a representative dynamic process model for simulating cast-in-place (CIP) concrete construction to evaluate the impact of innovations and design changes on the CIP concrete construction process. The objective was achieved in four steps. First, research on the CIP concrete construction process was conducted, and information on specific conditions [capable of affecting it] was gathered. Second, the framework for a general process model capable of being used to simulate construction of any CIP concrete building was created using all of the research information that had been gathered. Third, a prototype building was designed, and specific information relating to it was added to the framework of the general process model to establish a specific process model for simulating construction of the prototype building. Finally, the model was tested by simulating construction of the prototype building with and without innovations.

1.3 Thesis Organization

Chapter 2 is a detailed examination of the three basic types of modeling approaches that may be used to simulate the construction environment: queuing models, graphically based models, and dynamic process models. The advantages and limitations of each approach are described, and references are made to the latest research developments in each area.

Chapter 3 is an overview of the research methodology. Data sources and data collection strategies are reviewed, as are the techniques used to verify the reliability of all information that was gathered.

Chapter 4 is an in-depth description of the CIP concrete construction process. It begins with an overview of the general process, and then goes into considerable detail describing each of the different activities and alternatives within the general process.

Chapter 5 is the description of the computer-based dynamic process model developed for simulating CIP concrete construction. It includes an overview of the basic modeling strategy, an outline of the model structure and a description of the prototype building used in testing the model's reliability with simulation results.

Chapter 6 introduces and describes three innovations in CIP concrete construction that were evaluated using the in CIP concrete construction simulation model. Four simulation runs were conducted. The first three simulate each of the three innovations individually, and the fourth simulates the use of two of the three innovations at once. The results of each simulation are summarized and discussed.

Chapter 7 summarizes all of the research work performed in this thesis and outlines some of the applications that the CIP concrete construction simulation model is particularly well suited for. The chapter ends with a quick look ahead towards the future of dynamic process modeling in construction.

1.4 Summary of Major Results

A computer-based dynamic process model capable of simulating cast-in-place (CIP) concrete construction was successfully developed and was used to simulate construction of a prototype building both with and without innovations. The model is representative of actual CIP concrete construction, is easy to modify, and is responsive to the very same factors that affect the construction process (e.g., design, site management strategies, resource availability). It accounts for varying activity processing times (and the variables of which these are a function); it recognizes that resources are shared among different activities (and that this resource sharing is usually not cyclical in nature); and it considers the transformation and assembly of construction activity deliverables (i.e., pieces and elements) as they advance through the construction process. As an evaluation tool, the model is not only useful in assessing the impact of innovations and design changes on the CIP concrete construction process, but it is also useful in finding those aspects of the construction process where the greatest potential savings in time, cost, and worker safety can be achieved.

Chapter 2 : Background on Construction Simulation Modeling

This section focuses on the three basic types of computer-based models used to simulate the construction environment: queuing models, graphically based models, and dynamic process models. The purpose is to outline their aim, their characteristics, and the type of insight that they can provide into the construction environment. Since the construction environment is characterized by the interaction of numerous factors relating to resource usage, design, and construction process, a simulation model seeking to be representative of this environment must also account for these various factors and their interactions with one another. A trade-off exists, however, between a model's level of complexity and the degree to which it is representative of the actual construction environment.

2.1 Queuing Models

Perhaps the most established of the three types of computer models used to simulate the construction environment are queuing models. Queuing models are particularly useful in modeling standardized systems, where activity processing times follow some kind of standard distribution, much like in the manufacturing environment. Each activity unit within a queuing model can be thought of as a processing station, and the processing time for an entity passing through each station is a function of a predetermined time distribution associated with that particular station. Entities either wait in a queue or get processed in a station. They are, however, never modified or changed at these stations. Entities are only delayed by station processing times. A key premise of queuing models is that station processing times are not a direct function of the entities passing through them but rather are based on predetermined distributions. The following example should help to clarify the concept of queuing models.

Figure 2.1 is a schematic representation of a basic queuing model describing the loading and unloading of dump trucks in a cut and fill operation. This model has two basic entities (trucks and loaders), five activity processing stations (Fill Loader Bucket, Load Truck, Travel to Dump Site, Empty Truck, and Travel to Load Site), and four queuing stations. There are two repeating cycles in the model, the load/unload loader cycle, and the load/travel/unload/travel truck cycle. Each of

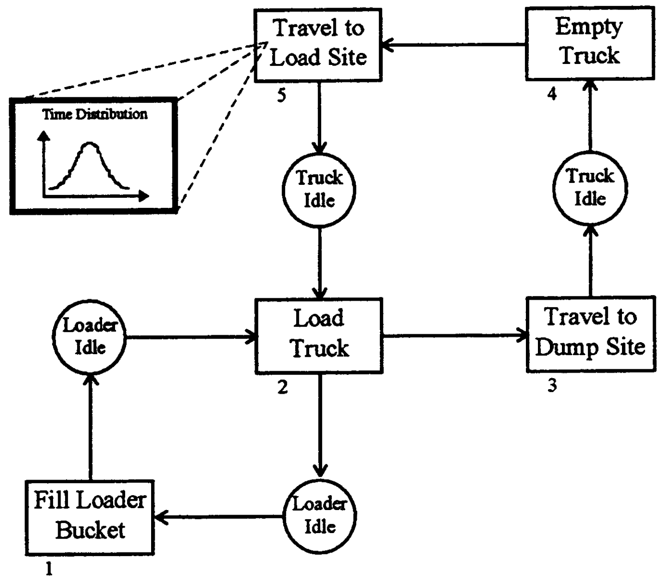


Figure 2.1: Queuing Model of Cut and Fill Operation

the five activity processing stations has an associated processing time distribution, and consequently, the time it takes for a particular truck to travel to the dump site, for instance, is independent of the truck in question. All of the trucks within the model are identical to the others, and the same can be said of all the loaders. None of the entities are transformed over the course of the simulation.

This queuing model, as with all others, is primarily concerned with entity waiting and processing times. The question it seeks to answer is, "What combination of loaders and trucks yields the lowest cycle time?" The focus is on resource efficiency, and on how a process can be optimized through proper resource allocation. For a given process, cycle time is just a function of resource allocation and user specified activity processing time distributions. The process itself doesn't change over the course of the simulation and nor do the attributes of the entities or the activities.

Perhaps two of the most commonly associated names with construction environment simulation modeling are CYCLONE and MicroCYCLONE. Both are computer software packages. The former is mainframe based, and the latter is for microcomputers. Both were developed by Professor Daniel W. Halpin of Purdue University, and they have come to characterize queuing model simulation in the construction industry.

The CYCLONE/MicroCYCLONE modeling system is made up of four basic elements: resource entities which move around within the model, square activity state nodes which represent work tasks (and which can be either constrained or unconstrained), circular idle state nodes which represent waiting positions, and directional flow arrows which represent the path of resource entity flow within the model. As with all other queuing models, the entities and the nodes are not altered over the course of a simulation run, nor is the entity flow path which is predefined and cyclical in nature. There are no decision branches, and if/then conditions only affect the starting times of the work tasks within the flow. When an activity node is empty, for instance, it checks to see if all the resource entities that it requires are available and if all of its predefined constraints are met. If these conditions are met then the activity is allowed to proceed.

There are numerous examples of queuing based simulation models of the construction environment. Alkoc and Erbatur (1997) used MicroCYCLONE to simulate the placing of slab, beam, and column concrete. They considered two methods of concrete placement: (1) with cranes and buckets; and (2) with pumps. Their models account for those activities occurring between when the concrete is ready at the batch plant all the way through to when it is trowelled and ready for curing. Moselhi and Hanson (1994) used MicroCYCLONE to simulate the placing and finishing of concrete slabs on grade. Their models were used to compare semi-automated placing techniques with conventional manual ones. Cheng and O'Connor (1993) used MicroCYCLONE to model the process of pipe construction in order to identify critical tasks and factors that could be contributing to piping construction inefficiencies. Shi and AbouRizk (1997) used CYCLONE for their resource specific "atomic" models used in their resource-based modeling (RBM) system. Their RBM system automatically generates project specific queuing models from a library of atomic models once a project's required resources and specifics are input by a user. The example given to demonstrate RBM was an earth moving project.

2.2 Graphically Based Models

A significantly different approach to construction environment simulation modeling involves the use of computer graphics. Unlike queuing models, which are only concerned with resource usage optimization, graphically based models are more concerned with the spatial feasibility of constructing something in a particular way. Resource usage optimization is somewhat of a lower order concern. Graphical models help to uncover time-space conflicts in construction projects, usefully communicate construction methods to contractors, and identify how certain design and construction decisions impact overall construction processes.

The interest in graphically based simulation models arose from the desire to link construction experience and knowledge to project planning and design. Computer-aided-design (CAD) was already quite prevalent in the industry, and as a result was quite naturally seen as a possible interface between design and construction. Graphical simulation models such as 4D-CAD and Interactive Visualizer ++ (IV++) stem from the combining of CAD drawings to a construction schedule.

The concept behind graphically based simulation models is a fairly straightforward one. First, the geometric information associated with each element involved in the construction process needs to be defined. Since design inherently requires that all elements involved in a construction project be defined geometrically, this step is generally taken care of during the design phase with a CAD package.

Next, once the geometry of all the elements has been established, the sequence in which each element will be erected during construction needs to be defined. This is probably the most difficult aspect of graphically based simulation models, especially in construction, since the number of individual elements is often very large. Usually simplifying assumptions are made to make this task more manageable. Some additional information that may also be tagged to each element include its original position prior to erection, its final position following erection, and the equipment resources required for its erection (e.g., a crane).

Once all of the data associated with each of the elements have been defined, the same must also be done with each of the equipment resources being used during construction. Pertinent information include their geometry, their degrees of mobility, and their rates of productivity.

Graphically based simulation models are specifically tied to design. The question that they seek to answer is, "Are there any spatial interferences that are likely to occur during construction as a result of this design?" The underlying assumption here is that construction process remains fixed over the course of the project. (Recall construction sequence is predetermined when a model is initialized.) This is important to note. Construction process is not the object of graphically based models, but rather it is an underlying assumption within them. For the sake of simplicity, construction process is assumed to be independent of design.

Advances in three dimensional imaging are leading to several exciting developments in graphically based simulation modeling. 4D-CAD work being done by Professor Martin Fisher at Stanford University combines "Responsive Workbench", a state-of-the-art 3D interactive graphics system that projects computer-generated stereoscopic images onto a tabletop, with the concepts of graphically based simulation modeling. The result is a more visually realistic and a more interactive modeling environment.

Other researchers have also worked on the concept of graphically based modeling. Vanegas and Opdenbosch (1994) described the use of the graphically based modeling package Interactive Visualizer ++ to simulate the construction of a simple building structural frame. They explained how use of their method allows designers and builders to visualize construction operations in a virtual environment while a project is still in its design phase and they also incorporated the concept of "building objects" (BO) within it. (Building objects is a way of listing elements in a hierarchical and sequential manner that simplifies the element sequencing task common to graphically based models.) Stouffs et al. (1993) developed their own graphically based simulation program named RUBICON, and used it to simulate the construction of a precast concrete residential building. Two equipment resources were considered in their model, a robot crane for handling heavy elements, and robot towmotor for handling palletized materials. The input for the model consisted of both a file containing a description of the elements and their erection sequence, and a file specifying the motional capabilities of each robot. The output was a 3D graphical representation of the construction process that included a visual display of each robot's activities.

2.3 Dynamic Process Models

Dynamic process models take a significantly different approach to modeling construction projects. Whereas queuing models follow the cyclical flow of resources from one construction activity to another, dynamic process models follow the flow of pieces and elements (i.e., the entities on which work is being done) from one activity to the next. The aim is to look at construction more from the perspective of industry and see it as a series of deliverable producing activities rather than simply as a cyclical flow of resources from one activity to another.

An important aspect of dynamic process modeling is that it seeks to address the dynamic nature of processes like construction. First developed for use in designing chemical processing facilities (Glasscock and Hale, 1994), dynamic process modeling considers the reality that work is performed on entities as they pass though activities. The result is that entity attributes can change over time. This is a key premise of dynamic process modeling, and a critical feature distinguishing it from the other model types. An additional feature which also sets dynamic process modeling apart from other modeling techniques is that entity attributes are capable of affecting activity processing times and even entire processes. Output from earlier activities can have a direct impact on later activities. The cyclical pattern commonly associated with queuing models and with the sequencing of graphically based models is replaced with decision branches and alternative courses of action. (Each entity only passes through the model once.) Dynamic process models therefore consider actual cause and effect relationships that exist within a process.

A further point worth mentioning is that resources in dynamic process models are not handled in quite the same fashion as they are handled in both queuing and graphically based models. In the latter case they are considered to be entities doing work, in the former case they are only thought of as conditions that must be met if work is to be done. In dynamic process models, each processing activity has various resource requirements assigned to it. Once an entity, such as a piece, arrives at a processing activity, before any work is done to that entity, the processing activity checks a pool of resources to see if those it requires are available. If they are available, it tags them and makes them unavailable to all of the activities until the one in question is complete. Once the processing activity is complete and the entity has passed through it, the tagged resources are re-released back into the pool for reuse by any other processing activity requiring them. Thus, resources perform numerous activities (i.e., are not dedicated to any particular group of activities), and are shared among these activities both spatially and temporally.

In this research, dynamic process models are made up of three key components: process flow, project specifics and overall project progress. The process flow represents the general process common to all projects of a particular type. For instance, one general process flow may represent all aspects of cast-in-place concrete construction while another may represent all aspects of structural steel erection. What is important is that all of the commonalities and construction alternatives within one particular group of projects be represented by that group's process flow. In addition, all of the entity attributes affecting the process or the duration of the individual activities within the process must also be incorporated into the process flow. Once the general process flow is established, it need not be significantly changed any further. Project specifics are used, rather, to tailor it to a specific project.

Project specifics are the characteristics of a given project that change from one project to the next. They include, but are not limited to, project design, resource availability, production rates, and site conditions. Project specifics are used to assign actual values to the attributes previously identified in the general process flow.

The overall project progress links the status of all sub-processes within a project temporally and spatially across that project. It is concerned with logical progression, technical constraints, regulatory constraints and shared resources. The combination of project flow, project specifics, and overall project progress leads to the establishment of a dynamic process model for a specific construction project.

The following example illustrates the concept of dynamic process modeling. The process that is considered is the preparation and erection of formwork. Figure 2.2 shows the general process flow. References are made to pieces and to elements. Here pieces make up elements, and elements are the components that are put in place on the job site. For instance, a site-fabricated panel is a form element made up of plywood and studs, which are form pieces.

In this example, two different entity types (form pieces, and pre-fabricated form elements) arrive on the job site. Each enters the process at one of two different starting points (identified as the thickly outlined boxes). The shading of each activity box identifies the type of entity that passes through it. No shading indicates form pieces, light shading indicates form elements, and dark

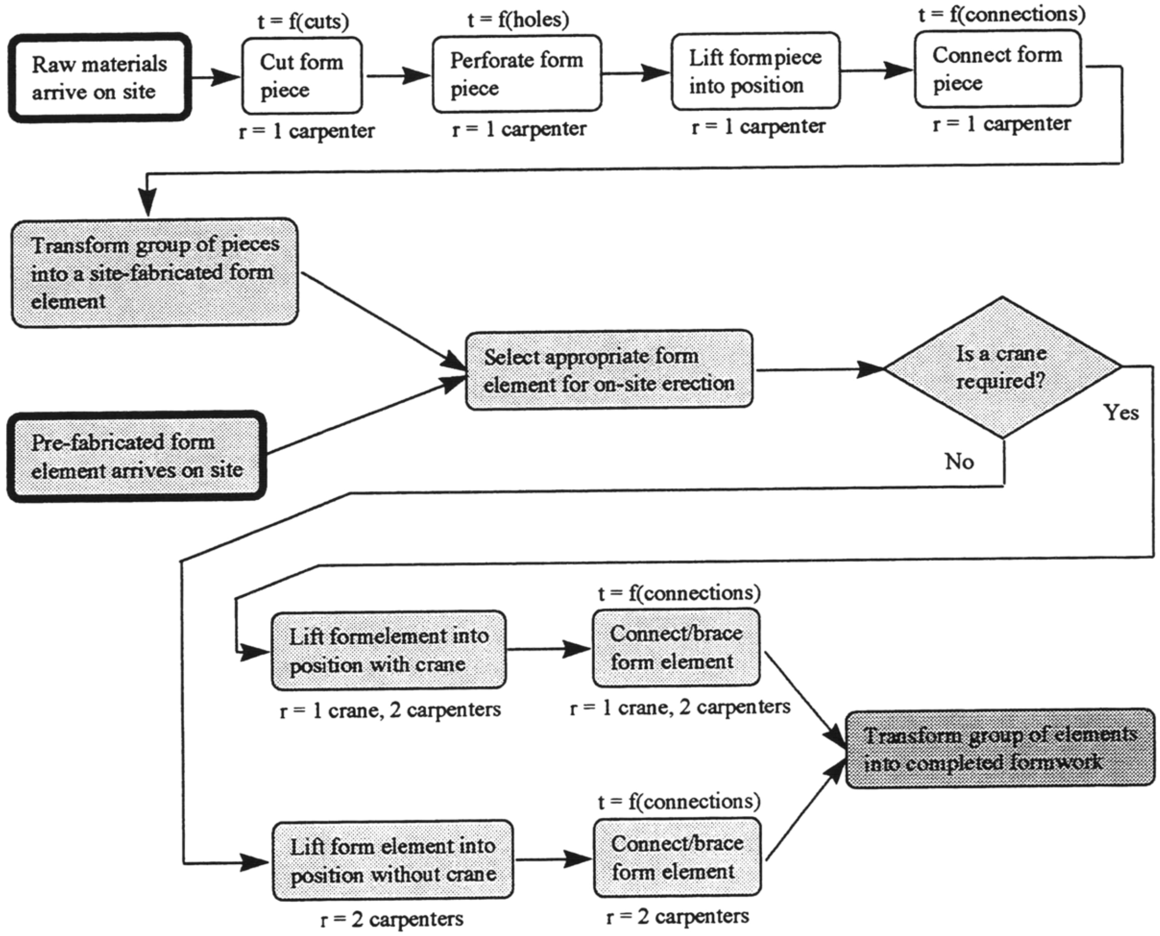


Figure 2.2: Dynamic Process Model of Formwork Preparation and Erection

shading indicates completed formwork. Over the course of the process, pieces are transformed into elements which are subsequently transformed into formwork.

Each entity has its own set of attributes which define the process. In this example, the attributes of a form piece are the number of cuts, holes, and connections it requires. The attributes of a form element are the number of connections it requires, its size/weight (to determine whether or not a crane is needed), and the number/type of pieces that make it up. Finally, the attribute of completed formwork is simply the number/type of elements that make it up. Each attribute defines either the process flow (e.g., to use a crane or not to use a crane) or the processing time of a particular activity within the process flow (e.g., the cutting time of a form piece requiring 8 cuts is twice that of a form piece requiring only 4).

Activity processing only proceeds on the condition that the required resources associated with a given activity are available from a pre-defined pool of resources. Notice how different activities require different resources and may even require combinations of resources.

Dynamic process modeling is a very new approach to modeling the construction environment. Up until now, only two dynamic process models with specific application to construction have been developed. Eraso (1995) developed the first of these which simulates the erection of structural steel members, and Attai (1997) developed the second which simulates the erection of exterior enclosure systems. The cast-in-place concrete construction model arising out of this thesis research will be the third dynamic process model developed for construction.

2.4 Summary

Queuing models, graphically based models, and dynamic process models differ significantly not only in terms of how simulation proceeds but also in terms of what is being simulated. Table 2.1 summarizes the basic differences that exist between queuing models, graphically based models and dynamic process models.

Table 2.1: Summary of Different Model Types

Dynamic Process Models	Queuing Models	Graphical Models
- Useful in modeling non-standard systems where activity processing times are a function of entity attributes.	- Useful in modeling standard systems where activity processing times may be treated as functions of predetermined time distributions.	- Useful in modeling applications where the spatial feasibility of constructing something in a particular way is the key concern.
- Well suited for modeling non-cyclical applications characterized by decision branches and alternative courses of action.	- Well suited for applications where resource usage is cyclical and where resource optimization is the primary concern.	- Well suited for communicating construction methods to contractors and allowing users to interact with the simulated construction environment.
- Entities are the units being assembled together.	- Entities are the resources.	- Entities are the units being assembled together.
- All entity attributes may be taken into account and all are free to change over the course of a simulation.	- Entity attributes are not taken into account.	- Only design related entity attributes are taken into account and these are held fixed during simulation.
- Process is non-cyclical and characterized by alternative courses of action. It is function of entity attributes and is free to change over the course of a simulation. (Design changes do influence construction process.)	- Process is fixed, pre-determined and cyclical. It is not a function of any entity attributes except for changes in quantities. (Design changes do not influence construction process.)	- Process is fixed, pre-determined and cyclical. Entity attributes simply define entity geometry and the order of entity flow through the process. (Design changes do not influence construction process.)
- Activity processing times are a function of entity attributes and are free to change over the course of a simulation.	- Activity processing times are a function of pre-determined distributions and are fixed over the course of a simulation.	- Activity processing times are a function of pre-determined distributions and are fixed over the course of a simulation.
- Resources are not dedicated to any particular group of activities but rather are shared among all activities both spatially and temporally.	- Resources are dedicated to a specific group of activities and are fixed.	- Resources are dedicated to a specific group of activities, are fixed, and must be defined in terms of their geometry and operational characteristics.

Chapter 3 : Research Methodology

The purpose of researching cast-in-place (CIP) concrete construction was to develop a dynamic process model capable of simulating the construction environment in order to be able to assess the impact of innovations and design changes on CIP concrete construction. (The concept of dynamic process modeling is introduced in Chapter 2.) Developing this dynamic process simulation model required that information on construction practices, resources, production rates, and costs be collected, analyzed and incorporated within the model.

3.1 Data Sources

Three data sources were used to conduct this research: literature, site observations, and interviews with people directly involved in CIP concrete construction. The literature review portion of the research involved the examination of engineering reference manuals, trade manuals, journal articles, and conference proceedings. Some of the more helpful pieces of literature used in this research are highlighted in Table 3.1.

Table 3.1: Some of the More Helpful Literature

Title	Authors
Formwork for Concrete (6th Edition, 1995)	Hurd, M.K.
Placing Reinforcing Bars (1992)	CRSI
Design and Control of Concrete Mixtures (5th Edition, 1991)	Kosmatka, S.H., *et al.*
Concrete Formwork (1988)	Koel, L.
Formwork: A Guide to Good Practice (1986)	Concrete Society
Steel Reinforcement (1984)	Trevorrow, A.
Concrete Construction & Estimating (1980)	Avery, C.
Construction Manual: Concrete & Formwork (1973)	Love, T.W.
Concrete Construction Handbook (1968)	Waddell, J.J.

The site observations portion of the research involved numerous construction sites visits in order to observe actual CIP concrete construction activities in progress. All of the sites visited were located in the Boston, MA metropolitan area, and several visits were often made to each of the sites in order to be able to observe the different construction activities that occur over the life of a project

Table 3.2: List of Construction Sites Visited for Data Collection

Project Name	Location	Description
Osco Drugstore	Cambridge, MA	Single story steel structure with cast-in-place concrete on grade (slabs and footings).
Doubletree Hotel University Park	Cambridge, MA	8 story steel framed hotel with concrete topping slabs on each floor and cast-in-place concrete on grade (slabs and footings).
University Park Garage	Cambridge, MA	8 story post-tensioned cast-in-place concrete parking garage.
Seaport Hotel & Parking Garage	Boston, MA	18 story steel framed hotel with concrete topping slabs on each floor above and adjacent to a 6 story post-tensioned cast-in-place concrete parking garage.
Museum Towers	Cambridge, MA	Two 25 story residential buildings made entirely of cast-in-place concrete.
Logan Airport West Garage	Boston, MA	7 story post-tensioned cast-in-place concrete parking garage with 2 stories housing office space.
Suffolk Law School	Boston, MA	7 story steel structure with cast-in-place concrete on and below grade.
Harvard University Gymnasium	Cambridge, MA	Steel framed gymnasium with cast-in-place concrete on grade.
MIT - Building 16	Cambridge, MA	Renovation of existing building with construction of a cast-in-place concrete utilities tunnel.
Suffolk County Courthouse	Boston, MA	Steel framed building with concrete topping slabs on each floor and high cast-in-place concrete structural columns.

(see Table 3.2). Additional sites were visited to obtain information on overall construction management and construction processes.

The interview portion of the research involved talking with various people directly involved in CIP concrete construction both in person and over the telephone. Interviews were conducted with people in the Boston metropolitan area and nationally. Since much of the data required for this research is tacit in nature and tied directly to the experience and knowledge of people involved in CIP concrete construction, these interviews were an invaluable data collection tool. Table 3.3 lists the names key people interviewed in conjunction with this research.

Table 3.3: List of Key Industry Contacts

Company Name	Contact Name	Contact's Location	Type of Company
Capform Inc.	Renaud, Jim	Carrollton,TX (phone)	Specialty Contractor
Cleveland Cement Contractors Inc.	Simonetti, Ronald	Cleveland, OH (phone)	Specialty Contractor
CM & B	Gallow, Tom	Cambridge, MA (site)	General Contractor
Colasanti Corp.	Colasanti, Chris	Macomb Twp, MI (phone)	Specialty Contractor
Dimeo-O'Connor Joint Venture	Oliver, Blair	Boston, MA (site)	General Contractor
Kent Companies Inc.	Krueger, Craig	Grand Rapids, MI (phone)	Specialty Contractor
Miller & Long Company Inc.	Cantrall, Mike	Bethesda, MD (phone)	Specialty Contractor
Morse Diesel International	Favazzo, Chuck	Boston, MA (site)	Construction Manager
Morse Diesel International	O'Brian, Gary	Boston, MA (site)	Construction Manager
S & F Concrete Contractors Inc.	Barb, Patrick	Hudson, MA (phone)	Specialty Contractor
Shawmut Design and Construction	Walfish, Joel	Boston, MA (office)	Construction Manager
Suffolk Construction Company Inc.	Mckasku, Bob	Cambridge, MA (site)	General Contractor
Tishman Construction Corp.	Chase, Joel	Boston, MA (site)	Construction Manager
Tishman Construction Corp.	Jenkins, George	Boston, MA (site)	Construction Manager

Each of the three data sources complemented one another other and provided a means of data verification. Talking to one individual about a certain aspect of the construction process and then seeing it done on another unrelated project, for instance, was useful in verifying the data. In addition, the appearance of discrepancies in data that was gathered from different sources helped to identify areas requiring further research in order to gain a better understanding of exactly what was going on. What is common to CIP concrete construction (as well as what varies) could be established from the three different yet complementary data sources.

3.2 Research Process Characterization

The first step in the research process was a literature review. It served as a starting point and provided insight into many of the common practices, resources, materials, and technologies involved in CIP concrete construction. In many ways, the literature review set the foundation for the remaining research work by defining the scope of CIP concrete construction.

Once a basic understanding of CIP concrete construction had been gleaned from the literature, the next step was the beginning of site visits and on-site interviews with individuals directly involved in construction activities. This stage served not only to provide real life examples of construction activities that had previously only been seen in the literature, it also helped to identify many of the variances that exist between construction theory and construction practice. Only through site visits and on-site interviews could distinctions be made between those aspects of the construction process that vary and those that do not, and, therefore, the real complexities involved in the CIP concrete construction process could really be appreciated.

Work began on a process flow diagram to try and capture all of the data that was being collected, and a list of various attributes and resources believed to be important in CIP concrete construction operations was also compiled. The process was iterative and involved constant verification and correction as more and more data was collected. For instance, when an inconsistency between what was being observed on site and what was in the flow diagram would arise, the flow diagram would be altered to account for the variance to reflect standard practice currently in use.

The process flow diagram and a comprehensive list of attributes and resources was sent out to several different people in the CIP concrete construction industry for review. At this stage, an effort was made to send out the package to some of the larger US cast-in-place concrete specialty contractors. Follow-up telephone interviews were conducted with high level officials within these companies to hear their responses and gain more insight into the CIP concrete construction process across the U.S. The responses added insights, and helped to validate the research work that had already been done. Any comments and insights offered were used to further modify and improve upon the work already done.

Both site visits and on-site interviews continued, and the information collected from these activities continued to be used to further enrich research findings. In addition, work also began in the collection of production rate (i.e., time/unit) numbers for eventual use in the simulation model. It should be noted at this stage, that the main objective of this research was not to establish a statistically representative sample of production rate data but rather to develop a model of the CIP concrete construction 'process' independent of specific production rates established. In fact, the goal was to develop a process model where production rates and project specific information could be easily modified so that the model could be used to simulate construction of any number of different CIP concrete buildings.

Once the framework for the CIP concrete construction process model was established (i.e., the process and the attributes affecting it were well defined), work began on the development of the actual computer-based simulation model itself. A commercially available simulation software package known as SIMPROCESS® was used as the modeling environment. Developed by CACI Products Company, SIMPROCESS® is a graphical interface tool used to simplify the creation and management of computer-based dynamic process models. Chapter 5 introduces SIMPROCESS® in greater detail and explains how it was used to model the CIP concrete construction process. All of the research findings were used to develop the computer-based simulation model.

To test the accuracy of the computer-based model, a prototype CIP concrete building was designed, and project specific information relating to its design and construction was put into the model. People involved in CIP concrete construction were consulted to verify the validity of the assumed project specific information, and they were also asked to estimate how long different stages of construction of the prototype building should be expected to take.

Once all the project specific information relating to construction of the prototype building was put into the model, its construction was simulated. The resulting simulated construction times were compared with those that had been estimated by people involved in CIP concrete construction, and these estimates were found to agree within 5%. This evidence demonstrates that computer-based simulation model is a reasonably accurate representation of the CIP concrete construction process.

Having established the model as a reasonably good CIP concrete construction simulation tool, it was subsequently used to assess the impact of several different innovations in construction of the prototype building. By incorporating each innovation one at a time into the simulation model and then comparing the results of each of the simulations runs with those obtained from the baseline model (i.e., the standard methods case), insight was gained into the relative impact of the each of the different innovations on CIP concrete construction for the prototype building. Chapter 6 discusses this portion of the research more thoroughly, and outlines the findings on each of the innovations that were tested.

3.3 Validity and Reliability of Results

Construction is both a science and an art. It is affected by some factors that are well defined, such as design, and by others which are far more nebulous, such as daily decisions made by project managers. Because of its large human component, construction cannot be fully modeled for simulation purposes. There will always be some degree of variance between simulation results and reality. Fortunately, however, reasonably good approximations of reality can be obtained from highly detailed and carefully designed models. The goal of this research was never to develop a 'perfect' CIP concrete construction simulation model, but rather one that could reasonably approximate the actual construction process and be responsive to the factors that are reasonably within the control of designers and planners such as the design elements, resources, and strategies for overall progress. The research approach of collecting data from three different sources (literature, site observations, and interviews), cross-checking the data from one source against that of another, developing the model framework through an iterative process, and testing the results of the simulation for construction of the prototype building against industry estimates provided an effective means to address the issues of validity and reliability of the CIP concrete construction simulation model as a reasonably good approximation of reality. The close results from the simulation model and the industry estimates demonstrate that this objective was achieved.

Chapter 4 : Cast-in-Place Reinforced Concrete Construction

As alluded to in Chapter 2, dynamic process modeling requires that a process being modeled be well understood and clearly defined. Activities must be known, alternative courses of action must be recognized, and potential disruptions in the process must be accounted for. Without a clearly defined process, dynamic process modeling is impossible. This section outlines the process of cast-in-place (CIP) concrete construction and summarizes all of the activities and alternative courses of action within it. Prior to introducing the CIP concrete construction process, however, a brief discussion of a few of concrete's physical properties is in order since these will help to explain why the CIP concrete construction process is the way it is.

First of all, in any CIP operation, concrete always arrives on site as a highly viscous fluid. It can be molded into virtually any shape, but cannot maintain its given shape without being continuously acted upon by outside forces. When it arrives, it cannot support its own weight nor can it bear any structural loading. Time is required for it to harden and cure before either of these can be accomplished. This has considerable impact on the CIP concrete construction process. It means that: (1) some kind of forming system needs to be put into place in order to mold and support the concrete while it is hardening; (2) concrete placement activities need to be specifically tailored for the placing of a fluid and not a solid; (3) any exposed concrete surfaces requiring finishing must be leveled and smoothed while the concrete is still wet; (4) any temporary forming systems used must be removed once they are no longer needed; and (5) sanding and finishing of formed concrete surfaces may be required following formwork stripping.

A second important property of concrete is that its tensile strength is but a fraction of its total compressive strength, generally somewhere between 8% and 12% (Kosmatka *et al.*, 1991). Since most structural applications require both tensile and compressive resistance, concrete alone is often not suitable as a construction material. It needs to be reinforced in some way so that tensile strength can be achieved. This impacts the CIP concrete construction process in that concrete reinforcing activities need to be included in the process.

Another very important property of concrete, and the final one to be presented here, is that concrete is very sensitive to its environment during curing. Both the ambient temperature and humidity during curing can greatly influence the quality of concrete not only in terms of its appearance but also in terms of its strength. Since CIP concrete construction often occurs on an open job site where fluctuations in ambient conditions are normal and expected, measures to minimize their impact often have to be included in the CIP concrete construction process.

4.1 General Process Flow

Three key sets of activities make up CIP reinforced concrete construction. There are the activities associated with the preparation, erection, and removal of forming systems; the activities associated with the preparation and erection of concrete reinforcing systems; and the activities directly associated with the placing, finishing, curing, and patching of the concrete.

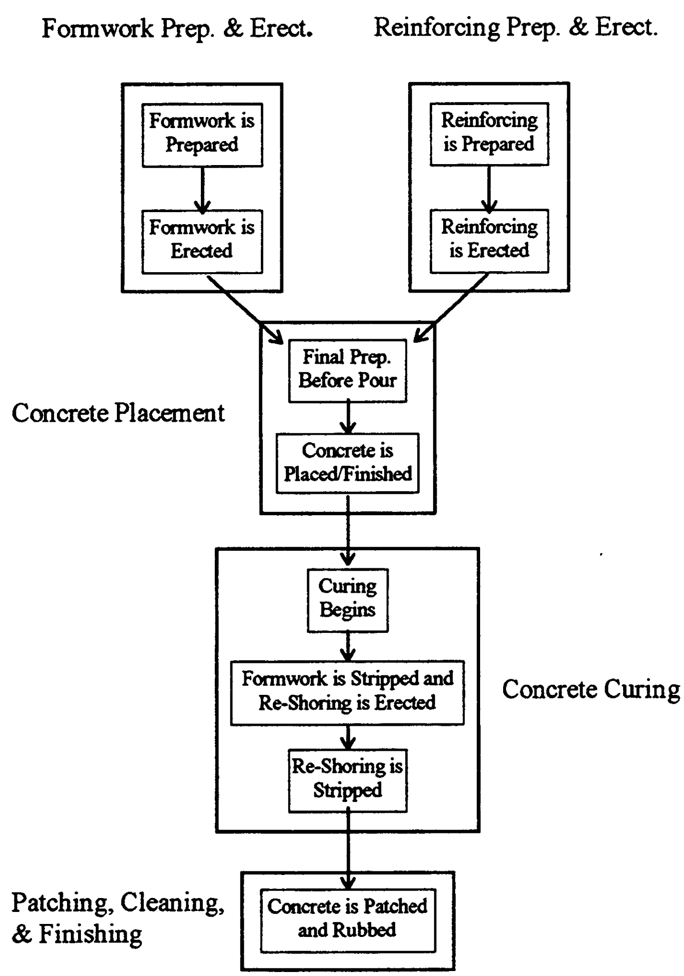


Figure 4.1: General Process Flow

A flow diagram that represents the general process of CIP concrete construction is illustrated in Figure 4.1. It is not specific to any one project but rather represents what all CIP concrete projects have in common. It seeks to capture not only all of the activities common to CIP concrete construction, but also all of the different alternatives courses of action and potential disruptions within the construction process.

The general process flow for CIP concrete construction starts off with formwork and reinforcing being prepared and erected. Although both the forming and reinforcing activities appear to be independent of each other, they are not. Sometimes formwork needs to be in place before reinforcing can be erected and sometimes it is the reinforcing that needs to be in place before the formwork can be erected. The circumstances under which each of the different alternatives can occur are discussed in Section 4.3.3. For now, it is sufficient to say that both formwork and reinforcing need to be in place before any concrete related activities can begin. Figure 4.2 illustrates what completed formwork and reinforcing for a beam awaiting concrete might look like.

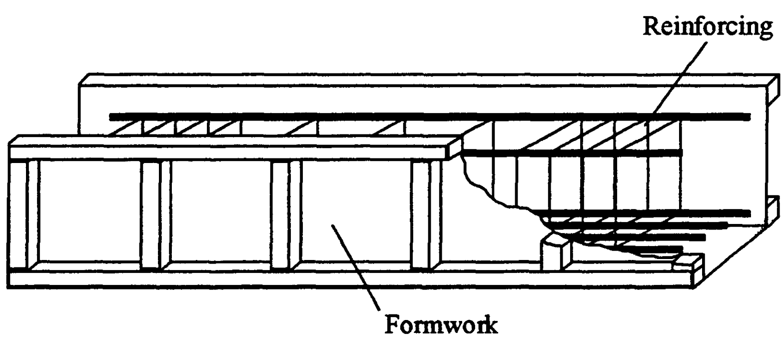


Figure 4.2: Beam Formwork and Reinforcing

When all of the required formwork and reinforcing are in place, wet concrete is then delivered to the site in trucks and is placed in the formwork around the reinforcing. Exposed concrete surfaces requiring leveling and smoothing are finished, and curing begins. During curing, steps are taken to control the temperature and moisture levels of the concrete, if deemed necessary, and then the concrete is left undisturbed for a period of time. Usually within a few days, the concrete is strong enough to support its design load and the formwork can be removed to be used elsewhere on the project. Re-shoring is used to replace the formwork and continue to support the concrete while construction loads are applied to it. Eventually additional loading from construction activities ceases and re-shoring is removed. Any surface flaws in the concrete that could not be repaired while the re-shoring was in place are subsequently patched and repaired.

4.2 Description of Entities

Before getting into the specifics of the CIP concrete construction process, this section describes the various entities used in the process. Entities are goods or deliverables that are, for the most part, produced by activities in a process. In this research, ten different entity categories were used to describe the CIP concrete construction process: buildings, floors, bays, members, pours, trucks, buckets, sections, elements, and pieces (see Figure 4.3).

Buildings are the highest order entity. They are made up of a number of floors, and each floor is made up of a number of bays. Bays are defined as structurally stable units consisting of vertical

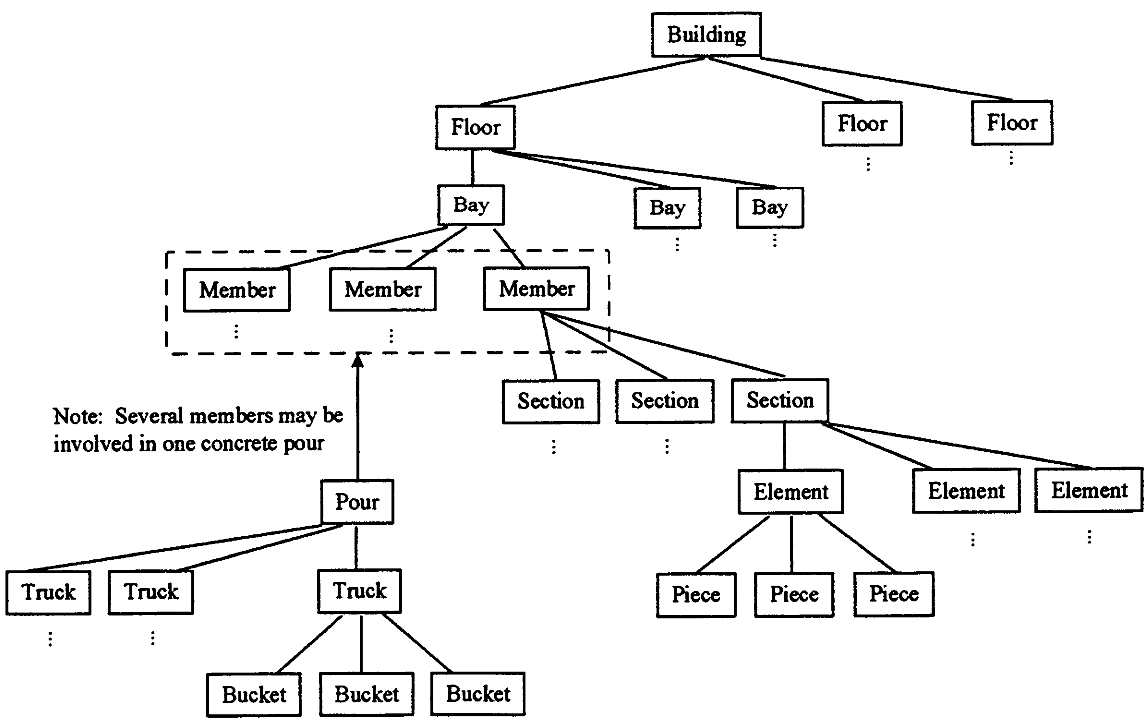


Figure 4.3: Entities Involved in CIP Concrete Construction

and horizontal load bearing members. There are 5 types of CIP concrete load bearing members: footings, columns, walls, beams, and slabs. Footings are structural units used in the foundation of buildings to transfer loads from the structure above to the soil and foundation piles below. Columns are slender structural units designed to transfer a building's vertical loads down its footings. Walls, much like columns, also transfer vertical loads to the footings, however, in addition, they are often also designed to provide a building with lateral stability. Beams are slender structural units which span horizontally between columns and/or walls and are designed to resist bending. Finally, slabs are the structural units which make up the floors of a building and span horizontally over the beams.

Concrete members arise from combining a concrete pour with sets of formwork and reinforcing sections. A concrete pour is defined as all of the concrete that is deposited during one placement operation, and is made up of a number of concrete truck loads which, depending on the selected placement technique, may be further reduced into a number bucket loads (see Section 4.3.4). A section is a set of elements which are placed sequentially in an uninterrupted manner. Formwork sections are made up of formwork elements and reinforcing sections are made up of reinforcing elements.

Elements are units of formwork or reinforcing which are placed directly into their final position on the construction site. They may be either pre-fabricated or site-fabricated. Pre-fabricated elements arrive on the job site all ready to be hoisted into position, whereas site-fabricated elements require on-site assembly and/or preparation before they can be hoisted into their final position. There are therefore four types of elements which define the CIP concrete construction process: pre-fabricated formwork elements, pre-fabricated reinforcing elements, site-fabricated formwork elements, and site-fabricated reinforcing elements.

Pre-fabricated elements are not made up of any smaller units; however, site-fabricated elements are made up of pieces. Pieces are the smallest order entities used in this research to define the CIP concrete construction process. Site-fabricated formwork elements are made up of formwork pieces and site-fabricated reinforcing elements are made up of reinforcing pieces. Pieces are thus defined as those units involved in the on-site assembly of site-fabricated elements. An example is provided in Figure 4.4 to better illustrate the different entities categories described above.

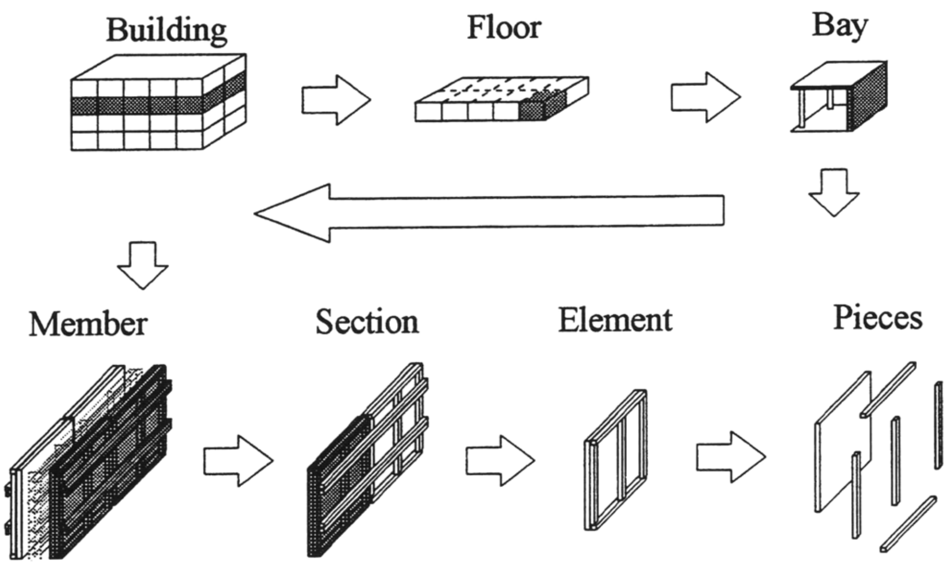


Figure 4.4: Example of Entity Hierarchy

4.3 Specific Processes

4.3.1 Formwork Preparation and Erection

Forms are structural units designed to support and mold freshly placed concrete while it cures and strengthens. They are generally temporary, requiring removal following usage; however, they are occasionally designed to be left permanently in place within a structure as stay-in-place formwork (Hurd, 1995).

When forming materials arrive onsite, they may or may not require some preparation before they are ready to be erected into place. Those materials requiring preparation (i.e., the formwork pieces) are prepared and eventually transformed into site-fabricated formwork elements. Those materials not requiring preparation (i.e., the pre-fabricated formwork elements) are simply stored until they are required for erection. Since timber studs and plywood sheathing make up the bulk of all formwork pieces, formwork preparation activities are largely performed by carpenters. Carpenters measure, cut, and drill into the formwork pieces, appropriately sizing them for their intended use, and then a number of them are assembled into site-fabricated formwork elements. A variety of hand held power and pneumatic tools including saws, drills, and nail guns are use by the carpenters to help maximize productivity.

Following formwork preparation is formwork erection. Formwork erection only occurs once a required formwork element is ready to be placed. By definition, pre-fabricated formwork elements are ready to be placed upon their arrival to the site whereas site-fabricated formwork elements are only ready after they have been prepared.

There are many different types of formwork elements. Some make up the concrete contact surface, the rest make up the bracing required to support those which make up the concrete contact surface. Table 4.1 lists some of the common types of formwork elements. Recall that elements are specifically those units that are placed directly into their final position on the construction site.

Table 4.1: List of Common Formwork Elements

Sheathing	Ties
Studs	Spreaders
Wales	Shoring
Strongbacks	Stakes
Panels	Inserts
Braces	Tension Cables
Brackets	

Formwork erection is a fairly straight forward process. First a formwork element is selected for placement and then, depending on its size and weight, it is either lifted into position and aligned by hand or with the help of a mechanical lifting device such as a crane (Koel, 1988). Stabilizing the element with preliminary connections then becomes the next concern. Sometimes, simply connecting the element to the existing formwork in place is sufficient. Other times, additional formwork elements are required for bracing. Whatever the scenario, the resources (such as workers and equipment) involved in the placing of the original formwork element cannot be released until that element is stable. If additional formwork elements are required to help stabilize it, then these elements must also be lifted into position and aligned before bracing of the original formwork element can proceed. It is quite common to see several formwork elements being lifted into position and aligned all at once before any bracing occurs. Once a formwork element is stabilized, the resources that were involved in its placement can be released, and any remaining connections, required not for the stability of the element but rather for the soundness of the formwork system, can be made.

Carpenters are generally used to erect wooden formwork elements, especially those that are site-fabricated, since these elements require special care if they are to be reused several times over. With pre-fabricated formwork elements, however, general laborers are usually sufficient (provided it is allowed by local labor rules) since these elements are typically more rugged and specifically designed for a large number of reuses.

On a final note, sometime during the formwork preparation and erection process, prior to the placement of reinforcing, those elements which make up the concrete contact surface generally need to be treated with a release agent. The purpose of the release agent is to ensure that the eventual removal of the formwork will proceed smoothly and will not damage the formed concrete surfaces or the formwork.

4.3.2 Reinforcing Preparation and Erection

Virtually all structural members are subjected to some degree of tension. Columns, for example, must resist buckling, and beams must resist bending. Since concrete has very poor tensile strength, it must be reinforced if it is to be useful in applications involving tension. Concrete is generally reinforced by embedding steel bars within it. These bars are assembled into cages or mats and placed into formwork where they are left to await the placing of concrete. They essentially make up the skeletal structure of reinforced concrete members and are the single reason why such members can be used in applications involving tension.

The process of preparation and erection of reinforcing steel is very similar to that of formwork preparation and erection. When reinforcing materials arrive on site, they may or may not require preparation before they are ready to be erected into place. If they do require preparation, then they are considered to be reinforcing pieces, and if they do not require any preparation, then they are considered to be pre-fabricated reinforcing elements.

Generally, individual reinforcing bars are delivered to a site already cut and bent into their required shapes (Trevorrow, 1984). If for some reason, however, some of the delivered bars are not properly shaped, on-site bar cutting and bending may occur in order to avert any construction schedule delays. These activities are considered to be part of the reinforcing preparation. Additional reinforcing preparation activities include the assembly of site-fabricated reinforcing elements, such as cages and mats, that are to be lifted into their final position during erection. Assembly of site-fabricated reinforcing elements involves lifting the reinforcing pieces into place and connecting these pieces together with tie wire. Site-fabrication is often done simply to allow some of the reinforcing work to proceed independently of the forming work. Ironworkers, typically working in crews of two people (Favazzo, 1997), are responsible for all reinforcing preparation activities. Their tools include cutting torches, rebar bending machines, hydraulic coupling clamps and plier-like devices known as nips which are used for twisting and cutting tie wire.

As with formwork erection, reinforcing erection can only proceed once a required reinforcing element is ready to be placed. Table 4.2 lists some of the common types of reinforcing elements. Once again, elements are specifically those units that are placed directly into their final position on the construction site and they can be either pre-fabricated or site-fabricated.

Table 4.2: List of Common Reinforcing Elements

Steel Reinforcing Bars (Rebar)
Stirrups
Spacers
Chairs
Rebar Cages
Rebar Mats
Wire Mesh Reinforcement

The process of erection of reinforcing steel is identical to that of formwork erection. A reinforcing element is first selected for placement and then lifted into position either by hand or with the help of a crane, depending on its size and weight. Occasionally wooden templates are used to assist in the placement (Hurd, 1995). The element is then stabilized with preliminary connections before any of the resources that were involved in its placement are released, and then finally any connections that are required, not for the stability of the element but rather for the soundness of the reinforcing system, are made. Typically all reinforcing erection activities are handled by ironworkers.

It is interesting to note that often during reinforcing erection, elements may be stabilized without any preliminary connections. This is especially apparent during the erection of reinforcing for a slab, where the simple act of placing a bar down on top of the other bars already in place is often enough for that bar to be stabilized. Obviously, connections are required between the bars for the soundness of the entire reinforcing system; however, no preliminary connections are required to stabilize the bar that has just been placed. It is therefore possible for numerous bars to be placed all at once before any connections need to be made. Of course, when the elements in question are not bars but are rather site-fabricated reinforcing cages, preliminary connections are essential if stability is to be achieved.

4.3.3 Interdependence of Formwork and Reinforcing Activities

Given that the activities involved in the preparation and erection of both formwork and reinforcing have been outlined, a brief discussion on the interdependence of formwork and reinforcing activities is in order. As mentioned earlier, on some occasions formwork needs to be in place before reinforcing can be erected and on other occasions, the reverse is true. Beams and elevated slabs, for instance, generally require their formwork to be in place before the erection of reinforcing can proceed, since this reinforcing typically sits on top of the formwork. In the case of columns, however, the reverse is often observed. Erection of reinforcing often precedes erection of formwork since access to the reinforcing steel at the base of the column is often required during erection of the reinforcing, which can be constrained by the presence of formwork (O'Brian, 1997). In the case of walls, reinforcing may be erected first and then followed by formwork, or sometimes one side of the formwork may go up first, followed by the reinforcing, and subsequently followed by the other side of the formwork. Depending on the member being constructed and, in some instances, on the preferences of the contractor, the precise sequence of formwork and reinforcing erection varies.

The conclusion that can be drawn is that although the preparation activities for formwork are largely independent of those for reinforcing, their erection activities are not. There are two reasons why the erection of formwork and reinforcing are not independent of each other. The first reason is that erection of an element cannot proceed if its placement hinders the erection of another element, and the second is that an element that relies on other elements for stability cannot be erected prior to the erection of those elements.

4.3.4 Concrete Placement Operations

When concrete is deposited around steel reinforcing bars within formwork, reinforced concrete members are the result. Section 4.2 defines reinforced concrete members as the combination of a concrete pour with sets of formwork and reinforcing sections. Up to this point in the general process of CIP concrete construction, only the preparation and erection of the formwork and reinforcing sections have been addressed. During concrete placement operations, however, a concrete pour is added, and reinforced concrete members are the result. Recall that a pour is defined as all of the concrete that is deposited during one placement operation.

There are two stages of concrete placement operations: (1) site preparation and inspection, and (2) concrete placement. The first stage cannot proceed until all of the formwork and reinforcing sections involved in the coming pour are in place, and the second stage cannot proceed prior to the first stage's completion. The stage of site preparation and inspection is specifically focused on helping to ensure that concrete placement will proceed smoothly and that it will result in an acceptable final product. Concrete placement, however, is mainly focused on getting concrete into the awaiting formwork and ensuring that it sets into its desired shape without voids.

4.3.4.1 Site Preparation and Inspection

Numerous activities occur during site preparation and inspection. For one thing, scaffolding is erected around column and wall forms to provide concrete placement workers with a workspace on which they can stand during concrete placement, if no such workspace already exists. Instances when such workspaces already exist, and no scaffolding is required, arise when the column and wall formwork sections are already outfitted with their own workspace platforms. Whether these workspaces come as platforms that are pre-attached to formwork, or are the result of erected scaffolding, elevated workspaces must be provided whenever concrete placement workers need to be elevated to do their job.

Another activity that can occur during site preparation and inspection is the erection of a temporary enclosure system. Recall that one of the properties of concrete is that it is very sensitive to its environment during its placement and curing. Because of this sensitivity, enclosures are often used to help protect the concrete placement site when weather is expected to be a problem. Enclosures are probably most frequently used when temperatures are expected to drop below what is considered optimum for concrete placing operations. Section 4.3.5 outlines in a little more detail exactly what the optimum concrete placing and curing conditions are. For now, however, it is sufficient to say that in instances when protection from the environment is required, enclosures are often used.

Perhaps one of the more important activities that occurs during site preparation and inspection is the cleaning of formwork and reinforcing with compressed air. Any debris, such as nails, sawdust, or pieces of tie wire, left behind at the bottom of formwork could completely ruin the finish of an otherwise perfect concrete member if it is not removed prior to concrete placement (Hurd, 1995). Consequently, the final activity just before inspection is the cleaning of the formwork and reinforcing. Not only is all the debris removed at this stage, but so are all the wooden spreaders and blocks that were used earlier as bracing during the erection of the formwork and reinforcing sections.

The last remaining activity of the site preparation and inspection stage is final inspection. Final inspection by no means represents the very first time that the formwork and reinforcing sections to be included in the coming pour are inspected for their workmanship. It does, however, represent the very last time that these will be inspected. It is a final check to make sure that all of the required reinforcing is where it is supposed to be, and that all of the formwork is clean, sound and ready to receive concrete. Following concrete placement, it is too late to revisit or rework any of the formwork or reinforcing that is included in the pour.

4.3.4.2 Concrete Placement

Following site preparation and inspection is the concrete placement stage. One single concrete placement event typically gives rise to numerous reinforced concrete members. Sometimes concrete is deposited in the formwork of each member individually, as with columns, but often it is deposited monolithically in the formwork of several members at the same time, as with beams and slabs. Monolithic concrete placement is when concrete is deposited in one large formwork system which is made up of several smaller formwork systems each corresponding to a different concrete member. Figure 4.5 illustrates a typical slab/beam formwork system awaiting monolithic concrete

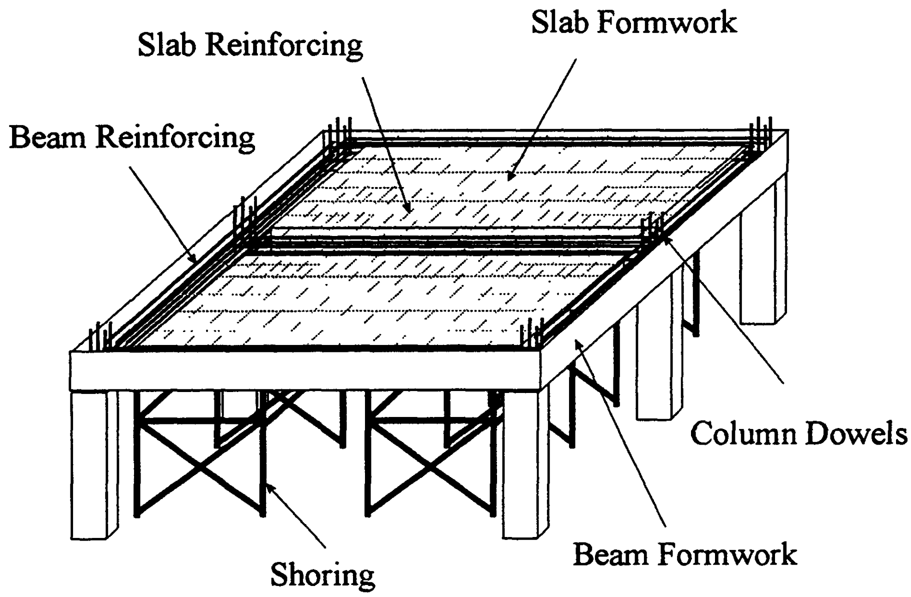


Figure 4.5: Typical Slab/Beam Formwork System Awaiting Monolithic Concrete Placement

placement. Since all of the connections between each of the concrete members involved in a monolithic pour are seamless, the result bears the likeness of a huge concrete structural unit.

The process of concrete placement begins with the arrival of concrete trucks transporting freshly batched concrete to the construction site. A truck load typically consists of approximately 10 cubic yards of wet concrete (McKasku, 1997). When a concrete truck arrives on site, a sample of the concrete it is carrying is taken by a field engineer for testing. A slump test is performed on the sample to verify that the concrete's consistency meets the job specifications, and then several small concrete test cylinders are cast for use later in determining the concrete's strength. Samples are generally drawn from every 50 cubic yards of concrete delivered to the site, which essentially means every fifth truck. If the field engineer is satisfied with the consistency of the concrete being delivered, the concrete trucks are allowed to proceed to concrete placement.

A concrete truck is typically unloaded via a chute located at its rear. In instances where this chute can reach the formwork involved in a pour, concrete placement proceeds directly from the rear of the truck (Waddell, 1997). Footings and on-grade slabs are occasionally poured in this manner. When the chute at the rear of a truck cannot reach the formwork involved in a pour, however, an intermediary on-site concrete distribution system is required to get the concrete from the truck to the formwork. Several different systems exist, and they may be thought of as being either continuous or discontinuous in nature. The continuous systems are characterized by the uninterrupted placement of one truckload of concrete within the awaiting formwork, whereas the discontinuous systems are characterized by interruptions in the exact same process. Conveyor belts and concrete pumps are examples of continuous concrete distribution systems. Power carts and crane hoisted buckets are examples of discontinuous concrete distribution systems.

The most common continuous distribution system encountered in CIP concrete construction in the U.S. involves concrete pumps. A concrete pump is typically mounted on a concrete pump truck which is outfitted with both an intake hopper for receiving concrete and a placement boom for distributing concrete (see Figure 4.6). When the placement boom mounted on the truck is not long enough to reach the formwork, hoses are attached. Sometimes concrete may need to be pumped up several stories above the reach of the placement boom. In these instances, the placement boom is connected to standpipes that have been specifically erected within a building for concrete distribution.

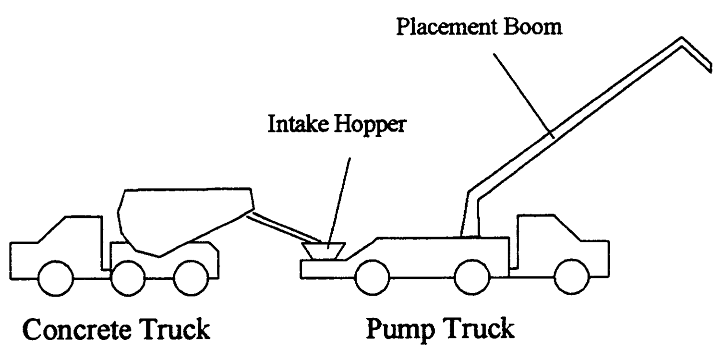


Figure 4.6: Transfer of Concrete to Pump Truck

In a typical concrete pumping operation, two concrete trucks are placed behind a concrete pump truck (O'Brian, 1997). One concrete truck unloads its concrete into the intake hopper of the pump truck, while the other awaits its turn. When the first truck is empty, the second one then begins to unload into the hopper while the first load is pumped to the final location. During this time the first truck pulls away and it is immediately replaced by another concrete truck. This other truck prepares to unload its concrete into the intake hopper once its turn arrives and the second truck is empty. The cycle repeats itself over and over again until all the concrete required for the pour is placed.

On the distribution end of a typical concrete pumping operation, concrete is deposited within the formwork by way of a hose which is handled by one or two concrete placement workers. The concrete is deposited as near as possible to its final position within the formwork as a means of preventing segregation of the aggregate from the rest of the concrete mix. Once the concrete is in place, other placement workers, operating hand held vibration tools, vibrate the concrete in order to release any air pockets that may be entrapped within the concrete. Vibration is not used to transport the concrete within formwork, but rather it is simply used to consolidate it. Over vibration leads to segregation of the concrete mix, whereas under vibration results in a honeycombed concrete matrix (see Section 4.3.6).

Unlike continuous concrete distribution systems, discontinuous ones include an interruption in the actual placement of concrete within the formwork. The most common discontinuous distribution system encountered in CIP concrete construction in the U.S. involves the use of crane hoisted buckets (see Figure 4.7). Crane hoisted bucket placement operations begin with the arrival of a concrete truck at its unloading site. The concrete truck deposits a portion of its load into an awaiting bucket, and this bucket is subsequently hoisted by crane to the formwork. Buckets typically have a capacity of either 1 or 2 cubic yards. Once the bucket is in the vicinity of the

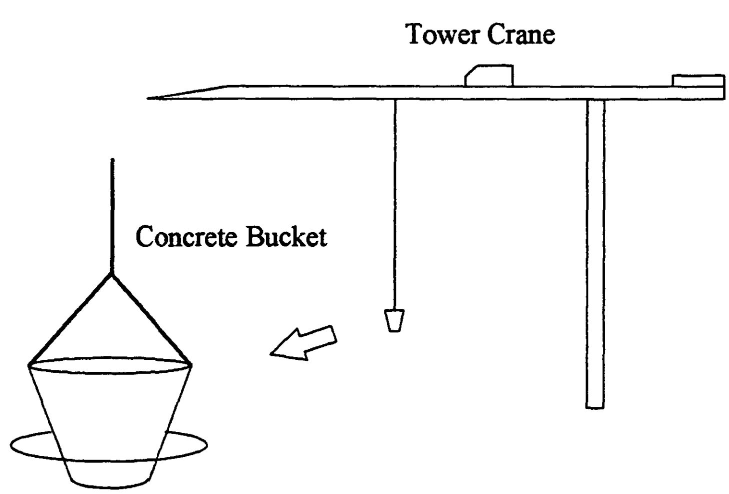


Figure 4.7: Crane Hoisted Concrete Bucket

required placement site, concrete placement workers align it above the formwork and then release its contents within the formwork through an opening in the bottom of the bucket. Again, the concrete is deposited as near as possible to its final position in order to prevent segregation. The bucket is then subsequently returned back to the concrete truck unloading site with the crane and the cycle starts all over again. Vibration of the freshly placed concrete in the formwork occurs while the bucket is being reloaded with concrete.

Regardless of whether a continuous or discontinuous distributions system was used, following concrete vibration is concrete leveling. Leveling of freshly placed concrete may be done for all member types, however, it is generally only a critical aspect of slab and footing concrete placement. Smaller areas are typically leveled with a hand trowel, whereas larger ones, such as those associated with slabs, are typically done with screeds. Screeds are long straightedges used to strike-off excess concrete. In regions where the problem is not an excess of concrete but rather a shortage of it, concrete placement workers redistribute concrete with the use of shovels. Figure 4.8 illustrates a typical concrete placement operation for a slab.

Finally, after the concrete is leveled it is finished. There are two types of finishing operations: those associated with formed concrete surfaces and those associated with non-formed concrete surfaces. The finishing discussed here is solely of non-formed concrete surfaces (i.e., slabs).

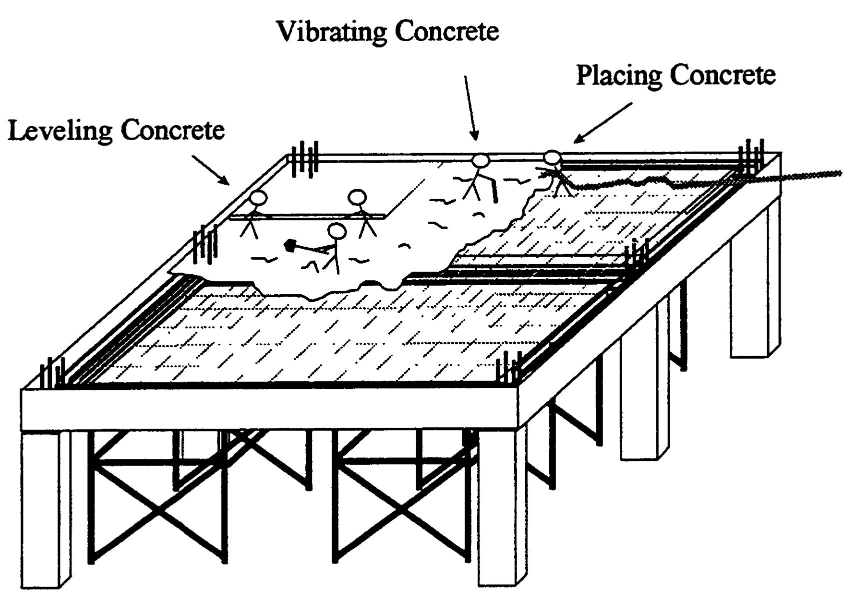


Figure 4.8: Concrete Placement Operation

Finishing of formed concrete surfaces is addressed in Section 4.3.6, and is not done until later on since it requires the prior removal of formwork.

There are two stages of non-formed concrete surface finishing. The first occurs just after leveling while the concrete is still wet and typically involves running a float over the surface of the concrete. This activity is performed to remove slight imperfections from the surface and to embed any exposed aggregate just below the surface of the concrete. The second stage is performed once the concrete is hard enough to support foot traffic, but soft enough to leave footprints (usually within a couple of hours of placement). It involves smoothing and polishing the concrete surface with power trowels, or, in instances where a rough slip-resistant surface is desired instead, scoring the concrete surface with fiber bristle brooms.

4.3.5 Concrete Curing

The period of time directly following concrete placement, during which freshly placed concrete strengthens and hardens, is perhaps the most critical stage of the entire CIP concrete construction process. Many of the properties of hardened concrete are at stake, including strength, resistance to abrasion, durability, volume stability, impermeability, and resistance to freeze and thaw (Kosmatka *et al.*, 1991). During this time, a chemical reaction between the water and the Portland cement within the concrete occurs. The chemical reaction is known as hydration, and the extent to which it is completed effects the properties outlined above. The internal temperature and moisture of concrete greatly influence hydration, both in terms of the extent to which it is completed and the rate at which it occurs.

The optimum internal concrete temperature for hydration is between 50 ^{o}F and 70 ^{o}F. All things being equal, when the internal temperature of the concrete is outside this range (i.e., either too hot or too cold), the actual ultimate strength of the concrete suffers. In the same way, lower actual strength concrete will result if insufficient moisture is available to drive the hydration reaction to completion. Pre-mature concrete shrinkage leading to surface cracking is also another possible outcome of insufficient moisture (Kosmatka *et al.*, 1991).

In order to prevent moisture loss and maintain the optimum temperature required for hydration, concrete curing operations are performed. These operations are most critical during the first few days following concrete placement, since hydration proceeds at its highest rate during this time. There are three basic types of curing operations, or strategies (Kosmatka *et al.*, 1991). The first involves saturating a finished concrete surface with water. This may be done by ponding water on the concrete surface, by spraying or fogging it with a water mist, or by covering it with a water saturated material such as burlap. The presence of moisture on the concrete surface not only helps to reduce cracking, but also helps to maintain sufficient moisture within the concrete for the hydration reaction. The strategy may also be used to help maintain concrete in its optimum temperature range. Steam can be used if heating is required while cold water and simple evaporation may be relied upon for cooling.

The second strategy involves preventing the evaporation of water that already exists within freshly placed concrete. This is achieved either by covering a finished concrete surface with an impervious membrane, such as a plastic sheet, or by spraying it with a membrane-forming curing compound. In both cases, the impervious membrane strives to retain the concrete's existing moisture without supplying any additional moisture to the concrete surface. It works best at lower temperatures, where evaporation is already at a minimum. Unlike the water saturation strategy, the impervious membrane strategy is little help in maintaining concrete in its optimum temperature range.

The third strategy focuses not on moisture control but rather on temperature control. It involves maintaining the internal temperature of concrete within its optimum range despite cold weather conditions. Section 4.3.4 already discussed one way, the use of enclosures. Another way is by covering the concrete with insulating blankets and covers. One important feature of hydration is that it is an exothermic reaction (i.e., releases heat). In an effort to maintain an optimum internal temperature despite cold weather conditions, insulating blankets and covers may be used to trap the heat of hydration within the concrete. Formwork that is left in place also provides insulation against cold weather, although to a lesser extent than blankets.

The concrete curing process continues until all of the concrete members within a pour have gained sufficient strength to bear their anticipated loads. Temporary structural systems are used throughout the entire curing process to support each of the members, and although many of the curing strategies outlined above are discontinued part way through the curing process, hydration and concrete strength gain proceed throughout.

Early in the curing process, support for each of the members is provided by the formwork. Section 4.3.1 discusses the role of the formwork. In order to minimize construction costs, formwork reuse is desirable. The greater the number of reuses, the lower the cost per concrete member. Evidently, there is considerable pressure to have formwork removed prior to the end of the curing process (i.e., prior to the concrete being able to go on unsupported), and as a result, some other means of concrete support is needed. Re-shoring provides this means of support. Vertical members such as walls and columns typically do not require re-shoring; however, horizontal members such as beams and slabs typically do (McKasku, 1997).

Formwork may generally be removed, or stripped, within a few days of concrete placement (Jenkins, 1997). The exact time of removal is specified by the engineer and is a function of the strength test results from the concrete test cylinders that were taken by the field engineer during concrete placement (see Section 4.3.4). As formwork is stripped, re-shoring is erected. Figure 4.9 illustrates a slab formwork system being replaced by a re-shoring. Carpenters typically handle the

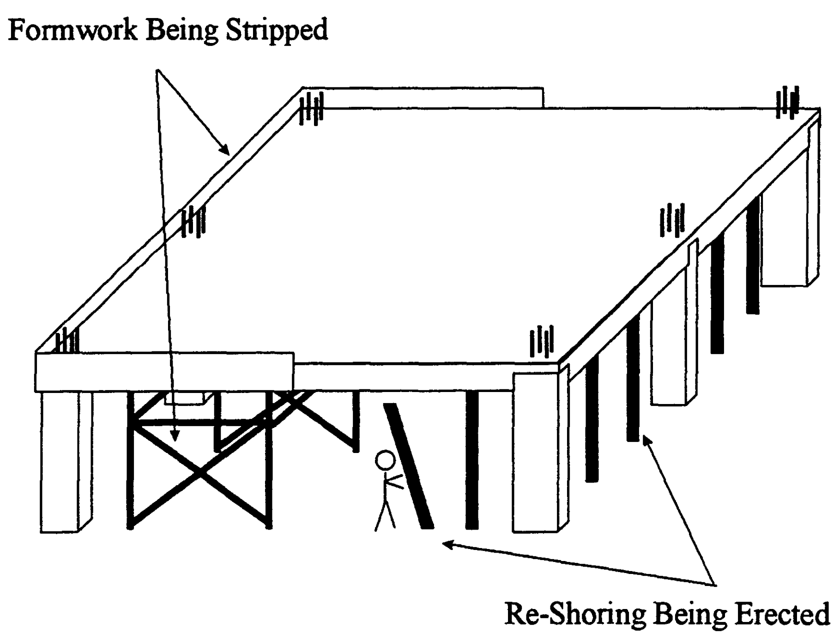


Figure 4.9: Stripping of Formwork & Erection of Re-Shoring

removal of wooden formwork that is to be reused, while laborers handle the stripping of all other formwork as well as the erection of re-shoring (Favazzo, 1997). Once formwork is removed, it is cleaned, repaired, and then stored on site for reuse elsewhere on the project.

Eventually, all of the concrete members within a pour gain sufficient strength to be able to support all remaining anticipated loads on their own, and re-shoring is no longer required. Laborers proceed to remove the re-shoring, and the concrete curing stage of the CIP concrete construction process comes to an end.

4.3.6 Patching, Cleaning, and Finishing of Formed Concrete Surfaces

The final stage of the CIP concrete construction process involves the patching, cleaning, and finishing of all the formed concrete surfaces. It may proceed only once formwork has been removed, and is intended to correct any surface flaws in the concrete that may arise during the concrete placement and curing stages (Love, 1973). Typical surface flaws include: bulges and fins which arise from concrete seepage through formwork joints; embedded nails, bolts, and tie-wire which arise from improper formwork cleaning; honeycombed areas which arise from insufficient concrete vibration; tie-rod holes which arise from the use of tie-rods for formwork bracing; and discoloration (e.g., mortar stains, rust stains, and staining from left over release agent).

The repair of surface flaws involves a number of different activities. Bulges and fins are removed through chipping, rubbing, and grinding of the concrete surface. Embedded material protrusions are dealt with either by completely extracting them, or by cutting them back a specified depth from the concrete surface. Cavities such as honeycombed areas or tie-bar hole are often cleaned using abrasive measures (e.g., sandblasting or waterblasting) to ensure that the surrounding concrete is clean and sound, and then mortar or concrete patches are applied. Rubbing and grinding of these patches occurs following their hardening. Finally discoloration is removed either with water, chemicals or mechanical abrasion, and, in some instances, a finishing coat may be applied to the concrete for its protection (Kosmatka *et al.*, 1991).

4.4 Progression Through Structure

Up until now, the general process involved in CIP concrete construction has only been defined in terms of the activities involved in the preparation and execution of individual concrete pours. CIP concrete buildings, however, are made up of numerous individual concrete pours. It follows, therefore, that CIP concrete construction is not only concerned with interactions that exist between activities in a single pour, but also with those interactions that exist between activities in different pours. Just as there are constraints that govern and define the relationships between activities in a single concrete pour (as discussed in Section 4.3), so too are there constraints that govern and define the relationships that exist between activities in different pours. These latter constraints define the progression of CIP concrete construction through a building as a whole.

Construction of a CIP concrete building typically starts with the preparation of a foundation. Before erection of any vertical members (i.e., walls and columns) can proceed, the foundation members on which these are to rest (i.e., strip footings and column footings) must be in place. Similarly, erection of elevated horizontal members (i.e., beams and elevated slabs) can only proceed once the vertical members on which they are to rest are in place, and erection of elevated vertical members can only proceed after the slab beneath them is complete. It follows that construction of any members requiring support from other members can only proceed once these other members are in place.

Sometimes simply having these 'supporting' members in place, however, is still not a sufficient condition for allowing construction of higher level members to proceed. Another important issue is access to the working surface. Construction of higher level members cannot proceed if it is going to end up cutting off access that is still required by some aspect of the process associated with construction of supporting members. If, for instance, column formwork cannot be stripped once erection of beam and slab formwork begins, then even though, following concrete placement and curing, a column 'exists', construction of the beam/slab system that column is to support cannot proceed until its formwork is stripped. Essentially, construction activities associated with one pour cannot proceed if they cut off any access required by activities which still need to be done in another pour.

There are also other constraints that define the progression of CIP concrete construction through a building as a whole. Resource based constraints are one example. With resource based constraints, activities that are seemingly completely unrelated can impact one another if they share a resource in common. A crane, for instance, cannot simultaneously be involved in the erection of a column reinforcing cage and in the hoisting of a concrete bucket. One activity will have to be put on hold while the other one is being performed. Although both activities may be associated with two completely different and unrelated concrete pours, performance of one activity is nevertheless impacted by performance of the other since they both share the same resource.

Additional constraints also arise from safety regulations. In CIP concrete construction, for instance, regulations require that formwork must be able to support all vertical and horizontal loads that may be reasonably be anticipated. Reinforcing steel for vertical members is required to be adequately supported to prevent overturning and collapse. All protruding reinforcing steel into which any worker could fall is required to be guarded or capped to eliminate the hazard of impalement. Fall protection is required for workers placing or tying reinforcing steel more than six feet above an adjacent working surface. Routing of concrete bucket hoisting is set to expose the fewest possible number of workers to overhead danger. Formwork and shoring cannot be removed until a concrete's actual strength is equal to or greater than its design strength. Re-shoring cannot be removed until concrete has gained sufficient strength to support its weight and all remaining anticipated loads (OSHA, 1991). These regulations constrain the progression of CIP concrete construction through a building as a whole.

Chapter 5 : Modeling Cast-In-Place Concrete Construction

As mentioned earlier, the purpose of this research was to develop a dynamic process simulation model of cast-in-place (CIP) concrete construction to assess the impact of innovations and design changes on this type of construction through simulation. Recall from that dynamic process models consider the flow of entities through non-cyclic processes characterized by decision branches and alternative courses of action. The entities flowing through these processes are not resources, but are rather the units of production arising out of these processes (i.e., the pieces or elements being produced), and their attributes, which can be altered by these processes, are also capable of modifying these same processes. The end result is that processes are free to change dynamically over the course of a simulation in response to events that occur during the simulation.

To develop a dynamic process model of CIP concrete construction, the first step was to understand and define both the general process associated with CIP concrete construction as well as all of the project specific attributes that could alter it. The findings from this step are summarized in Chapter 4. Once the general process associated with CIP concrete construction was understood and all of the project specific attributes that could alter it were defined, the next step was to convert the research findings into a computer-based dynamic process simulation model and then test the model by having it simulate the construction of a prototype CIP concrete building. SIMPROCESS® was used to help convert the research findings into a computer-based dynamic process simulation model of CIP concrete construction.

5.1 Fundamentals of SIMPROCESS®

SIMPROCESS® can be thought of as a computer simulation programming environment. It has a variety of built in modeling functions, known as *activities*, and these make up the building blocks of any SIMPROCESS® based simulation model. In all there are 18 different SIMPROCESS® modeling activities: Assemble, Assign, Batch, Branch, Copy, Delay, Dispose, Free Resources, Gate, Generate, Get Resources, Join, Merge, Replenish, Split, Synchronize, Transform, and Unbatch. If the need arises, each of these activities may be altered to some extent through the programming of expressions. SIMPROCESS® activities are represented with graphical icons, as illustrated in Figure 5.1.

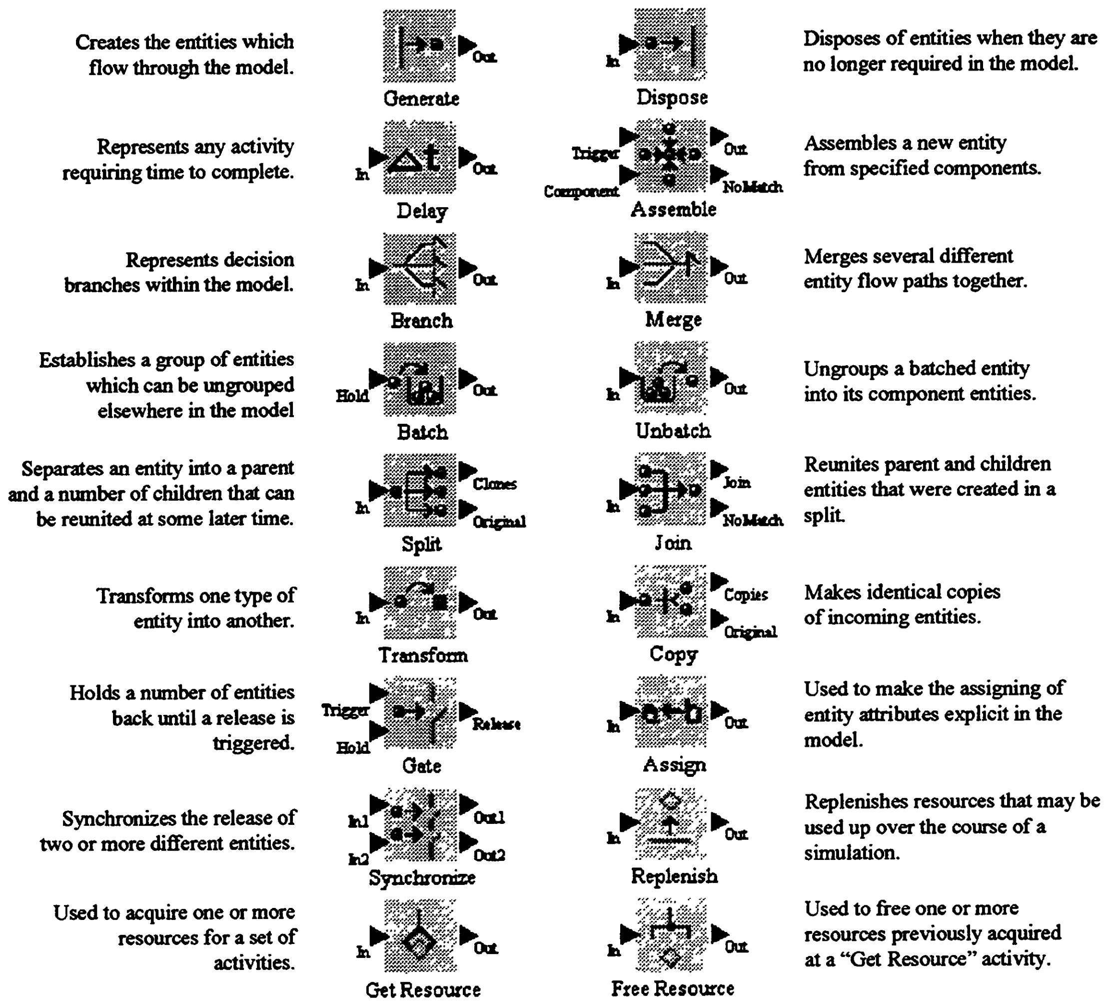


Figure 5.1: SIMPROCESS® Activity Icons

In SIMPROCESS®, a sequence of activities connected with a series of *connectors* creates a network referred to as a *process*. Processes may themselves may be used to make up higher order processes, and hence are hierarchical in nature. Information, people, or goods that flow through processes are referred to as *entities*, and the characteristics of each of these various entities are referred to as *attributes*. Attributes may be used to change activity processing times, regulate entity flows, and even alter processes. During a simulation run, when an entity arrives at an activity for processing, that activity may have resource requirements which must be met prior to the processing of the entity. When a *resource* is required by an activity, it is removed from a pool of available resources and is made unavailable to all other activities while it is in use. Any other activity also requiring that resource for the processing of an entity must wait until the resource is released back into the pool (upon completion of the original activity) and made available for reuse.

5.2 Model Development

The CIP concrete construction computer simulation model was developed with two fundamental objectives in mind. The first was that it be as representative of actual CIP concrete construction as possible, and the second was that it be easy to modify so that it could be used to model a wide variety of different CIP concrete building projects simply through changing the project specifics. The following section outlines how the model was developed with these two objectives in mind.

5.2.1 Modeling High Levels of Detail

In an effort to make the CIP concrete construction model as representative as possible, high levels of detail were incorporated into it. Activities, such as the cutting of individual formwork pieces and the connecting of individual steel reinforcing bars, for instance, were included, and every effort was made to have the model represent the entire process outlined in Chapter 4. The integration of this high level of detail into the model, however, translated into large numbers of entities and activities requiring significant effort to manage and sequence. Complicating matters even further was the fact that these numbers vary significantly from one project to another. A challenge therefore lay in finding not only a way of handling large numbers of entities and activities, but also a way of doing so that could be universally applied to a wide spectrum of CIP concrete construction projects.

5.2.1.1 Organizing Entities

At first, all of the various entities were considered to see if anything could be done to reduce their total number and thereby reduce the complexity involved in managing them. It was determined that lower level entities (i.e., pieces and elements) could be assembled into groups of pieces and groups of elements, all belonging to a single section, without significant model representativeness being lost. The reasoning used to justify this simplification was that, although significant differences exist between different sections, differences that exist between elements within a single section are far less pronounced, and those differences that exist between pieces within the elements of a single section are even less apparent. It was determined that knowing the precise sequence in which pieces (or elements) are assembled within a single section adds little value to the model since the basic steps involved in assembly are the same regardless of the piece (or element) in question. All that was really deemed to be important at this level was that the basic assembly process of pieces into elements into sections be represented, and that the total time involved in each level of assembly be known. Figure 5.2 illustrates how the various entities introduced in Section 4.2 are organized in the CIP concrete construction model.

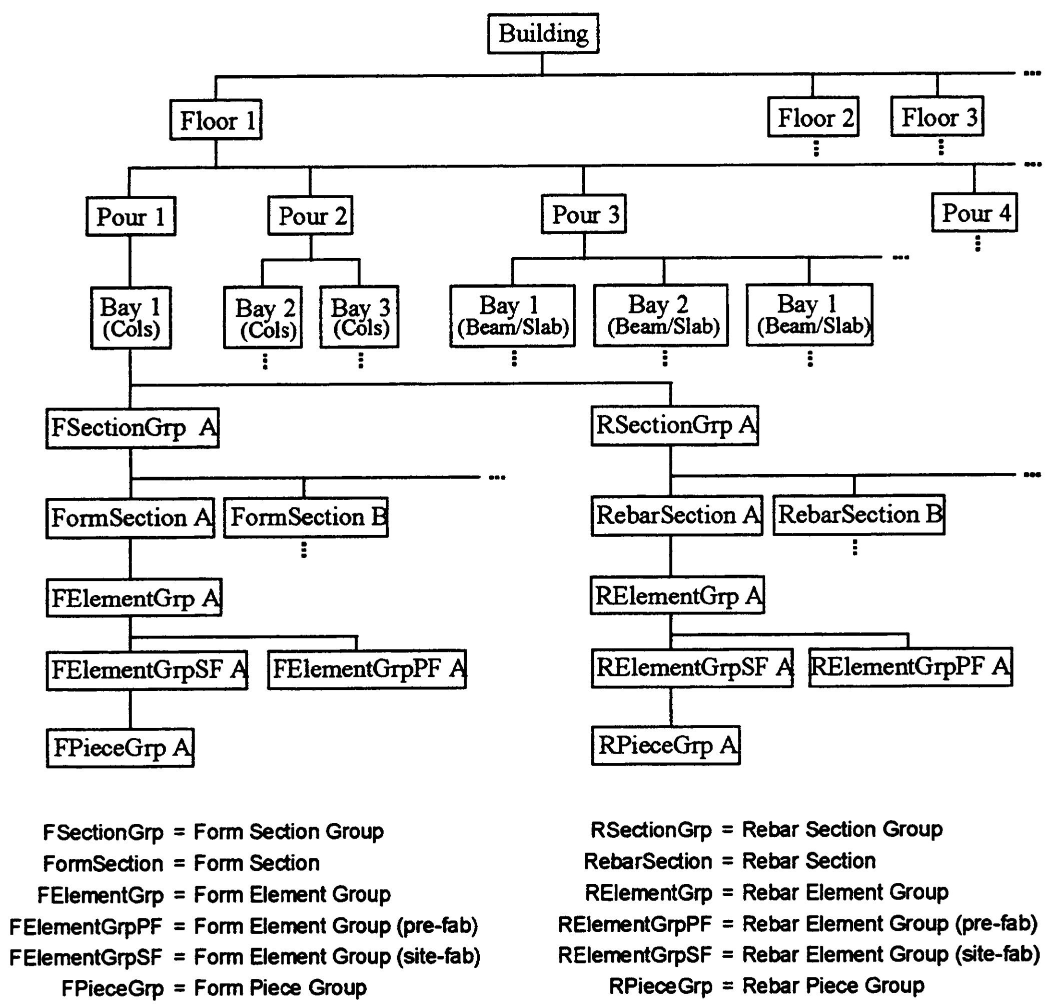


Figure 5.2: Entity Hierarchy

5.2.1.2 Organizing Activities

Once a system was in place to organize all of the different entities involved in CIP concrete construction, finding a way to organize all of the different activities involved became the next priority. A solution was found, whereby all of the construction activities were arranged into a series of repeatable standard process modules for use as the building blocks of the entire model. These modules were organized in a hierarchical fashion, with higher order modules being made up of a series of lower order ones, and each module was made general enough to represent any permutation of the process it corresponded to. Hence, the process module corresponding to the preparation of formwork, for instance, can be used in the preparation of column formwork just as easily as it can be used in the preparation of elevated slab formwork.

Differences between various process modules of a given type were established simply by making each of the process modules responsive to the attributes of the entities flowing through them (see Appendix A). Since by their very nature entity attributes tie directly into project specifics, each process module automatically became responsive to varying project specifics. Thus, in the preparation of formwork, since the activities involved include cutting, drilling, placing, and connecting of pieces, the time required for a group of pieces to be prepared is a function of the number of cuts required, the number of holes required, the number of pieces to place, and the number of connection to be made. Since the attributes of column formwork differ from those of beam formwork, and since the process module corresponding to the preparation of formwork is responsive to these attributes, the time required to prepare column formwork ends up differing from the time required to prepare beam formwork even though the same process module is used in both instances.

An example of the modular structure used to organize the processes involved in CIP concrete construction is shown in Figure 5.3. The figure illustrates the relationship that exists between each of the five highest order processes involved in the construction of concrete columns. Each process is represented by a process module, and each process module is made up of lower order modules. Figure 5.4 illustrates the hierarchical relationship between modules within the 'Prepare/Erect FSectionGrp' process module. It should be noted that each of the five highest order process modules (i.e., Prepare/Erect FSectionGrp, Prepare/Erect RSectionGrp, Place Concrete, Cure Concrete, and Patch/Clean/Finish Concrete) correspond to each of the five specific CIP concrete

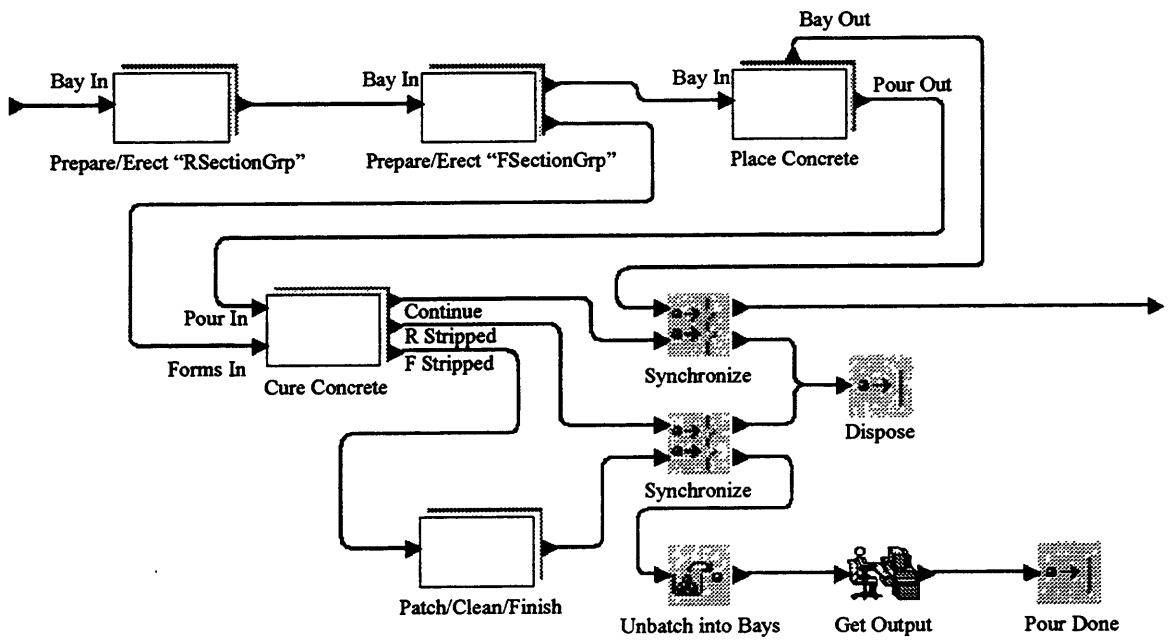


Figure 5.3: SIMPROCESS® CIP Concrete Model: Column Construction

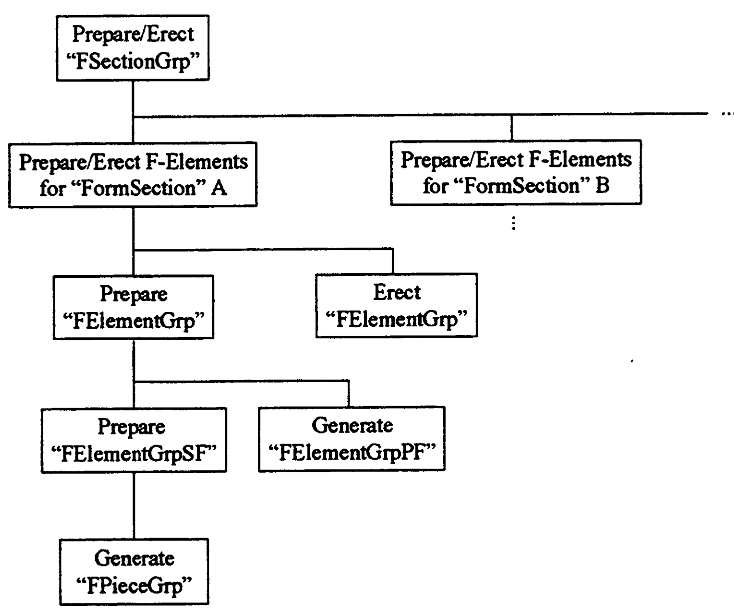


Figure 5.4: Process Module Hierarchy for 'Prepare/Erect FSectionGrp'

construction process outlined in Section 4.3. (A summary of all of the process modules incorporated within the CIP concrete construction simulation model is provided in Appendix B.)

5.2.1.3 Sequencing Entities Through Activities

Having established logical systems for organizing all of the entities and activities within CIP concrete construction, finding a way of sequencing the flow of entities through these activities remained a challenge. Two levels of sequencing had to be addressed by the model: micro-level sequencing (i.e., the sequencing of events involved in the construction of individual concrete members), and macro-level sequencing (i.e., the sequencing of the construction of concrete members relative to one another within the context of an entire building). Addressing each level of sequencing required different strategies.

Micro-level sequencing was addressed simply by arranging all of the process modules in an order consistent with the general CIP concrete construction process outlined in Section 4.3. Macro-level sequencing, on the other hand, was much more difficult to address since it required that the flow of every single entity through the entire process be regulated and tracked.

Every single entity has its own unique set of attributes and is part of its own entity hierarchy. Mixing up entities (e.g., using a column FElementGrp instead of a beam FElementGrp) could not be allowed and had to be guarded against. A strategy for tracking entities and having them called upon only when required was therefore developed.

The strategy involved the use of 'bay' entities. Recall from Section 4.2 that bays are defined as structurally stable units consisting of vertical and horizontal load bearing members. By subdividing an entire building into bays and assuming that construction activities proceed progressively from one bay to the next contiguous bay, macro-level sequencing could be achieved.

In the CIP concrete construction model, every bay is assigned attributes that identify, among other things, the type and number of formwork and reinforcing sections that make it up. Each bay entity uses these attributes to select the process modules corresponding to the preparation and erection of the particular formwork and reinforcing sections it requires. Selection of one of the process modules triggers its activation and leads to the erection of one of the required sections. Once all of the sections that make up a bay are complete, that bay proceeds on to concrete placement where it awaits the arrival of a specified number of other completed bays before triggering the start of a concrete pour.

Thus, if a bay is made up of four column reinforcing sections and four column formwork sections, for example, the corresponding bay entity first proceeds to the 'Prep/Erect R-Elements for Column' process module, where it triggers the erection of four column reinforcing sections, and then, upon completion of the reinforcing, it proceeds to the 'Prep/Erect F-Elements for Column' process module where it triggers the erection of four column formwork sections. In the end, when all of required sections are in place, the bay entity is allowed to proceed onto the next process module (i.e., 'Place Concrete') since columns are poured before the next floor's slab.

5.2.2 Incorporating Model Responsiveness to Resource Availability

In addition to sequencing the flow of entities through the model and making each of the activities within it responsive to the attribute of these entities, a strategy had to be developed to make each activity responsive to resource availability. Hence, an activity requiring a predetermined amount of time for a single worker to perform had to be set up so that less time would be required if more workers were available to perform it.

Recall from Section 5.1 that in SIMPROCESS® resource availability is a condition of an activity being performed. If, for example, performance of the activity 'Cut Formwork Pieces' required that one carpenter be available, then, when a group of formwork pieces (i.e. an FPieceGrp) would arrive to be cut, it would only be cut if a carpenter was available. Even if two carpenters were available, still only one would be involved in the cutting of the pieces within the FPieceGrp, and the second carpenter would simply wait idly by until another FPieceGrp arrived for cutting. The result would be that the time required to make all of the cuts in a single FPieceGrp would be the same regardless of the number of carpenters available to do the cutting. This was not an acceptable result since in reality one would expect any available carpenters (up to a feasible maximum number) to work simultaneously on one FPieceGrp together before proceeding together onto another. Consequently, measures had to be taken to make activity processing times a function of resource availability, and a method to model the simultaneous use of available resources by an activity had to be established. To this end, several steps were taken.

First, every activity within the entire CIP concrete construction process was reduced to its most basic state and defined in terms of the least number of resources required to perform it. For instance, the activity 'Cut Formwork Pieces' was reduced down to the making of a single cut, and the making of that single cut was defined in terms of the minimum number of resources required for it to occur (e.g., one carpenter with one power tool makes a single cut in 40 seconds). The productivity numbers associated with each of these activities were then incorporated into the model using model attributes in order to make changing them a very simple process. (Model attributes are simply variables that can be used throughout an entire SIMPROCESS® based model.)

Once all of the basic activities were defined in terms of their minimum required resources, a special module was developed to be used wherever activity processing times had to be set up as a function of entity attributes and resource availability. The module is illustrated in Figure 5.5.

In this particular case, the module is set up for use in the cutting of plywood. When a FPieceGrp entity arrives to be cut, it enters the module, and its attributes are immediately verified to see if it does indeed require plywood cutting. If it does, it proceeds further into the module where it is

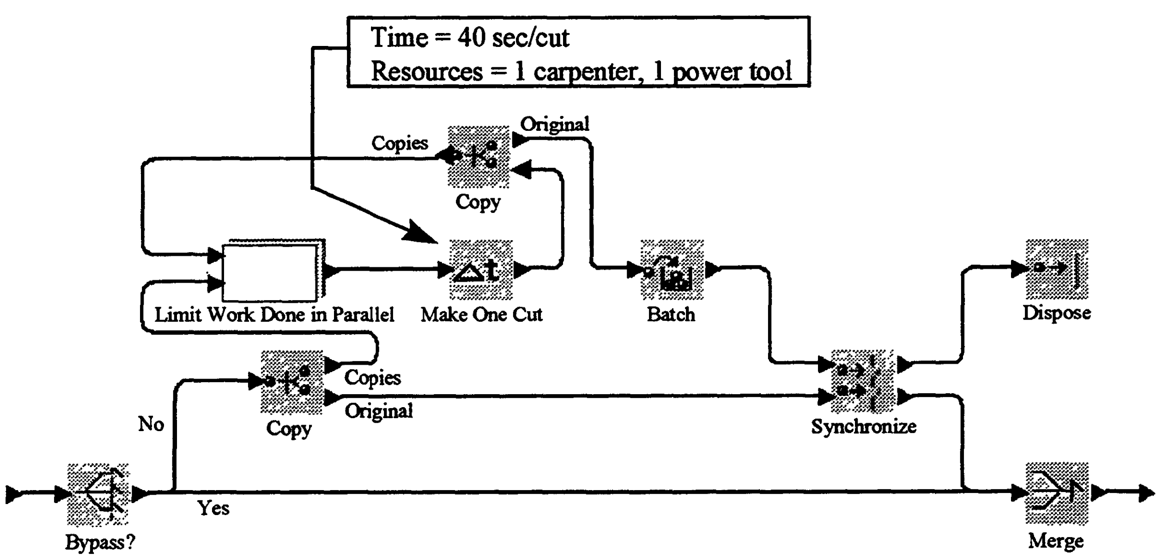


Figure 5.5: Basic Module Used for Making Activity Processing Times a Function of Resource Availability

copied as many times as there are cuts required, and these copies eventually make their way to the 'Make One Cut' activity (defined earlier in terms of its minimum number of required resources). Each entity copy gets processed by the activity once, and the number of entity copies that are processed simultaneously is solely a function of the total number of resources available in the resource pool (in conjunction with a predetermined maximum feasible limit). Hence, assuming that the FPieceGrp requires 10 plywood cuts, and assuming that each plywood cut takes one carpenter with one power tool 40 seconds to make, then processing all of the required cuts would take one carpenter with one power tool 400 seconds (i.e., (10 cuts) x (40 sec/cut/carpenter) / (1 carpenter)), whereas it would take two carpenters with two power tools only 200 seconds (i.e., (10 cuts) x (40 sec/cut/carpenter) / (2 carpenters)). In this way, activity processing times are responsive to resource availability.

5.2.3 Representing Activity Interdependencies

Although much of the CIP concrete construction simulation model was represented in terms of separate and distinct process modules to simplify sequencing, in reality, very few activities within CIP concrete construction are actually completely independent of each other. The processing of one activity is often a function of the processing of some other activities elsewhere in the process. For example, formwork cannot be erected unless it is first prepared nor can it be reused unless it is first stripped. Two methods were used to incorporate activity interdependencies within the model.

The first, already addressed in Section 5.2.1, involved regulating the flow of entities through the model and transferring information between interdependent activities in the form of entity attributes. One activity could be set up to modify an entity's attribute which could then be used to affect the behavior of another activity elsewhere in the model. This approach was the most common one used in representing activity interdependencies within the CIP concrete construction model. Its limitation, however, lay in fact that entities and connectors had to be involved in the transfer of information between the activities in question. In instances where this requirement was deemed to make modeling too complicated (in terms of regulating the flow of the entities involved), the second approach was used.

The second approach involved using model attributes (as opposed to entity attributes) to transfer information from one activity another. It eliminated the need for entities to travel between interdependent activities to pass information status, and thus simplified model layout. With the second approach, when an entity passes through one activity that affects the behavior of another activity elsewhere in the model, a model attribute is altered. By making the second activity a function of that model attribute, its dependence on the first activity is accounted for. Figure 5.6 illustrates the differences that exist between the two methods used to account for activity interdependencies.

In the CIP concrete construction model, the second approach is specifically used to identify when a particular group of formwork elements is stripped and ready for reuse elsewhere on the site. When an entity representing a group of formwork elements (i.e., an FElementGrp) is stripped, a model attribute indicating the total number of these entities that are available for reuse is incremented up by one. In the formwork erection portion of the model, this very same model attribute is checked at regular intervals to see if any FElementGrp entities were stripped and are now ready for reuse. When the model attribute indicates that there are indeed FElementGrp entities ready to be reused, copies of the original FElementGrp entities are introduced back into the model for reuse in formwork erection. The introduction of one entity back into the model reduces the value of its corresponding model attribute by one.

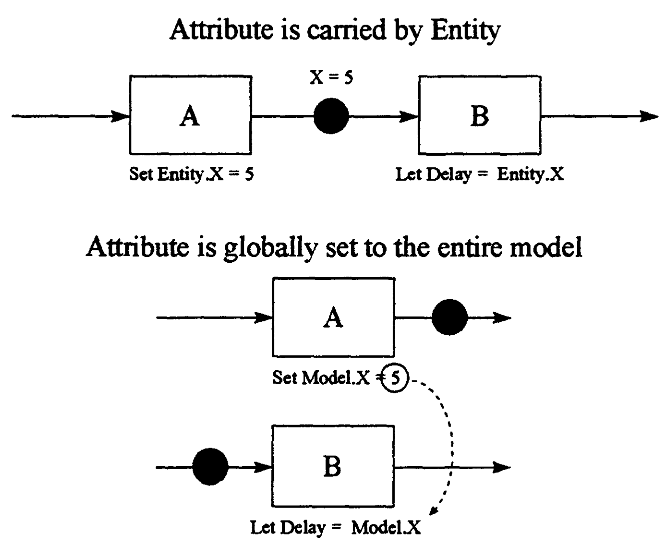


Figure 5.6: Two Methods for Accounting of Activity Interdependencies

5.3 Simulating Construction of a Prototype CIP Concrete Building

Once the general process model for simulating CIP concrete construction was developed, the next step was to incorporate within it the project specifics associated with construction of a prototype building. The details of these project specifics are summarized in this section. (Recall from Section 2.3 that project specifics are the characteristics of a particular project which are used to tailor a general process model to a specific project.)

For CIP concrete systems, project specifics consist of design-related and construction-related attributes. Design-related attributes are a direct function of project design and arise from decisions made by designers (e.g., dimensions of building, number of columns per floor, layout of steel reinforcing within each member), whereas construction-related attributes are a function of selected construction methods and arise from decisions made by construction contractors (e.g., type of formwork system used, type of concrete placement system used, number and type of resources available on site). Both design-related and construction-related attributes together distinguish one particular CIP concrete construction project from another.

5.3.1 Prototype Building Design

Design of the prototype building was done using CSA Standard A23.3-94, which provides the requirements for designing reinforced concrete building structures in accordance with the National Building Code of Canada. The Canadian Building Code was used for design of the prototype building simply because it was the one with which this author was most familiar at the time that this research was conducted. A schematic representation of the prototype building is shown in Figure 5.7.

The prototype building is 5 stories high with a floor to floor height of 10 ft (3.05 m). Each floor is made up of 20 bays (5 bays x 4 bays) and each bay spans 25 ft (7.62 m). Four columns are positioned at each of the corners of every bay, and beams span from each of the columns in both directions. Edge beams are located along the building's perimeter and center beams are located

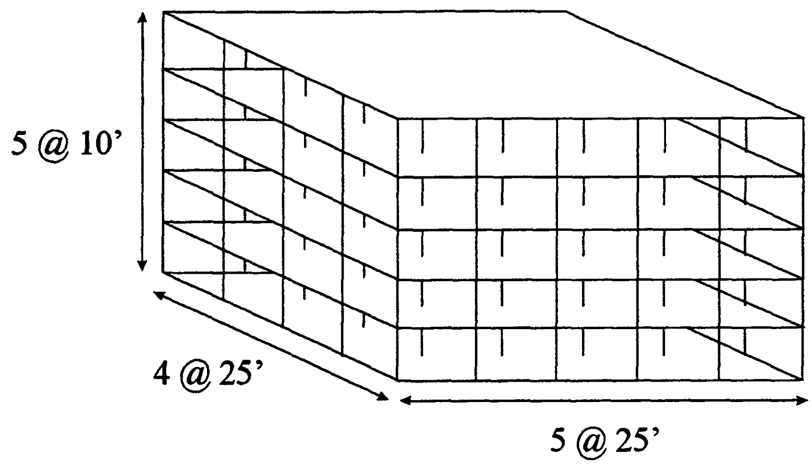


Figure 5.7: Prototype Building Layout

within its interior. A two-way slab that is 8 in (200 mm) thick spans between all of the beams. Table 5.1 summarizes the type and number of members within the prototype building.

The prototype building was designed to support a superimposed dead load of 27 psf (1.3 kPa) and a live load of 50 psf (2.4 kPa). The design strength of the concrete was assumed to be 3,600 psi (25 MPa) and that of the steel reinforcing was assumed to be 58,000 psi (400 MPa). Figure 5.8 illustrates both the cross-sectional dimensions and the reinforcing requirements of each of the columns and beams within the prototype building.

Table 5.1: Members Within Prototype Building

	Number per	
	Floor	Building
Columns	30	150
Edge Beams	18	90
Center Beams	31	155
Slabs	20	100

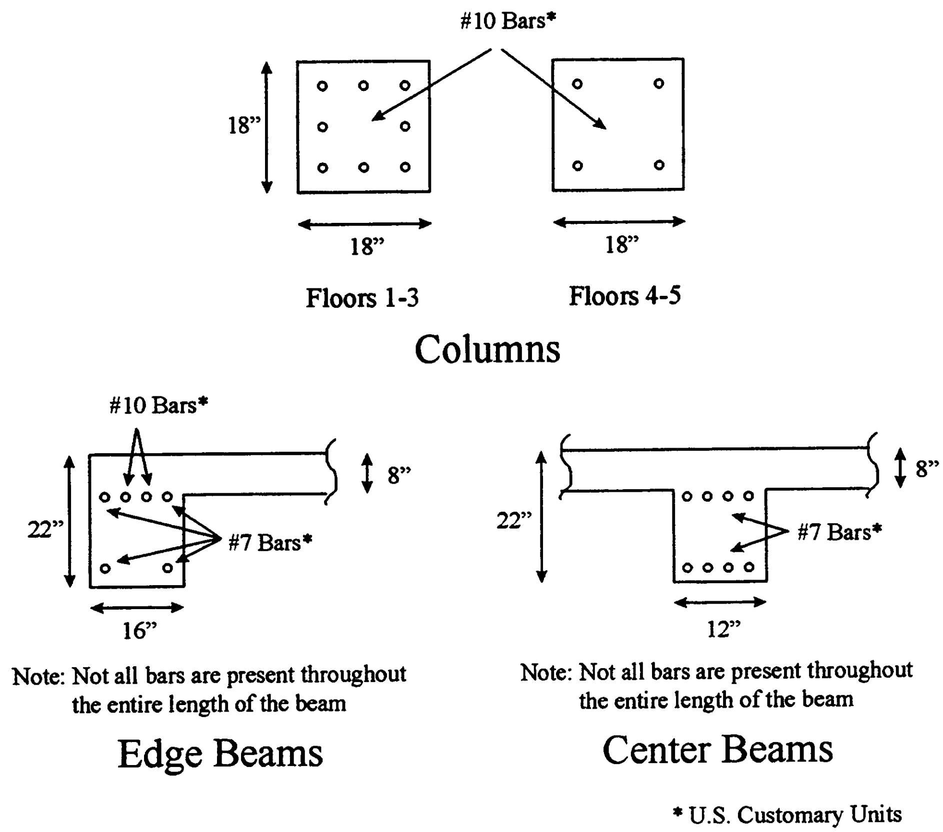


Figure 5.8: Column and Beam Cross-Sectional Dimensions

5.3.2 Prototype Building Bay Types

It is important to note that not all bays require erection of exactly the same type and number of formwork and reinforcing sections. In the prototype building, for instance, although every bay is required to have a column in each of its four corners, only construction of the very first bay requires erection of formwork and reinforcing sections for four columns. Adjacent bays share columns, and, as a result, all other bays only require erection of formwork and reinforcing sections for one or two columns. The same phenomenon is observed when edge beams and center beams are considered as well.

An analysis of the formwork and reinforcing section requirements of each bay was conducted and revealed that some bays require exactly the same type and number of sections as others, while other bays are unique and one of a kind. All bays were divided into various bay types, and bays with similar requirements were grouped together into the same bay type. In all, nine different bay types arose out of the exercise. Figure 5.9 illustrates these bay types.

Fortunately, a pattern in the bay type structure was discovered which enabled the development of an algorithm capable of determining the bay type of every bay within a rectangular building of any size. This algorithm was incorporated into the model, and its discovery meant that a bay's physical location within a building floor plan could be easily tied into its formwork and reinforcing section requirements. The algorithm only requires the dimensions of a building to be given in terms of bays (e.g., 5 bays x 4 bays) in order to establish the bay types of every bay within the building. Since every bay type is predefined in terms of the number of different formwork and reinforcing sections that make it up, and since the algorithm automatically determines the bay types of each bay within a rectangular building of any size, simply providing the model with the dimensions of a building in terms of bays is sufficient to establish the type and number of all the different formwork and reinforcing sections required within each bay of the entire building.

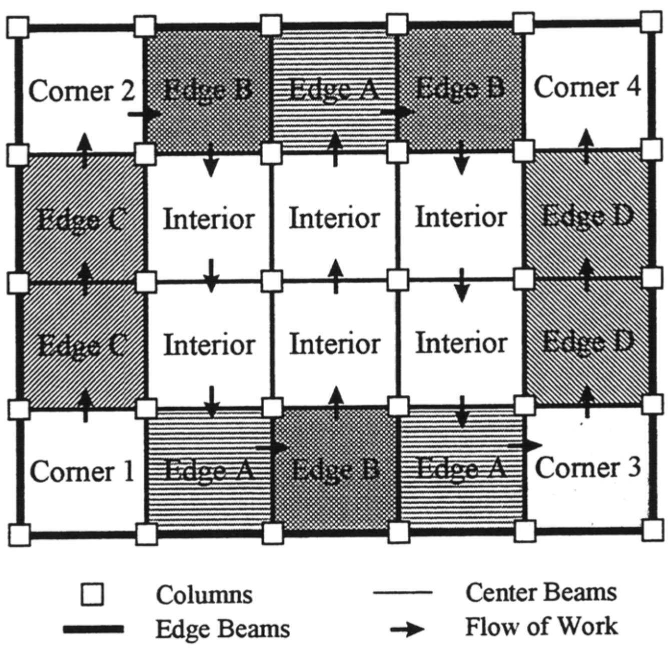


Figure 5.9: Bay Type Pattern Within Prototype Building (Plan View)

5.3.3 Prototype Building Construction

Several assumptions were made in order to characterize the methods involved in construction of the prototype building. These assumptions are for the most part based on construction practices that were observed during visits to CIP concrete construction sites.

First, construction activities are assumed to proceed bay by contiguous bay, and, in each bay, columns are assumed to be completely constructed before construction of any overhead beams and slabs is allowed. Column construction involves erection of a site-fabricated steel reinforcing cage, followed by erection of aluminum pre-fabricated formwork panels. The steel cages are hoisted into place with a crane, whereas the formwork panels are placed by hand. Use of a crane hoisted concrete bucket is assumed to be the means by which concrete is placed within column formwork. (Table 5.2 summarizes the key resources and costs incorporated into the simulation model. The costs are from a construction cost index and include hourly wages, worker's compensation (U.S. averages) and Sub-Contractor's overhead and profit.)

Erection of beam and slab formwork follows the stripping of column formwork. In the prototype building, beam and slab formwork is assumed to be made up of both pre-fabricated and site-fabricated elements. The pre-fabricated elements are part of the "PERI SKYDECK" formwork system, developed by PERI® Formwork Engineering, whereas the site-fabricated elements are simply made of wood. (This prefabricated formwork system is functionally similar to

Table 5.2: Key Resources Incorporated within Model

Resource	Quantity	Cost
Carpenter	20	$ 41.65 /hr
Iron Worker	10	$ 51.15 /hr
Laborer	20	$ 32.50 /hr
Concrete Worker	10	$ 37.90 /hr
Pump Truck & Operator	1	$ 128.90 /hr
Crane & Operators	1	$ 960.40 /day

Source: Means, 1998

other existing pre-fabricated formwork systems.) The use of site-fabricated elements is assumed to be limited only to instances where pre-fabricated elements are unable to fully accommodate the design of the prototype building on their own (e.g., in the forming of beam sides or in the forming of connections between slabs and beams or slabs, beams, and columns). It is important to note that with the "PERI SKYDECK" system, vertical shoring elements used during formwork erection do not need to be removed prior to formwork stripping. Stripping may simply proceed while the original vertical shores are left in place, thereby eliminating the need for re-shoring.

Once the beam and slab formwork within a bay is in place, erection of beam and slab reinforcing may proceed. Erection of beam reinforcing precedes that of slab reinforcing. In construction of the prototype building, both beam and slab reinforcing are assumed to be erected in place by hand one reinforcing bar at a time. In instances where reinforcing bars are required to span across two adjacent bays, both bays must be ready for reinforcing erection before any such bars may be placed. Hence, erection of beam and slab formwork in two adjacent bays must be completed before any beam reinforcing bars spanning across them may be placed, and erection of beam reinforcing in two adjacent bays must be completed before any slab reinforcing bars spanning across them may be placed. In construction of the prototype building, it is assumed that reinforcing elements contained within just one bay may be placed as soon as that bay is ready. Only those particular reinforcing elements spanning across two bays must wait until both bays are ready.

In construction of the prototype building, concrete placement within the beam and slab formwork of an entire floor is assumed to proceed upon completion of slab reinforcing erection. (It is recognized that slab pours are often done by floor sections rather than by entire floors. In the interest of simplifying the simulation, however, only one concrete pour is assumed to occur per floor.) Use of a concrete pump truck is assumed to be the means by which beam and slab concrete placement occurs. A curing compound is assumed to be applied to the concrete surface following placement and finishing. All weather conditions are assumed to be optimal for concrete placement and curing operations. The values assigned to all of the required user defined attributes associated with construction of the prototype building are in Appendix A.

5.4 Prototype Building Construction Simulation

Once all of the project specifics associated with construction of the prototype building (outlined in Section 5.3) were incorporated into the general process model for simulating CIP concrete construction, a specific process model for simulating construction of the prototype building was the outcome. This SIMPROCESS® based simulation model was run and the results were captured for analysis (see Table 5.3).

The model calculates the total time for construction of the prototype building to 55 eight-hour workdays or about 11.0 weeks (this includes the time for curing, stripping of re-shoring, and patching/rubbing of concrete). The last concrete pour occurs on the 45th day (i.e., 9.0 weeks into the project), which means that the average time per floor for formwork, reinforcing and concrete placement activities is 9 days (i.e., 1.8 weeks). The activity-based resource cost for construction of the prototype building is $ 217,500. (Activity-based costing only considers the resource costs associated with the actual performance of work and does not consider the cost of idle resources on the job site.) The danger index for construction of the prototype building was calculated to 947.79. (The danger index is a measure of worker exposure to dangerous conditions calculated from sources of construction injury (OSHA, 1992) by work hours per task (see Appendix C). It is used in this research to measure relative changes in worker safety for innovations.)

Figure 5.10 illustrates the progress of construction activities over the course of the simulation. (Note that 20 bays make-up a floor, and hence bays 41-60 are on the 3rd floor.) The simulation times for construction of the prototype building were compared to expected construction duration times furnished by industry professionals and these values were found to be equivalent within 2 days over the 11 week duration.

Table 5.3: Summary of Prototype Building Simulation Results

Days until last concrete pour	45
Days until end of construction	55
Fixed Cost (crane)	$ 38,416
Variable Cost (labor and equipment rental)	$123,500
Overhead & Profit (45% of Variable Cost)	$ 55,575
Total Activity-Based Cost	$217,491
Danger Index	947.79

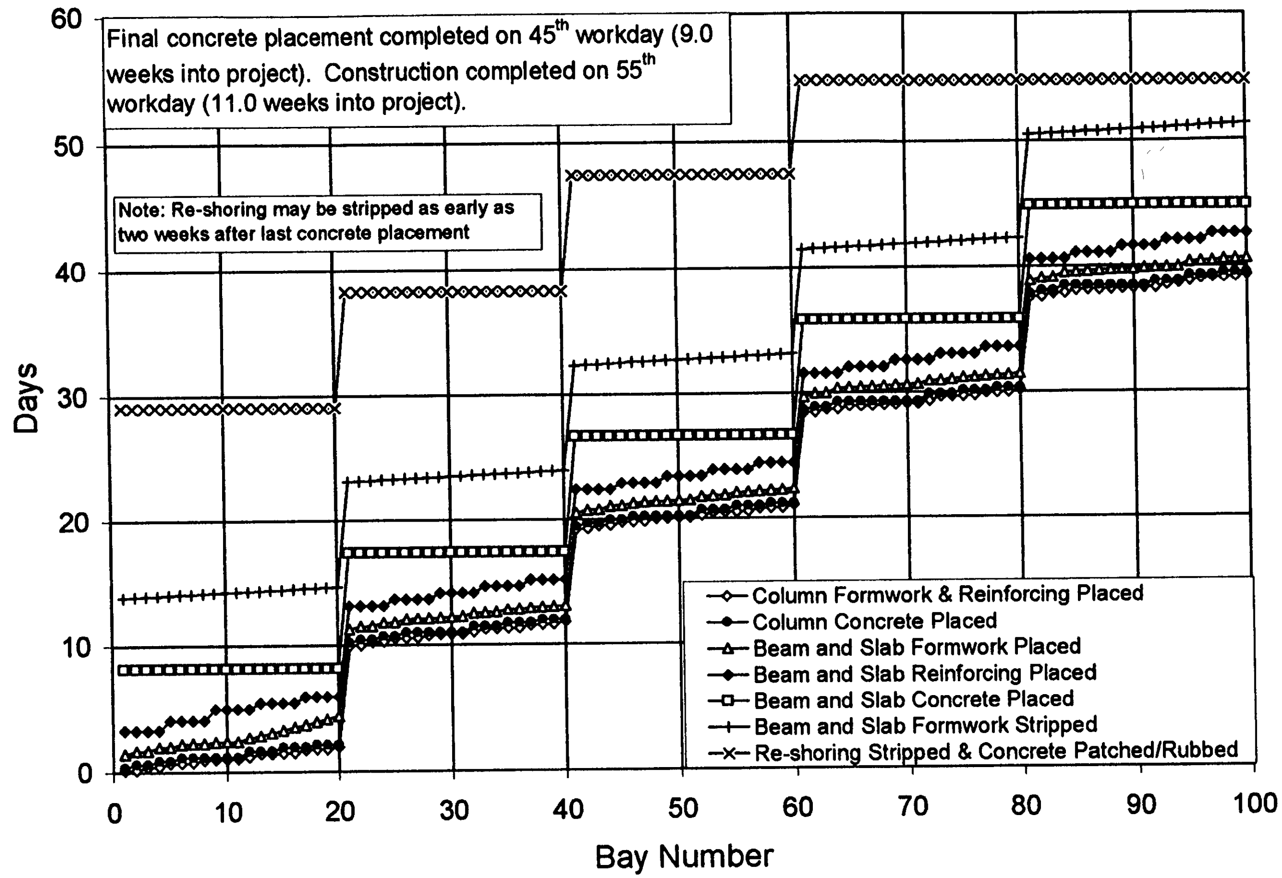


Figure 5.10: Progress of Prototype Building Construction

Chapter 6 : Analysis of Innovations

Because cast-in-place (CIP) concrete construction is such an involved process made up of significantly different sets of activities (see Section 4.1), there is ample opportunity within it to innovate. A CIP concrete construction innovation, for instance, can affect some aspect of formwork preparation, erection, or stripping; it can affect some aspect of reinforcing preparation or erection; it can affect some aspect of concrete placement, finishing or curing; or it can affect several of these at once. The diverse nature of the CIP concrete construction process means that the types of innovations capable of affecting the construction process are diverse as well.

Three very different innovations were selected to demonstrate the use of the CIP concrete construction model as a tool in evaluating the impact of innovations on the construction process: the Talon ^{2}360 Rebar Crosstie System, Self-Compacting High-Performance Concrete, and Precast Concrete Stay-In-Place Forms. A description of each innovation is provided, the steps taken to incorporate each of them within the simulation model are outlined, and the results of each simulation are presented. In all, four different simulations runs were performed. The first three simulate construction of the prototype building with each of the three innovations being used individually, and the forth simulates construction of the prototype building with both the Talon and stay-in-place form innovations being used at the same time.

6.1 Innovation 1: Talon ^{2}360 Rebar Crosstie System

6.1.1 Description

The Talon ^{2}360 Rebar Crosstie System is a hand held automatic rebar tying tool that was developed by a small group of construction workers to eliminate the need for tying steel reinforcing bars together by hand. It operates by spinning tie wire out around steel reinforcing bars, grabbing this wire, twisting it, and then cutting it free once a reinforcing connection is made (see Figure 6.1). The device is currently in the prototype stage of development and involved in field studies. It is expected to cost around $5,000, and the special tie wire it requires is expected to cost approximately four times as much as standard tie wire (Cone, 1997).

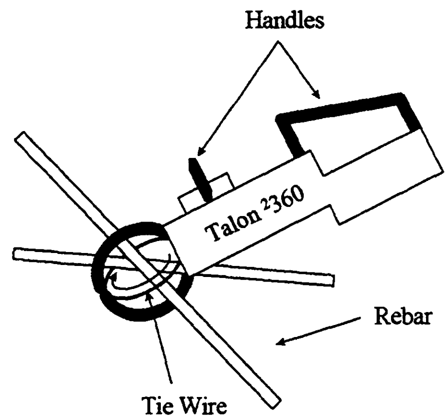


Figure 6.1: Talon ^{2}360 Rebar Crosstie System

The Talon ^{2}360 Rebar Crosstie System is capable of operating at a rate of 30 ties per minute, it uses 16 Gauge semi-annealed PVC coated wire (rated at 85,000 psi), and can tie approximately 400 precision knots without reloading (Talon Industries, 1996). Each tie is made a standard 50 lb. tight, and the amount of wire used per tie is significantly less than when the operation is done by hand. Because the quality of each tie is standardized by the device, fewer ties are required to make a reinforcing system sound. As a result, the Talon ^{2}360 system could reduce the total number of required reinforcing connections by as much as much as 50% (Talon Industries, 1996). In addition, the ease with which the device may be operated means that general laborers could use it to make all routine rebar connections required for the soundness of a reinforcing system while iron workers could be used specifically for placing reinforcing and making any preliminary connections required for bar stability (Cone, 1997). Finally, a harness feature is available for use in slab rebar tying.

6.1.2 Modeling Implications

In order to simulate the use of the Talon ^{2}360 Rebar Crosstie System in construction of the prototype building , a few modifications were made to the simulation model. First, since the Talon ^{2}360 impacts the total time required to connect reinforcing steel pieces and elements together (both in terms of the time per connection and in terms of the total number connections required), the time per rebar connection used in the simulation model was changed from 10 seconds (observed in the field) to 2 seconds (Talon Industries, 1996), and the total number of required connections was assumed to be reduced by 10%. In addition the resources involved in the tying of one rebar connection were changed from a single iron-worker, to one laborer and one Talon ^{2}360 Rebar Crosstie System. Use of the Talon ^{2}360 system was assumed to eliminate worker exposure to bodily reaction injuries during rebar tying, and five Talon ^{2}360 systems were assumed to be on site. No other changes were made to the model.

The results from the simulation run involving the use of the Talon ^{2}360 Rebar Crosstie System in construction of the prototype building are summarized in Figure 6.2. The total duration of construction worked out to be 56 days (i.e., 11.2 work weeks), a 2% increase relative to the construction duration of the baseline model; the total activity-based cost of all the resources (not including the cost of the Talon ^{2}360 systems) worked out to be $205,333, a 6% decrease relative to the cost of the baseline model; and the danger index worked out to be 877.22, a 7% decrease in worker exposure to construction hazards relative to the baseline model.

These results suggest that use of the Talon ^{2}360 system improves worker safety and reduces total construction resource costs. Although a slight increase in project duration is also observed, it is believed to be the result of a shortage of Talon ^{2}360 systems available for use on the construction site. (Had more then 5 systems been defined within the model, it is conceivable that no increase in overall project duration would have occurred.) Observed worker safety improvements arise from the elimination of bodily reaction injuries from the rebar connecting process, and observed cost reductions arise from both the use of unskilled laborers in the rebar connecting and the reduction in time required to make a single rebar connection.

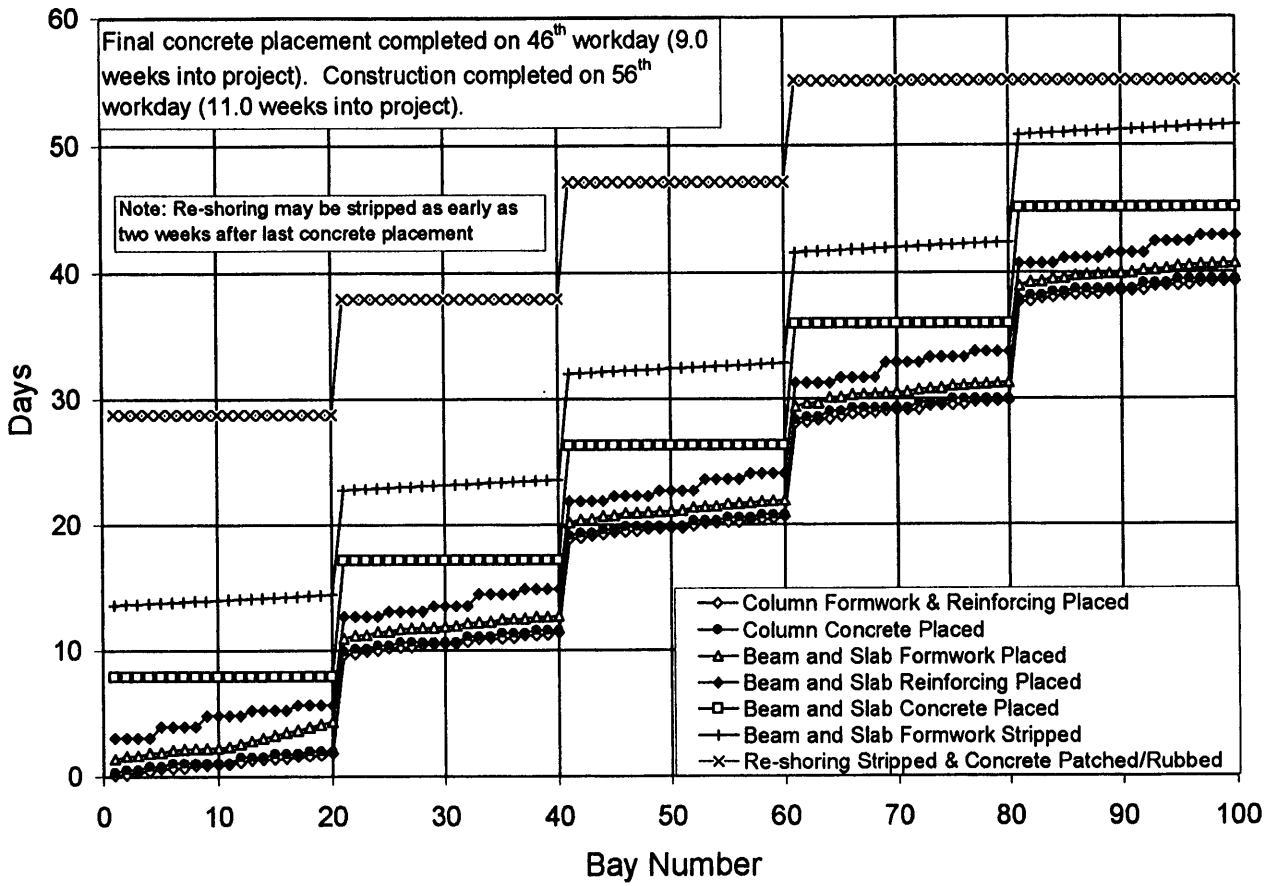


Figure 6.2: Progress of Prototype Building Construction with Talon System

6.2 Innovation 2: Self-Compacting High Performance Concrete

6.2.1 Description

Developed in 1988 at the University of Tokyo, self-compacting concrete is a type of concrete mixture that does not require any mechanical vibration for consolidation. It is made of the same standard components found in conventional concrete (cement, fine aggregate, coarse aggregate, water, and admixtures), and differs only in that the proportioning of these components yields a concrete that is both flowable and viscous (Okamura, 1997). In order to achieve self-compacting concrete, the quantity of coarse aggregate within a concrete mixture must be limited to no more than 50% of the total volume of solids within that mixture, and a predetermined amount of superplasticizer admixture (which is a function of the quantity of water and fines in the concrete) must also be present in the concrete mixture (Okamura and Ozawa, 1996). Since the components of self-compacting concrete are no different from those of conventional concrete (i.e., only their proportions differ), the properties of hardened self-compacting concrete are comparable to those of conventional concrete and can be estimated with the same techniques used to estimate the properties of hardened conventional concrete (Ozawa, 1997).

Several implications arise out of the use of self-compacting concrete. Probably the most obvious is the fact that concrete workers do not need to be trudging through freshly placed concrete or standing on elevated platforms adjacent to vertical member formwork in order to vibrate concrete since no vibration is needed. A further implication is that concrete placement within deep formwork does not need to occur in lifts since vibration of lower level concrete does not have to precede placement of upper level concrete. Finally, the design of formwork and reinforcing systems does not need to be constrained by the condition that access be provided for mechanical vibration during concrete placement since, once again, no mechanical vibration is required (Okamura, 1997).

Self-compacting concrete has been used in construction of several actual structures, the most notable being the Akashi Straights Bridge. At the time of its completion the Akashi Straights Bridge was the longest suspension bridge (6530 ft [1990 m]) in the world. Self- compacting concrete was used in construction of the two bridge anchorages (Okamura, 1997).

6.2.2 Modeling Implications

Two changes were made to the baseline model in order to simulate the use of Self-Compacting High-Performance Concrete. The first was the removal of all concrete vibration activities from within the baseline model to account for the fact that self-compacting concrete does not require any vibration, and the second was the replacement of all concrete bucket placement activities with concrete pumping activities to take full advantage of self-compacting concrete's highly flowable nature. Everything else within the model was left unchanged. The rate of concrete placement with a pump was assumed to be the same, the methods involved in concrete curing were assumed to be the same, and the total amount of time required for concrete curing was assumed to be the same. Formwork and reinforcing system designs were also assumed to remain unchanged, despite removal of the design constraint which requires that access be provided for mechanical vibration during concrete placement.

The results form the simulation involving the use of Self-Compacting High-Performance Concrete in the construction of the prototype building are summarized in Figure 6.3. The total duration of construction worked out to be 52 days (i.e., 10.3 work weeks), a 7% decrease relative to the construction duration of the baseline model; the total activity-based cost of all the resources worked out to be $211,428, a 3% decrease relative to the cost of the baseline model; and the danger index worked out to be 877.72, a 7% decrease in worker exposure to construction hazards relative to the baseline model.

These results suggest that the use of Self-Compacting High-Performance Concrete not only cuts down on construction time and cost, but also improves worker safety. Time is saved since concrete placement activities are not constrained by the need for vibration. Resource cost is reduced slightly since the labor involved in concrete vibration is eliminated. Finally, safety is improved since concrete buckets are not swinging around, since workers do not have to be up on elevated platforms to vibrate concrete in column formwork, and since less work is involved overall in concrete placement operations.

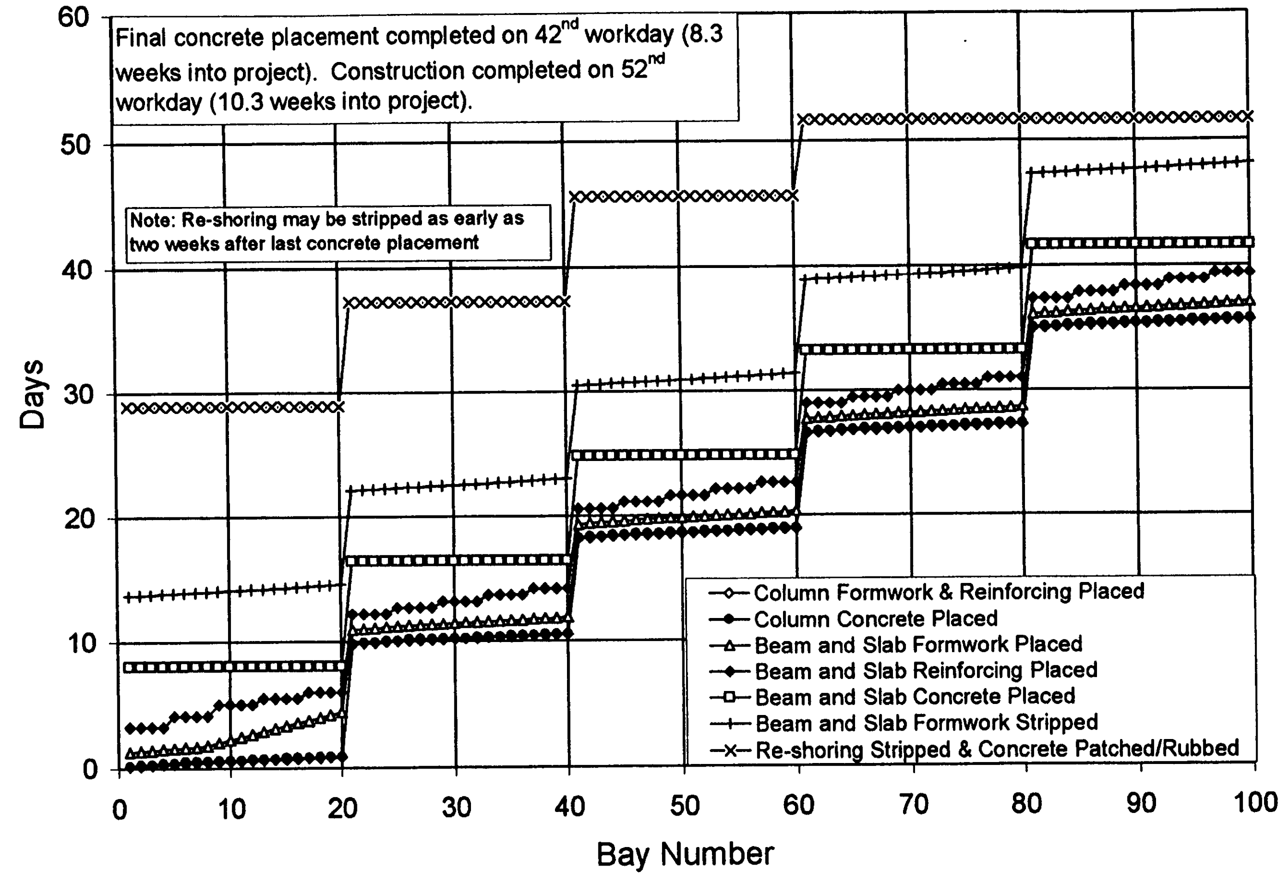


Figure 6.3: Progression of Prototype Building Construction with Self-Compacting Concrete

6.3 Innovation 3: Precast Concrete Stay-In-Place Forms (Filigree)

6.3.1 Description

Precast concrete stay-in-place forms are reinforced concrete units that serve as permanent formwork. The Filigree Wideslab System is a good example. Originally developed in Great Britain under the name OMNIDEC, the Filigree system came to the United States in 1972, and has been used in construction of both parking garages and multistory buildings (Prior *et. al.*, 1993).

With the Filigree system, precast concrete beam and slab forms are custom made at a plant and then transported to a construction site, where they are hoisted into position with a crane. Slab forms are cast with steel trusses projecting from one side to provide the forms with sufficient rigidity for erection, and these steel trusses ensure composite behavior between the precast forms and the cast-in-place concrete (see Figure 6.4). For the Filigree system, beam forms are typically designed to span up to 25 ft. and slab forms are typically designed to span up to 70 ft. Slab form widths are typically 8 ft across. It should be noted that sufficient reinforcing steel is typically cast within each Filigree precast slab unit to eliminate the need for bottom steel erection during construction operations (Prior *et. al.*, 1993).

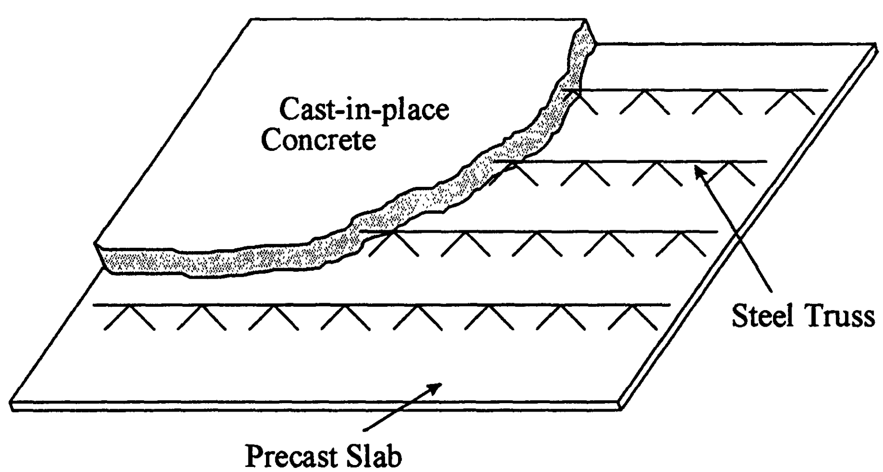


Figure 6.4: Precast Stay-In-Place Slab Form

6.3.2 Modeling Implications

The Filigree system was used to simulate the use of precast concrete stay-in-place forms in construction of the prototype building. Each of the custom made precast concrete forms were assumed to be delivered to the construction site already appropriately sized for their use on the project, and, as a result, all formwork site fabrication activities were eliminated from the simulation model. Each beam was assumed to be made up of a single precast unit designed to span between two columns, and each slab was assumed to be made up of three separate precast units designed to span over an entire bay. All precast units were set to be hoisted into place with a crane, and shoring was used wherever support for these units was required. Bottom steel erection activities were eliminated from the model (since sufficient reinforcing already exists within each precast slab unit to meet bottom steel requirements), and, of course, all formwork stripping activities were also eliminated (since the Filigree forms are meant to be left in place).

The results from the simulation involving the use of the Filigree precast concrete stay-in-place forms in construction of the prototype building are summarized in Figure 6.5. The total duration of construction worked out to be 54 days (i.e., 10.7 work weeks), a 2% decrease relative to the construction duration of the baseline model; the total activity-based cost of all the resources worked out to be $132,173, a 39% decrease relative to the cost of the baseline model; and the danger index worked out to be 547.98, a 42% decrease in worker exposure to construction hazards relative to the baseline model.

These results suggest that use of the Filigree precast concrete stay-in-place forms has significant impact on resource cost and worker safety (due to the fact that much of the formwork preparation and erection activities were shifted off site to a precast plant), but limited impact on overall project duration (in spite the fact that all formwork and preparation activities were eliminated from the process). It is important to recognize that the simulation model does not account for material costs, and that the observed reduction in cost is only a reduction in resource cost, not a reduction in total cost.

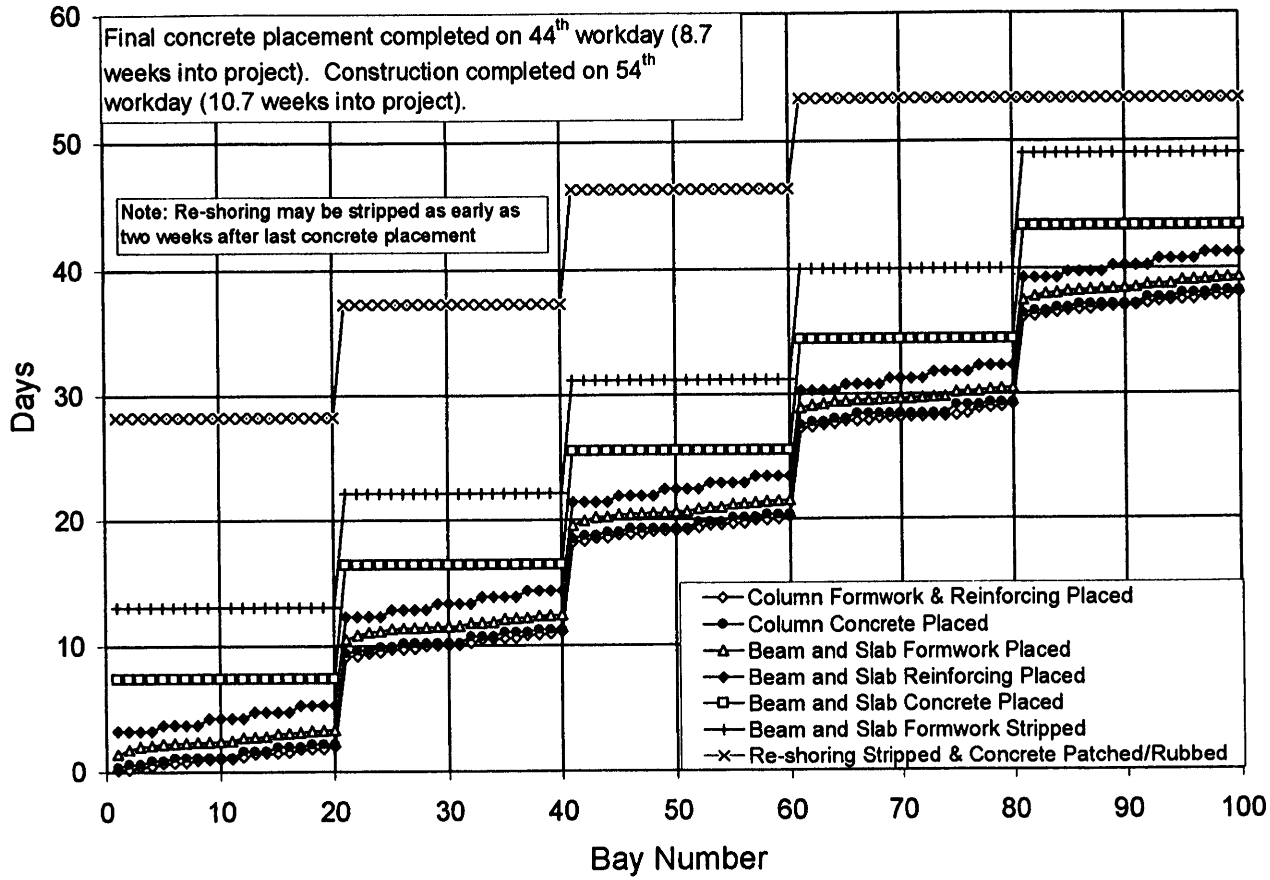


Figure 6.5: Progression of Prototype Building Construction with Filigree Precast Concrete Stay-In-Place Forms

6.4 Talon System & Stay-In-Place Forms Combined

The fourth simulation run was performed to see how combining two completely different innovations in construction of the prototype building might impact the overall construction process. Both the Talon ^{2}360 Rebar Crosstie System and the Filigree precast concrete stay-in-place forms were considered. The exact modifications that were made earlier for simulating each of the two innovations individually were combined together for simulating their joint use in construction of the prototype building.

The results from the simulation run involving the combined use of both the Talon and the Filigree systems in construction of the prototype building are summarized in Figure 6.6. The total duration of construction worked out to be 41 days (i.e., 8.2 work weeks), a 9% decrease relative to the construction duration of the baseline model; the total activity-based cost of all the resources worked out to be $122,122, a 44% decrease relative to the cost of the baseline model; and the danger index worked out to be 481.3, a 49% decrease in worker exposure to construction hazards relative to the baseline model.

When these results are considered in light of those obtained earlier from the simulations involving the individual use of the Talon and Filigree systems, an interesting observation is made (see Table 6.1). Although the impact on cost and safety, from combining both innovations, is approximately equivalent to sum of the cost and safety impacts of each individual innovation, the impact on project duration is far greater than the sum of duration impacts observed when each of the innovations are considered individually.

Table 6.1: Summary of Innovation Results

	Innov 1	Innov 3	Innov 1&3
% Savings in time relative to baseline simulation	-2.2%	2.2%	8.9%
% Decrease in cost relative to baseline simulation	5.6%	39.2%	43.8%
% Increase in safety relative to baseline simulation	7.4%	42.2%	49.2%

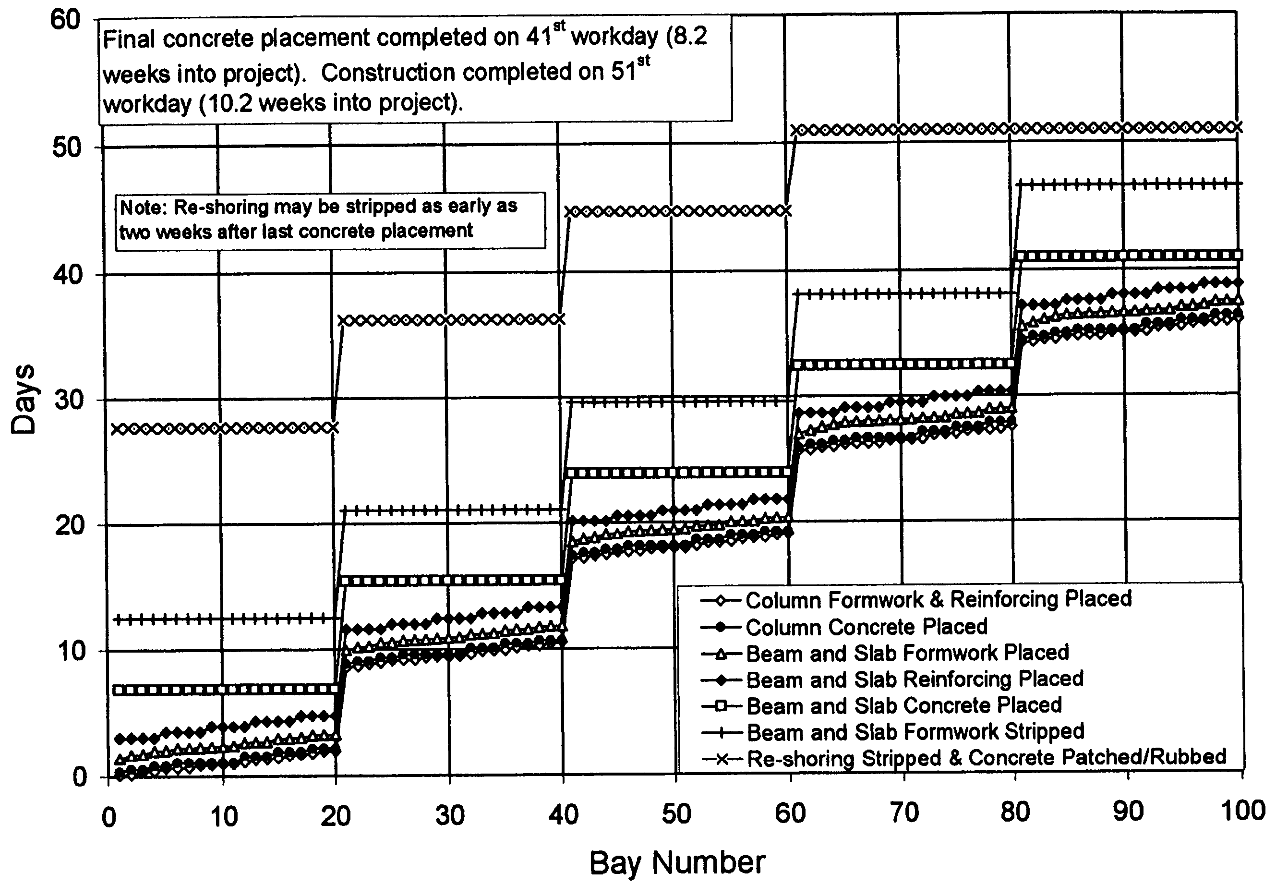


Figure 6.6: Progress of Prototype Building Construction with Talon and Filigree Systems Combined

6.5 Summary of Results

The results of all the simulation runs are summarized in Table 6.2. In the table, 'Innov 1' refers to the Talon ^{2}360 Rebar Crosstie System, 'Innov 2' refers to the Self-Compacting High-Performance Concrete, and 'Innov 3' refers to the Filigree precast concrete stay-in-place formwork system.

Table 6.2: Summary of Innovation Results

	Baseline	Innov 1	Innov 2	Innov 3	Innov 1&3
Days until last concrete pour	45	46	42	44	41
Days until end of construction	55	56	52	54	51
Fixed Cost (crane)	$ 38,416	$ 38,416	$ 38,416	$ 38,416	$ 38,416
Variable Cost (labor and equipment rental)	$123,500	$115,115	$119,318	$ 64,660	$ 57,728
Overhead & Profit (45% of Variable Cost)	$ 55,575	$ 51,802	$ 53,693	$ 29,097	$ 25,978
Total Activity-Based Cost	$217,491	$205,333	$211,428	$132,173	$122,122
Danger Index	947.79	877.22	877.72	547.98	481.3

The Talon ^{2}360 system improved worker safety, reduced resource costs, and slightly increased project duration (although this increase is likely due to a shortage of Talon systems defined within the simulation run). Self-compacting concrete reduced both the time and cost of construction, and improved worker safety. The Filigree system slightly decreased project duration, improved worker safety, and reduced resource cost (but this reduction in resource costs by no means indicates a reduction in total construction costs since the material costs of the precast forms are not considered in the simulation). Finally, the combined use of the Talon and Filigree systems improved worker safety, reduced resource costs, and reduced project duration. Interestingly enough, this observed reduction in project duration turned out to be far greater than the sum of the duration impacts observed when both the Talon and Filigree systems were considered individually.

Chapter 7 : Summary & Conclusions

7.1 Summary

The purpose of this thesis research was to develop a computer-based model for simulating cast-in-place (CIP) concrete construction capable of assessing the impact of design changes and innovations on the construction process. Three different simulation approaches for modeling construction activities were found to exist: the queuing approach, the graphical approach, and the dynamic process approach. Queuing models are useful in modeling cyclical and repetitive processes where activity processing times can be represented using standard probability distributions. Likewise, graphically based models are also useful in modeling cyclical and repetitive processes, however, in addition, they are particularly well suited for uncovering time-space conflicts within processes. Dynamic process models are unlike the other two in that they are particularly useful in modeling non-cyclical processes characterized by decision branches and alternative courses of action. Both process and activity processing times are free to change in response to events that occur within dynamic process models. The details of each model approach were presented in Chapter 2.

The dynamic process approach was selected for use in modeling the CIP concrete construction environment. Developing a dynamic process model of CIP concrete construction required that detailed information be gathered on the CIP concrete construction process and on all the specific attributes affecting it. Data were gathered from three different sources: literature, construction site visits, and interviews with industry professionals. The information from each source was cross-checked and reviewed with the help of industry professionals to verify its validity, accuracy, and reliability.

A general process flow describing the CIP concrete construction process was developed. The process consist of five sets of activities: (1) the preparation and erection of formwork; (2) the preparation and erection of reinforcing; (3) the placement of concrete; (4) the curing of concrete; and (5) the patching, cleaning, and finishing of formed concrete surfaces. Formwork preparation and erection activities focus on the fabrication and assembly of formwork which is required to support and retain freshly placed concrete. Reinforcing preparation and erection activities focus on the fabrication and assembly of steel reinforcing systems which are required to impart tensile resistance to concrete members. Concrete placement activities focus on the placing, vibrating, leveling and finishing of wet concrete. Concrete curing activities focus on maintaining adequate temperature and moisture levels within freshly placed concrete to promote concrete strength, and end with the stripping of formwork, the erection of re-shoring and the eventual stripping of re-shoring once the concrete has sufficiently cured to support all remaining anticipated loads. Finally, concrete patching, cleaning, and finishing activities focus on repairing and touching up any formed concrete surfaces that may require some additional work. Details of the general process were presented in Chapter 4.

With the general process established and well defined, work began on the development of an actual computer-based dynamic process model for simulating CIP concrete construction. The model was created with SIMPROCESS®, a computer-based dynamic process modeling tool. Two fundamental objectives were sought during model development. The first was that the model be made as representative of reality as possible, and the second was that it be made easy to modify so that it could be used to simulate construction of a wide variety of different CIP concrete building projects. Both of these objectives introduced a number of complicating factors into the model development process. For instance, strategies had to be developed for organizing, managing, and sequencing large numbers of entities and activities, a system had to be put in place for making the model responsive to resource availability, and schemes had to be contrived for representing activity interdependencies. In the end, however, a computer-based dynamic process simulation model of CIP concrete construction was established.

A prototype building was designed, and project specific information associated with its construction was incorporated within the CIP concrete construction model to verify the model's reliability. For CIP concrete systems, project specifics consist of design-related and construction-related attributes. Design-related attributes are a direct function of project design and arise from decisions made by designers, whereas construction-related attributes are a function of selected construction methods and arise from decisions made by construction contractors. Together, design-related and construction-related attributes distinguish one particular CIP concrete construction project from another.

Construction of the prototype building was simulated with the CIP concrete construction model, and the resulting simulation times were found to agree with those that were estimated by CIP concrete specialty contractors. An analysis of the activity-based cost and danger index associated with construction of the prototype building was performed, and these values (along with the construction duration time) were recorded for use later in evaluating the impact of innovations on the construction process.

Finally, construction of the prototype building was simulated with innovations. Three innovations were considered (Talon ^{2}360 Rebar Crosstie System, High-Performance Self-Compacting Concrete, and Filigree precast concrete stay-in-place forms), and four different simulation runs were performed. The first three runs considered construction of the prototype building with each of the three innovations individually, and the fourth run considered construction of the prototype building with both the Talon ^{2}360 system and the Filigree stay-in-place forms being used at the same time.

7.2 Conclusion

A computer-based dynamic process model capable of simulating cast-in-place (CIP) concrete construction was successfully developed. It is unlike any other model previously developed for simulating the CIP concrete construction process in that it tracks the flow of pieces and elements used in construction (rather than the resources that do the work), and these pieces and elements are assembled and transformed over the course of a simulation run. Work is done to them as they pass through activities in the model in the same manner that work is done to them on the construction site. In addition, this work is a function of the individual characteristics of each different piece and element, just as it is a function of the characteristics of each different piece or element on the construction site. Thus the simulation model directly maps the actual activity/entity relationships observed in construction. Activities transform entities and the attributes of these entities influence the performance of future activities.

Because activities are a function of entity attributes and entity attributes can be changed by activities, one single general process model representing all forms of CIP concrete building construction could be created. The general process model need only to account for all of the relationships that exist between activities, entities, and resources within CIP concrete construction (which are common to all CIP concrete building projects). The project specifics can be used to define the attributes of these activities, entities, and resources, thereby automatically tailoring the general process for use in simulating the construction of a specific building. The result is a model that is easy to modify and simple to use.

This thesis demonstrates the usefulness of the CIP concrete construction model in assessing the potential impact of innovations on the CIP concrete construction process. The model has several other applications as well. It can be used to determine the potential impact of design or site management strategy changes on the actual CIP concrete construction process (e.g., how would having two cranes on site as opposed to just one impact the construction process in terms of schedule, cost, and worker safety?); it can be used to identify areas within the CIP concrete construction process where 'bottlenecks' often occur and where the greatest potential savings in time, cost, and worker safety can be achieved; and it can also be used to help innovators identify where in the construction process innovation research should be focused in order to maximize its impact.

The dynamic process simulation model developed in this research is expected to be combined with others that have been or are currently being developed as part of ongoing research at MIT. The construction processes having been modeled thus far include: structural steel erection; exterior enclosure erection; and now, CIP concrete construction. Those currently being researched include: plumbing installation; HVAC systems installation, electrical services installation, and interior finishing. Incorporating all of these models into a single dynamic process meta-model will enable the impacts from changes in one building system to be carried over to the others, and would clearly be a remarkable achievement in construction process modeling.

When this research began, the ultimate question was really whether or not a reasonably accurate model of the cast-in-place concrete construction process could in fact be developed. Could a computer model actually be made responsive to the very same factors that affect construction (i.e., design, site management strategies, and resource availability)? Could a complicated construction process actually be mapped out in very fine detail to capture all of the various alternative courses of action within it? Could the variables affecting activity processing times be defined and accounted for in a model? Could the manner in which resources are shared on the construction site be represented in a simulated environment? Could the transformation and assembly of pieces and elements, which is common in construction, be duplicated on a computer? The evidence brought forth by this research (i.e., the successful development of a cast-in-place concrete construction dynamic process simulation model) suggests that the answer to all of these questions is yes.

Appendix A: User Defined Attributes

List of User Defined Entity Attributes

Name	Description
NumRCuts	Number of cuts to make within a reinforcing group
NumRBends	Number of bend to make within a reinforcing group
GrpSize	Total number of units within a formwork or reinforcing group
NumConnects	Total number of connections to make within a formwork or reinforcing group
MLGrpSize	Number of units within a group that require mechanical leverage
MLNumConnects	Number of connections within a group that need to made while mechanical leverage is in use
NumFCutsPl	Number of plywood cuts to make within a formwork group
NumFCutsSt	Number of stud cuts to make within a formwork group
NumPerfs	Number of holes to be drilled within a formwork group
NumStripLater	Number of formwork elements that are only to be stripped during re-shoring
NumSuppShores	Number of supplemental shoring elements to be erected just prior to formwork stripping
NumReShores	Number of re-shoring elements to be erected following formwork stripping
SizeOfEnclosure	Size of any enclosure (in thousands of sqft) required prior to concrete placement
MoistConType	Type of moisture control to be used during curing
ThermConType	Type of thermal control to be used during curing

List of User Defined Model Attributes

Name	Description
Xmax	Total number of bays spanning the x-direction
Ymax	Total number of bays spanning the y-direction
XSpan	Bay width in the x-direction (ft)
YSpan	Bay width in the y-direction (ft)
FElementGrpReuses	Total number of times the same forms can be reused on the project
TruckVol	Volume of concrete in a concrete truck (cyds)
ColVol	Volume of a column (cyds)
EdgeVol	Volume of an edge beam (cyds)
CenterVol	Volume of a center beam (cyds)
SlabVol	Volume of a slab within a bay (cyds)
BucketVol	Volume of bucket used in concrete placement (cyds)
(Production Rates)	All production rates are set to default values but are free to change

Formwork Section Attributes:

Section Name: Column		
Prep.=>Dummy17, Erect =>Dummy18		
Entity	**Attribute**	**Value**
FPieceGrp	NumFCutsPl	0
	NumFCutsSt	0
	NumPerfs	0
	GrpSize	0
	NumConnects	0
FElementGrpSF	GrpSize	0
	MLGrpSize	0
FElementGrpPF	GrpSize	4
	MLGrpSize	0
	NumStripLater	0
FElementGrp	NumConnects	36
	MLNumConnects	0
	SurfaceArea	60
	TagNum	51
FormSection	NumSuppShores	0
	NumReShores	0

Section Name: Edge		
Prep.=>Dummy19, Erect =>Dummy20		
Entity	**Attribute**	**Value**
FPieceGrp	NumFCutsPl	15
	NumFCutsSt	58
	NumPerfs	0
	GrpSize	72
	NumConnects	288
FElementGrpSF	GrpSize	12
	MLGrpSize	0
FElementGrpPF	GrpSize	28
	MLGrpSize	0
	NumStripLater	10
FElementGrp	NumConnects	60
	MLNumConnects	0
	SurfaceArea	84
	TagNum	1
FormSection	NumSuppShores	0
	NumReShores	0

Section Name: Center		
Prep.=>Dummy21, Erect =>Dummy22		
Entity	**Attribute**	**Value**
FPieceGrp	NumFCutsPl	15
	NumFCutsSt	58
	NumPerfs	0
	GrpSize	72
	NumConnects	288
FElementGrpSF	GrpSize	12
	MLGrpSize	0
FElementGrpPF	GrpSize	16
	MLGrpSize	0
	NumStripLater	10
FElementGrp	NumConnects	44
	MLNumConnects	0
	SurfaceArea	62
	TagNum	2
FormSection	NumSuppShores	0
	NumReShores	0

Section Name: Slab		
Prep.=>Dummy23, Erect =>Dummy24		
Entity	**Attribute**	**Value**
FPieceGrp	NumFCutsPl	0
	NumFCutsSt	0
	NumPerfs	0
	GrpSize	0
	NumConnects	0
FElementGrpSF	GrpSize	0
	MLGrpSize	0
FElementGrpPF	GrpSize	79
	MLGrpSize	0
	NumStripLater	25
FElementGrp	NumConnects	44
	MLNumConnects	0
	SurfaceArea	416
	TagNum	52
FormSection	NumSuppShores	0
	NumReShores	0

Section Name: ColConnectI		
Prep.=>Dummy25, Erect =>Dummy26		
Entity	**Attribute**	**Value**
FPieceGrp	NumFCutsPl	36
	NumFCutsSt	40
	NumPerfs	0
	GrpSize	52
	NumConnects	116
FElementGrpSF	GrpSize	12
	MLGrpSize	0
FElementGrpPF	GrpSize	20
	MLGrpSize	0
	NumStripLater	12
FElementGrp	NumConnects	36
	MLNumConnects	0
	SurfaceArea	38
	TagNum	4
FormSection	NumSuppShores	0
	NumReShores	0

Section Name: ColConnectE		
Prep.=>Dummy27, Erect =>Dummy28		
Entity	**Attribute**	**Value**
FPieceGrp	NumFCutsPl	23
	NumFCutsSt	28
	NumPerfs	0
	GrpSize	36
	NumConnects	82
FElementGrpSF	GrpSize	8
	MLGrpSize	0
FElementGrpPF	GrpSize	20
	MLGrpSize	0
	NumStripLater	10
FElementGrp	NumConnects	28
	MLNumConnects	0
	SurfaceArea	28
	TagNum	5
FormSection	NumSuppShores	0
	NumReShores	0

Section Name: ColConnectC		
Prep.=>Dummy29, Erect =>Dummy30		
Entity	**Attribute**	**Value**
FPieceGrp	NumFCutsPl	14
	NumFCutsSt	18
	NumPerfs	0
	GrpSize	23
	NumConnects	53
FElementGrpSF	GrpSize	5
	MLGrpSize	0
FElementGrpPF	GrpSize	15
	MLGrpSize	0
	NumStripLater	7
FElementGrp	NumConnects	20
	MLNumConnects	0
	SurfaceArea	18
	TagNum	6
FormSection	NumSuppShores	0
	NumReShores	0

Section Name: SBConnect		
Prep.=>Dummy31, Erect =>Dummy32		
Entity	**Attribute**	**Value**
FPieceGrp	NumFCutsPl	6
	NumFCutsSt	56
	NumPerfs	0
	GrpSize	68
	NumConnects	288
FElementGrpSF	GrpSize	8
	MLGrpSize	0
FElementGrpPF	GrpSize	0
	MLGrpSize	0
	NumStripLater	0
FElementGrp	NumConnects	40
	MLNumConnects	0
	SurfaceArea	36
	TagNum	3
FormSection	NumSuppShores	0
	NumReShores	0

Reinforcing Section Attributes:

Section Name: ColumnA		
Prep.=>Dummy1, Erect =>Dummy2		
Entity	**Attribute**	**Value**
RPieceGrp	NumRCuts	0
	NumRBends	0
	GrpSize	12
	NumConnects	60
RElementGrpSF	GrpSize	1
	MLGrpSize	1
RElementGrpPF	GrpSize	0
	MLGrpSize	0
RElementGrp	NumConnects	24
	MLNumConnects	24

Section Name: ColumnB		
Prep.=>Dummy3, Erect =>Dummy4		
Entity	**Attribute**	**Value**
RPieceGrp	NumRCuts	0
	NumRBends	0
	GrpSize	8
	NumConnects	28
RElementGrpSF	GrpSize	1
	MLGrpSize	1
RElementGrpPF	GrpSize	0
	MLGrpSize	0
RElementGrp	NumConnects	12
	MLNumConnects	12

Section Name: Edge		
Prep.=>Dummy5, Erect =>Dummy6		
Entity	**Attribute**	**Value**
RPieceGrp	NumRCuts	0
	NumRBends	0
	GrpSize	0
	NumConnects	0
RElementGrpSF	GrpSize	0
	MLGrpSize	0
RElementGrpPF	GrpSize	7
	MLGrpSize	0
RElementGrp	NumConnects	20
	MLNumConnects	0

Section Name: Center		
Prep.=>Dummy7, Erect =>Dummy8		
Entity	**Attribute**	**Value**
RPieceGrp	NumRCuts	0
	NumRBends	0
	GrpSize	0
	NumConnects	0
RElementGrpSF	GrpSize	0
	MLGrpSize	0
RElementGrpPF	GrpSize	11
	MLGrpSize	0
RElementGrp	NumConnects	60
	MLNumConnects	0

Section Name: Edge1		
Prep.=>Dummy9, Erect =>Dummy10		
Entity	**Attribute**	**Value**
RPieceGrp	NumRCuts	0
	NumRBends	0
	GrpSize	0
	NumConnects	0
RElementGrpSF	GrpSize	0
	MLGrpSize	0
RElementGrpPF	GrpSize	11
	MLGrpSize	0
RElementGrp	NumConnects	52
	MLNumConnects	0

Section Name: Center1		
Prep.=>Dummy11, Erect =>Dummy12		
Entity	**Attribute**	**Value**
RPieceGrp	NumRCuts	0
	NumRBends	0
	GrpSize	0
	NumConnects	0
RElementGrpSF	GrpSize	0
	MLGrpSize	0
RElementGrpPF	GrpSize	20
	MLGrpSize	0
RElementGrp	NumConnects	122
	MLNumConnects	0

Section Name: EdgeX
Prep.=>Dummy13, Erect =>Dummy14

Entity	Attribute	Value
RPieceGrp	NumRCuts	0
	NumRBends	0
	GrpSize	0
	NumConnects	0
RElementGrpSF	GrpSize	0
	MLGrpSize	0
RElementGrpPF	GrpSize	14
	MLGrpSize	0
RElementGrp	NumConnects	96
	MLNumConnects	0

Section Name: CenterX
Prep.=>Dummy15, Erect =>Dummy16

Entity	Attribute	Value
RPieceGrp	NumRCuts	0
	NumRBends	0
	GrpSize	0
	NumConnects	0
RElementGrpSF	GrpSize	0
	MLGrpSize	0
RElementGrpPF	GrpSize	11
	MLGrpSize	0
RElementGrp	NumConnects	60
	MLNumConnects	0

Section Name: SlabBottom
Prep.=>Dummy33, Erect =>Dummy34

Entity	Attribute	Value
RPieceGrp	NumRCuts	0
	NumRBends	0
	GrpSize	0
	NumConnects	0
RElementGrpSF	GrpSize	0
	MLGrpSize	0
RElementGrpPF	GrpSize	60
	MLGrpSize	0
RElementGrp	NumConnects	120
	MLNumConnects	0

Section Name: SlabTop
Prep.=>Dummy35, Erect =>Dummy36

Entity	Attribute	Value
RPieceGrp	NumRCuts	0
	NumRBends	0
	GrpSize	0
	NumConnects	0
RElementGrpSF	GrpSize	0
	MLGrpSize	0
RElementGrpPF	GrpSize	290
	MLGrpSize	0
RElementGrp	NumConnects	580
	MLNumConnects	0

Model Attribute Values:

Attribute Name	Value
Xmax	5
Ymax	4
XSpan	25
YSpan	25
TruckVol	10
ColVol	2.5
EdgeVol	1.3
CenterVol	1.0
SlabVol	15.4
BucketVol	1
FElementGrpReuses	4
(Production Rates)	Vary

Appendix B: CIP Concrete Construction Model Layout

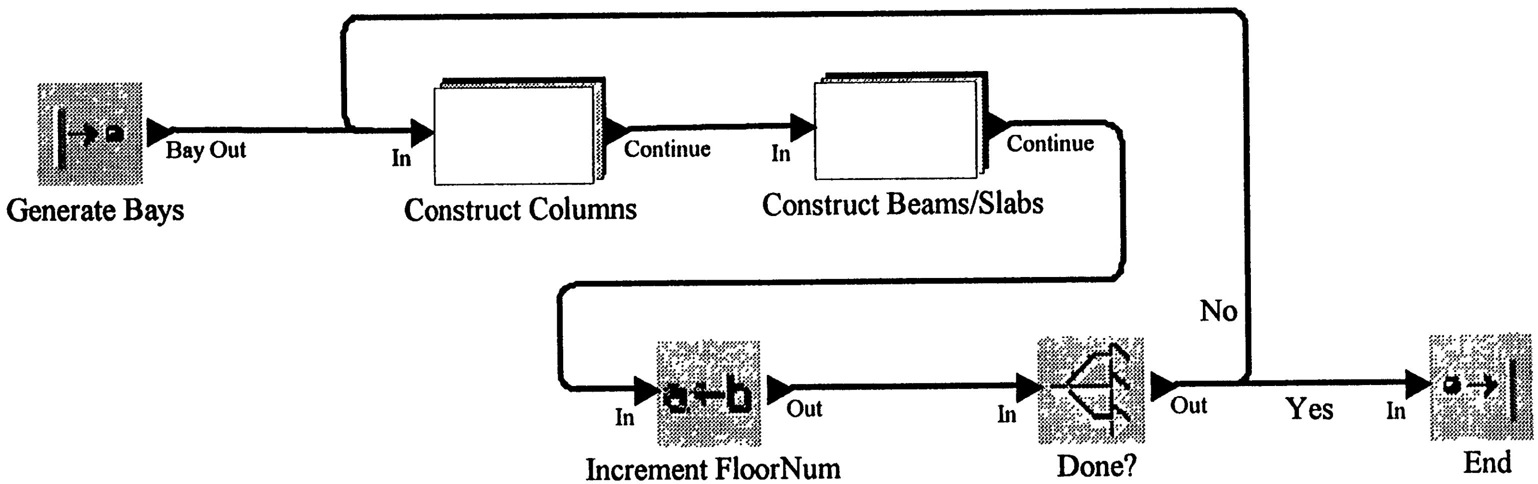


Figure B.1: CIP Model

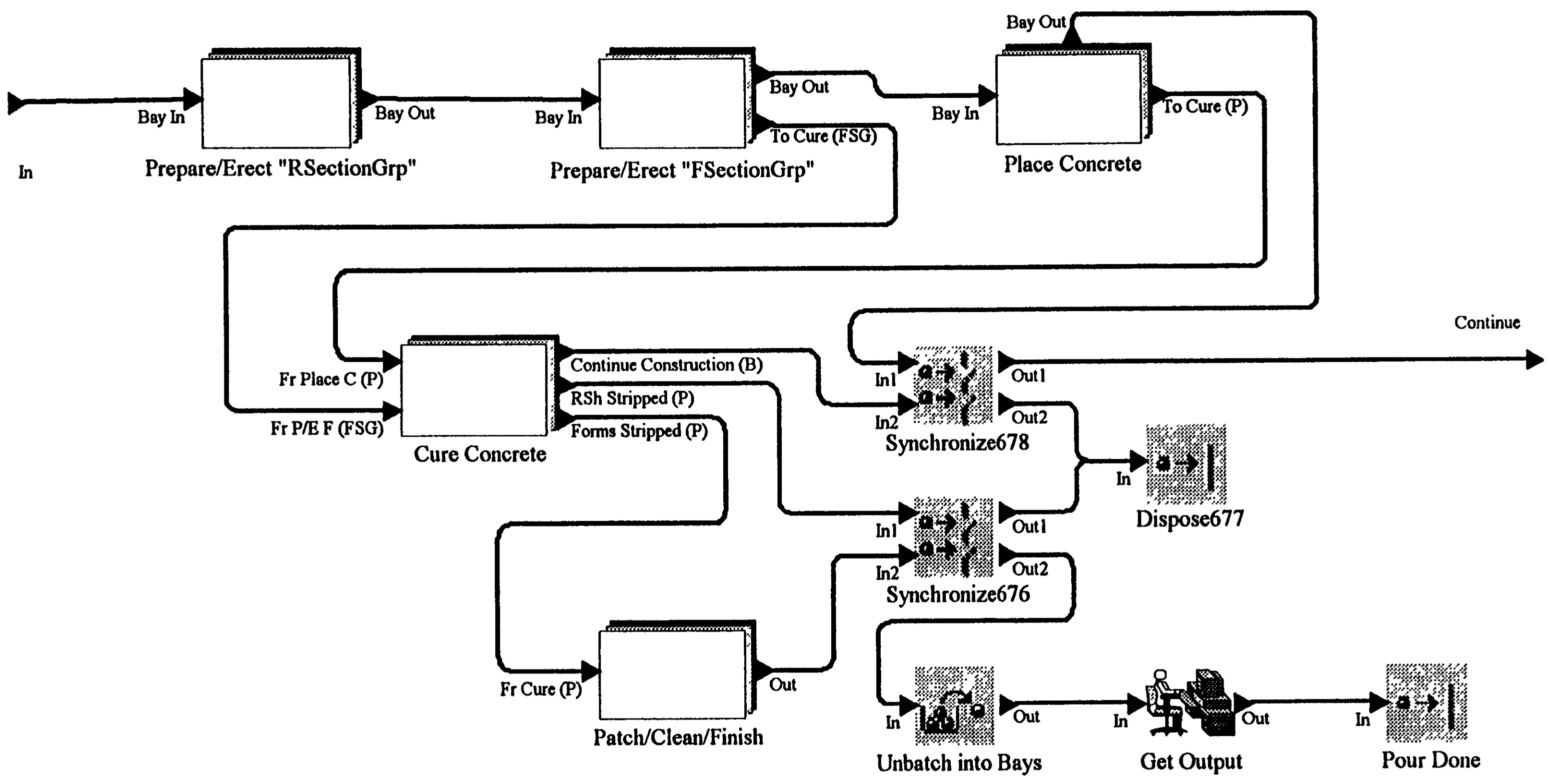


Figure B.2: CIP Model: Construct Columns

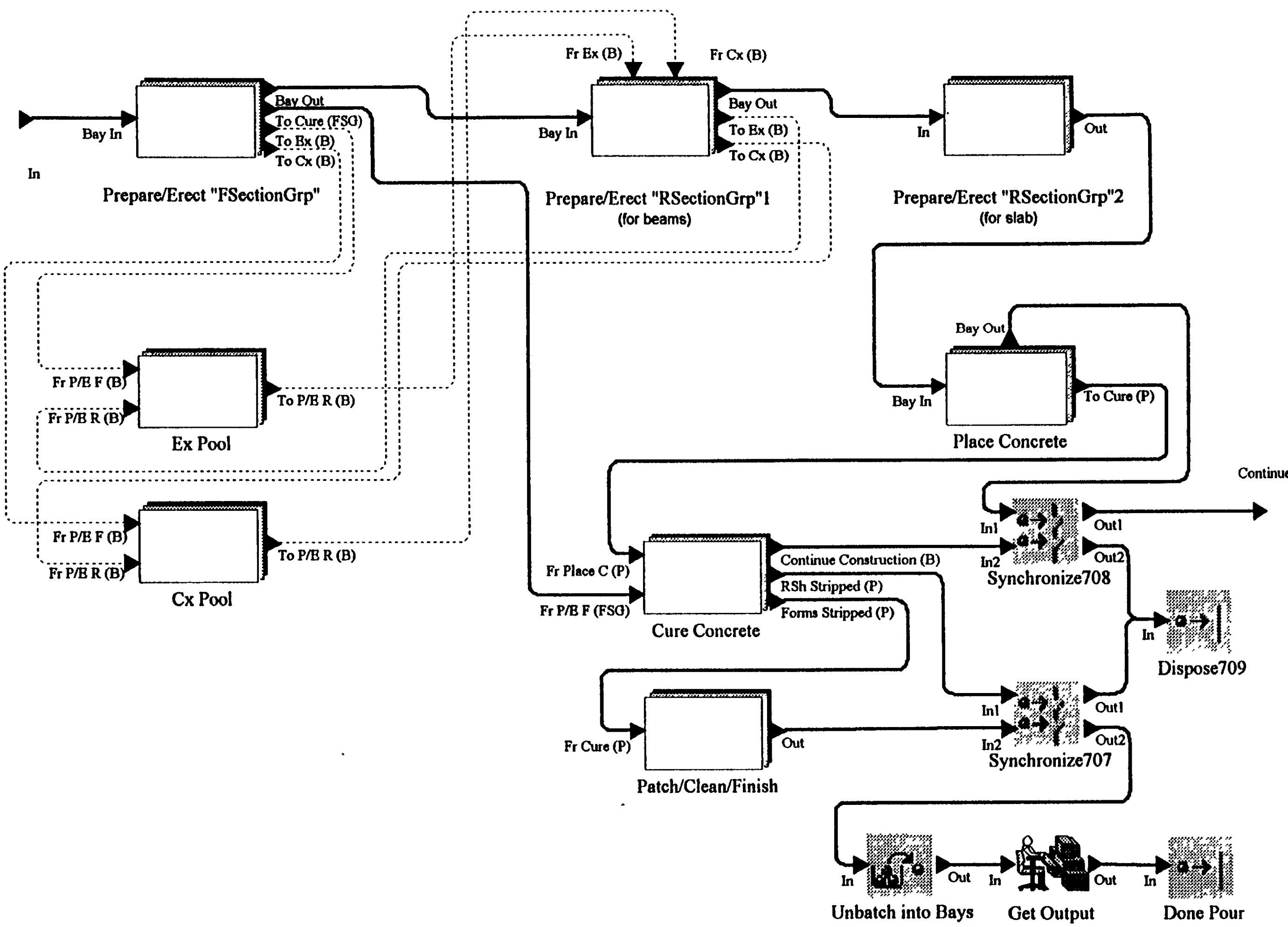


Figure B.3: CIP Model: Construct Beams/Slabs

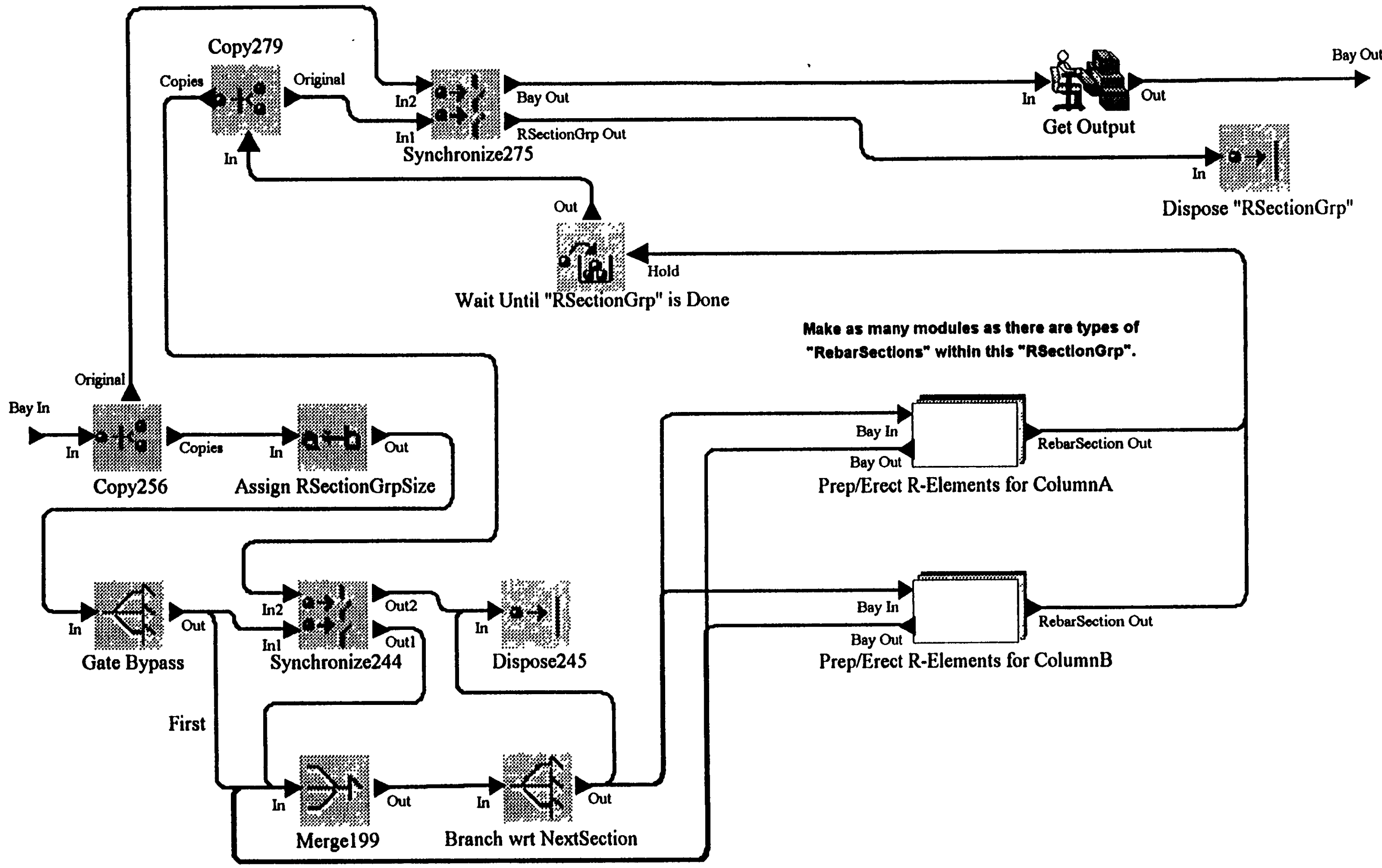


Figure B.4: CIP Model: Construct Columns: Prepare/Erect "RSectionGrp"

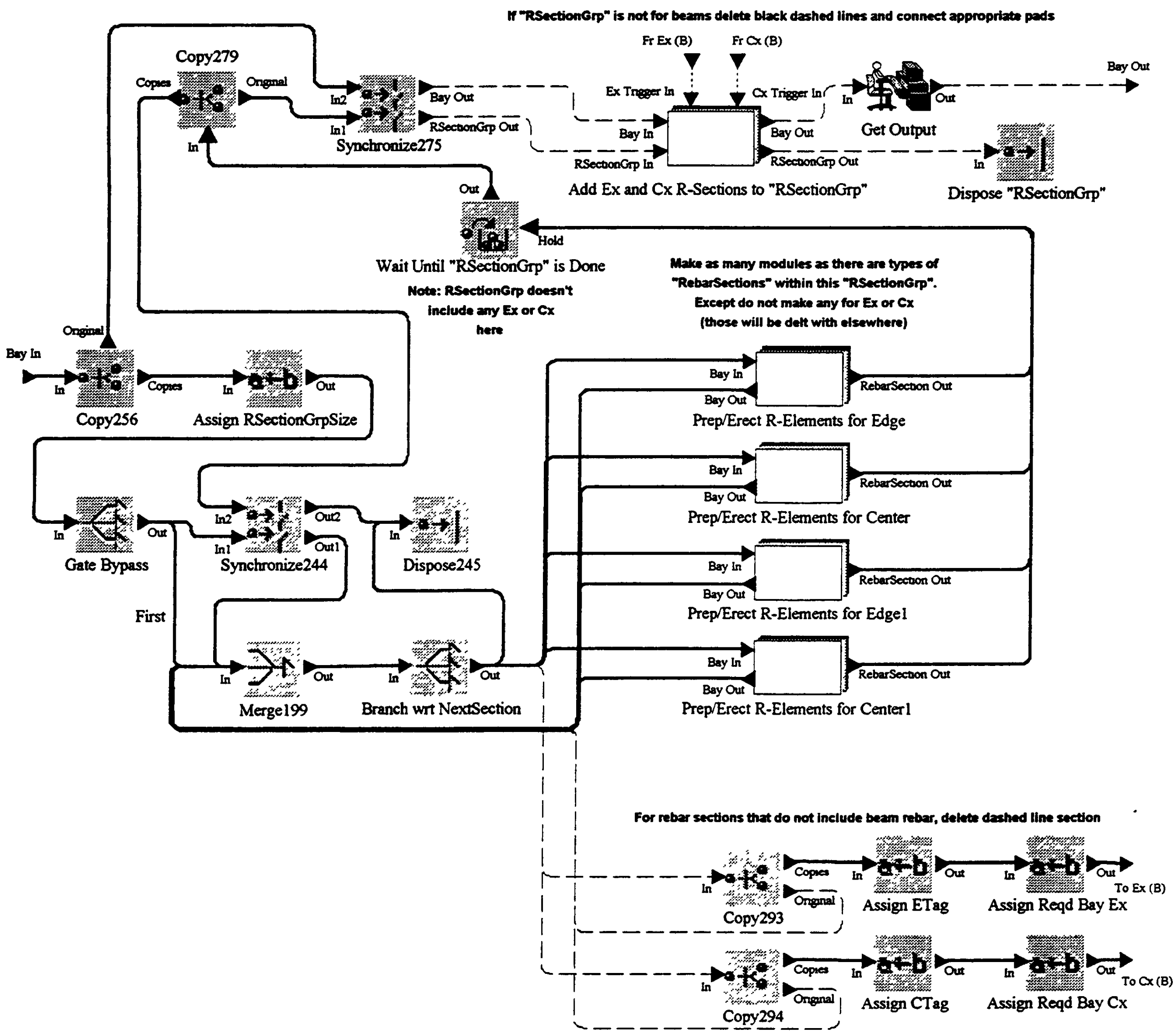


Figure B.5: CIP Model: Construct Beams/Slabs: Prepare/Erect "RSectionGrp"1

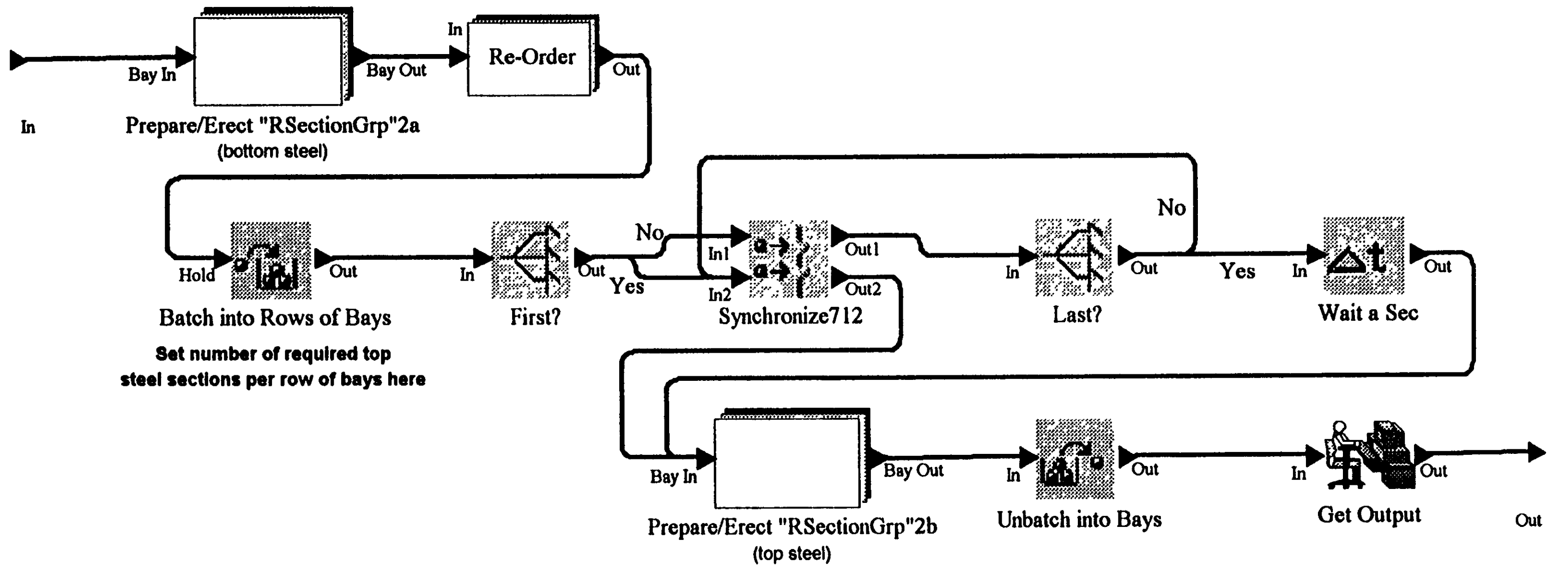


Figure B.6: CIP Model: Construct Beams/Slabs: Prepare/Erect "RSectionGrp"2

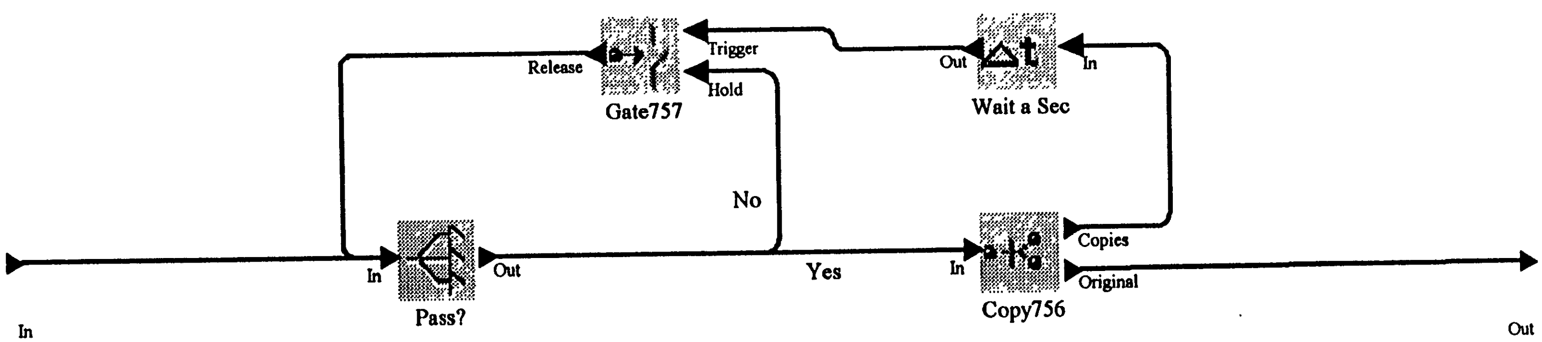


Figure B.7: CIP Model: Construct Beams/Slabs: Prepare/Erect "RSectionGrp"2: Re-Order

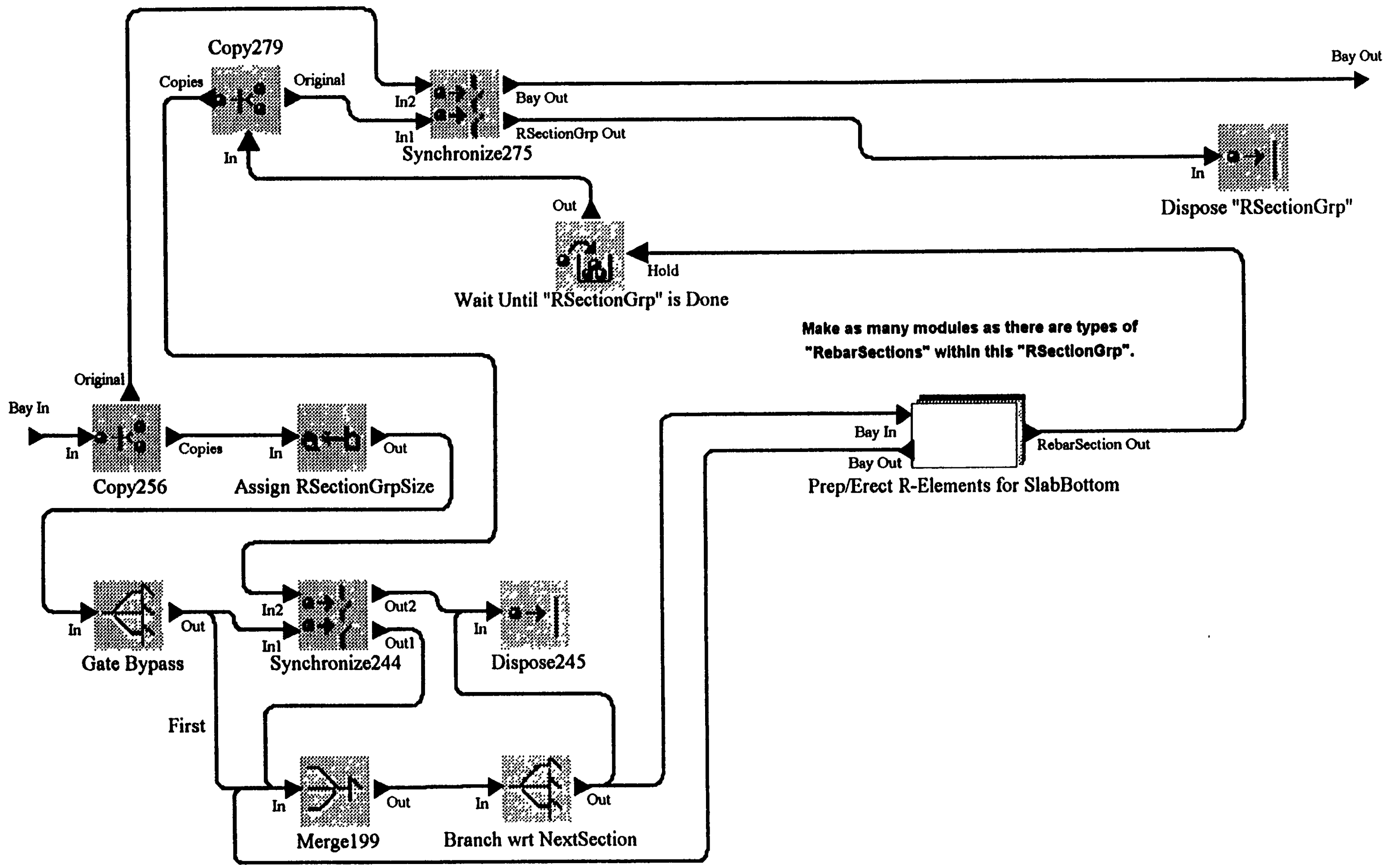


Figure B.8: CIP Model: Construct Beams/Slabs: Prepare/Erect "RSectionGrp"2: Prepare/Erect "RSectionGrp"2a

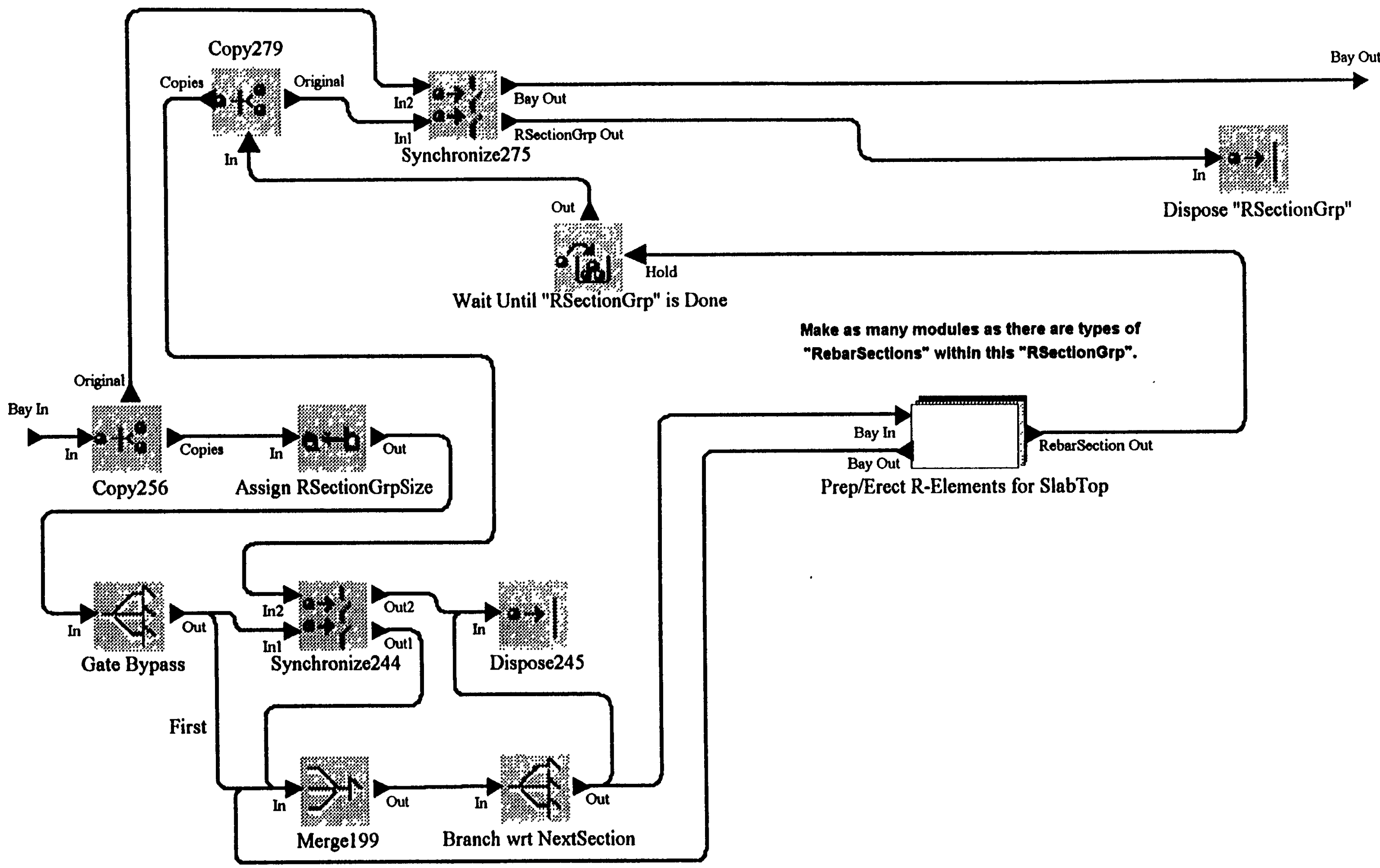


Figure B.9: CIP Model: Construct Beams/Slabs: Prepare/Erect "RSectionGrp"2: Prepare/Erect "RSectionGrp"2b

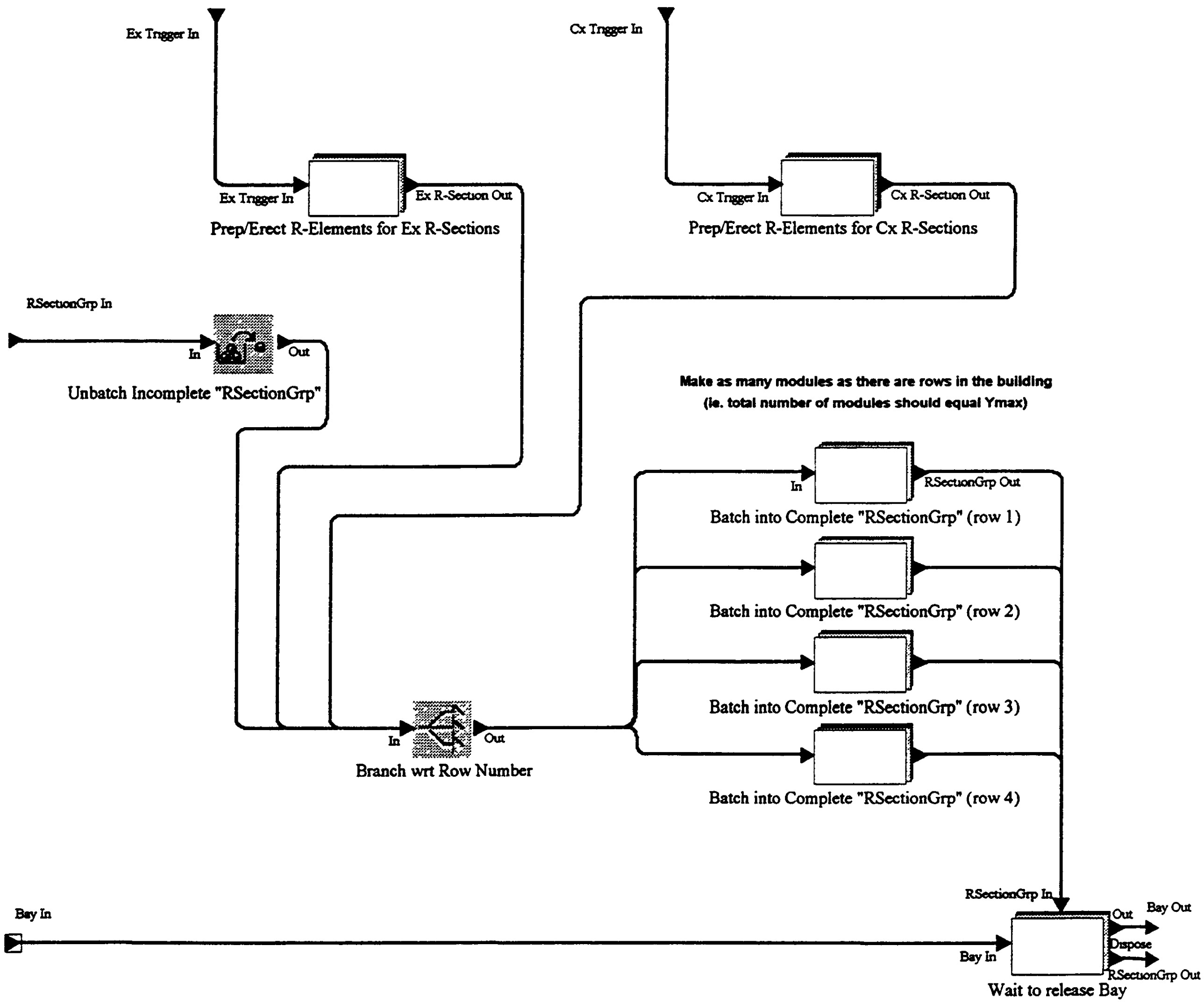


Figure B.10: CIP Model: Construct Beams/Slabs: Prepare/Erect "RSectionGrp"1: Add Ex and Cx R-Sections to "RSectionGrp"

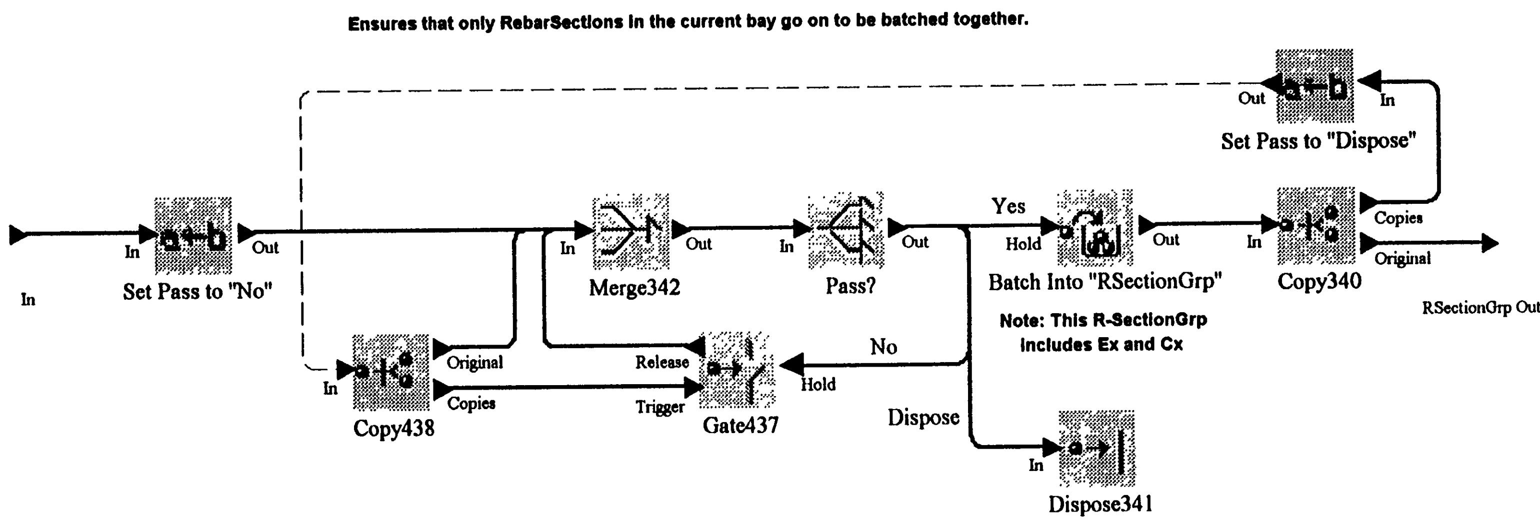


Figure B.11: CIP Model: Construct Beams/Slabs: Prepare/Erect "RSectionGrp"1: Add Ex and Cx R-Sections to "RSectionGrp"CIP: Batch into complete "RSectionGrp"

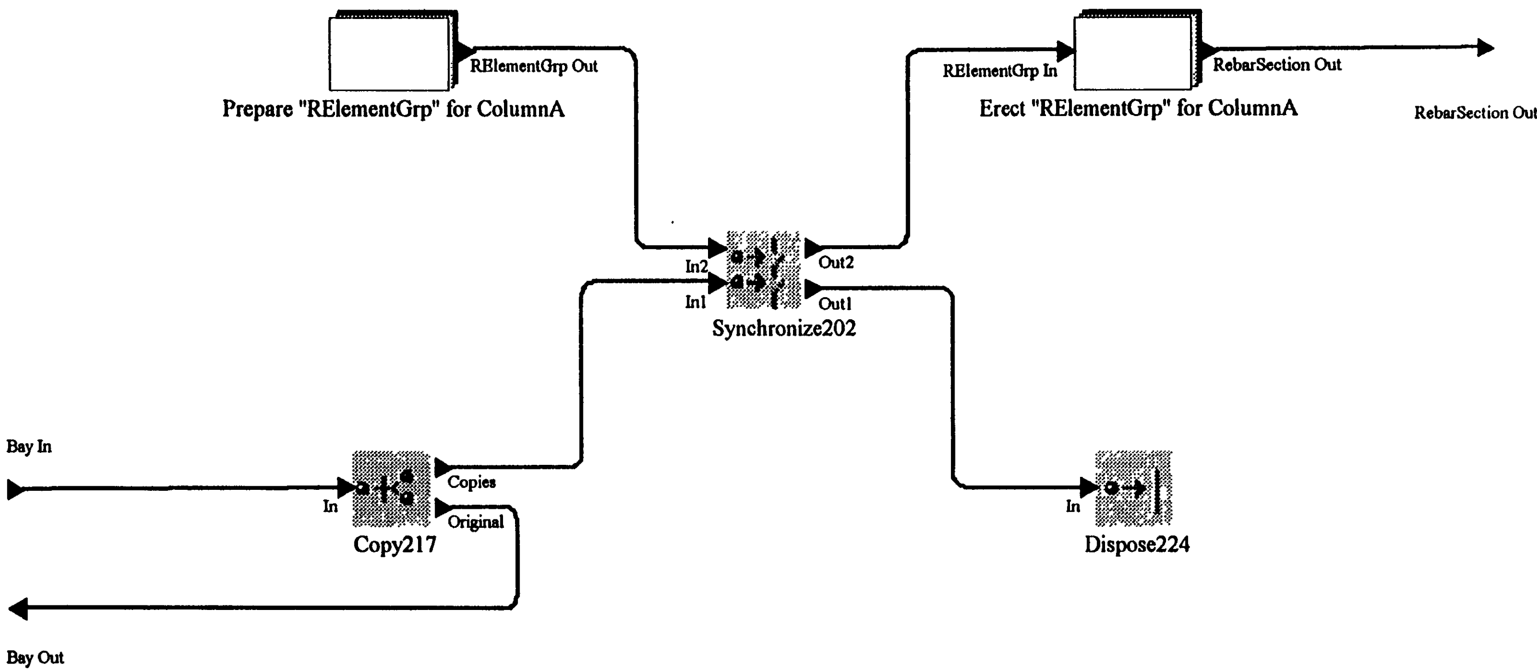


Figure B.12: CIP Model: Typical: Prepare/Erect "RSectionGrp": Prepare/Erect R-Elements

If the section has no pre-fabricated rebar elements, remember to adjust the assemble activity by removing the requirement for one "RElementGrpPF" so that assembly may proceed without it. In the same way, if there are no site fabricated elements in the section, remove the requirement for one "RElementGrpSF".

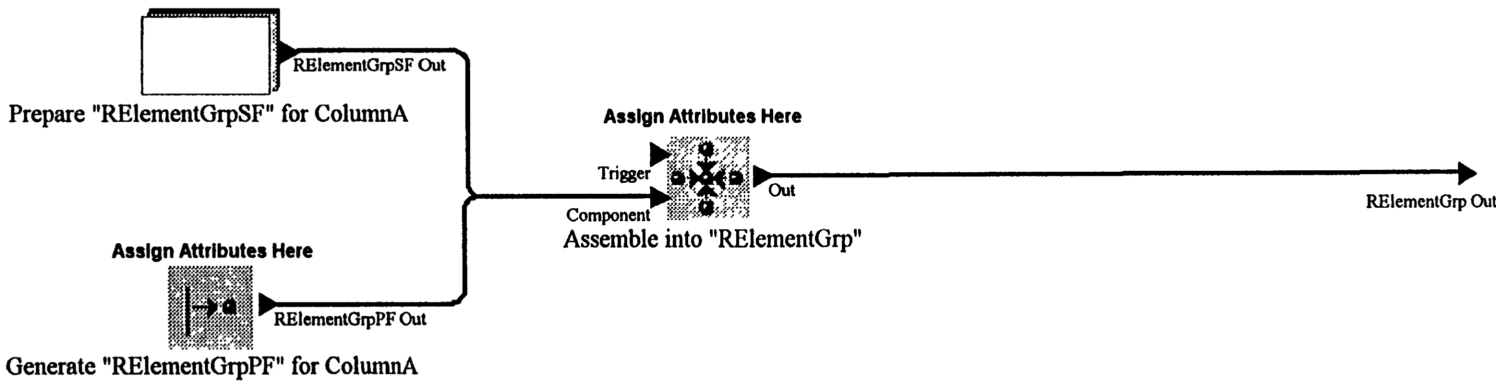


Figure B.13: CIP Model: Typical: Prepare/Erect "RSectionGrp": Prepare/Erect R-Elements: Prepare "RElementGrp"

RPieceGrp = all rebar pieces required to make all the site fabricated rebar elements
for the given rebar section (i.e. rebar for columns on floors 1-3, rebar for columns on floors 4-6,
rebar in edge beams (E, E1, Ex), rebar in center beams (C, C1, Cx),
bottom steel in each direction, top steel in each direction ...)

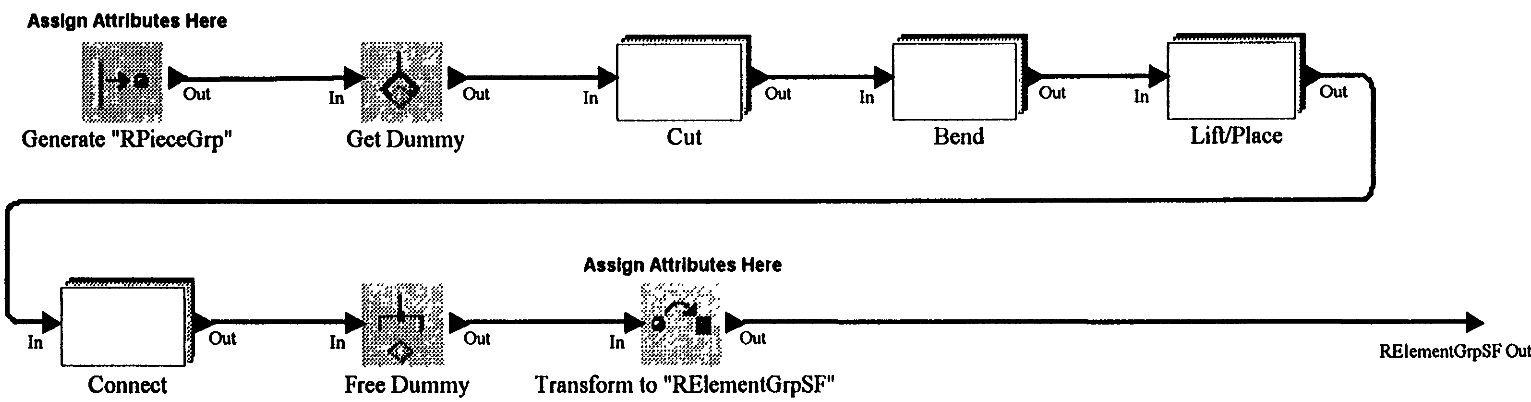


Figure B.14: CIP Model: Typical: Prepare/Erect "RSectionGrp": Prepare/Erect R-Elements: Prepare "RElementGrp": Prepare "RElementGrpSF"

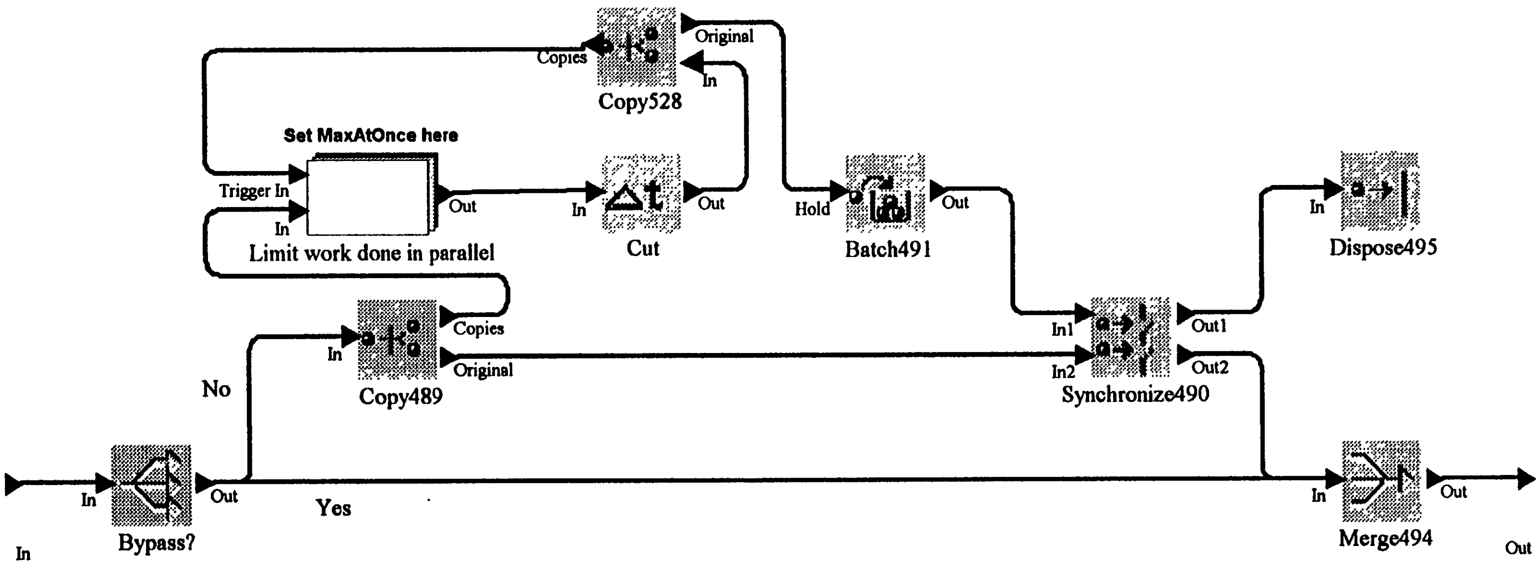


Figure B.15: CIP Model: Typical: Prepare/Erect "RSectionGrp": Prepare/Erect R-Elements: Prepare "RElementGrp": Prepare "RElementGrpSF": Activity

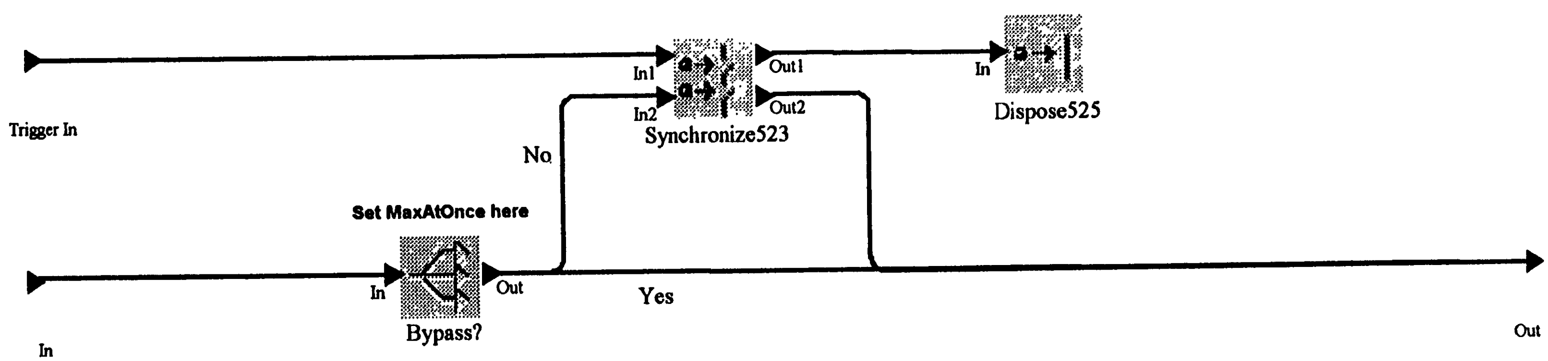


Figure B.16: CIP Model: Typical: Prepare/Erect "RSectionGrp": Prepare/Erect R-Elements: Prepare "RElementGrp": Prepare "RElementGrpSF": Activity: Limit Work Done in Parallel

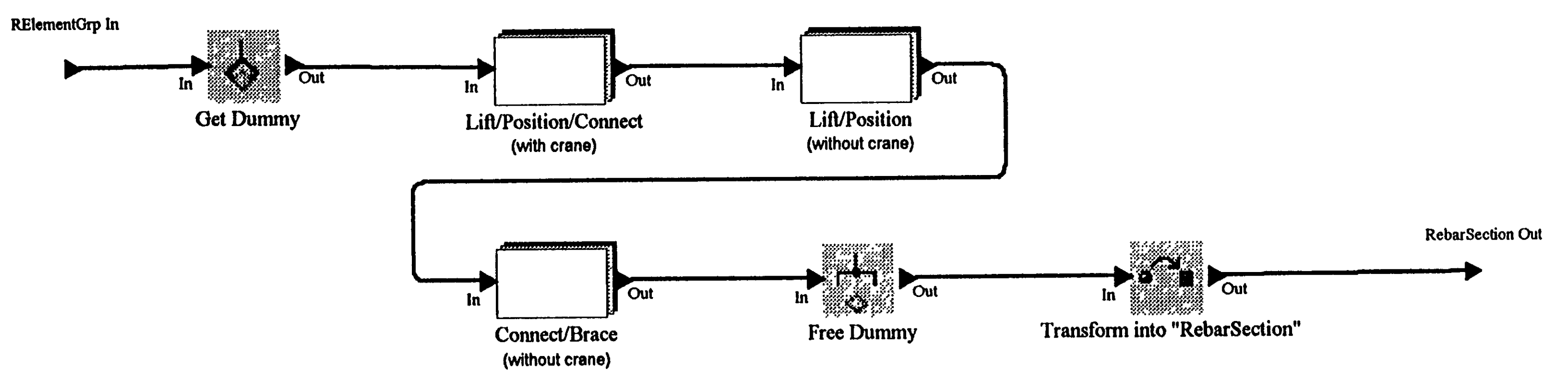


Figure B.17: CIP Model: Typical: Prepare/Erect "RSectionGrp": Prepare/Erect R-Elements: Erect "RElementGrp"

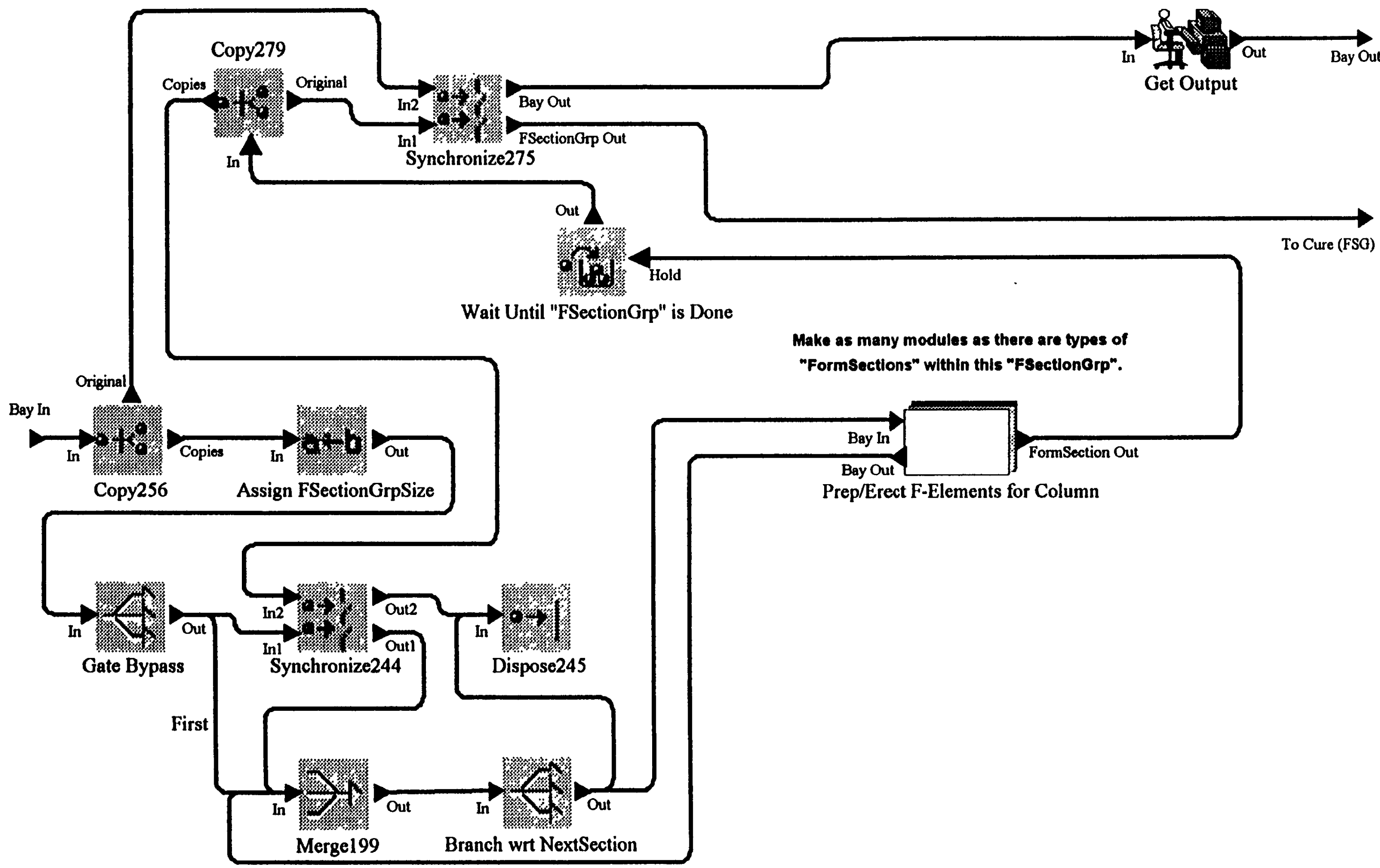


Figure B.18: CIP Model: Construct Columns: Prepare/Erect "FSectionGrp"

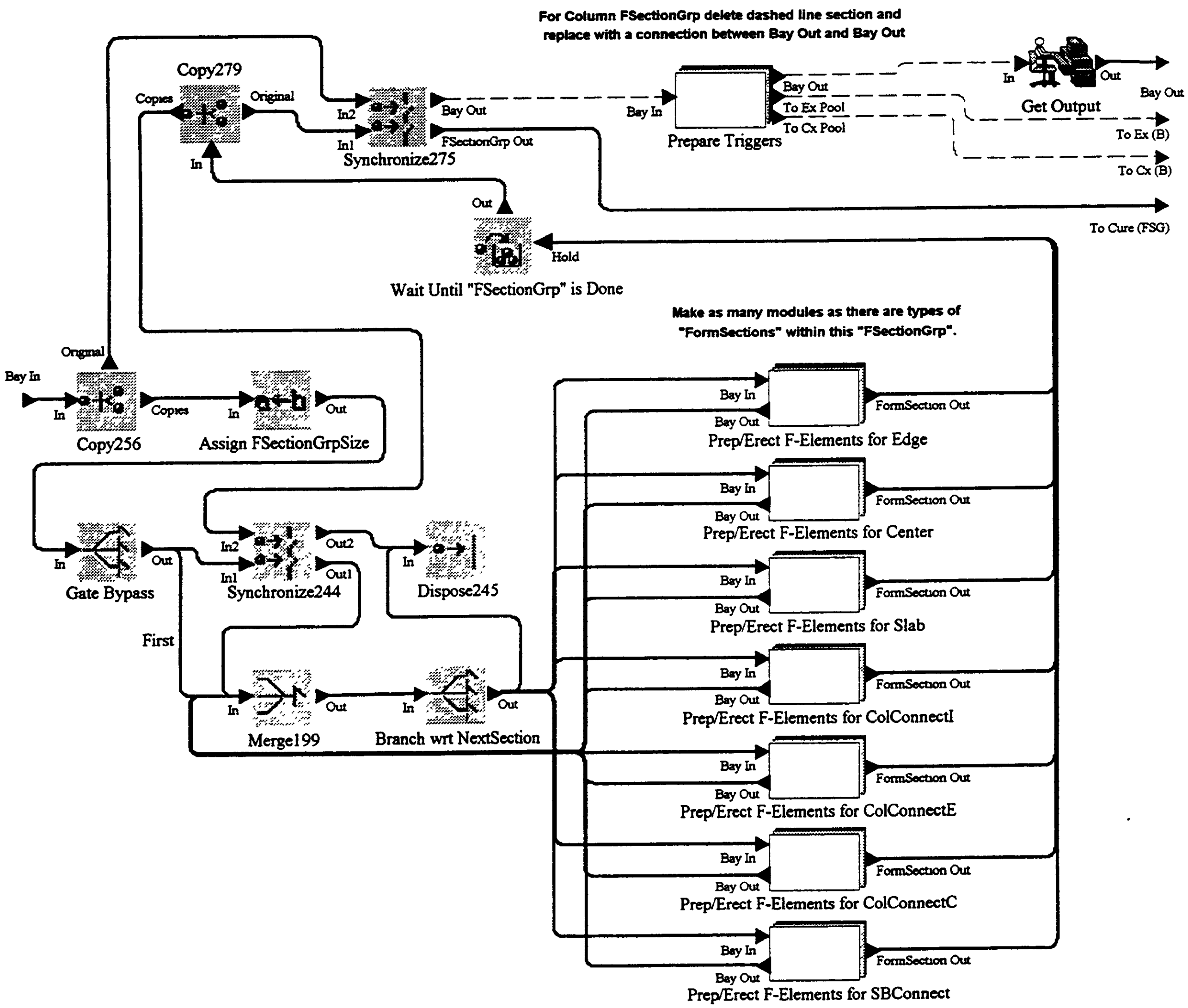


Figure B.19: CIP Model: Construct Beams/Slabs: Prepare/Erect "FSectionGrp"

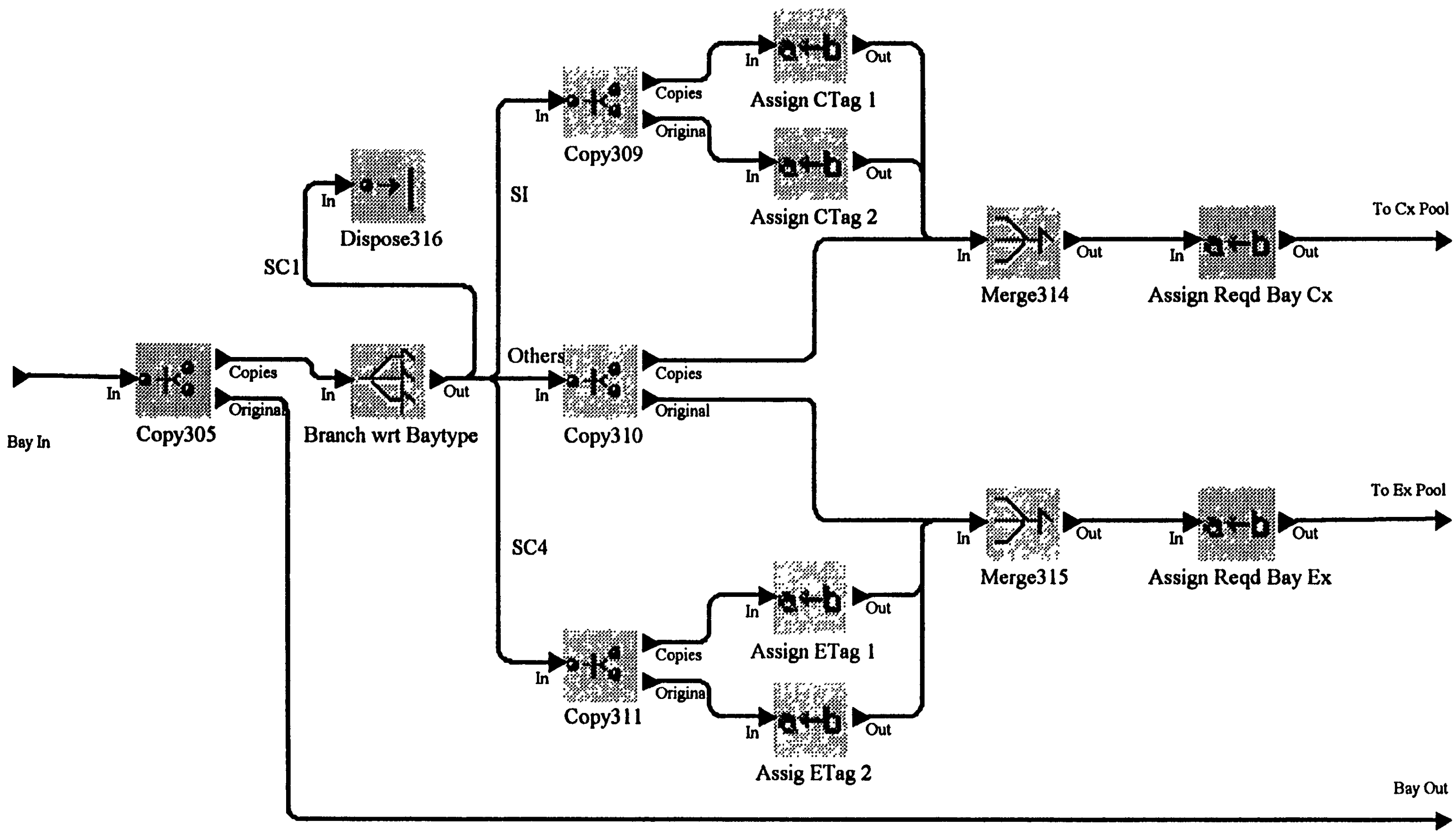


Figure B.20: CIP Model: Construct Beams/Slabs: Prepare/Erect "FSectionGrp": Prepare Triggers

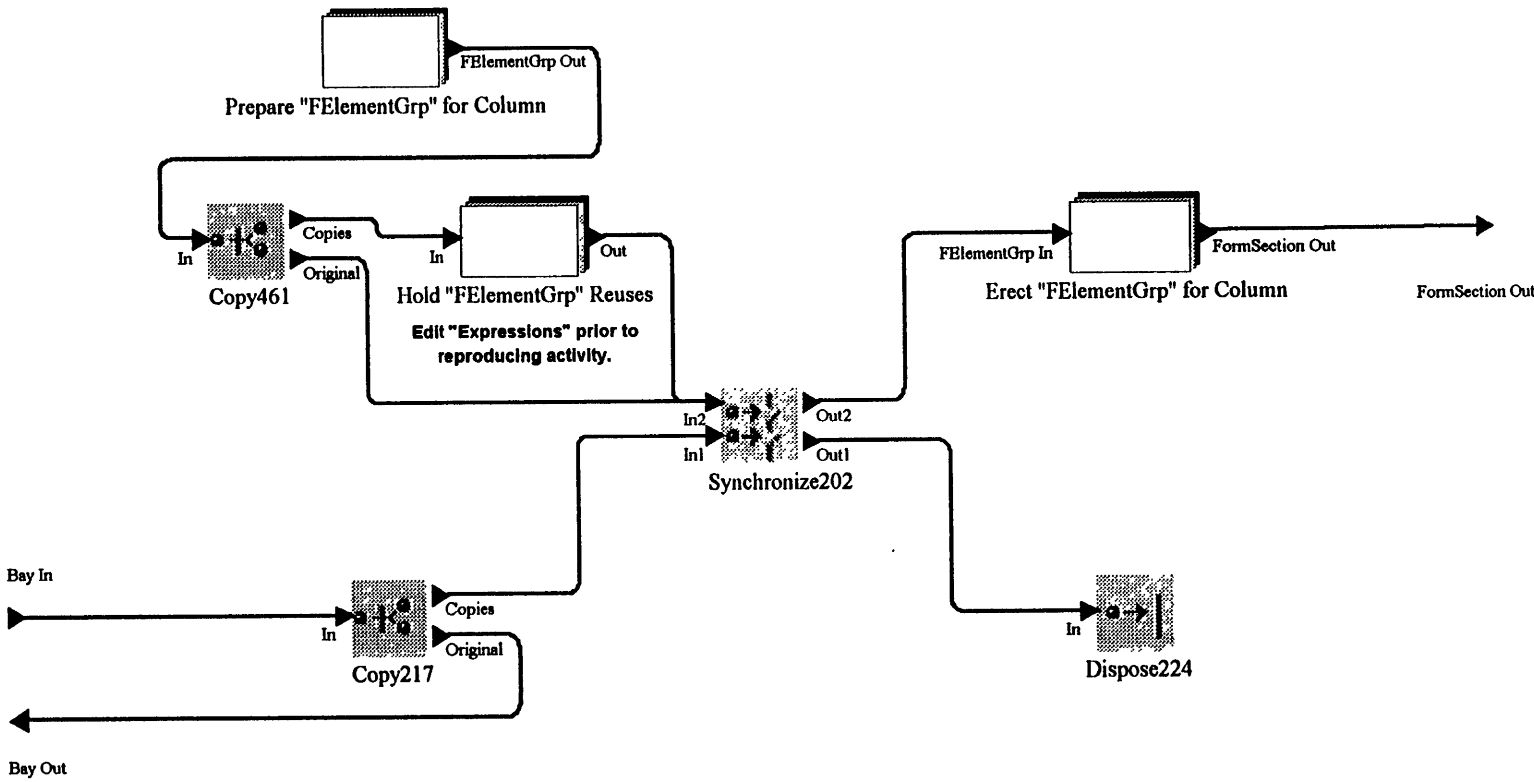
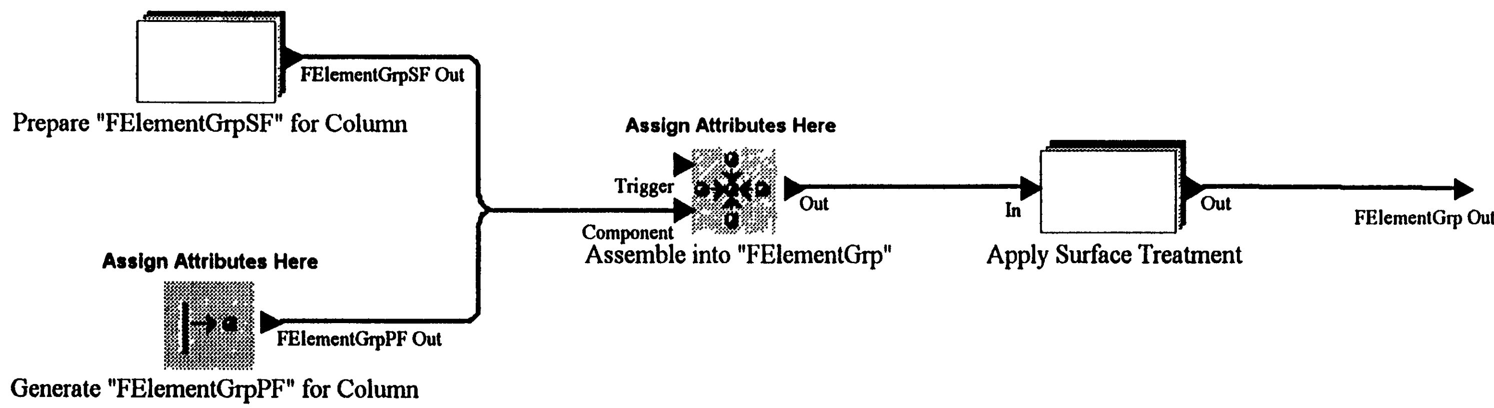


Figure B.21: CIP Model: Typical: Prepare/Erect "FSectionGrp": Prep/Erect F-Elements

If the section has no pre-fabricated form elements, remember to adjust the assemble activity by removing the requirement for one "FElementGrpPF" so that assembly may proceed without it. In the same way, if there are no site fabricated elements in the section, remove the requirement for one "FElementGrpSF".



TagNum = 51

Figure B.22: CIP Model: Typical: Prepare/Erect "FSectionGrp": Prep/Erect F-Elements: Prepare "FElementGrp"

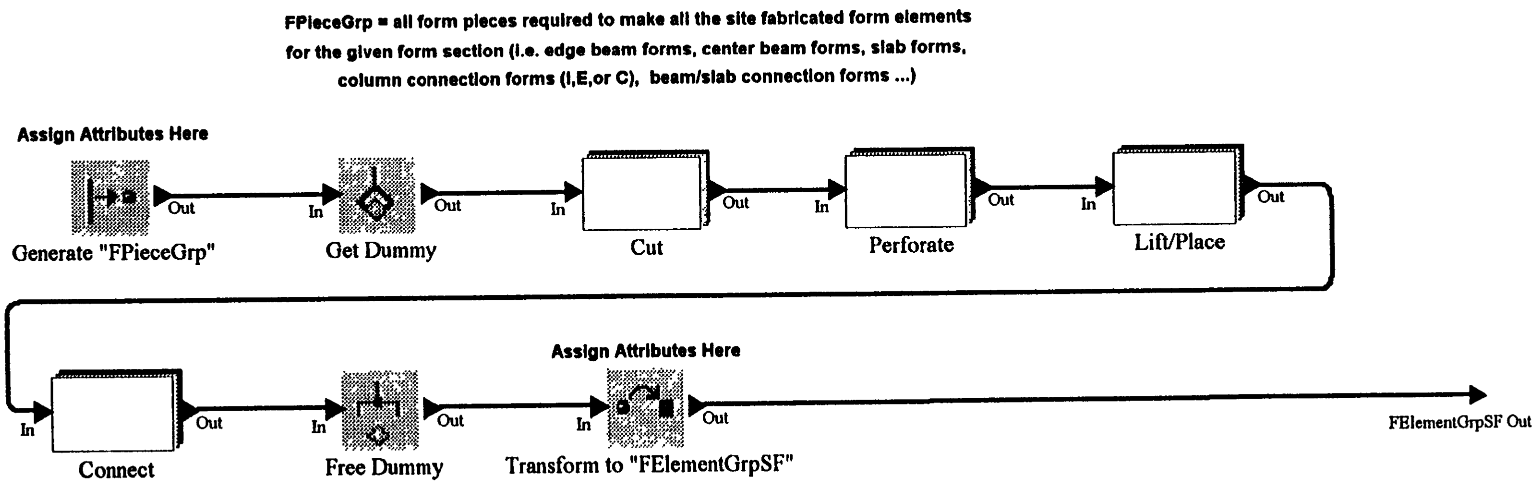


Figure B.23: CIP Model: Typical: Prepare/Erect "FSectionGrp": Prep/Erect F-Elements: Prepare "FElementGrp": Prepare "FElementGrpSF"

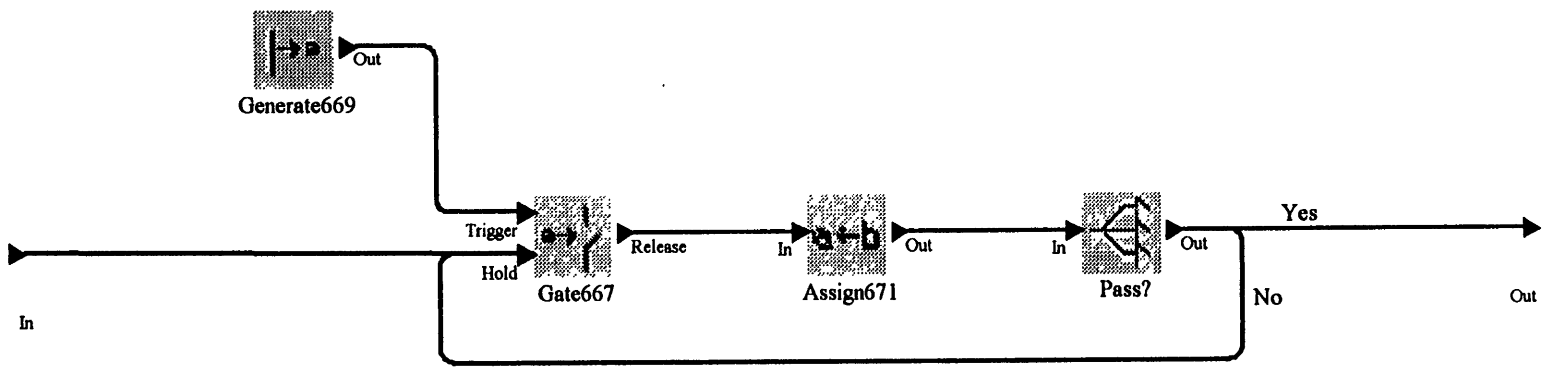


Figure B.24: CIP Model: Typical: Prepare/Erect "FSectionGrp": Prep/Erect F-Elements: Hold "FElementGrp" Reuses

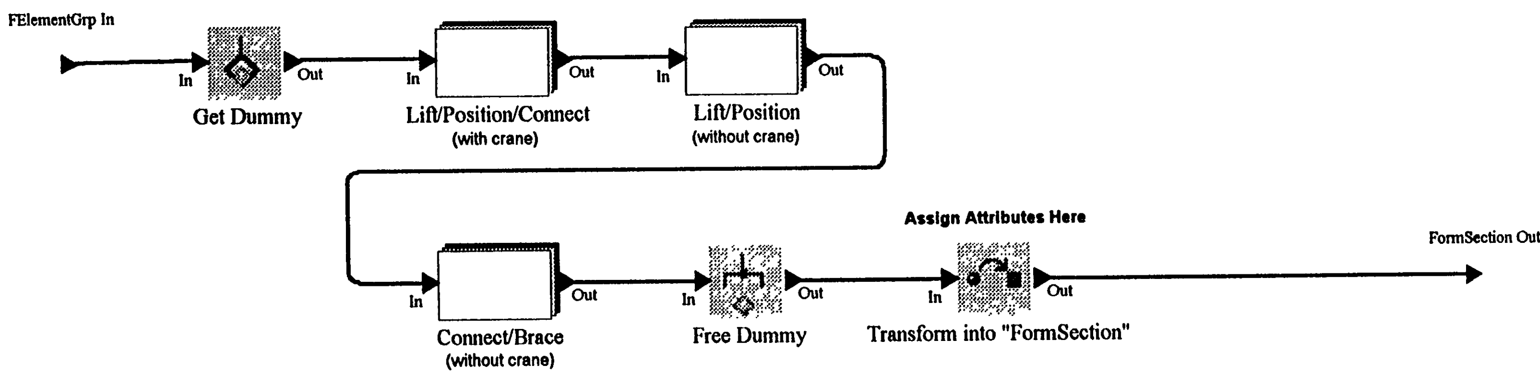


Figure B.25: CIP Model: Typical: Prepare/Erect "FSectionGrp": Prep/Erect F-Elements: Erect "FElementGrp"

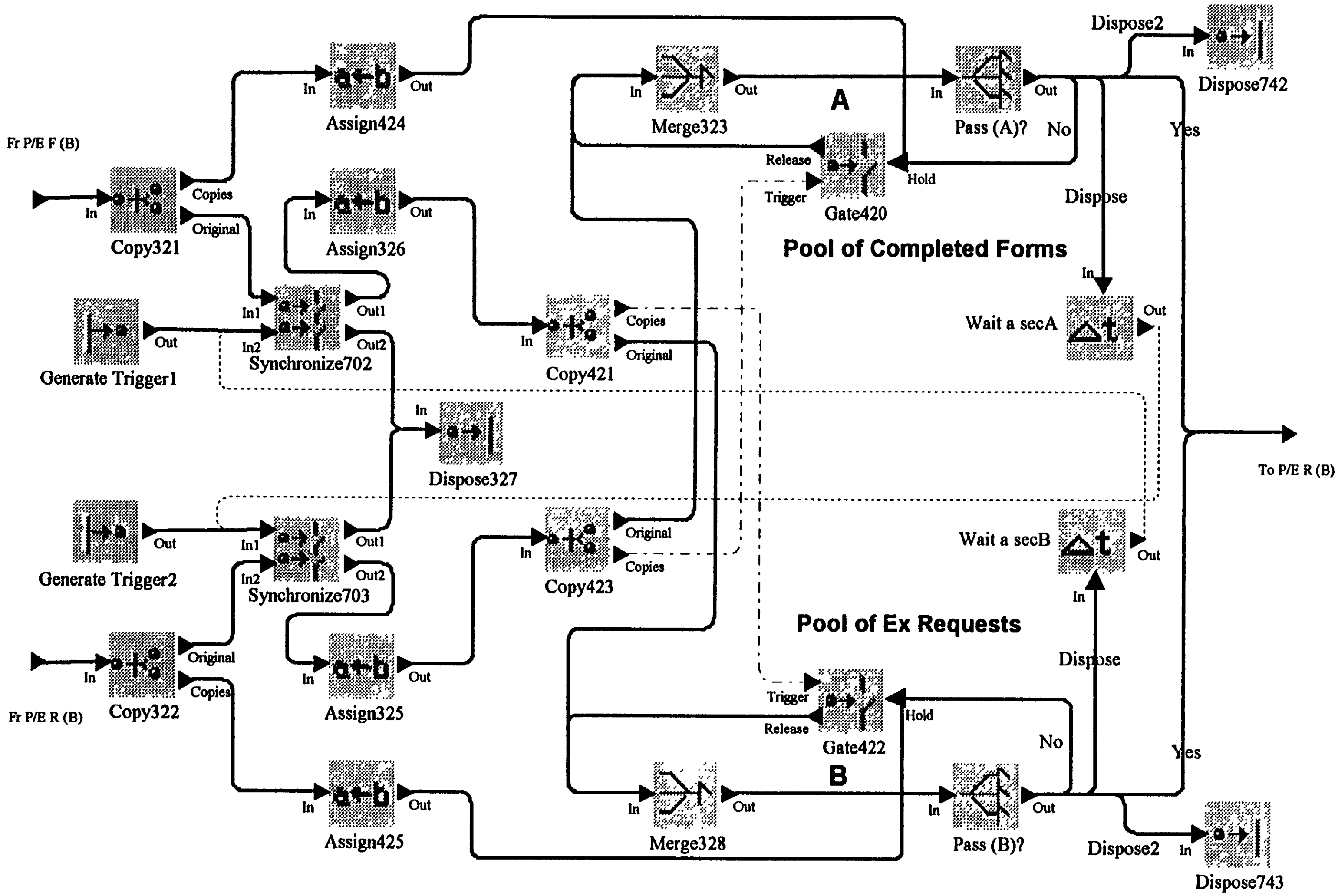


Figure B.26: CIP Model: Construct Beams/Slabs: Ex Pool

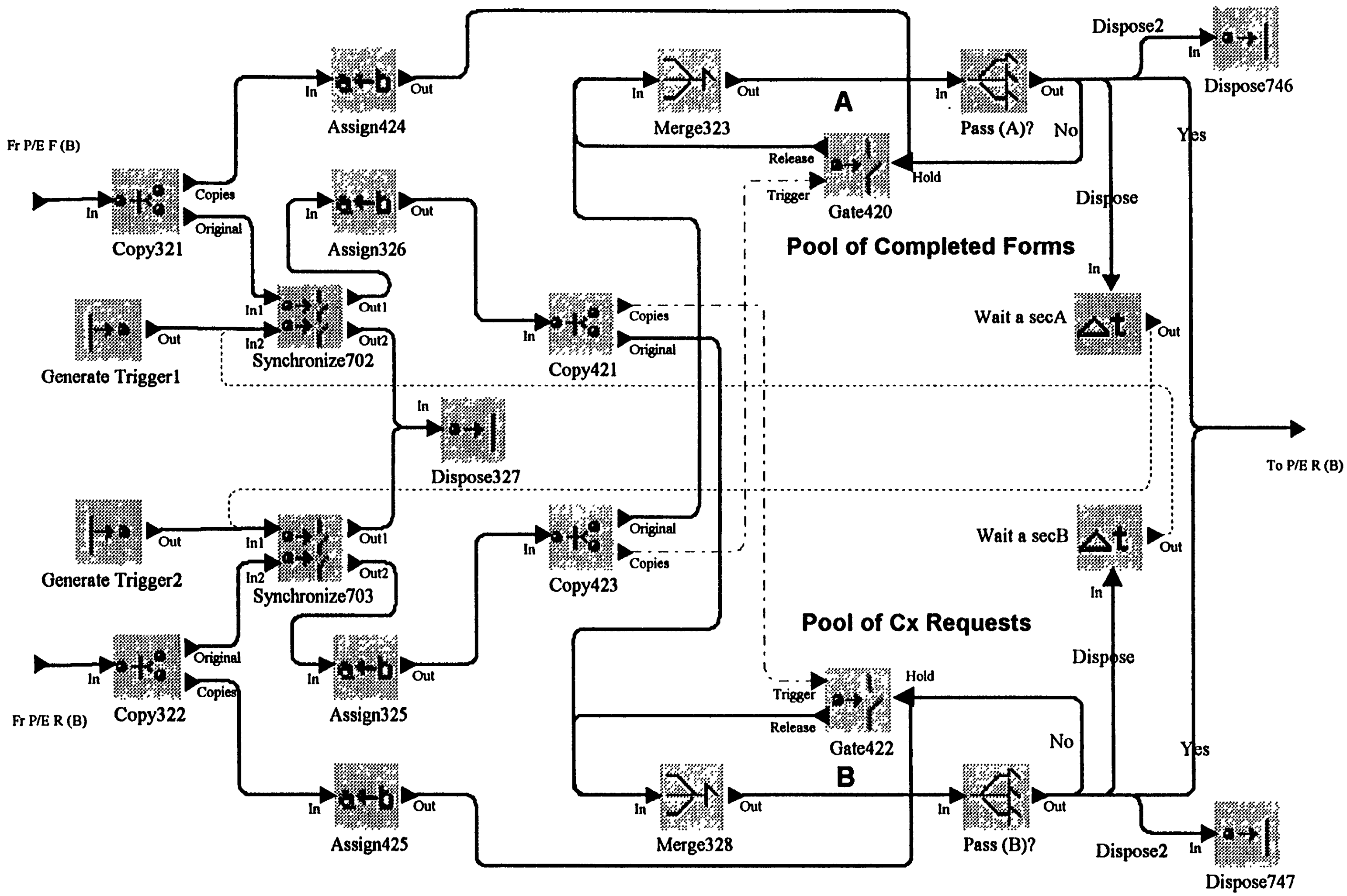


Figure B.27: CIP Model: Construct Beams/Slabs: Cx Pool

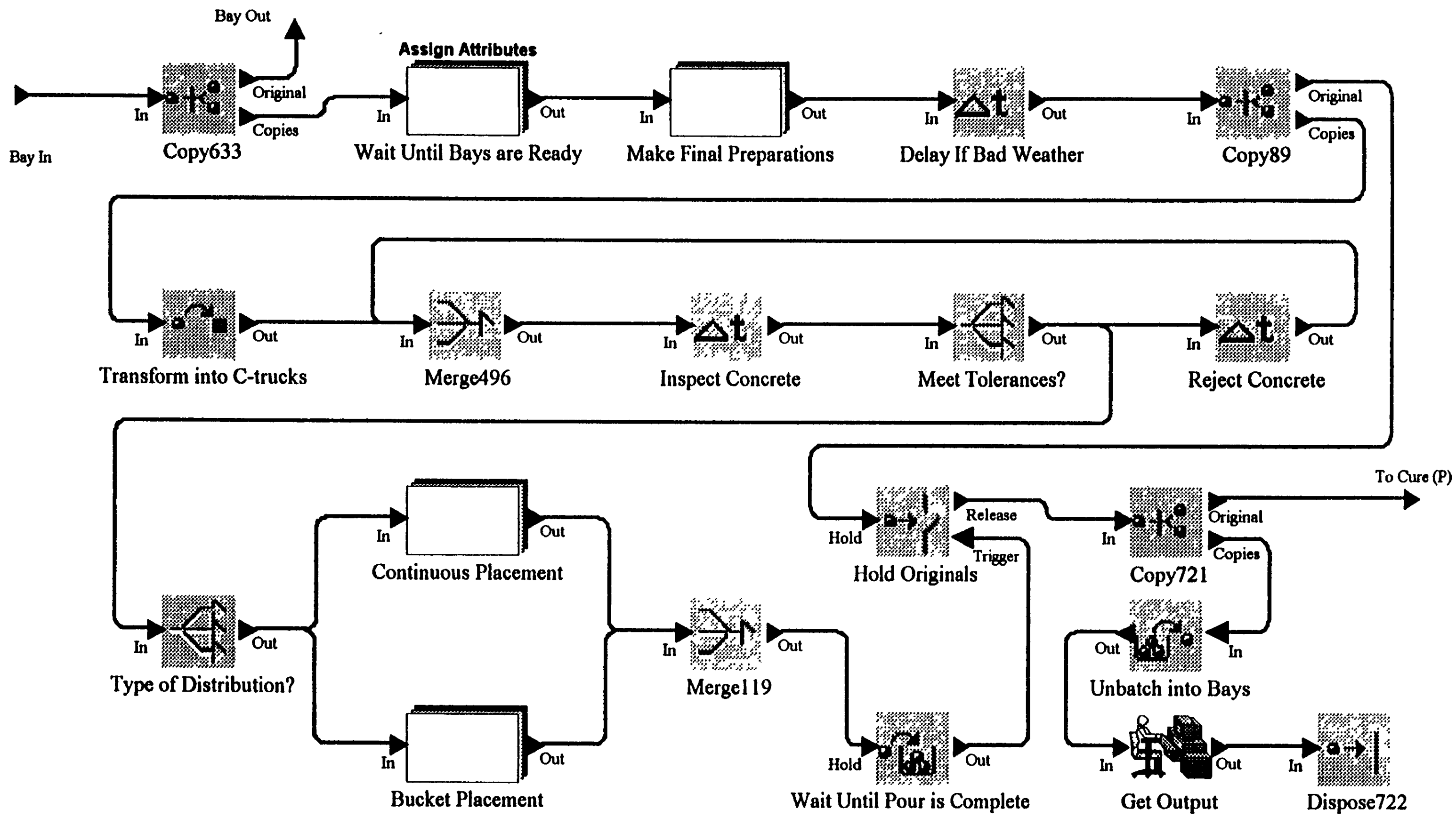
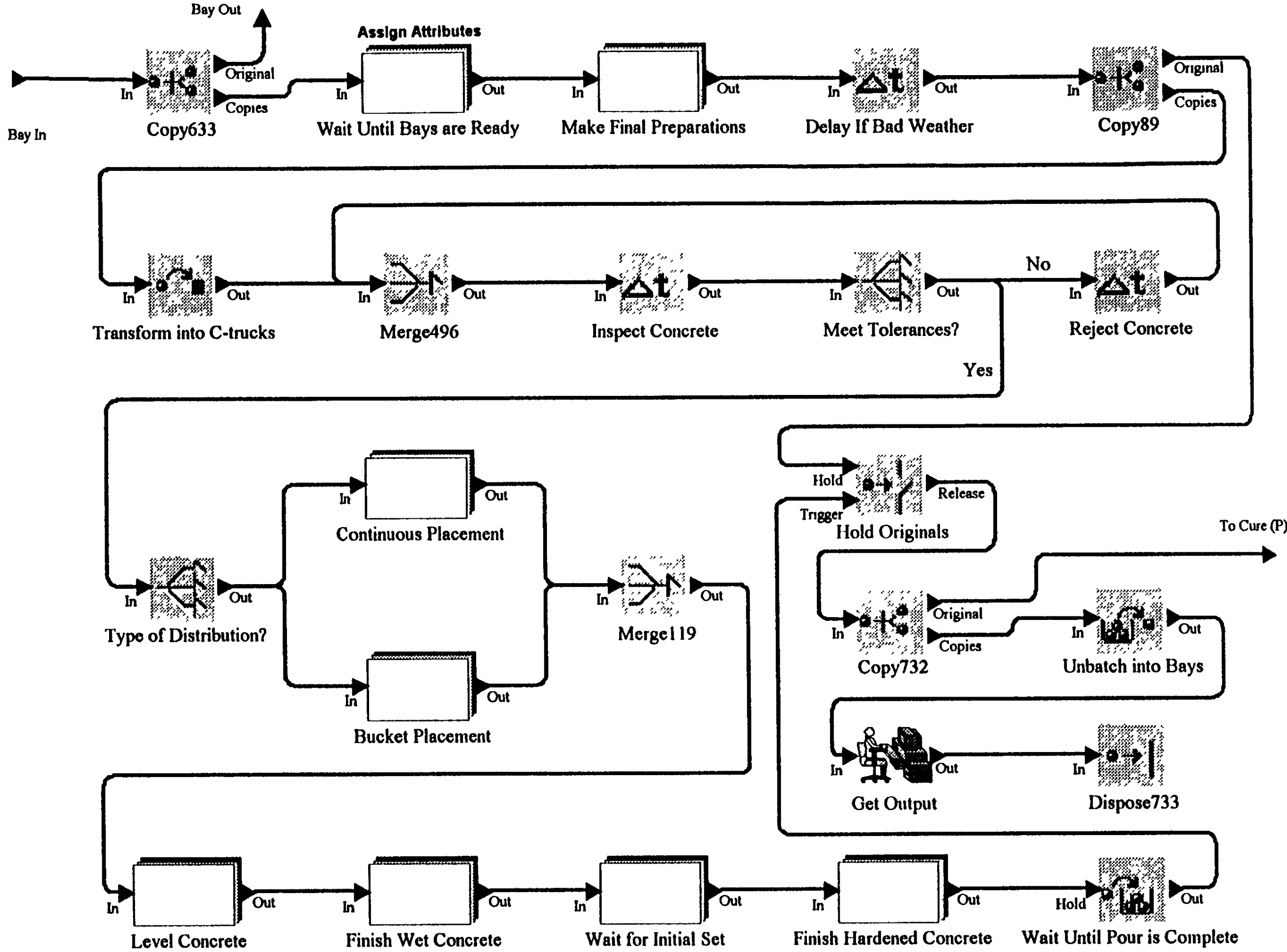


Figure B.28: CIP Model: Construct Columns: Place Concrete



"Level Concrete" through to "Finish Hardened Concrete" is only done for slab pours

Figure B.29: CIP Model: Construct Beams/Slabs: Place Concrete

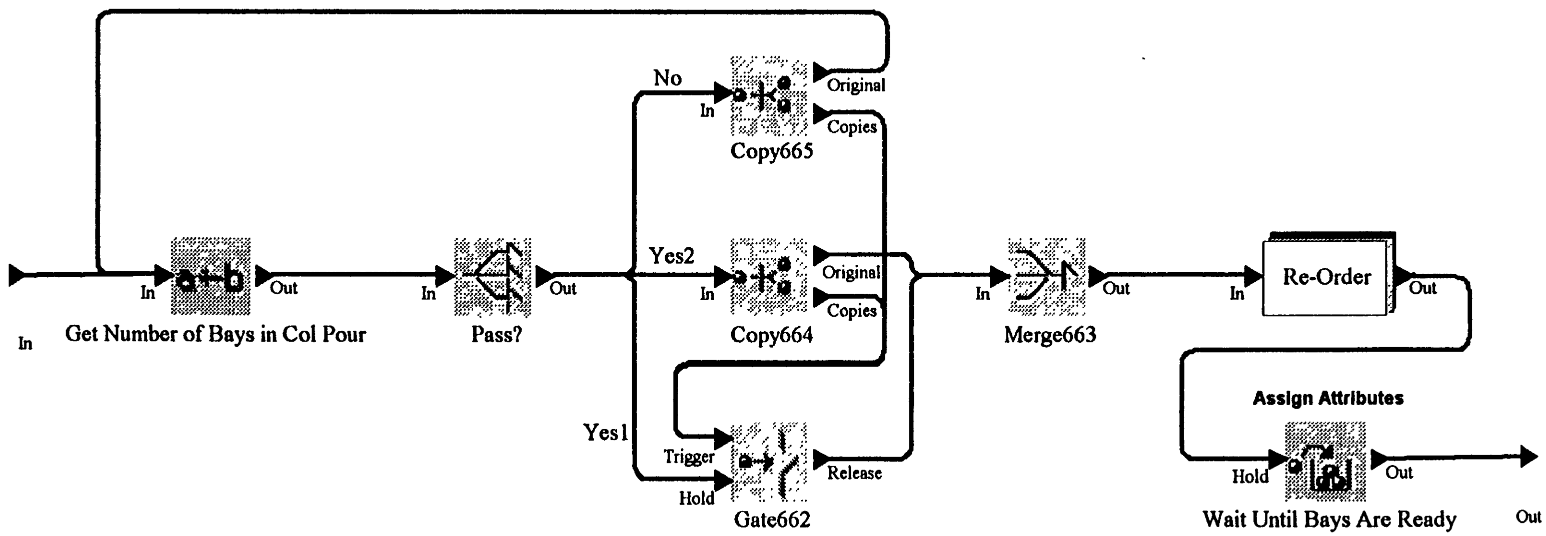


Figure B.30: CIP Model: Construct Columns: Place Concrete: Wait Until Bays are Ready

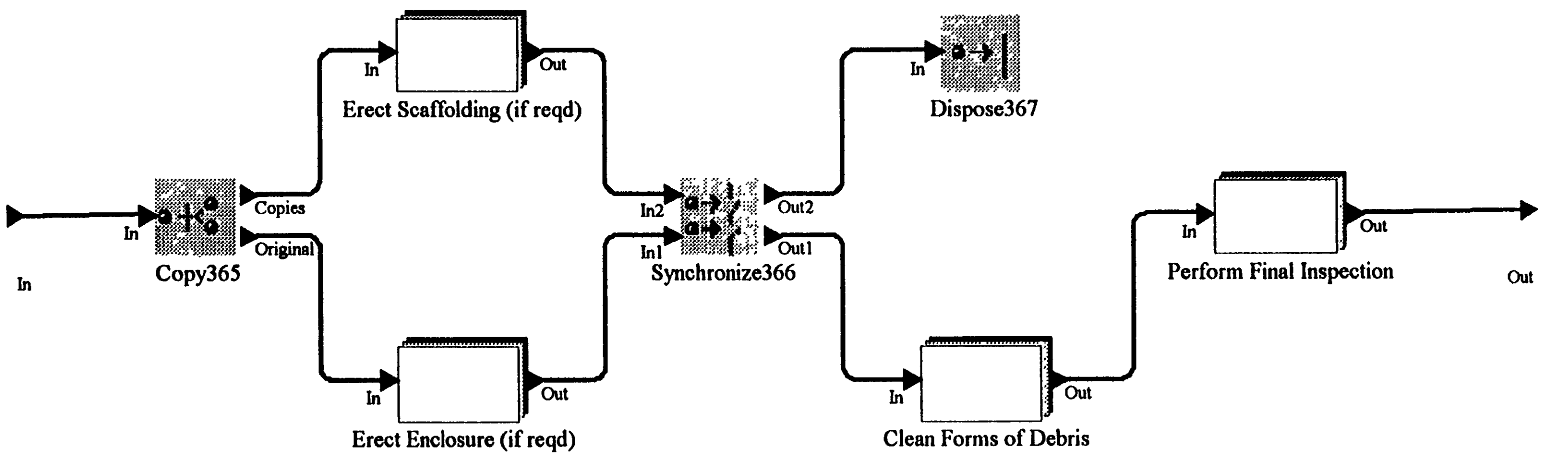


Figure B.31: CIP Model: Typical: Place Concrete: Make Final Preparations

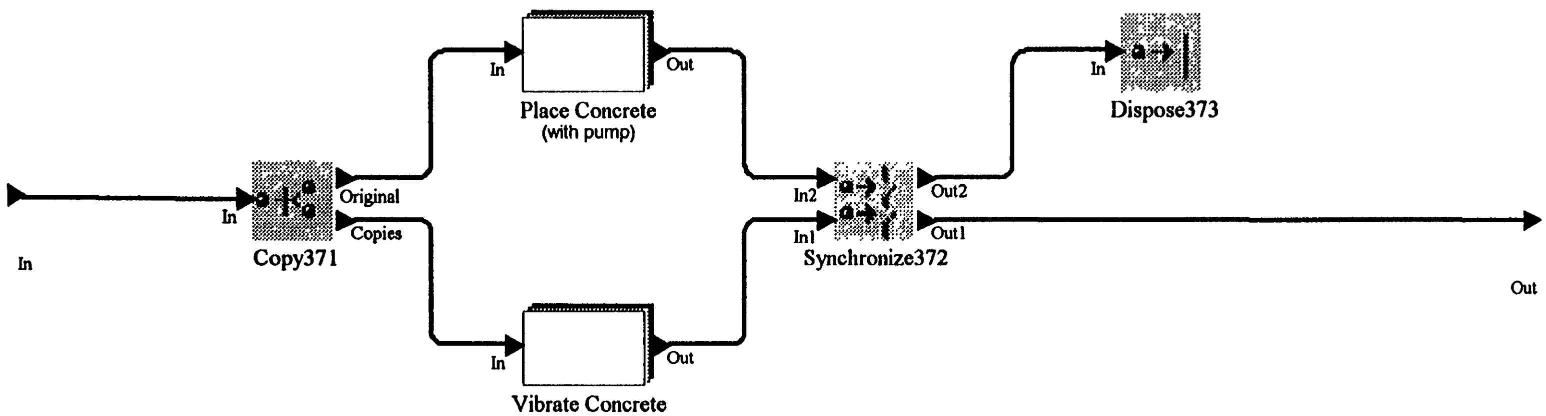


Figure B.32: CIP Model: Typical: Place Concrete: Continuous Placement

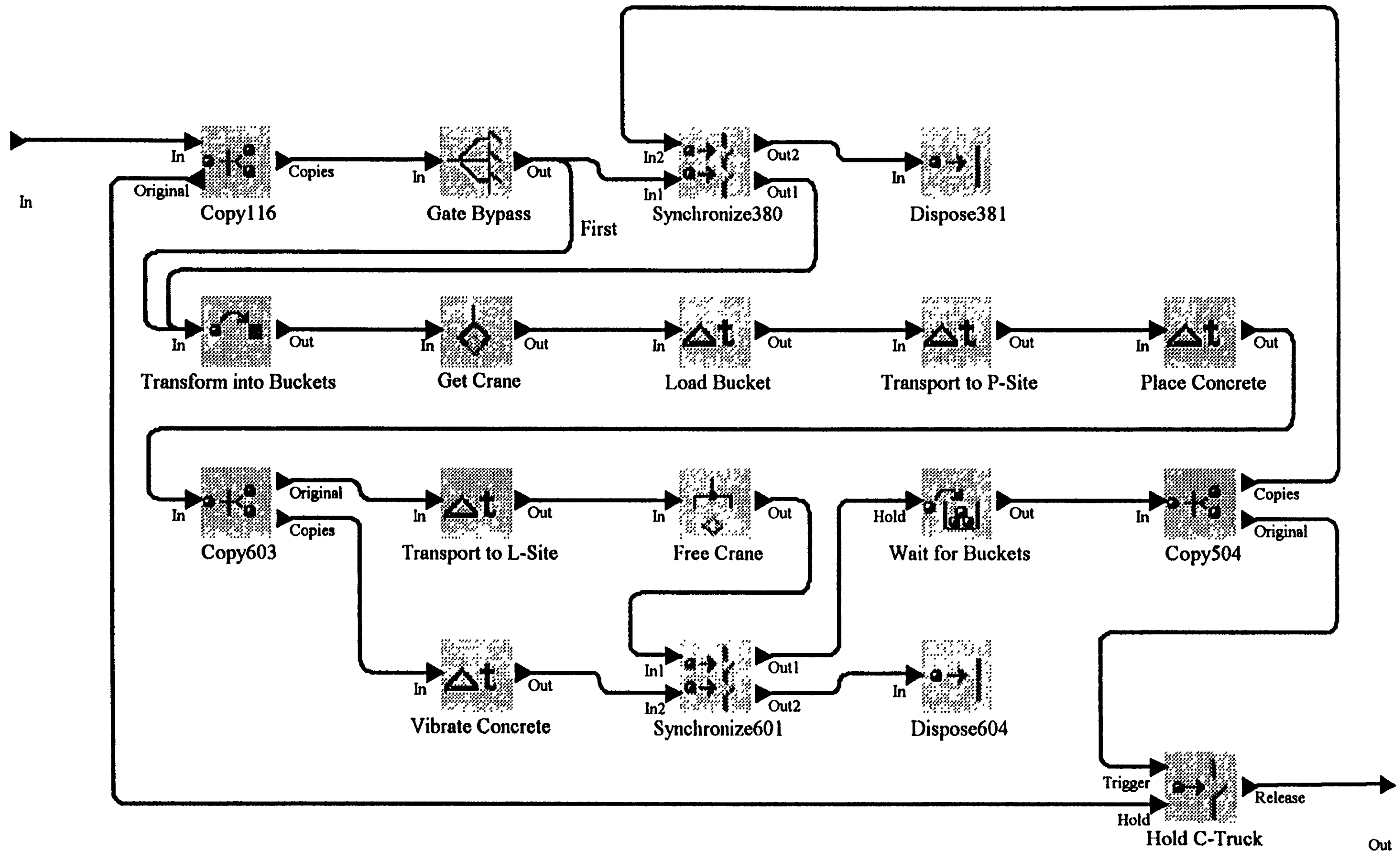


Figure B.33: CIP Model: Typical: Place Concrete: Bucket Placement

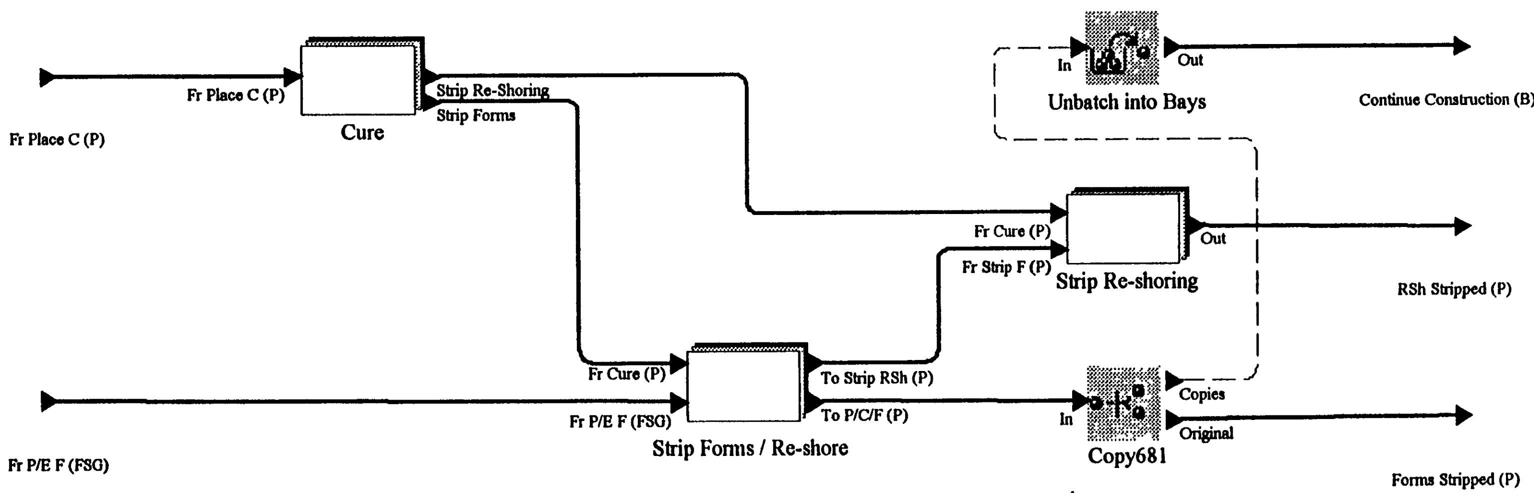


Figure B.34: CIP Model: Construct Columns: Cure Concrete

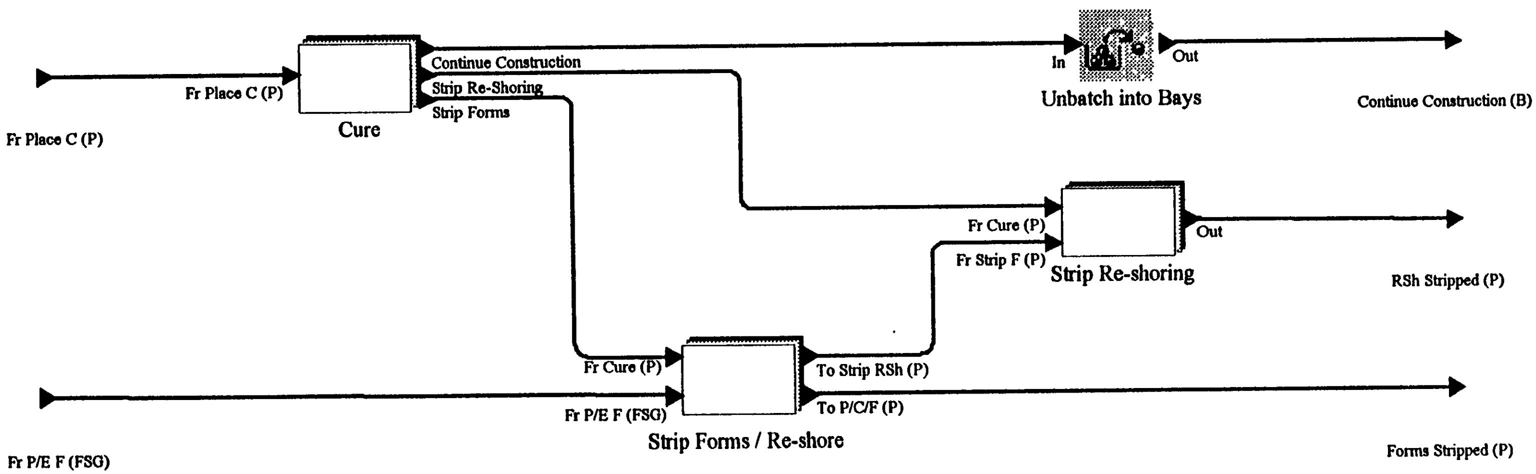


Figure B.35: CIP Model: Construct Beams/Slabs: Cure Concrete

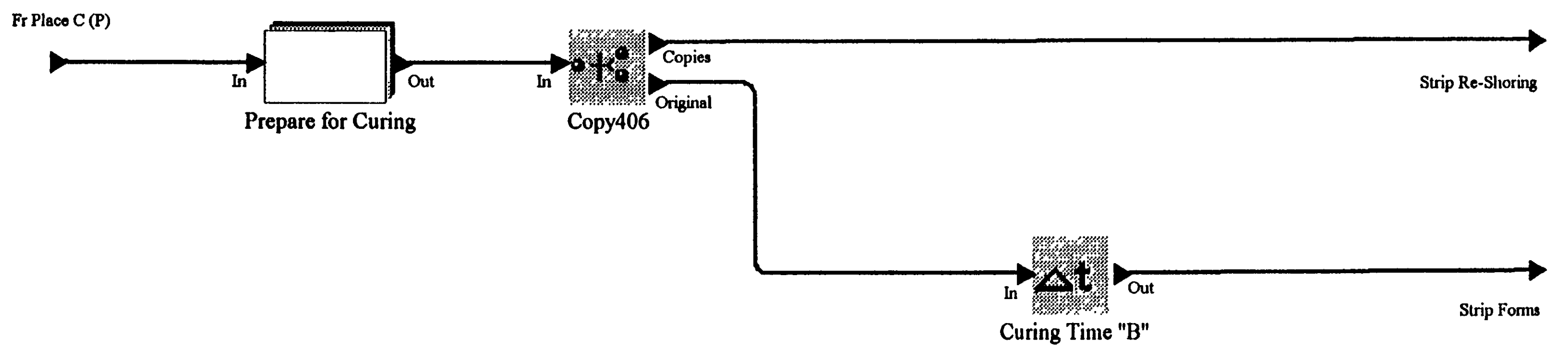


Figure B.36: CIP Model: Construct Columns: Cure Concrete: Cure

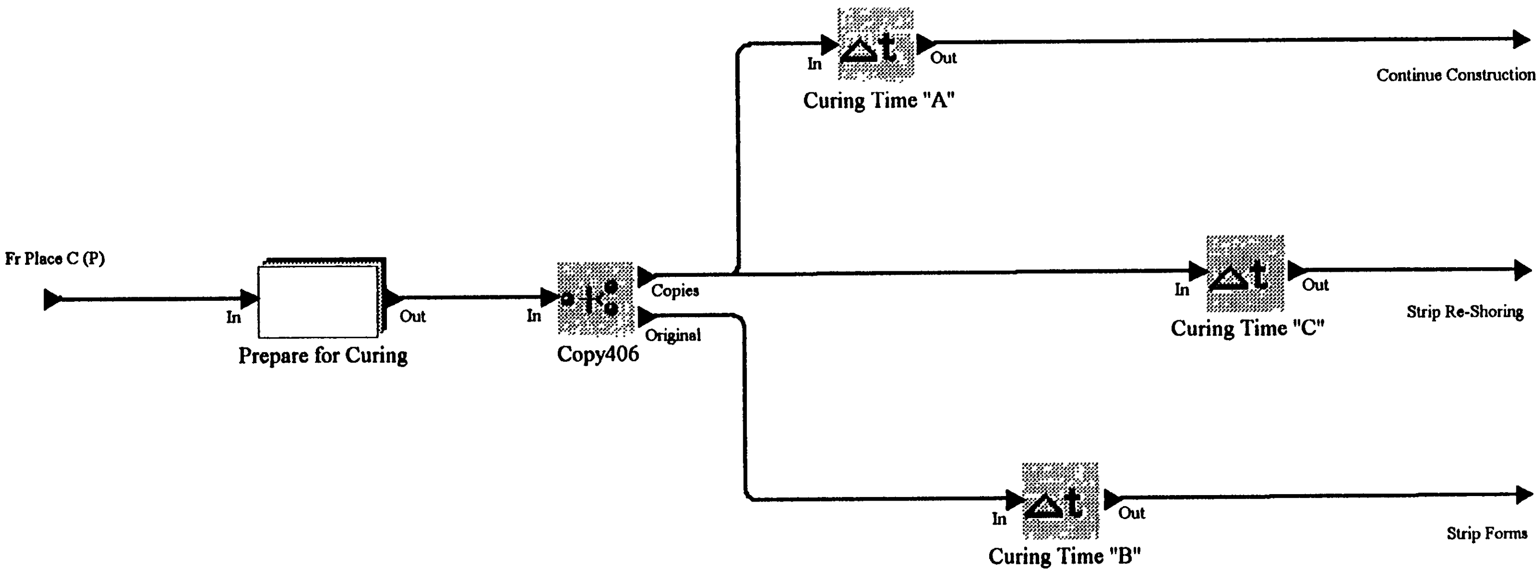


Figure B.37: CIP Model: Construct Beams/Slabs: Cure Concrete: Cure

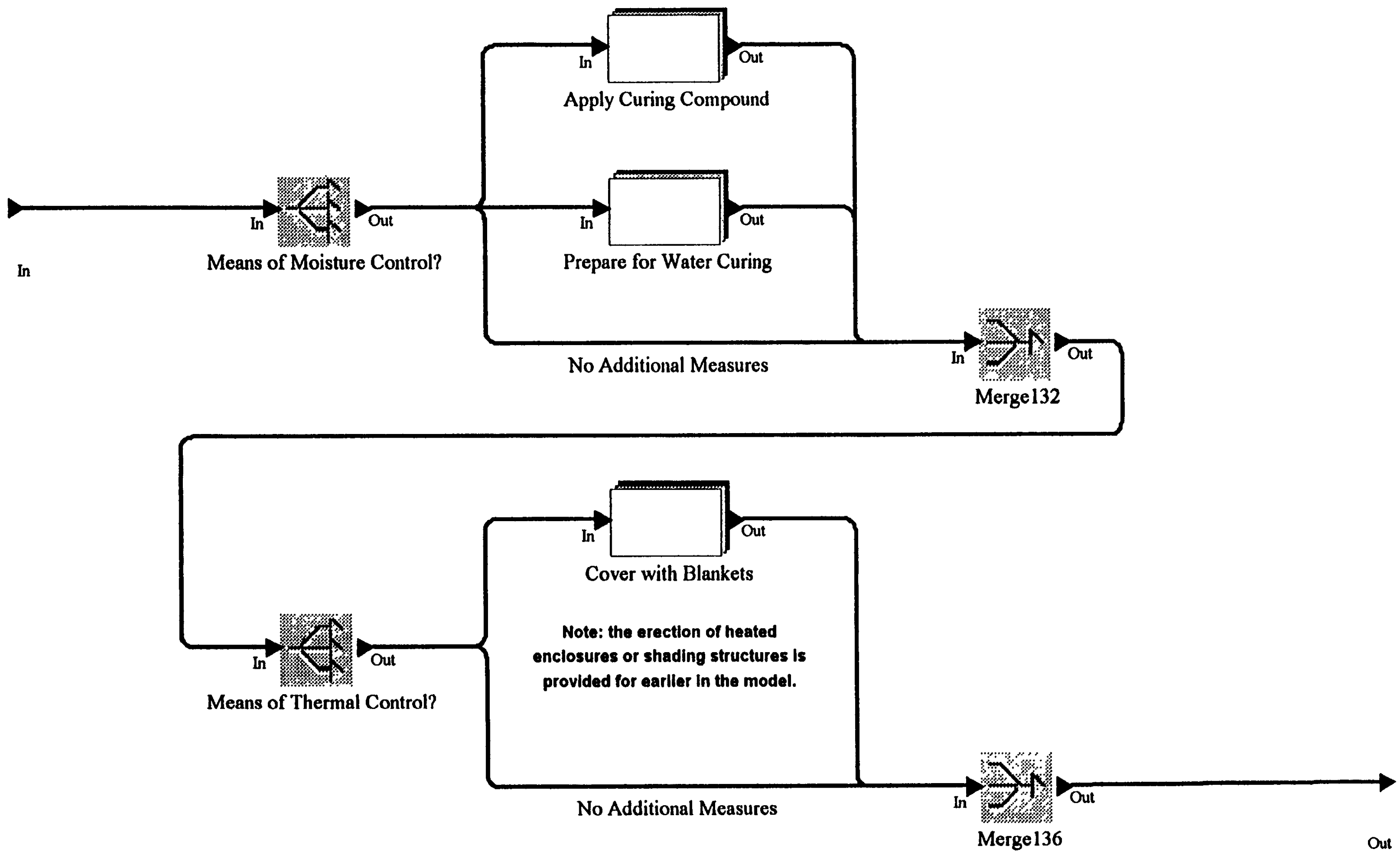


Figure B.38: CIP Model: Typical: Cure Concrete: Cure: Prepare for Curing

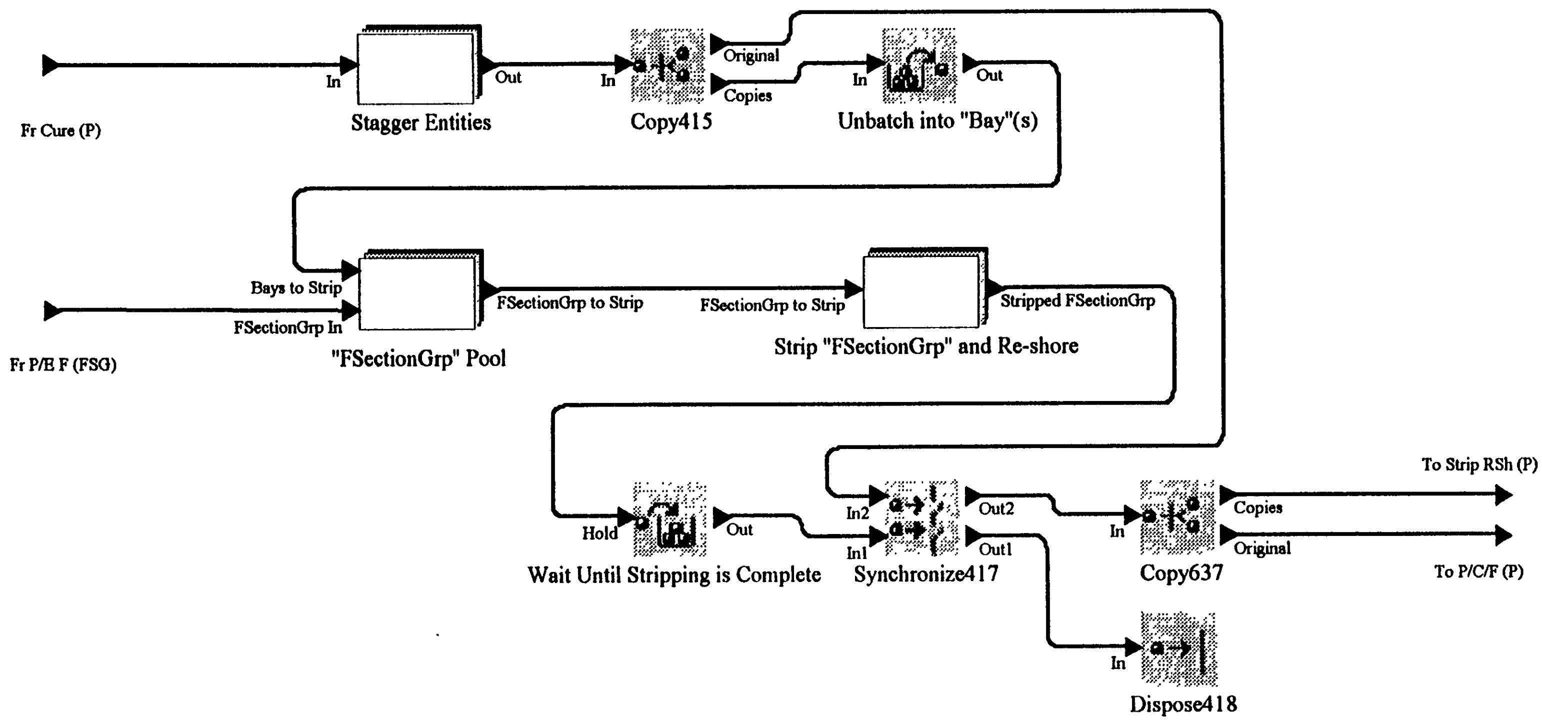


Figure B.39: CIP Model: Typical: Cure Concrete: Strip Forms / Re-Shore

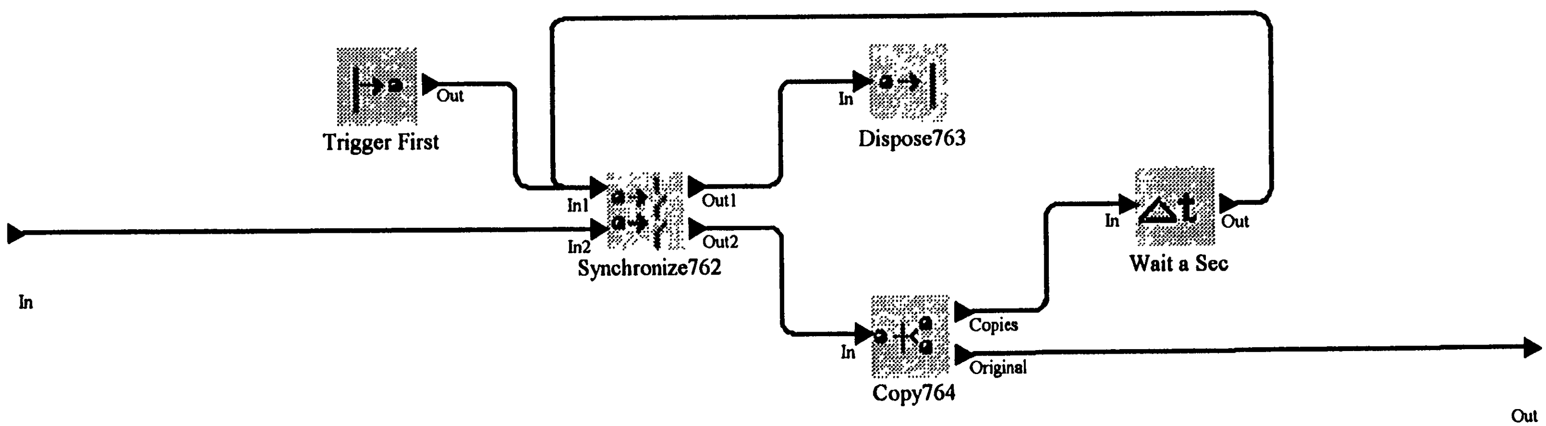


Figure B.40: CIP Model: Typical: Cure Concrete: Strip Forms / Re-Shore: Stagger Entities

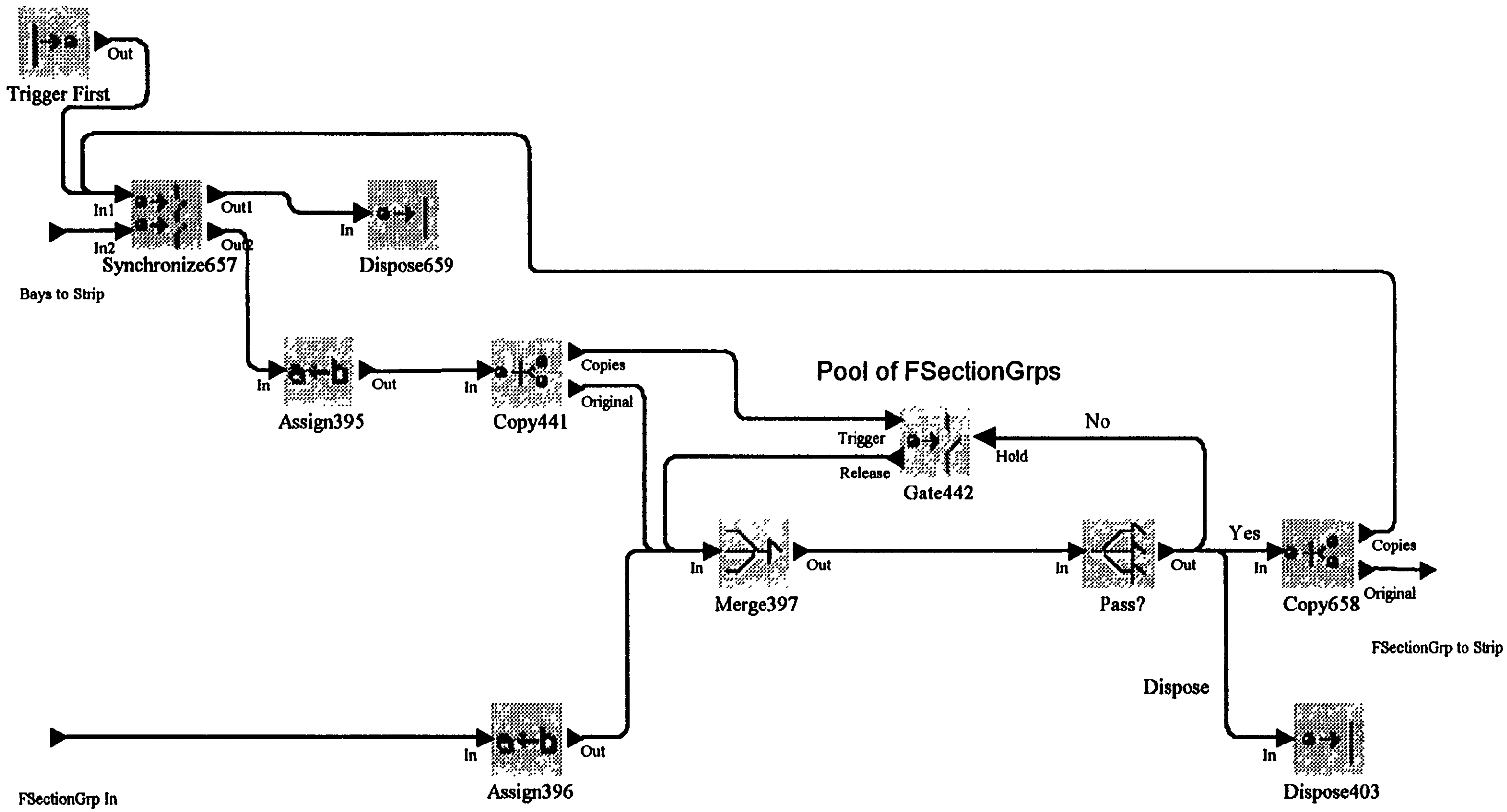


Figure B.41: CIP Model: Typical: Cure Concrete: Strip Forms / Re-Shore: "FSectionGrp" Pool

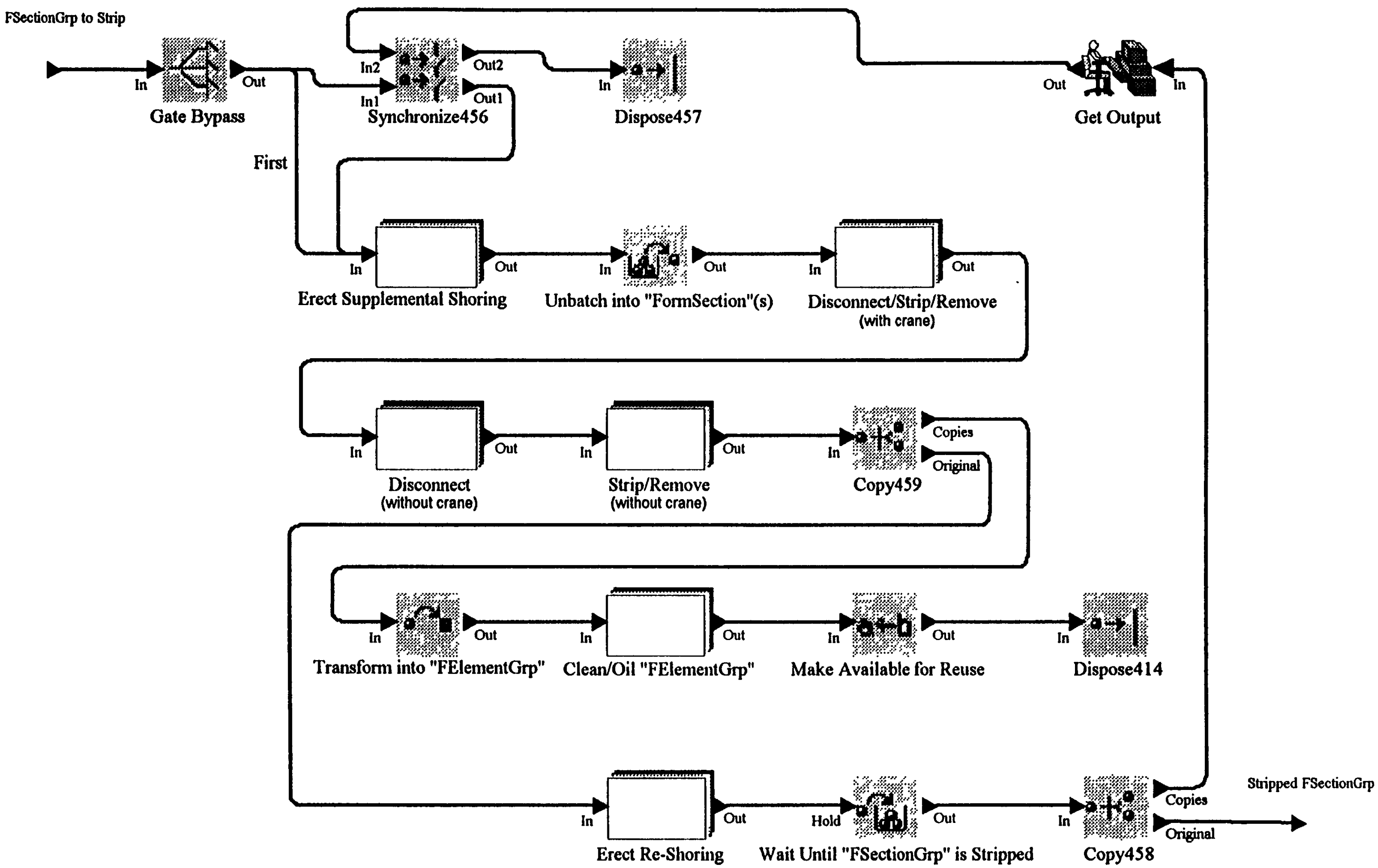


Figure B.42: CIP Model: Typical: Cure Concrete: Strip Forms / Re-Shore: Strip "FSectionGrp" and Re-Shore

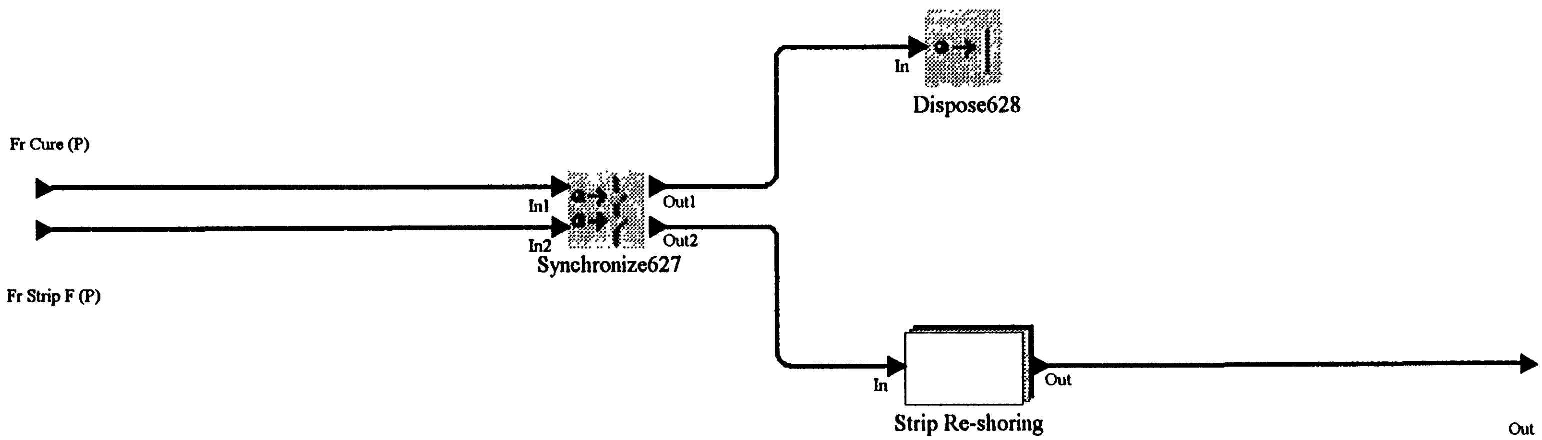


Figure B.43: CIP Model: Typical: Cure Concrete: Strip Re-Shoring

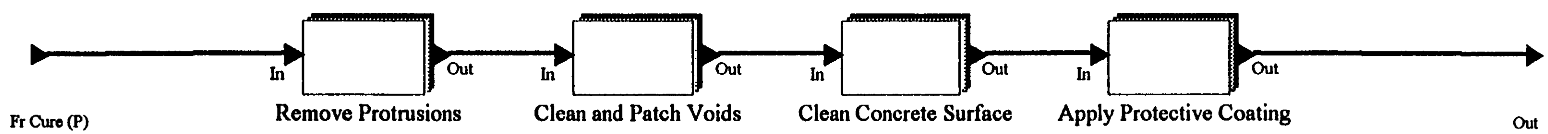


Figure B.44: CIP Model: Typical: Patch/Clean/Finish

Appendix C: Danger Index Calculations

Table C.1: Incidence Rates of Causes of Injury in the Construction Industry

Cause of Injury in the Construction Industry	Percentage
Struck against	8.0%
Struck by	21.0%
Caught in or between	4.1%
Rubbed, abraded, or penetrated	3.5%
Fall of person (different level)	14.9%
Fall of person (same level)	7.0%
Bodily reaction	31.6%
Other (contact with electic current, temperature extremes, radiation, caustics, etc.)	9.9%
Total:	100.0%

Source: OSHA, 1992

The percentages in Table C.1 are used to calculate the rate of injury incidence associated with the performance of each activity within the CIP concrete construction process. The danger index of a particular activity is simply the sum of all the incidence rates associated with that activity multiplied by the total time workers spend performing the activity, and the danger index of the entire CIP concrete construction process is simply the sum of all the danger indices associated with each of the activities within the process.

Baseline

	Lift/Position rebar by hand	Connect Rebar	Lift/Position Rebar with crane	Cut Formwork	Lift/Position & Strip Formwork by hand	Connect / Disconnect Formwork	Clean / Oil Formwork	Connect / Disconnect Formwork
	Iron W.	Iron W.	Iron W.	Carp.	Carp.	Carp.	Laborer	Laborer
Struck against								
Struck by			21.0%					
Caught in or between	4.1%	4.1%	4.1%		4.1%	4.1%		4.1%
Rubbed, abraded or penetrated	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Fall of person (different level)								14.9%
Fall of person (same level)	7.0%	7.0%					7.0%	
Bodily reaction	31.6%	31.6%	31.6%		31.6%			31.6%
Other								
Incidence Rate (%)	46%	46%	60%	4%	39%	8%	11%	54%
x Exposed Time (hr)	432.33	186.39	57.50	136.84	303.08	209.29	795.30	19.72
Index	199.74	86.11	34.62	4.79	118.81	15.91	83.51	10.67

	Place / Strip anything by hand	Load Bucket	Transport Bucket	Place Concrete (bucket)	Vibrate / Power Trowel Concrete	Place (pump), Level, Finish	Repair / Clean Concrete
	Laborer	Concr. W.	Concr. W.	Concr. W.	Concr. W.	Concr. W.	Concr. W.
Struck against			8.0%				
Struck by			21.0%				
Caught in or between	4.1%						
Rubbed, abraded or penetrated	3.5%				3.5%		3.5%
Fall of person (different level)	14.9%		14.9%	14.9%			
Fall of person (same level)							
Bodily reaction	31.6%		31.6%	31.6%	31.6%	31.6%	
Other							
Incidence Rate (%)	54%	0%	76%	47%	35%	32%	4%
x Exposed Time (hr)	406.19	3.17	69.67	15.83	55.00	290.48	81.25
Index	219.75	0.00	52.60	7.36	19.31	91.79	2.84

Danger Index = 947.79

Innovation 1 (Talon)

	Lift/Position rebar by hand	Lift/Position Rebar with crane	Cut Formwork	Lift/Position & Strip Formwork by hand	Connect / Disconnect Formwork	Clean / Oil Formwork
	Iron W.	Iron W.	Carp.	Carp.	Carp.	Laborer
Struck against						
Struck by		21.0%				
Caught in or between	4.1%	4.1%		4.1%	4.1%	
Rubbed, abraded or penetrated	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Fall of person (different level)						
Fall of person (same level)	7.0%					7.0%
Bodily reaction	31.6%	31.6%		31.6%		
Other						
Incidence Rate (%)	46%	60%	4%	39%	8%	11%
x Exposed Time (hr)	432.33	57.50	136.84	303.08	209.29	795.30
Index	199.74	34.62	4.79	118.81	15.91	83.51

	Connect / Disconnect Formwork	Connect Rebar	Place / Strip anything by hand	Transport Bucket	Place Concrete (bucket)	Vibrate / Power Trowel Concrete	Place (pump), Level, Finish	Repair / Clean Concrete
	Laborer	Laborer	Laborer	Concr. W.	Concr. W.	Concr. W.	Concr. W.	Concr. W.
Struck against				8.0%				
Struck by				21.0%				
Caught in or between	4.1%	4.1%	4.1%					
Rubbed, abraded or penetrated	3.5%	3.5%	3.5%			3.5%		3.5%
Fall of person (different level)	14.9%		14.9%	14.9%	14.9%			
Fall of person (same level)		7.0%						
Bodily reaction	31.6%	31.6%	31.6%	31.6%	31.6%	31.6%	31.6%	
Other								
Incidence Rate (%)	54%	46%	54%	76%	47%	35%	32%	4%
x Exposed Time (hr)	19.72	33.60	406.19	69.67	15.83	55.00	290.48	81.25
Index	10.67	15.52	219.75	52.60	7.36	19.31	91.79	2.84

Danger Index = 877.21

Innovation 2 (Self-Compacting Concrete)

	Lift/Position rebar by hand	Connect Rebar	Lift/Position Rebar with crane	Cut Formwork	Lift/Position & Strip Formwork by hand	Connect / Disconnect Formwork
	Iron W.	Iron W.	Iron W.	Carp.	Carp.	Carp.
Struck against						
Struck by			21.0%			
Caught in or between	4.1%	4.1%	4.1%		4.1%	4.1%
Rubbed, abraded or penetrated	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Fall of person (different level)						
Fall of person (same level)	7.0%	7.0%				
Bodily reaction	31.6%	31.6%	31.6%		31.6%	
Other						
Incidence Rate (%)	46%	46%	60%	4%	39%	8%
x Exposed Time (hr)	432.33	186.39	57.50	136.84	303.08	209.29
Index	199.74	86.11	34.62	4.79	118.81	15.91

	Clean / Oil Formwork	Connect / Disconnect Formwork	Place / Strip anything by hand	Vibrate / Power Trowel Concrete	Place (pump), Level, Finish	Repair / Clean Concrete
	Laborer	Laborer	Laborer	Concr. W.	Concr. W.	Concr. W.
Struck against						
Struck by						
Caught in or between		4.1%	4.1%			
Rubbed, abraded or penetrated	3.5%	3.5%	3.5%	3.5%		3.5%
Fall of person (different level)		14.9%	14.9%			
Fall of person (same level)	7.0%					
Bodily reaction		31.6%	31.6%	31.6%	31.6%	
Other						
Incidence Rate (%)	11%	54%	54%	35%	32%	4%
x Exposed Time (hr)	795.30	19.72	406.19	18.50	299.03	81.25
Index	83.51	10.67	219.75	6.49	94.49	2.84

Danger Index = 877.72

Innovation 3 (Stay-In-Place Forms)

	Lift/Position rebar by hand	Connect Rebar	Lift/Position Rebar with crane	Lift/Position Formwork by hand	Connect Formwork (no crane involved)	Lift/Position Formwork with crane	Connect Formwork (crane involved)	Clean / Oil Formwork
	Iron W.	Iron W.	Iron W.	Carp.	Carp.	Carp.	Carp.	Laborer
Struck against						8.0%	8.0%	
Struck by			21.0%			21.0%	21.0%	
Caught in or between	4.1%	4.1%	4.1%	4.1%	4.1%	4.1%	4.1%	
Rubbed, abraded or penetrated	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Fall of person (different level)								
Fall of person (same level)	7.0%	7.0%						7.0%
Bodily reaction	31.6%	31.6%	31.6%	31.6%				
Other								
Incidence Rate (%)	46%	46%	60%	39%	8%	37%	37%	11%
x Exposed Time (hr)	299.00	153.06	57.50	33.89	14.31	24.50	3.40	145.50
Index	138.14	70.71	34.62	13.28	1.09	8.97	1.25	15.28

	Place / Strip Formwork by hand	Connect Formwork (no crane involved)	Lift/Position Formwork with crane	Connect Formwork (crane involved)	Transport Bucket	Place Concrete (bucket)	Vibrate / Power Trowel Concrete	Place (pump), Level, Finish	Repair / Clean Concrete
	Laborer	Laborer	Laborer	Laborer	Concr. W.	Concr. W.	Concr. W.	Concr. W.	Concr. W.
Struck against			8.0%	8.0%	8.0%				
Struck by			21.0%	21.0%	21.0%				
Caught in or between	4.1%	4.1%	4.1%	4.1%					
Rubbed, abraded or penetrated	3.5%	3.5%	3.5%	3.5%			3.5%		3.5%
Fall of person (different level)					14.9%	14.9%			
Fall of person (same level)									
Bodily reaction	31.6%	31.6%			31.6%	31.6%	31.6%	31.6%	
Other									
Incidence Rate (%)	39%	39%	37%	37%	76%	47%	35%	32%	4%
x Exposed Time (hr)	186.11	7.50	30.00	12.50	69.67	15.83	55.00	290.48	61.46
Index	72.96	2.94	10.98	4.58	52.60	7.36	19.31	91.79	2.15

Danger Index = 547.98

Innovation 1 & 3 (Talon & Stay-In-Place Forms)

	Lift/Position rebar by hand	Lift/Position Rebar with crane	Lift/Position Formwork by hand	Connect Formwork (no crane involved)	Lift/Position Formwork with crane	Connect Formwork (crane involved)	Clean / Oil Formwork	Connect Rebar
	Iron W.	Iron W.	Carp.	Carp.	Carp.	Carp.	Laborer	Laborer
Struck against					8.0%	8.0%		
Struck by		21.0%			21.0%	21.0%		
Caught in or between	4.1%	4.1%	4.1%	4.1%	4.1%	4.1%		4.1%
Rubbed, abraded or penetrated	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Fall of person (different level)								
Fall of person (same level)	7.0%						7.0%	7.0%
Bodily reaction	31.6%	31.6%	31.6%					
Other								
Incidence Rate (%)	46%	60%	39%	8%	37%	37%	11%	15%
x Exposed Time (hr)	299.00	57.50	33.89	14.31	24.50	3.40	145.50	27.60
Index	138.14	34.62	13.28	1.09	8.97	1.25	15.28	4.03

	Place / Strip Formwork by hand	Connect Formwork (no crane involved)	Lift/Position Formwork with crane	Connect Formwork (crane involved)	Transport Bucket	Place Concrete (bucket)	Vibrate / Power Trowel Concrete	Place (pump), Level, Finish	Repair / Clean Concrete
	Laborer	Laborer	Laborer	Laborer	Concr. W.	Concr. W.	Concr. W.	Concr. W.	Concr. W.
Struck against			8.0%	8.0%	8.0%				
Struck by			21.0%	21.0%	21.0%				
Caught in or between	4.1%	4.1%	4.1%	4.1%					
Rubbed, abraded or penetrated	3.5%	3.5%	3.5%	3.5%			3.5%		3.5%
Fall of person (different level)					14.9%	14.9%			
Fall of person (same level)									
Bodily reaction	31.6%	31.6%			31.6%	31.6%	31.6%	31.6%	
Other									
Incidence Rate (%)	39%	39%	37%	37%	76%	47%	35%	32%	4%
x Exposed Time (hr)	186.11	7.50	30.00	12.50	69.67	15.83	55.00	290.48	61.46
Index	72.96	2.94	10.98	4.58	52.60	7.36	19.31	91.79	2.15

Danger Index = 481.30

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