University of Alberta

Simulation-Based Project Control

By

Nader N. Chehayeb ©

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **SIMULATION-BASED PROJECT CONTROL** submitted by **NADER N. CHEHAYEB** in partial fulfillment for the degree of **DOCTOR OF PHILOSOPHY in CONSTRUCTION ENGINEERING AND MANAGEMENT.**

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DEDICATION

In memory of my Late Father

Abstract

Construction projects rarely proceed exactly as planned due to the conditions under which projects are implemented. The need for short term interval planning, long term planning, efficient progress reporting, and effective feedback mechanisms has, for a long time, been recognized by contractors. Short term planning involves numerous detailed activities showing interactions of resources, required quantities, expected production rates, and personnel involved. On the other hand, incorporating many detailed activities in a schedule places an overburden on management as related to the time and cost required to update the plans during project execution.

This thesis describes the development of the SimCon (SIMulation-based project CONtrol) system that is geared towards 1) providing the capability to report project progress by exception in order to minimize data input and to generate variance analysis reports based on significant deviations, 2) providing planning facilities at multiple levels in such a manner that incorporates the dynamic nature of a construction process and its complex interrelated components, and 3) providing methods for better project control. New simulation constructs are developed to store project progress information, simplify the logical linking of simulation processes, and calculate various statistics.

SimCon is implemented in a production breakdown structure by identifying cost control centers at the top of the hierarchy, followed by location breakdown centers and then construction process centers. Construction process centers are defined at various location centers and linked to each other using continuous and single production links that provide a more accurate representation of activity sequencing than traditional scheduling

methods such as the critical path method. The computer prototype SimCon is implemented using object oriented concepts, event driven programming, relational database, and a simulation program language.

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CHAPTER 1

OVERVIEW ON RESEARCH MOTIVATION

1.1 INTRODUCTION

Success of a construction project is heavily dependent on the effective planning and control of labor, material, equipment, and money. A construction project usually needs short term plans and a long term plan. During project execution it is important to report, measure, and analyze project performance. The task of tracking costs and durations of large and complex projects requires an efficient reporting and feedback mechanism, especially in the risky and competitive industry of construction. Virtually every step in the construction process is dependent on project planning and past construction experience. An effective monitoring and progress reporting phase in a project is dependent on having an efficient planning system that provides the mechanism for project control. Similarly, an effective documentation of project history for future projects is highly dependent on the progress reporting phase.

Most construction projects employ some form of cost and schedule control. Progress reporting involves the recording of construction history for detection of deviations from the plan and for forecasting project performance (reporting in this thesis refers to data collection and updating of a project plan). Any construction project can be comprised of summary level activities for higher level management (long term planning) and/or very detailed level of activities and sub activities with numerous cost accounts for day to day control (short term planning). Representing project information and level of detail in activities depends on control objectives, available collection tools, and justifiable reasoning for the recommended level of detail. Short term planning requires numerous detailed level activities showing interaction of resources, required quantities, expected production rates, and personnel involved. On the other hand incorporating such a highly detailed level of planning in a schedule places an overburden on management as related to the time and cost required to update the plans during execution of the project.

A number of systems currently exist for representing project information. Some of the current management systems provide a mechanism to summarize information at various levels of detail using techniques such as a work breakdown structure (WBS). A WBS is an organization of project activities in a hierarchical format. Development of activities in a WBS helps to organize the structure of activities for project summary evaluation and reporting for upper level management. Due to the nature and definition of a WBS in the current control system, the lowest level of detail is the level at which progress is measured. The traditional WBS as defined in an activity-based structure is shown in Figure 1.1. A WBS provides a good mechanism to review cost budgets and schedule plans of specific project areas or sections (columns, walls, floors, etc.) at various levels of detail.

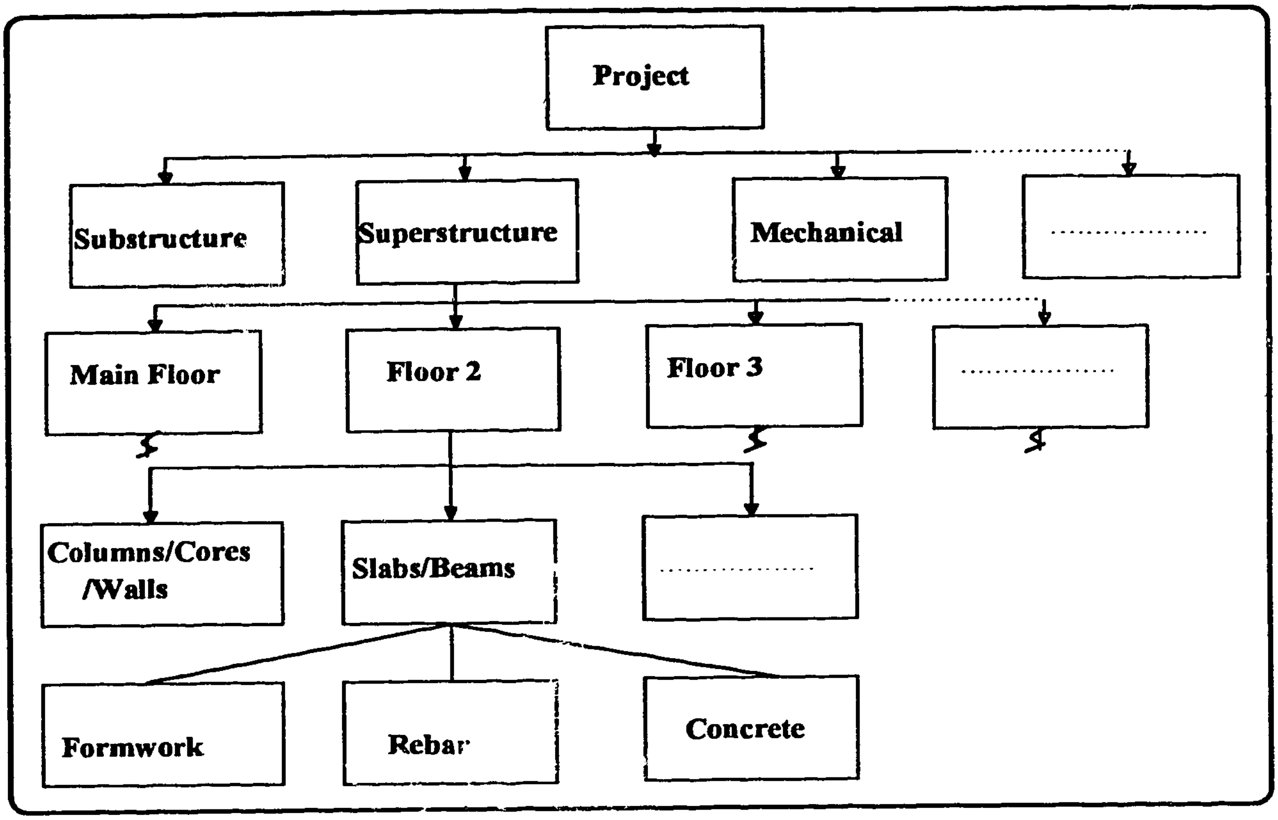


Figure 1.1 *WBS of a Construction Building Project*

In an effort to minimize progress reporting at the very detailed level, some contractors maintain two planning systems: one for short term planning; and one for long term planning. There are problems with either of the two approaches. Short term planning requires numerous detailed level activities showing interaction of resources, required quantities, expected production rates, and personnel involved. However, incorporating such a highly detailed level of planning in a schedule places an overburden on management as related to the time and cost required to update the plans during execution of the project. On the other hand, long term planning does not consider the specifics of construction methods and the interaction of resources at the detailed level.

Hence, such a schedule can not determine non-value added tasks and resource idle and busy times.

Many techniques have been developed to assist contractors in performing the functions of scheduling activities at the lowest level in a WBS. Network techniques that belong to the Critical Path Method (CPM) type of analysis are used to determine a project duration, early and late start dates, float time, critical path, logical constraints, and a number of other activity characteristics. Activity relationships in CPM are based on time only. CPM modeling limitations have been outlined and documented by a number of researchers (McCrimmon and Rayvec, 1964; Pritsker et. al. 1989, Pultar 1990; Jennett 1983; Hendrickson et al., 1987; and Fiedler 1985). Most existing progress reporting mechanisms are dependent on CPM technology and accordingly has the CPM limitations. Basic limitations include the following:

1. Time is the only logical constraint used between activities in a network schedule
2. Progress reporting is performed only at the lowest level of detail in a WBS
3. Repetitive cycles can not be modelled
4. Network branch decision making is not modelled
5. Resource utilization, interaction and waiting time can not be modelled
6. Resource allocation is not dynamic (resource quantities are fixed for each activity)

The use of system simulation to represent activities at the lowest level in a WBS overcomes some of the above limitations of CPM as demonstrated by Odeh et al. (1992) in CIPROS and Sawhney (1994) in HSM. However, the effort of reporting progress at the process level (lowest level in a WBS) in a construction project is not justified by the use of simulation. Tremendous input of data reporting is required at the process level in a simulation model for progress control. In general, more tasks and resources have to be updated (report on progress during construction) in a simulation model than in a CPM model.

1.2 RESEARCH PROBLEM DEFINITION

Short term planning requires numerous detailed level activities showing interaction of resources, required quantities, expected production rates, and involved personnel. Estimating and detailed planning are done at this level to ensure an accurate estimate for a project. On the other hand incorporating such a highly detailed level of planning in a schedule places an excessive burden on management as related to the time and cost required to update project plans. However, without such a level of detail in a schedule, the interaction of and between most resources is lost. Moreover, construction methods are only incorporated at the lowest level of a WBS. An example of resource sharing in a construction site is a tower crane which is required by a number of processes such as formwork erection, concrete placing, and general material handling. Without the lowest level of detail in a WBS, the performance factor of the tower crane cannot be adequately determined and the construction method is not represented. Improving crane performance, within a specific construction method, can best be done by studying production rates, non-value added tasks, and resource idle and busy times.

Controlling all details in a project is required only if a project is not progressing according to plan (control in this thesis is used to mean progress reporting and feedback within a scheduling system). "*A sure sign of schedule planning failure occurs when project control engineers can be found spending all their time updating schedules ...*" as stated by the Construction Industry Institute 1987. Variance analysis reports in the current scheduling systems compute the variance of actual progress from a single estimated value. In many cases actual progress should be compared to user-defined lower and higher significant deviation points. This will provide a project manager with a list of only those tasks and resources that deviate significantly from estimates. The author's experience with a major general contractor in Alberta, Canada, shows that there is not enough time to collect data to support current scheduling techniques. Minimum progress reporting is required in construction projects to control production and resources. For example, if reporting progress on formwork erection shows a delay or cost overrun then more details must be collected at a lower level in the WBS for corrective actions. Display of summarized information at various levels in a WBS is only part of the control process. In a typical WBS, progress is measured at the lowest level of detail. None of the current management systems provide a mechanism to report progress and project performance at a higher hierarchical level.

It is important to study and analyze the strengths and weaknesses of any system in order to understand it. The critical path method (CPM) such as that used by most commercial packages provides a mechanism to control cost and resources. However, CPM does not handle repetitive cycles, randomness and probabilistic estimates, network branch decision making, and event scheduling driven by production rather than time. Moreover, it does not provide feedback on resource utilization and waiting time. Event-driven scheduling in CPM is based on time only (i.e., relationships between activities are only time dependent). However, relationships between most construction activities are based on an activity's progress (i.e., production-based). For example, lead and lag values in a CPM network is specified in terms of time which creates difficulties especially at updating times, when lead and lag relationships are meant to be in terms of an activity progress rather than time.

On the other hand simulation-based project planning overcomes the above limitations but is limited for a number of reasons:

1) In general a simulation system includes more details (ex., resource nodes, probabilistic branching and durations, queue nodes, statistical nodes) than a CPM system. It is important to maintain the very detailed level of activities for a more accurate control by representing the resource sharing, interaction and utilization, and specific construction methods. This means more time is required to update schedule and cost data for control of activities.

2) Current simulation-based systems do not handle progress reporting and production variance analysis. Additional functions must be provided to compare budgeted production against actual production.

3) Linking of cyclic processes can be very complex and time consuming and especially for multiple and continuous links between two or more processes. In many cases the logical relationships between construction processes are not simple and one time relationships. Instead, relationships can be cyclic or requiring a constant buffer space for a logical separation. For example, in a paving operation, placing sub-base is continuously being performed after excavation and leveling. Linking of these independent processes requires an experienced simulation modeller to represent the continuous links between the processes (this is explained in more detail in Chapter 3).

Graphical and interactive simulation construction simulation systems have made it easier to understand and apply simulation. AbouRizk and Halpin (1990) state that simulation deficiencies, however, remain in the area of experimentation. These deficiencies and special requirements were the research motive to provide a new modeling methodology for construction projects that will incorporate new activity relationships and enable progress reporting and feedback from a higher WBS level and still maintain an integrated process/project level system.

1.3 RESEARCH OBJECTIVES

The theme of this thesis is "*Developing a SIMulation-based project CONtrol (SimCon) system that improves construction management productivity in project control by implementing progress reporting by exception, incorporating detailed resource level interactions in project modeling, and modeling new activity relationships*".

The main goals of this research include:

1. Establish a hierarchical breakdown structure to implement progress reporting from a higher level in order to keep progress reporting to a minimum.
2. Produce variance analysis reports based on significant deviations to make effective utilization of project management's time.
3. Develop simulation constructs to implement progress reporting by exception for project control and simplify the logical linking of simulation processes
4. Automate the suggested methodology in a form that allows validation and testing of the concepts using an actual case study.

The basic research concept is best represented in Figure 1.2. Comparison between current traditional methods and SimCon's method can be easily identified as shown Figure 1.2. Traditional methods represent project modeling in either a cost breakdown structure CBS or a WBS where the lowest level is an activity-based CPM model. Progress reporting is implemented at the lowest level in a CPM model. On the other hand, SimCon's method includes a production breakdown structure represented by cost centers, locations, and construction methods. Progress reporting by exception is reported on production achieved and resources consumed at the location level in the production breakdown structure. This is similar to management by exception. However, it is reporting progress by exception at a higher level unless more details are required. Chapter 3 fully outlines SimCon's modeling methodology.

Modeling needs that were identified include: 1) Representing progress reporting and feedback within a general simulation system environment. This includes providing simulation constructs to store project progress information for variance analysis and developing a technique that provides variance analysis reports on significant deviation basis. 2) Modeling and representing activity relationships in a form that will allow progress reporting by exception from higher levels in a production breakdown structure. Current activity-based systems provide time as the only logical constraint between activities. In this research the issue of providing activity relationships based on production and incorporating these relationships in cyclic processes within a progress reporting system are suggested and implemented in a prototype system. 3) Modeling progress reporting and feedback to incorporate repetitive network schedules and resource utilization and waiting times.

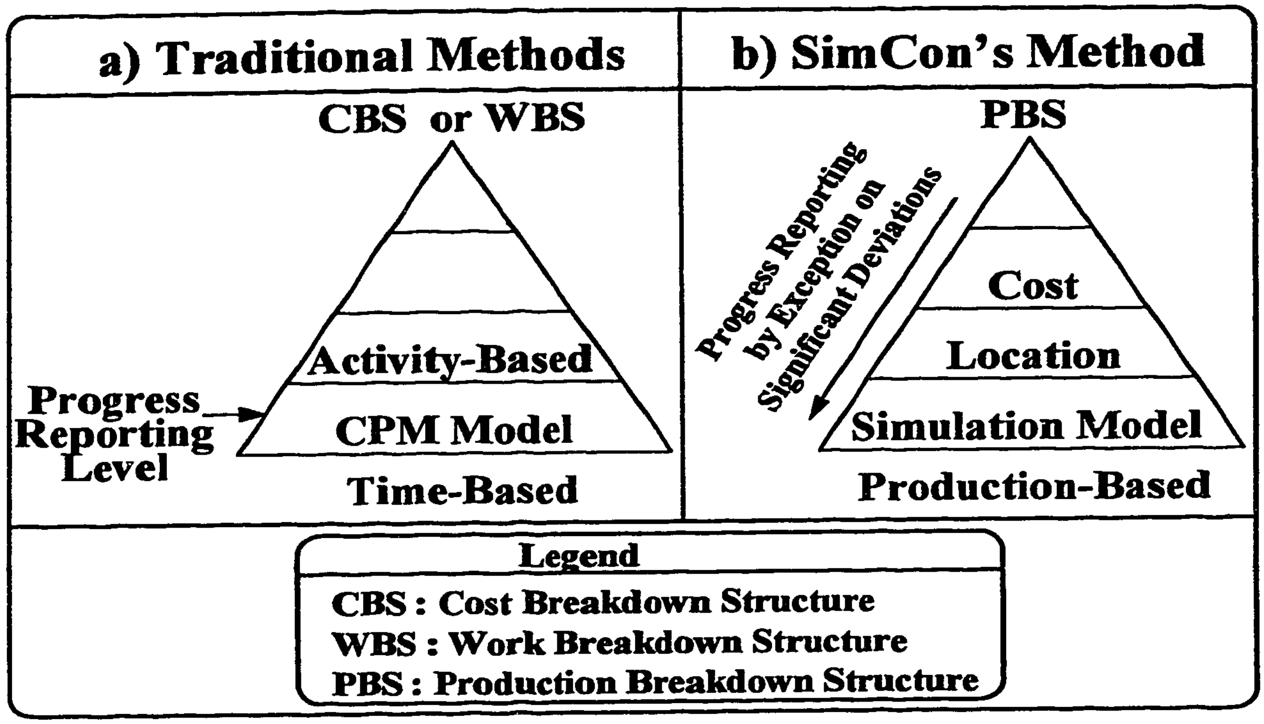


Figure 1.2 ***SimCon's Basic Research Concept***

Many construction companies are attempting to integrate construction management functions and consequently provide one system for short term and long term planning. The author's experience with PCL Constructors Inc. in Edmonton, Canada, showed that there is a great need for integrating activity-based estimating, cost/schedule control, risk analysis, project control and forecast reports, and advanced automated techniques for progress reporting and feedback. However, some of the issues that were of concern include the level of detail for collecting data and the technical skills required for using the advanced technology. It was recommended to have the level of detail dependent on the complexity and requirement of each project. And that the technical skills required for advanced modeling should be kept to a minimum not exceeding those required in the current modeling systems.

1.3.1 Research Scope

The research scope of SimCon (SIMulation-based Construction Project CONtrol) is the following:

- Develop a hierarchical breakdown structure that will provide progress reporting by exception and minimize the effort of reporting progress at the very detailed level
- Develop simulation constructs to store project progress information and simplify the logical linking of simulation processes
- Automate the suggested methodology in a form that allows validation and testing of the concepts using an actual case study.

1.3.2 Research Methodology

The hierarchical organization of products or activities within a WBS has a direct impact on the progress reporting details. Every type of construction project has its own unique representation within a WBS (i.e., WBS for building projects, industrial projects, and highway projects are organized differently). A cost breakdown structure (CBS) as shown in Figure 1.3 provides a good mechanism to review cost budgets of labor, material, equipment, and sub-trade at various levels of detail. Many construction projects maintain both a CBS and a WBS for project control.

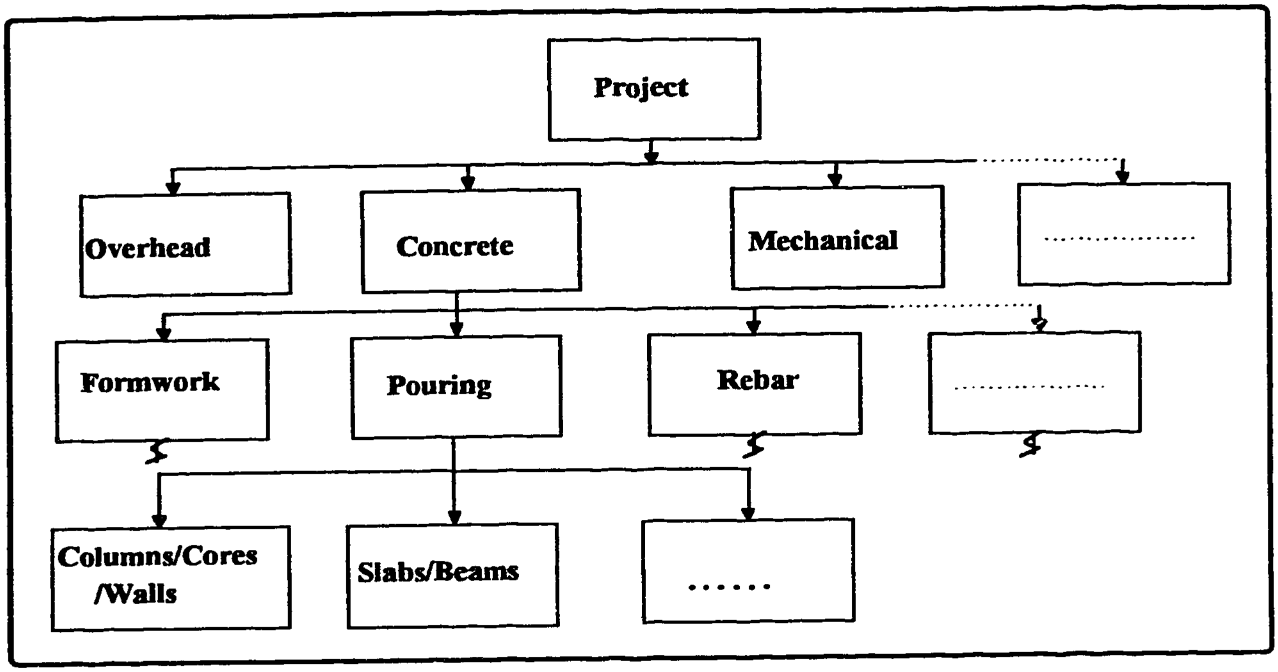


Figure 1.3 CBS of a Construction Building Project

Selection of a breakdown structure for a simulation-based project control was based on providing an easy-to-use progress reporting system and corrective action mechanism. It is more important to control production of a single process than an activity with combined processes. For example, it is more efficient to manage and control pour of concrete process or erect of formwork process than to control the activity grade-beam or slabs. In general, a concrete crew would be responsible for the concrete process and a formwork crew responsible for formwork process. It is easier to point out problem areas and identify corrective actions in single production processes than in complex activities because it is easier to identify the responsible crew.

The most important aspects to control in a project are production and resources. SimCon is implemented by constructing a hierarchical production breakdown structure as shown in Figure 1.4. The first step requires identifying cost centers in a project. Second, location breakdown centers are defined and attached to respective cost centers. Third, construction process centers are defined at various location centers and linked to each other using the new continuous and single production links as will be discussed in Chapter 3.

There are a number of advantages for using the production breakdown structure as will be explained in more detail in Chapter 3. The basic advantages are the following: 1) provides a ***short term planning tool*** from the very detailed representation at the process level; 2) provides a ***production-based*** identification structure and a better way to link processes, classify problem areas, and track project progress; and 3) provides ***progress reporting by exception*** capability to provide variance analysis reports on significant deviation basis and to update a project control schedule at a higher level in the production breakdown structure.

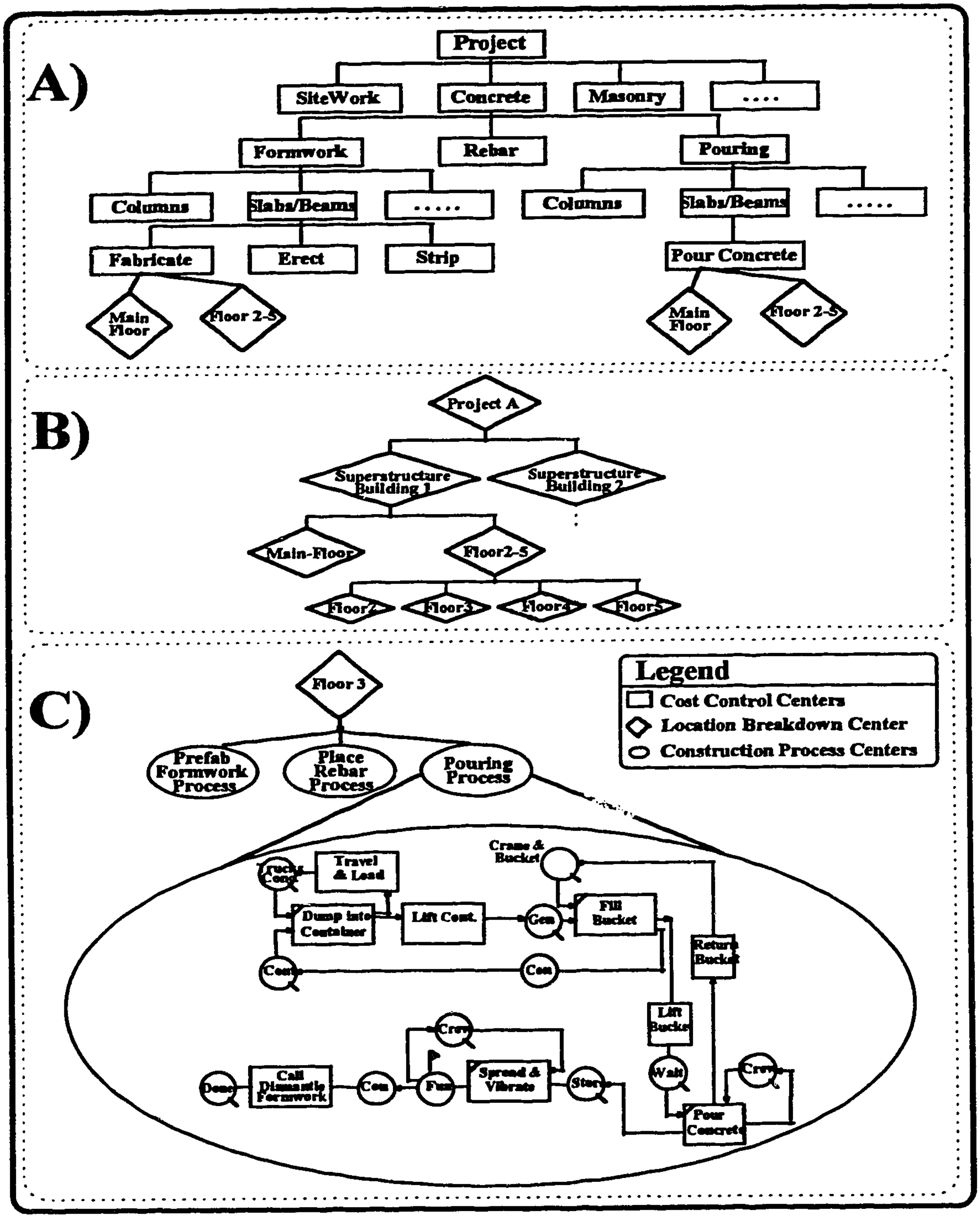


Figure 1.4 ***Schematic View of SimCon's Production Breakdown Structure for Building Construction: a) Cost Control Centers; b) Location Breakdown Centers; and c) Construction Process Centers.***

Updating information at the lowest level in a production breakdown structure as shown in Figure 1.4 can be done by reporting on production achieved. Simulation modeling provides the capability to measure performance by production. Similarly production achieved can be used to validate a simulation process, and hence provides a two-way feedback system from and to a construction site. This means that data and feedback from actual construction methods can be used to improve a simulation model by making it more realistic, and furthermore a simulation model can be used to improve performance of a specific construction method.

1.4 RESEARCH CONTRIBUTIONS

This research produced new progress reporting concepts within a simulation-based project control system prototype that can assist in improving construction management productivity. The research work contributions and solutions to currently existing needs are shown in Figure 1.5. The research work was aimed at achieving an academic and an industrial contribution. The academic contribution includes the following:

- Implementation of progress reporting and feedback from a simulation system
- Simplifying cyclic process inter-relationships in a project level simulation model
- Developing a production-based approach for progress reporting by exception (i.e., the mechanics of a production breakdown structure and variance analysis reports)
- Developing the required computer simulation constructs to report project progress information and simplify the logical linking of simulation processes in SimCon

The specific academic contribution lies in the development of a methodology to control cost, time, and project information from a truly integrated system. Originally simulation was used to study individual processes. Advanced simulation research was done in simulation-based project planning. This research focused on the application of simulation in project progress reporting and feedback.

The industrial contribution was aimed at the development of the following methodologies:

- Provide a better estimate on progress by the use of a more accurate representation of activity relationships
- Overcome the complexity of recording project progress at the extremely detailed level
- Provide variance analysis reports based on significant deviations which allow a project controller to focus on processes that need more attention
- Provide a scheduling system that will take less time to update while maintaining the required details for short term interval planning.
- Provide probabilistic estimates during project progress from system simulation risk analysis. Simulation can provide a more accurate and more realistic schedule for planning and controlling a construction project than many other analytical techniques.

Part of the industrial contribution started with a research work that was implemented at PCL Constructor's Inc., head office in Edmonton.

Needs & Solutions

Needs	Solutions
■ **Advanced project control** • Dynamic resource interactions & utilization • Production-based system	■ **Simulation System**
■ **Flexible system** • Short term & long term planning • Advanced Activitiy Linking	■ **Hierarchical System** • Lower & higher level • SimCon Links for continuous and smooth flow of production
■ **Progress reporting** • Minimum data reporting • Effective feedback system	■ **Progress Reporting by Exception** • Update from a higher level • Feedback based on significant deviations

Figure 1.5 Schematic View of SimCon's Solutions

1.5 THESIS ORGANIZATION

This thesis is organized in six chapters. Chapter 2 provides a general background on project control systems and introduce the current state of the art upon which later chapters build. Chapter 2 reviews four key project control concepts and practices. These are progress reporting, forecasting techniques, activity relationships, and simulation-based project planning. Chapter 3 describes the conceptual implementation and methodology formulation of SimCon. It focuses on five issues; cost and production control; location breakdown centers; modeling construction methods; progress reporting mechanism; and construction process's logical sequencing. Chapter 4 describes the computer modeling prototype of SimCon. Chapter 4 is directed towards demonstration of development feasibility. Implementation of SimCon is demonstrated through the use of object oriented concepts, event driven programming, relational database, and a simulation program. Chapter 5 illustrates the concepts and benefits of SimCon using an actual case study from building construction. Finally, Chapter 6 concludes this study by summarizing findings and contributions. It also outlines future research areas that can potentially be studied.

CHAPTER 2

STATE OF THE ART

2.1 INTRODUCTION

This chapter reviews the concepts of existing work breakdown structure, progress reporting mechanisms, activity relationships, simulation-based project planning, and the application of object-oriented programming within the research objectives. In general, emphasis in this thesis is placed at the integration of the above concepts to achieve simulation-based project control.

2.2 WORK BREAKDOWN STRUCTURE

A work breakdown structure (WBS) is based on the premise that a project can be controlled by managing and controlling the parts of a project. More formally, a WBS divides the scope of a project into discrete and definable components by forming a hierarchical division of end products and services. A WBS starts out with the total project at the top and then divided into successively smaller subdivisions at lower levels, with the resulting levels referred to as levels 2, 3, 4 and so on.

A work package is the basic building block of the WBS. The work-packaging model modified the traditional WBS by using work packages as the basis for control. A work package may exist at a higher level than the actual activity level. Work packaging model was developed by the National Aeronautics and Space Administration (NASA) and

United States Department of Defense (DOD). The model is based on the WBS of a project. In the model the work package level is used as the basis of control. The Work packaging model creates a unified view of project data by adding cost data to the WBS and eliminating the cost breakdown structure.

The work packaging model is based on the establishment of manageable units of work termed "control accounts" within a given set of work packages. At the start of the project the planning and budgeting for the project is done at the level of these work packages using the control accounts as the basis. Once this is done, throughout the project cycle, data is collected for each control account related to cost, time and resource consumption. During the implementation phase of the project the desired data for each control unit is to be collected based on the standard forms designed for the project. In order to support the work packaging model, an identification system is developed. This is basically achieved by designing a coding system for identifying all the processes and resources of a construction project.

A work package can be defined at any level of the WBS. Some people view work packages to be the lowest level of detail in a WBS (Neil 1982 and Diekman and Thrush 1986). On the other hand, others think that every element in the WBS can be considered a work package (Halpin et al 1987). The objective of the work-packaging model was to perform an integrated cost and schedule control. In this respect the work packaging model addresses well the data processing and representation aspects but ignores the data-acquisition phase (Rasdorf and Abudayyeh, 1991). Resistance to the model stem from the fact that large amount of data are still required at the lowest level in the WBS. Measurement of work progress is similarly done in all models using the traditional WBS.

In this research, a new way of defining a WBS is implemented to model and control a project as will be discussed in the next chapter. The next section outlines some of the current progress reporting mechanisms that can be implemented from within a WBS.

2.3 PROGRESS REPORTING

Progress reporting and activity relationships are directly related to an integrated cost/schedule control system. Ibbs et. al. (1987) stated that "*The subject of project control pertains to the concepts, procedures and techniques used to measure, analyze and report performance.*" Both an owner and a contractor are interested in delivering a project on schedule, within budget, and at the desired quality. Throughout the life of a project the monitoring function is continuous. Russell (1993) states that the most significant insights to the features required for practical implementation come from the updating phase.

A number of techniques currently exist to report work progress and evaluate project performance. The use of any of the methods depends on a number of factors: 1) type of work to be measured; 2) objective of the progress report (i.e., cost control, schedule control, accounting, general information, etc.; and 3) availability of tools to measure and report progress.

One of the objectives of reporting progress is determining the earned value of work completed. Progress reporting aims at determining the percent complete to date. The percent complete of a specific activity to date can be determined by a number of techniques as used by a number of owners and contractors in the construction industry and as outlined by Riggs (1987) are the following:

2.3.1 Units Completed

The percent of work completed is measured as the actual quantities or units placed to date divided by the total forecast quantities or units at completion. This technique is basically used for easily quantifiable bulk items such as concrete placing.

2.3.2 Cost Ratio

The percent of work completed is measured as the actual cost to date divided by the total forecast cost at completion. This technique is suitable for linear cost to time relationship such as administration overhead, power costs, general project management expenses.

2.3.3 Start/Finish Percentage

The percent of work completed is measured by a predetermined percentage ratio for starting or completing a specific activity. For example, 30 percent of work task A is completed as soon as it starts. The basic usage is for tasks that have a clear signal of work completed such as delivery of items or erection of temporary support.

2.3.4 Incremental Milestones

This method is very similar to the start/finish percentage with additional intermediate points for specifying percentage completed at milestone dates. For example, 30 percent of Activity A is completed when equipment is received, 50 percent is completed when equipment is installed, 90 percent is completed when testing is done, and 100 percent is completed when accepted by owner.

2.3.5 Supervisor's Estimate

The percent of work completed is subjectively measured by a supervisor. This method can basically be used for non-critical work items in a project. The technique's basic shortcoming is bias from a supervisor.

2.3.6 Earned Value

Earned value method is used to measure progress in a project with dissimilar units of measure by converting these units of measure into either man-hours or dollars. For example, the earned value in terms of cost is equal to percent complete times budgeted cost for that account (i.e., budgeted cost of work performed). The percent complete can be calculated using any of the above methods.

Basically, each of the above measurement techniques has its advantages and disadvantages. Some methods are more accurate than others but require more time and cost effort. Therefore, the use of any of the methods has to be justified before it can be used. A major consideration that affects all of the above methods is the level of detail that is defined in activities. The conventional definition of work breakdown structure allows for measurement of work progress at the greatest level of detail. Riggs (1987) suggest that the minimum duration at the lowest level in a WBS be one week to overcome the complexity of recording progress at the very detailed level. However, by modeling a project in this way, the resource interactions and non-value added tasks can not be identified.

2.4 FEEDBACK (FORECASTING TECHNIQUES)

Effective management of a project requires getting some future projections on specific activity performance and total project performance. Basically, an appropriate feedback constitutes having the right documents produced during the life of a project (Tavakoli, 1990). A common technique on getting feedback on project performance is to compare actual progress to expected progress. Some of the forecasting techniques as outlined by Riggs (1987) include comparing estimated productivity to actual productivity, estimated man-hours to complete to projected man-hours to complete, and budgeted cost for remaining work to forecasted cost to complete. These methods are not accurate until 25 percent of the work is completed. The methods 'estimated man-hours to complete compared to projected man-hours to complete' and 'budgeted cost for remaining work compared to forecasted cost to complete' do not take into account the variation in productivity over the life of a project. The task of tracking costs and durations of a project is still difficult and challenging (Chrzanowski & Johnston 1986 and Eldin 1989).

In a WBS some form of roll-up technique is used to summarize project progress from lower levels to upper levels. The different units of measurement of sub-component activities prevented the summation of the progress achieved. The earned value of a work completed is calculated by multiplying percent complete by budget for the specific account. Calculating the earned value for a group of activities with dissimilar units of measure can be calculated by converting the activities unit of measure into a common unit such as man-hours or dollars. A weighted percent complete (WPC) method (Clark and Lorenzoni, 1979) involves a lengthy procedure of calculations. The procedure of the WPC includes the following:

- Determine the percentage progress of each work item at the lowest level of a WBS.
- Multiply the percent complete by the weight factor (WF) for each account to determine the weighted percent complete (WPC). (WF is equal to an activity budget divided by the total budget of the next higher level in a WBS)
- The percent complete at the next higher level in a WBS is equal to the summation of the WPC of the directly lower level in a WBS. The WF at the higher level is equal to the budget of the lower level account divided by the total budget to which it belongs. The WPC at this level is computed by multiplying WF by WPC.

Eldin (1989) developed an enhanced WPC method that is based on identifying each activity by control points. For example, control points in footing foundation may include excavation, forming, steel reinforcement, concrete placing, and backfilling. Recording progress in Eldin's system requires identifying percentage completion of each control point in an activity. An activity's percentage completion is then computed by multiplying the control points by earning percentages and then summing the control points. Earning percentages for each control point are expressed as percentages of the activity's budget, duration, or an arbitrary work unit. The summation of earning percentages for each activity is equal to 100 percent. Eldin's work is valuable as a roll-up summary technique. However, work progress was still measured at the lowest level of a WBS.

Variance analysis is usually done to analyze items that require special attention. Typical variance analysis is usually done on budget cost versus actual cost, budgeted unit cost versus actual unit cost, budget man-hours versus actual man-hours, and budget percent complete versus actual percent complete. Forecasting using some risk analysis techniques or simulation can provide better results (Riggs, 1987).

2.5 ACTIVITY RELATIONSHIPS IN PROJECT SCHEDULING

The process of project scheduling is directly related to the relationships between activities. An activity constraint relationship is defined as the logical connection between activities in a network type model. There are a number of models that represent some kind of activity relationships for determining a project time schedule. These models include bar-charts, progress graphs, line of balance technique, activity network models, queuing theory models, artificial intelligence models, and simulation models.

Bar-charts and similar type of graphical displays are an excellent tool for display of final schedule analysis. However, bar-charts by themselves are limited and do not provide activity connector relationships, resource allocations, or any other complex relationships. The main drawback of bar charts is that they can not detail the logical inter-relationships between activities. If an activity is behind schedule, it may not be possible to ascertain the effect of delays on the completion of a project.

Activity network theory models include a number of network models belonging to the CPM family such as Arrow Diagram Method (ADM), Precedence Diagram Method (PDM), Program Evaluation and Review Technique (PERT), Monte Carlo Simulation (on a CPM), and a number of others. CPM models have been widely accepted as the project planning tools in the construction industry. There are a number of advantages to using CPM, however CPM does not handle repetitive cycles, resource utilization percentage and waiting time, randomness and probabilistic estimates, network branch decision making, and event scheduling driven by quantity rather than time. Event driven scheduling in CPM is basically time dependent (i.e., although complex algorithms can be written to transfer production into time, relationships between activities are based on time).

Pultar (1990) realized as many other researchers (Jennett, 1983; Hendrickson et al., 1987; and Fiedler 1985) that the lead/lag factors (CPM convention for relationships) in terms of time are actually meant to be in terms of progress. Pultar attempted to provide a solution by using progress charts and Gantt (bar) charts. Although new relationships were suggested by using non-linear relationships between activities, Pultar was still using time-based relationships. Relationships between activities were still based on time and recording quantity and cost progress was not considered. Scheduling in a simulation system is based on production and, hence, activity relationships and progress reporting can be implemented from production as will be discussed in the next chapter in the research methodology.

Line of balance (LOB) scheduling technique is aimed at modeling repetitive construction projects and has been used since the 1950s. LOB is based on production curves and is some times called time-distance, or velocity diagrams since they relate to quantities or distance per time. The slope of the curve relates the increase in units of production on the y-axis with the increment of time on the x-axis. The LOB technique shows the impact of delays on a specific activity but not on the completion date of the project. Halpin and Riggs (1992) summarized the LOB technique and used it for high-rise building construction. In order to insure a smooth flow of production, a schedule should account for continuous flow of various activities in construction. For example the continuous production of erecting forms, placing reinforcing steel, placing concrete, and dismantling forms in a high rise building, as shown in Figure 2.1, can be somehow maintained by dividing the typical floor construction into four zones. Crews proceed, as shown in Figure 2.1, from section A to B to C and to D. Production can be measured in this case as the number of sections completed per week.

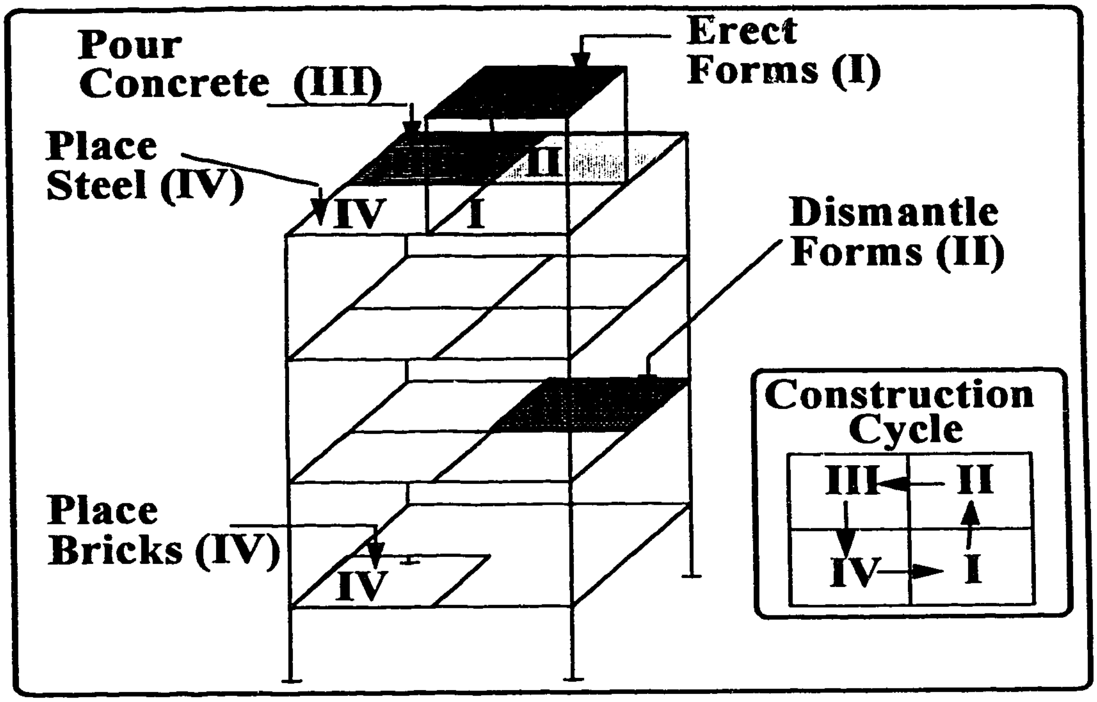


Figure 2.1: Schematic of Floor Cycle Work Tasks

The basis of the LOB technique is to provide project control to top management through reallocation of resources from fast progressing activities to slower ones. A major limitation of the LOB methodology is the assumption that the process production rates are constant throughout the project. Sarraj (1990) suggests in his literature review that the LOB method was not in an acceptable form for efficient application in construction and concluded that this was the reason for its limited use in project management.

A number of researchers have modified and applied the LOB technique to a number of projects. Of those, Lumsden (1968) applied LOB technique to the scheduling of multi-unit housing project. Khisty (1970) applied the LOB technique to manufacturing of construction units such as the training of a large number of supervisors in the production and supply of precast concrete beams, and improvements and repair of a harbor. Carr and Mayer (1974) did some of the earliest work towards the formalization of the line of balance technique. O'Brien (1975) developed what is termed as the Vertical Production Method (VPM) which is a continuation of the LOB technique.

Integration of LOB and CPM have been attempted by a number of researchers to overcome the limitations in both systems (Schoderbek and Digman, 1976; Rahbar and Rowing, 1992; Russell and Wong, 1993; Suhail, 1993, and many others). Many researchers have concluded that the LOB technique is better than network methods for repetitive construction. An important drawback of the line of balance technique is the modeling of resource allocation and utilization.

Queuing theory models analyze a model performance by studying the busy and idle time of servers and customers. For example, Shaffer (1961) applied queuing theory to model trucks as customers and shovels as servers. Queuing theory models are generally applied to analyze resource interaction in one operation. They become difficult and complex to solve when the model size and resource interactions increase (Winston 1987). Construction processes are generally made up of many operations with interacting resources.

2.6 SIMULATION-BASED PROJECT PLANNING

2.6.1 Simulation Systems

A few decades ago many simulation systems had to be developed from general purpose programming languages (Teicholz 1963, Carr, 1971, etc.). Although it is still possible to accomplish specific modeling requirements it might demand a substantial programming effort. Following that general-purpose simulation systems were developed such as GPSS (Schriber, 1974, 1991), Q-GERT and SLAM II (Pritsker, 1979, 1986), and SIMAN (Pegden, 1982). The time and effort required to develop a construction simulation system resulted in the development of construction-specific simulation systems.

The most significant body of research in the area of construction simulation started with the work of Halpin (1977) in the development of CYCLONE (CYCLic Operation Network). CYCLONE was basically developed to represent modeling capabilities at the process level. Over time, CYCLONE was enhanced by various researchers in many areas. Extensive research has been done on process-level simulation (Van Slyke, 1963; Pritsker; 1989; Halpin 1990; Halpin and Riggs, 1992; Ioanou, 1989).

RESQUE (RESource-based QUEuing network simulation system) developed by Chang and Carr (1987) uses the same basic modeling elements of CYCLONE but enhances the resource attributes and properties by adding a Process Description Language (PDL). PDL provides additional element properties to track resource type, operation functions, model variable conditions, and resource dependency property rules. However, RESQUE does not model multiple processes.

Paulson, et al. (1987) developed a simulation program, INSIGHT (Interactive Simulation of Construction Operations Using Graphical Techniques), that links field observations to computers. Repetitive field operations are recorded on videotape and then viewed rapidly on computer screen (CRT screen) in order to select the steps required for analysis. Following that a CYCLONE notation is developed of the operation to be analyzed. Event durations are identified on the computer by pointing out when each specific event in the flow diagram begins and ends. These durations are then analyzed by a specific computer program that determines the mean time value for each step in the operation (coefficients can also be determined for a pre-selected statistical distribution such as constant, normal, or log-normal).

Lluch and Halpin (1981) developed a microcomputer version of CYCLONE and called it MicroCYCLONE. Following that many enhancements have been made to MicroCYCLONE. A number of programs have been developed that facilitate the use of simulation such as integrated expert systems/simulation (Touran, 1990), knowledge based simulation (Farimani-Toroghi and Peck, 1990), object oriented simulation (Liu and Ioannou, 1992), computer animation in simulation modeling (Johnson and Poorte, 1988), visual interactive simulation (Bell and O'Keefe, 1987, Huang et al, 1994, and many others).

Martinez and Ioannou (1995) outlined the advantages of STROBOSCOPE, an acronym that stands for STate and ResOurce Based Simulation of COnstruction ProcEsses. Stroboscope is a programming simulation language specifically designed to model construction operations. The state of the simulation refers to resources waiting in a queue, current simulation time, the number of occurrences of a specific activity, and the last time a particular activity started. Stroboscope provides access to properties of resources (size, weight, and cost).

2.6.2 Project Planning Simulation Systems

There has been a number of attempts to incorporate simulation at the project level for project planning. Riggs (1989) in his literature review provided a summary of the attempts made to use simulation modeling for project planning. Dabbas (1981) describes a project planning technique that integrates process level simulation with CPM network scheduling. An object oriented discrete event simulation network, CIPROS, was developed by Odeh et al. (1992). CIPROS does not provide process-level interactions in its hierarchical modeling tool for planning projects. Interactions of processes in a hierarchical simulation-based (HSM) project planning was achieved by Sawhney (1994). A project plan can be developed in HSM using a symbolic graphical format. HSM is limited to planning a project and does not provide progress reporting and feedback nor provides a methodology to represent activity relationships other than time.

There is great potential for integration of expert systems and simulation by incorporating qualitative decision-making ideas in the less flexible simulation system. On the other hand simulation modeling can be used to test and validate rules in an expert system since the performance of expert systems can not always be validated quickly due to complexity of the parameters involved. Using an integrated expert system / simulation system for providing on-site information can be of great help to novice computer users.

2.6.3 Integration With Expert Systems

Artificial intelligence models were mainly concentrated on the use of expert systems for planning. Determination of precedence relationships and activity identification require experience-based decisions from knowledge of construction processes, construction methods, and available technologies. An integration of more than one system has been attempted by a number of researchers. Touran (1990) presented a prototype system, called Simulation Expert (SIMEX), that allows the user to perform simulation analysis without having to be an expert in simulation modeling. The expert system acts as an interface between the user and the simulation software. The prototype system integrates an expert system shell and the INSIGHT simulation software. The system developed allows the user to choose a suitable earth-moving system under a given set of job conditions, and evaluates the cost and production performance. Both simulation and knowledge-based expert systems (KBES) are interrelated and address the same type of issues but their method of function is different and according to Reddy (1987): "A KBES provides a prescription, a simulation model provides a prediction".

Giorgio et al (1989) developed a frame based approach for semantic representation of an integrated system of model base, knowledge base, and data base. Giorgio's system is designed to free the scientific expert from details about computer science and to let him concentrate on the actual simulation problems. A statistical expert system was developed by Mellichamp (1989) to make available an expert advise to simulation analysis. This came from the fact that every phase of simulation analysis involves one or more statistical issues and that many simulation practitioners have neither the statistical skill nor the access to qualified statisticians to effectively address crucial issues.

An interesting integration of two expert systems and a simulation model is described by Reuven (1988). The first expert system checks the consistency of input variables and the second expert system makes recommendations based on experimentations with the simulation model. The Hybrid Expert Simulation System (HESS) is composed of (1) simulation model i.e., simulator, (2) input expert system (IES), (3) output expert system (OES), and (4) knowledge-based management system (KBMS). Reddy (1987) describes the combination of artificial intelligence concepts with traditional simulation methodologies as an approach that turns a descriptive simulation tool into a prescriptive tool. Reddy says that a higher degree of integration would be for the expert system to explain the recommendations and cite the reasons for arriving at them. A prototype knowledge-based computer system, developed by Hill (1987), mimics the diagnostic (intelligent) process performed by the course instructor and teaching assistants, finds logical errors in INSIGHT simulation models and recommends appropriate corrective measures.

The validation stage is very important in a simulation project. Simulation results will frequently be considered as a support for assisting important decisions, which may be related to investments. A new architecture for designing the integrated intelligent simulation environment, in which different expert systems and numerical simulation packages work together, has been suggested to solve the qualitative decision in traditional simulation (Shanon et al, 1985).

2.6.4 Object-Oriented Simulation

An object is a package consisting of both data and procedures. Object-oriented is a way of building complex data structures with attached procedures, whereby, objects can interact via message passing. The way information is structured in the system has a direct bearing on the effectiveness of the application. Object oriented approaches minimizes the need to fully understand a model and bridge the gap between physical systems and their computer representation (Oloufa, 1993).

Oloufa (1993) pointed out the advantages of objected-oriented representation in his comparison of an object-oriented simulation language to a regular procedural simulation language. A number of benefits were accrued as a result of using an object-oriented language. Some of these benefits are modular approach in modeling (i.e., objects provide both data abstraction and information-hiding), inheritance capability (minimizes repetition), ease of modifying the simulation modeling, and eventually leads to a reduction in the resulting code. Polymorphism is a major benefit of using object-oriented programming (i.e., sending the same message to different objects causes different actions depending on the receiving object declared methods).

The hierarchical and modular modeling concepts were introduced by Zeigler (1987). This is similar to a WBS concept but is applied to simulation modeling by 'coupling' multiple sub-models. For example a new model can be created by specifying how input and output ports of two proper modular models can be connected to each other and to external ports. The concepts of hierarchy and modularity were implemented in a simulation environment using an object-oriented language (Smalltalk) by Luna (1991, and 1992).

Sause, et al. (1992), discuss the benefits of using an object-oriented approach for representing product and process models towards computer integrated design systems. A product model would describe the physical product to be developed. A process model would describe the activities comprising a design process.

Construction object-oriented process simulation (COOPS) was developed by Liu and Ionannou (1992) as a new general purpose discrete-event simulation system for construction process modeling. COOPS system follows similar network-based simulation models such as Q-GERT and CYCLONE (Halpin 1976) and utilizes a similar set of modeling elements, while providing additional capabilities for modeling construction processes. Resources as defined in COOPS can be identified as generic, using the same scheme as in CYCLONE, or identified as specific and are individually selected.

2.7 CHAPTER CONCLUSIONS

Based on an extensive literature review, no documentation of progress reporting by exception using simulation was found. The research concept and methodology formulation of simulation-based project control are developed in Chapter 3.

CHAPTER 3

SIMCON MODELING METHODOLOGY

3.1 INTRODUCTION & METHODOLOGY FORMULATION

The basic fundamentals of the current scheduling mechanisms focus on reporting progress at the lowest level of detail in a WBS and on linking activities based on time as described in Chapters 1 and 2. The methodology adopted in the development of a WBS for a construction project greatly affects the progress reporting process. In this research a methodology based on hierarchical representation of project information allows simulation-based project control of a project. The implementation of SimCon addresses five important issues: 1) cost control centers; 2) location breakdown centers; 3) construction process centers; 4) progress reporting mechanism on production-basis; and 5) logical sequencing of construction processes. Figure 3.1 shows a general schematic overview of SimCon's modeling representation. Planning is meaningless without control and control is not efficiently performed without planning. Project control in SimCon depends on building an effective project plan as shown in Figure 3.1. Some of the topics discussed in this Chapter identify the required project planning features for effective project control.

The Production Breakdown Structure (PBS), as shown in Figure 1.4, was formulated from the need to use existing PCL field reports to update a project schedule, to control cost, and to record progress in a form useful for future projects. The existing field reports are quantity worksheets that summarize production achieved on a list of cost accounts.

PBS is made of cost control centers, location breakdown centers, and simulation process centers. Cost control centers facilitate collecting costs and productivities of various activities and resources. Cost centers are used to track labor productivity and overall project cost. However, cost centers, as defined in this thesis, do not identify locations within a project for schedule and production control. A specific cost center can be used at various locations and a specific location can include various cost centers. For example, erecting column formwork is a cost center that can be used at various floor locations within a building. Similarly, a floor location includes many cost centers such as pouring column concrete, erecting column formwork, pouring slab concrete, and many others. Geographic/physical location centers are necessary for selecting and sorting project activities and schedule control. Moreover, resources can be assigned and tracked from various location centers. Construction process centers are used to analyze production, to study non-value adding tasks, and to show implemented construction methods. Construction process centers are identified at location centers and include new modeling elements to facilitate production reporting and linking simulation processes to formulate a project schedule. SimCon's modeling representation, as shown in Figure 3.1, is discussed in more detail in the next sections.

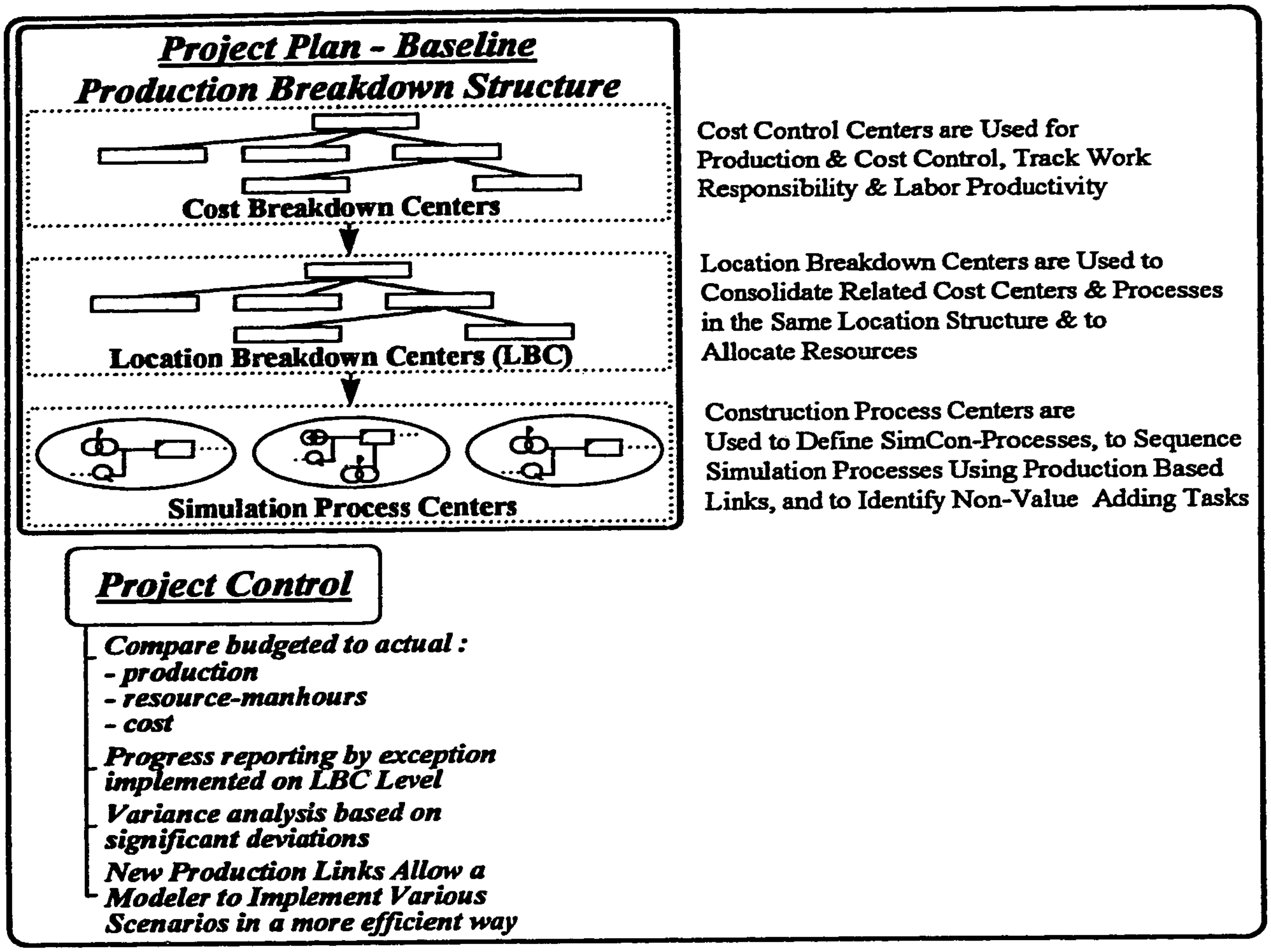


Figure 3.1 ***A General Schematic Overview of SimCon's Modeling Representation***

3.2 GENERAL MODELING CONCEPTS

Controlling a project using SimCon requires building a hierarchical breakdown structure as shown in Figure 3.1. Centers as defined in SimCon are needed for a number of reasons: *Cost control centers* are currently used by many construction companies for estimating, planning, progress reporting and feedback, and for maintaining historical records for future projects. A modeling scheme that builds on cost centers will help to bridge the gap between current cost control techniques and new modeling techniques.

Location breakdown centers are used to link construction methods and project schedule to associated cost centers. It further provides a mechanism to group together cost centers and construction methods in the same location, and to report on schedule progress in a project by location. *Construction process centers* model production and time and are used to represent the logical constraints between activities in a network schedule. Repetitive cycles, randomness and probabilistic estimates, network branch decision making, and dynamic resource utilization, interaction and waiting time can be modelled.

3.2.1 Cost Control Centers

Cost control centers are identified by the user and depend on the project type and general contract requirements. For building construction, cost control centers can build on the standard master list of cost accounts as used in any construction company. Figure 3.2 shows a sample format for formwork cost centers in building construction. A similar format is used by many construction companies to track cost expenditures and labor productivity in building projects. A modeling scheme that builds on this format will help to bridge the gap between current cost control techniques and new modeling techniques. A recent research work with a major general contractor in Edmonton, Alberta, revealed the need to build on existing company information data structures to improve project control. The general objective from the research work with the general contractor was to suggest new techniques towards building an integrated cost/schedule system from their existing standard cost breakdown structure. The benefits of a cost control center are many. It documents actual performance for establishing cost trends during the course of a project by identifying problem areas and unfavorable trends. It feeds into a historical database so that future planning of comparable work can be more accurate (Construction Industry Institute 1987).

A hierarchical cost code structure is used for estimating, progress reporting and feedback, and for maintaining historical records for future projects. The implementation of cost control centers as shown in Figure 3.2 aids in hierarchic control. However, cost centers do not show specific locations for detailed control purposes. A further drawback of such a breakdown is the inability to link and sequence activities in a logical flow diagram. Identifying specific locations within a general hierarchic location structure and linking them to cost centers has many advantages as discussed in the next section.

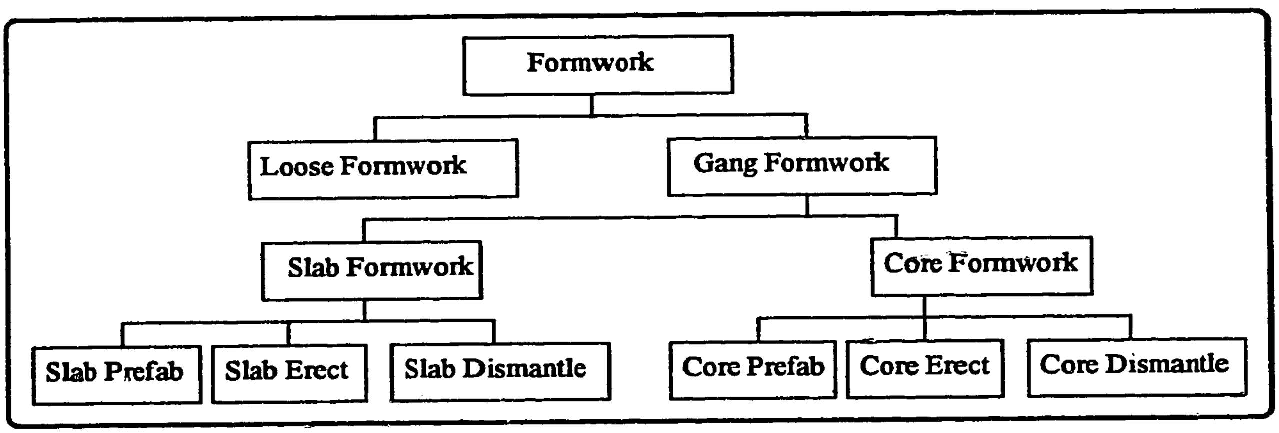


Figure 3.2 A Sample of Cost Control Centers for Building Construction

3.2.2 Location Breakdown Centers

Location breakdown centers are used to enable and simplify linking construction processes and project schedule to associated cost centers. A hierarchical location breakdown center (LBC), as shown in Figure 3.3, simplifies defining locations and controlling information within each location. Specific location breakdown centers in a lower level of the location hierarchy inherit the immediate higher level location characteristics. An LBC is flexible to accommodate any type of location hierarchy and does not necessarily represent the sequence of construction. For example, Floor 2-4 can include one type of repetitive construction, where as, Floor 2-5 can include another type of repetitive construction.

An LBC is used to allocate resources and to define specific attributes such as space constraints and location access requirements. Resources naturally occupy space in a specific location. For example, a project consisting of two buildings can be allocated two cranes; one for each building. On the project level a truck can be shared by both buildings, hence, allocated at a higher level in the hierarchical location breakdown center. Furthermore, an LBC is used as a mechanism to group construction processes within the same location. The location structure as shown in Figure 3.3 can be used to report on schedule progress in a project by location. An LBC can include locations in multiple projects to provide office managers with a systematic way of tracking and allocating resources in various project locations.

Russell and Wong (1993) suggest that the concept of work locations should be thought of in general terms, embracing off-site processes and as well as on-site physical locations. Off-site processes which are usually contained in the same schedule include different stages of design, permits, and procurement. Figure 3.3 shows an example of on-site physical locations. Russell and Wong further suggest that a hierarchy of locations would be ideal for large scale facilities and/or micro-planning (this feature was not implemented in their research work).

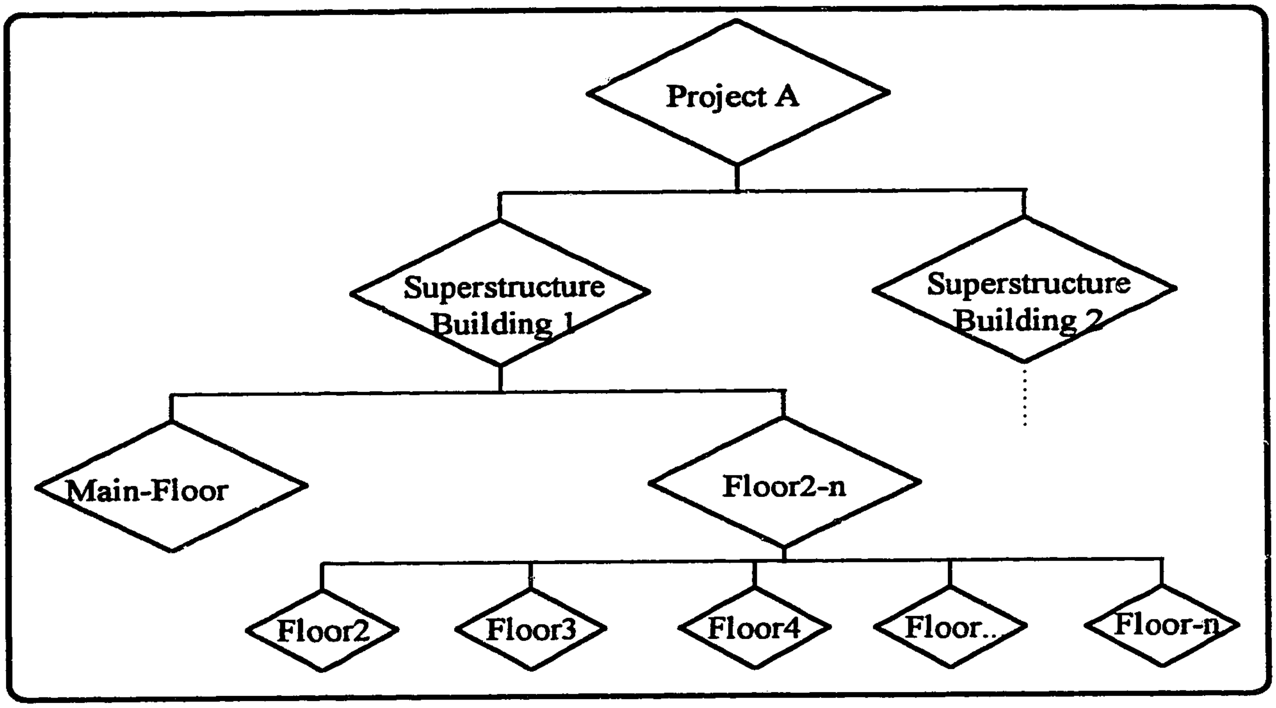


Figure 3.3 *A Sample of Location Breakdown Centers for Building Construction*

3.2.3 Construction Process Centers

Construction process centers represent the simulation processes at the lowest level of the production breakdown structure. Construction processes are required to be attached to an LBC because an actual construction has to be done in a location(s). If a process is attached to a higher level location in LBC then repetitive or cyclic sequencing of tasks can be used for completing the processes at lower level locations.

Construction methods can be identified in the sequencing of tasks in a simulation process. The methodology followed in SimCon for progress reporting starts by constructing a production-based simulation process (SimCon-process) that will provide the mechanism to record progress at a location center and produce variance reports based on significant deviations. This methodology of recording progress and producing variance analysis reports based on significant deviations is referred to in this thesis as ***reporting progress by exception***. Simulation modeling includes numerous tasks and resource interactions and hence requires extensive time for updating purposes. A SimCon-process is constructed to include one specific type of production with a certain unit of measure. This will allow progress reporting on any SimCon-process to be implemented from a higher hierarchical level. Less time will be spent on updating unnecessary progress and focusing on processes that require improvement.

Recording progress on a SimCon-process such as erecting slab formwork process, placing slab concrete process, placing slab rebar process, or any other process with an identifiable and measurable production, can be implemented from any location level that is directly connected to the process. For example, a repetitive slab concrete process can be updated from the 'Superstructure Location', as shown in Figure 3.3, as long as the cyclic process is connected under the location hierarchy. Duration of a SimCon process and the total project schedule are updated by reporting on production achieved at the LBC level.

Total process production and duration are maintained and updated through reporting by exception. This means that enough details are maintained to report progress at a lower level in SimCon's hierarchy in case it is required in the future. Moreover, variance analysis reports are produced that identify processes that require more control (i.e., significantly deviate from the plan).

The method of developing a SimCon-process and construction process centers in the production breakdown structure effectively facilitate keying on problem areas. Reporting by exception is implemented on processes that do not experience significant deviations from project plan.

As expected there are drawbacks for updating at higher levels. Detailed data on actual duration of process nodes cannot be determined and maintained except by collecting additional information from field. If a manager requires more control on a specific process then additional data must be collected at the detailed level of a simulation model.

The detailed level of a SimCon-process required constructing new modeling elements to represent the logical flow of work and deal with progress reporting and logical sequencing of processes. The next sections analyze and describe the new modeling elements that explain the data extraction in the progress reporting by exception concept.

3.3 MODELING ELEMENTS & ENTITY PROCESSING

3.3.1 CYCLONE Modeling Elements

CYCLONE modeling elements which were originally developed by Halpin (1973) are used to model a construction process. The CYCLONE nodes used to represent construction modeling are shown in Figure 3.4. Work states in CYCLONE modeling of a construction operation focus on the involved resources and their interactions. Work states and entity flow modeling can be graphically represented using three basic modeling shapes (Halpin and Woodhead, 1976): 1) a square node of a work task representing the active state; 2) a circle node representing the idle state of a resource entity; and 3) a directional flow arc model to represent the logical flow diagram and the change between idle and active states. As shown in Figure 3.4, the NORMAL node is a non-constraint work task in its starting logic. The COMBI node element is a constrained work task in its starting logic and requires more than one resource type to process entities. Entities represent information flowing through a simulation model. The QUEUE node represents the idle state of a resource entity showing queuing state of resources. The FUNCTION node is a function element that is used to add or remove entities from the model. The COUNTER node is a counter that is used to keep track of the number of entities that pass through it. The ARROW is used as a directional flow modeling element for entities. For information on the use and application of each node refer to Halpin (1990a, 1990b) and Halpin and Riggs (1992).

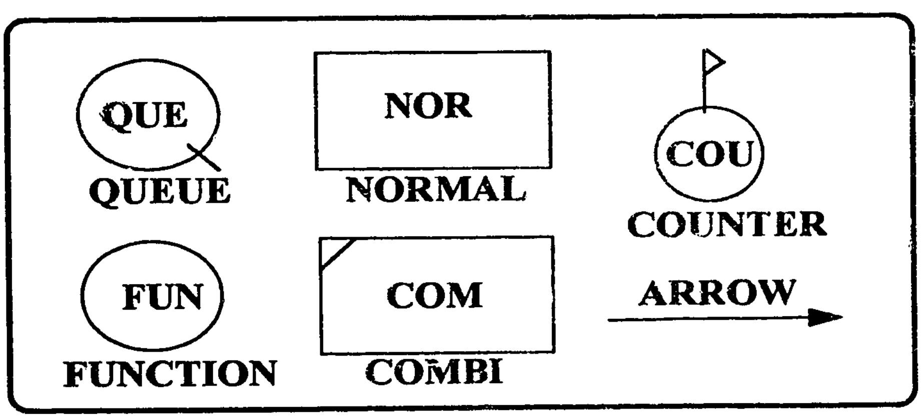


Figure 3.4 CYCLONE Modeling Elements (source Halpin 1973).

CYCLONE is a simple and powerful tool for construction process planning as demonstrated by many researchers (Liu and Ioanou 1992, McCahill and Bernold 1993, Huang et. al. 1994, and many others). However, CYCLONE has two major drawbacks when tackling hierarchical planning and project control:

- CYCLONE considers the modeling of single processes and single production systems (i.e., only one counter node can be defined in a CYCLONE model) with no mechanism for hierarchical organization of information. The logical relationships, linking and dependencies between processes are not straightforward and require an experienced simulation modeller. Moreover, process strategies such as dynamic routing of entities or conditional branching of entities can not be formulated with flexibility.
- CYCLONE and other simulation-based systems do not handle progress reporting and production variance analysis for project control. Additional functions must be provided to track and compare budgeted production against actual production for multiple processes.

3.3.2 Basic Modeling Elements of SimCon

Construction methods are constructed and identified in the sequencing of tasks in a simulation process. Some additional elements besides the CYCLONE elements were required to implement the SimCon concepts. The additional elements are basically used to keep track of progress achieved in SimCon's hierarchical breakdown structure and to simplify the linking of processes. Figure 3.5 shows the new modeling elements with a brief description of each.

A production counter node (PRO) is used to keep track of production achieved and to convert actual production to a simulation counter parameter. A Link Gate node (LINK) is used to link processes and maintain a smooth and continuous flow of production between processes. A Free Gate node (FREE) is used in conjunction with a LINK node to represent the predecessor and successor processes. A Track Variable node (TRACK) is used to track the start and finish of processes and assign variables to simulation processes for progress reporting and statistical output purposes.

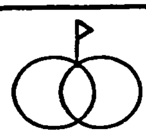
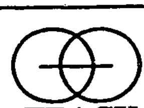
SimCon Element	Name	Usage
 PRO	Production Counter Node	Keeps track of hierarchical production achieved for within-process & between-process production - report by exception
 LINK	Link Gate Node	Used to link processes and maintin continuous and smooth flow of production between processes. N denotes the buffer zone between two processes
 FREE	Free Gate Node	Used in conjunction with a Link Node to Free the buffer zone. The number 1 denotes one entity to free
 TRACK	Track Variable Node	Used to assign variables & track statistics. Variables can be durations, scheduled production, constants, & other parameters

Figure 3.5 SimCon Modeling Elements

SimCon elements in conjunction with CYCLONE modeling elements are combined in several ways to model construction operations. The next sections provide detailed examples of the application and use of each SimCon element to model a construction project.

3.3.2.1 SimCon PRO (Production Counter) Node Implementation

A production counter (PRO) node is used to control production within and between processes. It is modelled, as shown in Figure 3.6a, in two circles format with an added flag symbol. Five user-defined attributes, PRO-Q, PRO-Loc, PRO-Count, PRO-Link, and PRO-Name are required for every production counter node as shown in Figure 3.6b. The PRO-Q parameter represents the total production required. The PRO-Loc parameter represents the number of typical repetitions required. The PRO-Count parameter represents the number of simulation cycles required. The PRO-Ratio is calculated as PRO-Q divided by PRO-Count and PRO-Loc (PRO-Q/((PRO-Count)x(PRO-Loc))). The PRO-Ratio is used to convert actual production achieved into a simulation counter (PRO-Count). Once the cumulative register of the production counter exceeds the PRO-Count specified, the entity exits the current process. The PRO-Link parameter represents the number of cycles required to release the first entity to the next process. As shown in Figure 3.6b, a production counter with PRO-Q = 800 m^2, a PRO-Loc equal to 20 repetitive locations, and a PRO-Count equal to 80 has a PRO-Ratio of 0.5 (800/(20x80)). For example, erecting 800 m^2 of formwork in a slab process (PRO-Q = 800 m^2) on a 5 floor and 4 zones (i.e., 20 repetitions (4 x5)) per floor repetitive construction has a PRO-Ratio of 0.5. A PRO-Link equal to 20 means that the next process will start when twenty entities pass through the counter. In this way activity dependencies in a schedule can be linked based on production in addition to being based on time. For example, in construction of five typical floors in a building that is divided into four zones per floor, placing rebar process on zone j follows erecting formwork on zone j-1. In this precedence relationship rebar process always follows formwork process and is based on acquiring a certain production in formwork erection (i.e., erecting 20 m^2 of formwork per zone having four zones per floor). A PRO-Name is used to identify the location breakdown center that is linked to the PRO node. The topological syntax indicates the nodes that can precede and follow a PRO node as shown in Figure 3.6c.

A PRO node *within* a process is used inside a process to count production and link processes based on achieving a certain production. A PRO node ***between*** processes is used to initialize and control the sequencing of repetitive processes. For example, a PRO node inside a rebar process counts the amount of steel that is placed, and a PRO node between the rebar process and the formwork process counts the number of zones that are completed. Both types of production counters are used for the following purposes:

- linking a specific process to a location breakdown center in the production breakdown structure to allow for progress reporting by exception,
- transferring actual production to a simulation counter node using a specified production ratio,
- linking processes based on acquiring a certain count in the production counter, and
- keeping track of production achieved by a simulation process (i.e., similar to CYCLONE's functional counter).

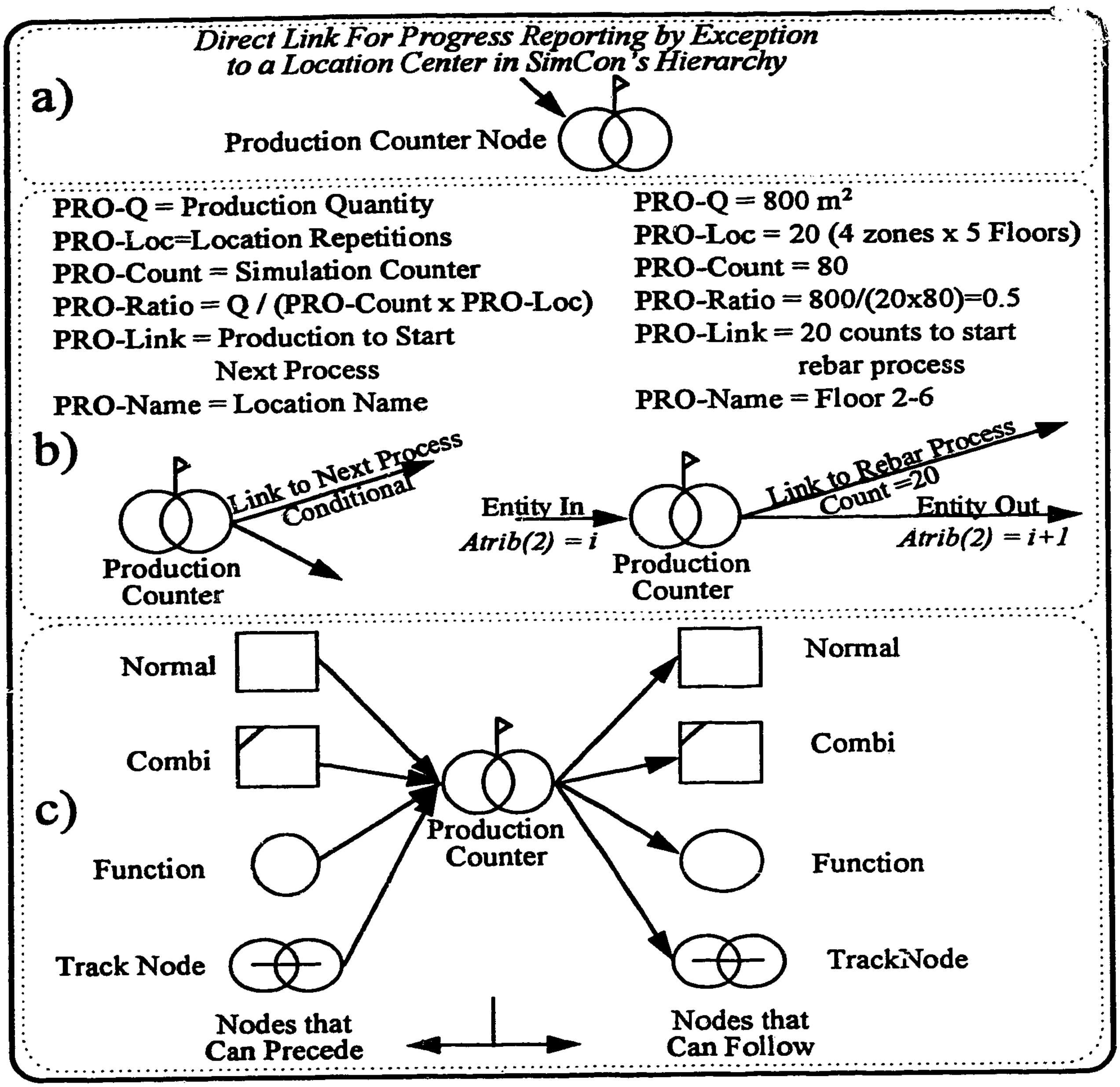


Figure 3.6 ***Entity Flow in The Production Counter Node; a) Graphical Symbol of a Production Counter; b) User-Defined Production Quantity, Number of Cycles, Production to Start Next Process, and Location Name; c) Linking Syntax for the Production Counter Node.***

A typical production counter within a process, as shown in Figure 3.7, keeps track of production achieved and converts actual production to a simulation counter. A typical production counter between processes is shown in Figure 3.8. It keeps track of internal processes by re-initializing specified variables after every cycle and managing locations separately. Implementation of both types of production counters are explained in more detail in the progress reporting section.

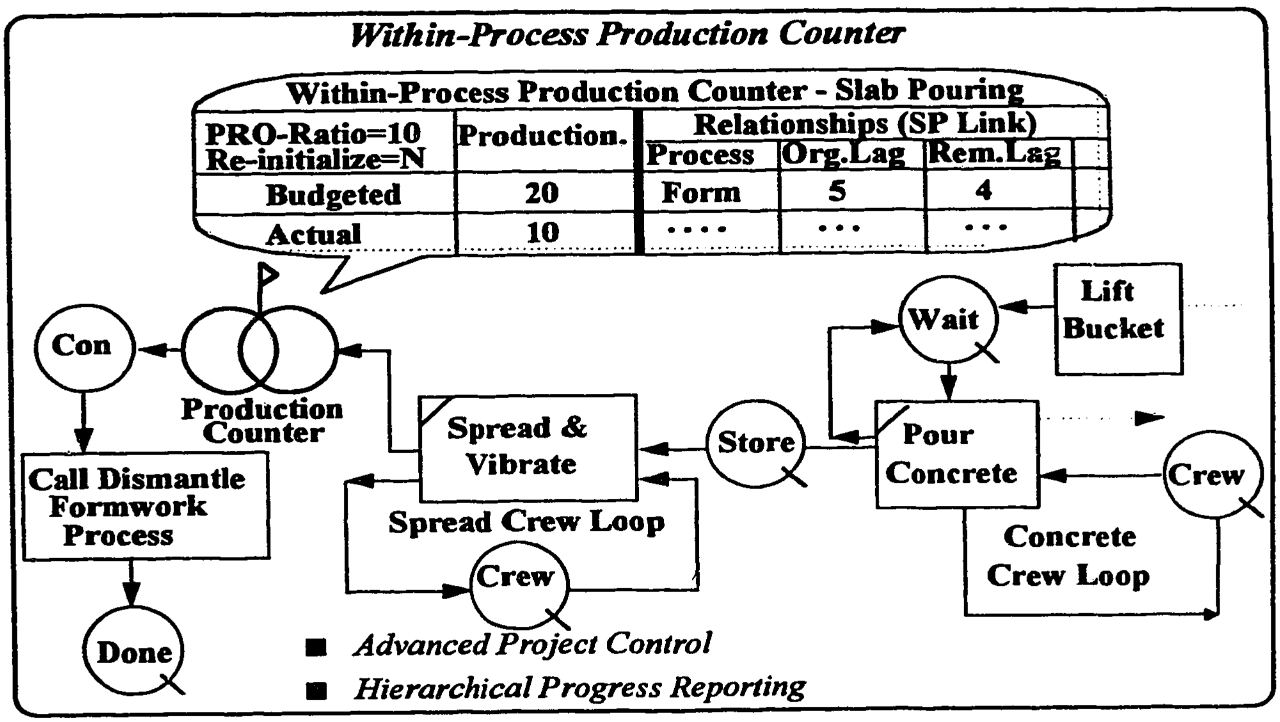


Figure 3.7 *A Schematic View of a Production Counter Within a Process in a Simulation Model*

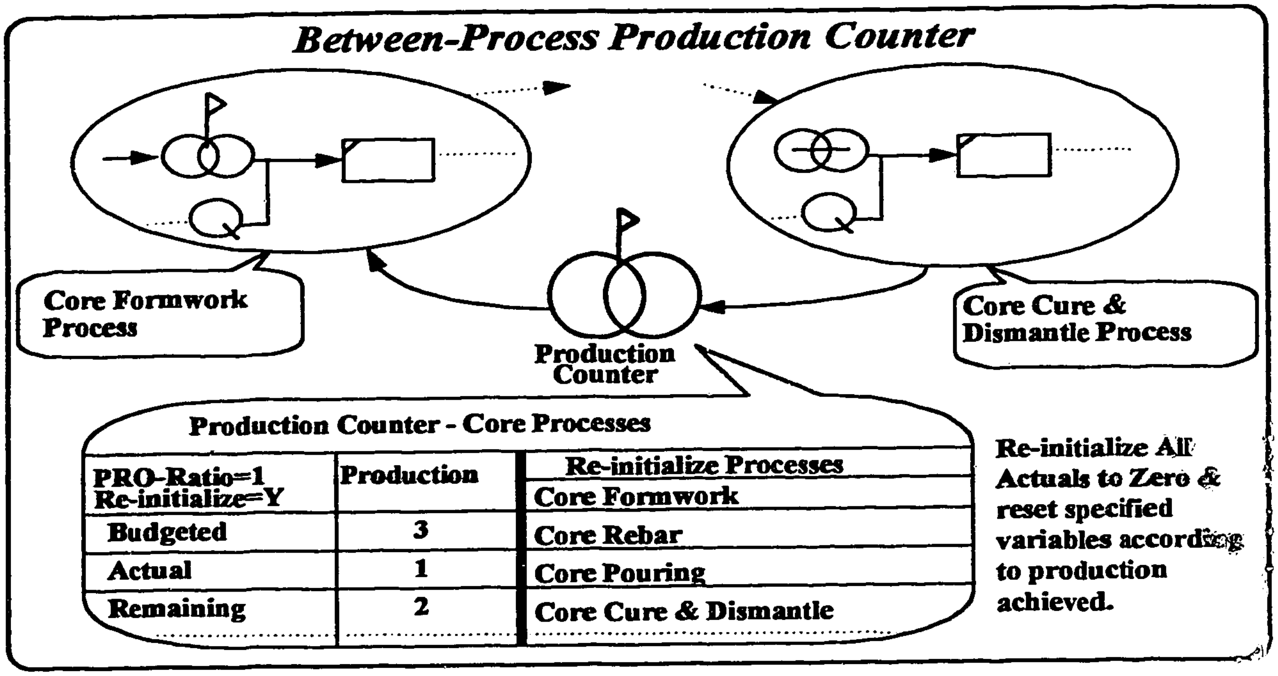


Figure 3.8 *A Schematic View of a Production Counter Between Processes in a Simulation Model*

3.3.2.2 SimCon LINK and FREE Node Implementation for Logical Sequencing of a SimCon-Process

Current activity-based systems provide time as the only constraint between activities. This research addresses the issue of providing activity relationships based on production and incorporating these relationships in a progress reporting system. Many researchers have identified the need for better mechanisms to linking activities. Pultar (1990) realized as many other researchers (Jennett, 1983; Hendrickson et al., 1987; and Fiedler 1985) that the lead/lag factors in terms of time are actually meant to be in terms of progress. Pultar attempted to provide a solution by using progress charts and Gantt (bar) charts. Although new relationships were suggested by using non-linear relationships between activities, Pultar was still using time-based relationships. Relationships between activities were still based on time and do not consider other means for progress relationships.

In SimCon two types of links are used: 1) single production links such as those formed using a PRO node; and 2) continuous production links using a LINK and a FREE node (Link Gate Node and Free Gate Node). A single production link is a simple one-time link between processes. It is used to determine the production required before the next process can start as described in the PRO-Link example in Figure 3.6b. If the next process starts at completion of the predecessor process then the single production link is equal to total actual production at the predecessor process. For example, the placing steel process will start when a certain production is achieved in its predecessor formwork erection process. The representation of this relationship in simulation is more realistic than traditional methods like CPM that only provide time-based relationships.

A continuous production link is a more complex type relationship requiring multiple and continuous links between two processes. It is used to sequence cyclic processes continuously by specifying a buffer zone between two processes. The buffer zone is used to control both the predecessor process and the successor process to make sure that the spacing in terms of production between both processes is in the range specified in the continuous production link. This means that a continuous production link can be used to provide a smooth and continuous flow of production to account for the inter-relationships of many activities.

A Link Gate node (LINK) and a Free Gate node (FREE) are used to control the start and finish of a predecessor process and a successor process, respectively. They are modelled, as shown in Figure 3.9a, in two circles format with a triangle. The triangle that is directed into the two circles resembles the LINK node and the triangle that is directed away from .. two circles resembles the FREE node. Three user-defined attributes, LINK-N, LINK-P, and LINK-D, are required for every LINK node, and two-user defined attributes, FREE-P and FREE-D, are required for every FREE node, as shown in Figure 3.9b. The LINK-N parameter determines the buffer zone between a predecessor and a successor process by specifying the maximum number of entities that can pass through the LINK node before an entity passes through the FREE node. For example, placing plywood in a formwork erection process can be processed a maximum of four times before an entity passes through a FREE node after concrete sets in the concrete process as shown in Figure 3.9c. In this way, formwork erection process can only commence a maximum of four zones ahead of the concrete pouring process. The LINK-P and FREE-P parameters specify the process names of the predecessor and successor process. The LINK-D and FREE-D parameters specify the process nodes in the predecessor and successor processes. The topological syntax indicates the nodes that can precede and follow LINK and FREE nodes as shown in Figure 3.9d.

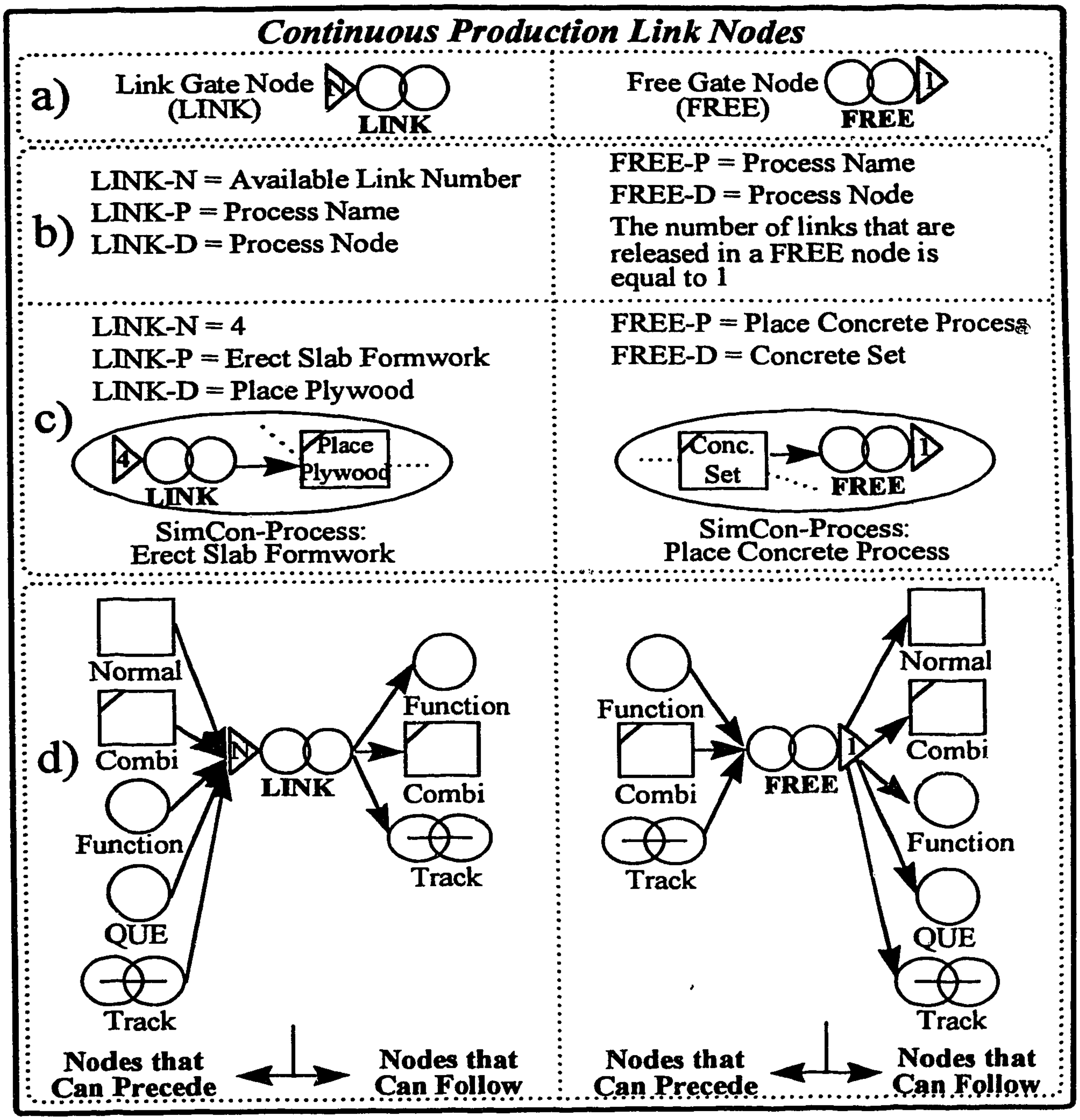


Figure 3.9: ***Entity Processing in The Link Gate and Free Gate Node; a) Graphical Symbol of a Link Gate and Free Gate Node; b) User-Defined Variables; c) An Example Applying the User Defined Variables; and d) Linking Syntax for the Link Gate and Free Gate Node.***

The best way to explain the basic advantages of using SimCon's continuous link is with an example. Construction sequence of building core in a typical high-rise building is assumed to lead floor-slab by one floor. Representing this sequence in a CPM network can be very time consuming as shown in Figure 3.10. Moreover, data collection and progress reporting can become very costly and inefficient in such a schedule.

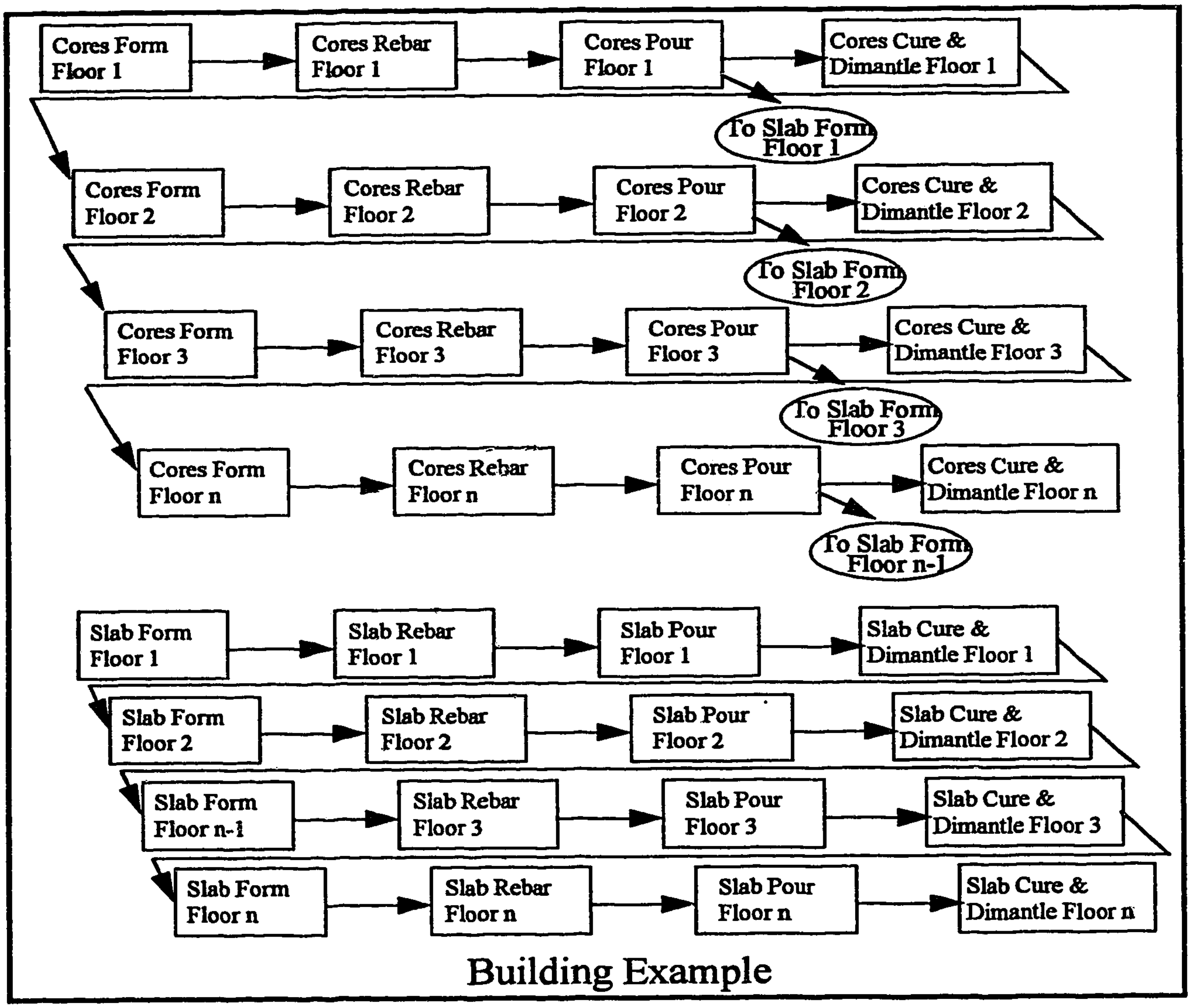


Figure 3.10 ***Activity Sequencing in a Typical CPM Schedule for Building Construction***

Simulation offers an advantage by the modeling of repetitive activities. The repetitive tasks of constructing a building core is modelled by four cyclic processes that have a single production link relationship as shown in Figure 3.11. Entities move through the cores form process until the number of floors are completed. Every time an entity passes through the cores concrete process another entity goes to the slab form process through a continuous link process with a LINK-N = 2. This means that a maximum of two cores can be constructed before a slab operation is completed (i.e, slab concrete is set). This is required in many cases so that core construction does not preclude complete rotation of the tower crane. Moreover, the core leads floor-slab construction so that it is not critical.

Continuous floor construction is maintained by dividing each floor into four zones as shown in Figure 3.11. Slab formwork construction starts in zone 1 on floor i. Then it moves to zone 2, zone 3, and zone 4 on floor i, followed by zone 1 on floor i+1, and so on. The continuous production link between slab formwork and slab concrete set ensures that formwork construction in zone j of floor i+1 is not started until concrete sets in zone j of floor i.

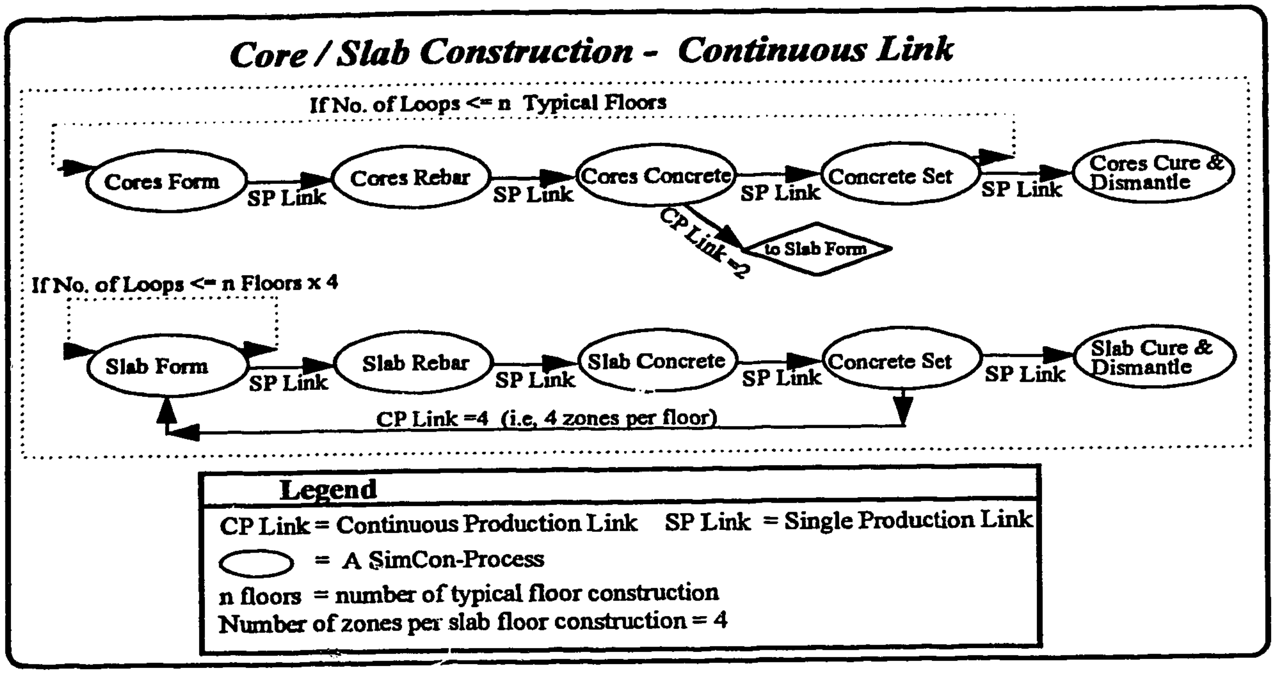


Figure 3.11 Demonstration of Continuous Link and Single Link in SimCon for Building Construction

Every SimCon-process shown in Figure 3.11 represents a simulation process consisting of CYCLONE and SimCon nodes. The continuous link is established in simulation terminology by requiring a maximum of four entities to be processed in formwork construction until an entity is released from slab concrete setting. The programming implementation details of a continuous link and a single link are explained in Chapter 4.

Modeling of slab construction operation can not be represented in a similar way to that of the core construction operation because of the division of floor construction into four zones. For example, the repetitive processes of slab construction operation should not be represented as shown in Figure 3.12a if formwork crew is required to be working on the next zone even if rebar process of the current zone is not completed. Linking of simulation processes can become very complex by certain logical constraints. Representing such sequencing as shown in Figure 3.12b requires an experienced simulation analyst and considerable time to model a project to make sure that continuous use of slab forming and formwork crew is maintained. The continuous link allows the formwork crew to work up to four zones before an entity is released from the concrete set process, based on having the available resources. In this regard a continuous link helps to represent the logical relationships between activities more realistically.

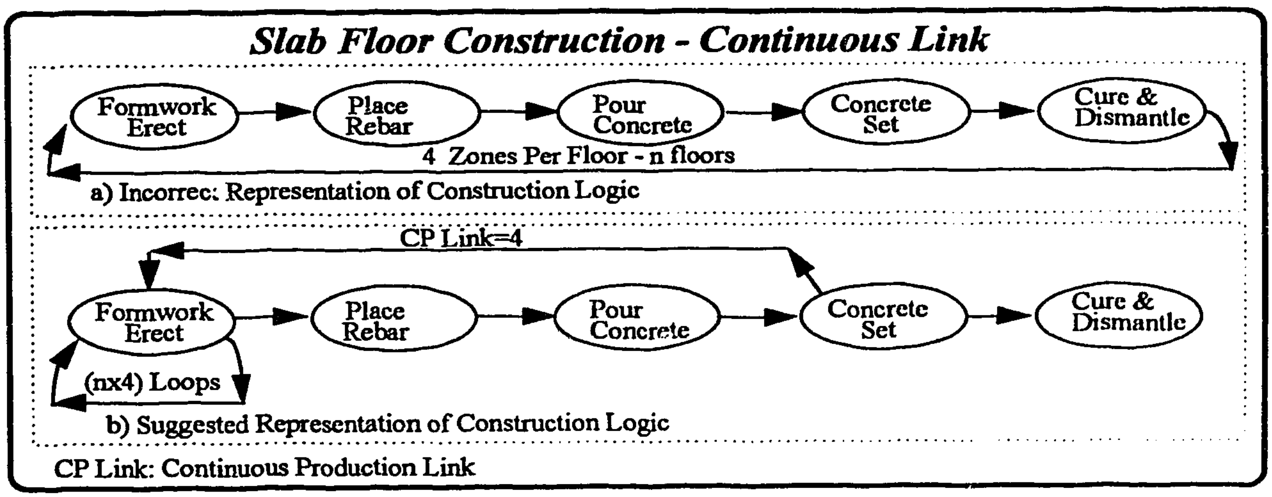


Figure 3.12 ***Schematic View for Modeling Slab Concreting Operation; a) Incorrect Way to Represent Cyclic Operations; b) Suggested Representation of Construction Logic.***

The syntax representation of the continuous production link in SimCon is shown in Figure 3.13. A continuous production link between formwork erect and concrete set has a LINK-N = 4. The LINK-N =4 means that a maximum of four entities can move through the formwork erect activity before an entity passes through the concrete set activity where a FREE node is activated.

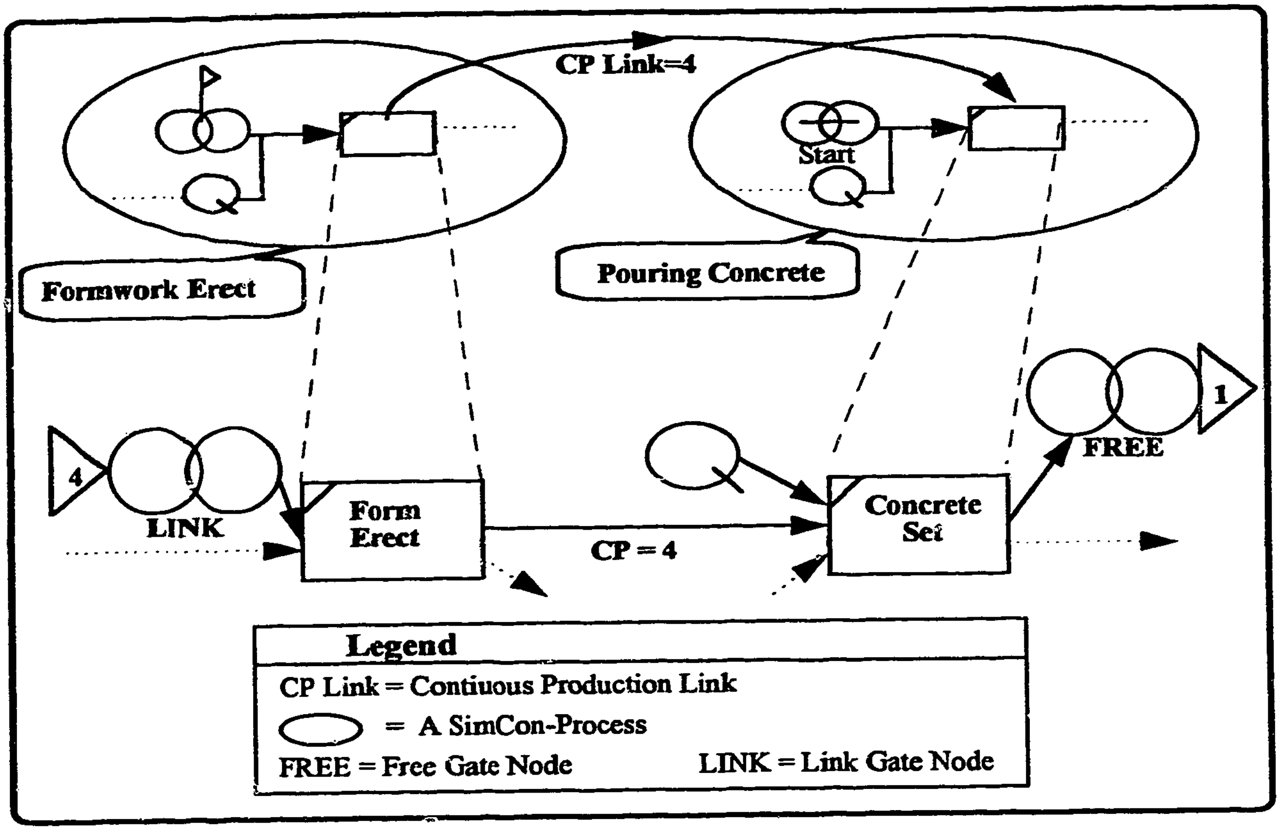


Figure 3.13 ***SimCon Implementation Details of a Continuous Production Link Showing a Link Gate Node and a Free Gate Node***

3.3.2.3 SimCon TRACK Node Implementation

The types of data which need to be collected to support a project planning and control system include data for describing and modeling the system, data measuring actual performance of the system, and data describing the alternatives to be evaluated (Pritsker, et. al., 1989). A Track Variable (TRACK) node is used to assign actual values to variables defined in simulation processes and to signal start and finish of processes for statistical output requirements. Statistics can be collected on three different types of variables at the TRACK node. The first type is the arrival time of entities (i.e., schedule time of events in the system) to the TRACK node. The second type is the scheduled production estimate as determined by arriving entities to the TRACK node. And the third type is scheduled resource-hours which is automatically calculated from the allocated resources.

A TRACK node is modelled, as shown in Figure 3.14a, in two circles format with a line connecting the center of both circles. Four user-defined attributes, TRACK-Stat, TRACK-Var, TRACK-Link, and TRACK-Name are available for every TRACK node, as shown in Figure 3.14b. The TRACK-Stat parameter determines the statistic type to collect information on. It can be *process start time*, *process finish time*, or *process production*. For example, a formwork erection process can have three TRACK nodes; one node to collect statistics on start of process, one node to collect statistics on finish of process, and one node to collect statistics on scheduled formwork production. The TRACK-Var parameter is used by simulation modellers to prescribe values to defined variables. These variables can be used for production control, activity duration, as a routing condition, and in program user-inserts (i.e., hard coded program inserted into a simulation model for specific calculations and modeling). The TRACK-Var parameter is directed at experienced simulation analyst to control special attributes and entities as they traverse through the system. The TRACK-Link and TRACK-Name parameters are used in conjunction with each other to determine the production required (i.e., TRACK-Link) from the predecessor process (i.e., TRACK-Name) to initialize the start of the current process.

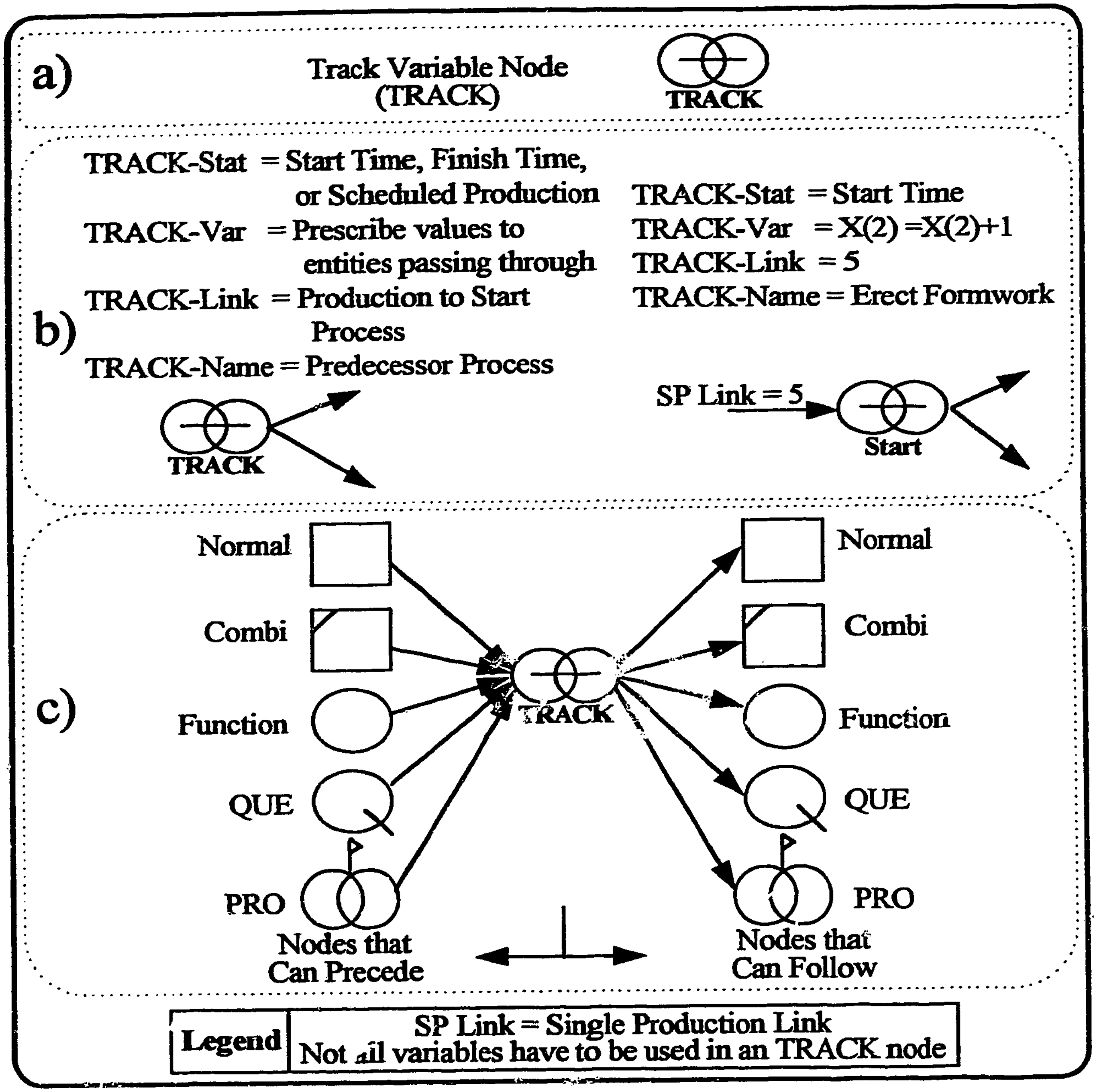


Figure 3.14 *Entity Processing in The Track Variable Node; a) Graphical Symbol of a Track Variable Node; b) User-Defined TRACK-Statistics, TRACK-Variable, and TRACK-Link and TRACK-Name; c) Linking Syntax for the Track Variable Node.*

The main uses of a Track node are to signify the start and finish of processes, capture statistics, and re-initialize variables between processes. Re-initializing of variables is sometimes required when a PRO-node between processes is used to control the number of locations completed. For example, a PRO-node between processes can be used to represent the completed floors in construction of a building or the completed sections in a paving operation..

Figure 3.15 shows a Track node and a single production link representation in SimCon. A single production link of 5 means that after five entities pass through the PRO node in the core formwork process then the core rebar process can start. A Track node in Figure 3.15 is used to represent the start of the process and to assign various values to process variables. The scheduled production of the core rebar process is assigned an X(2) variable and the placing of rebar duration is assigned an X(3) variable. The definition of activity durations and production requirements as variables provides a mechanism to update schedule information without going into the simulation model during the progress reporting phase.

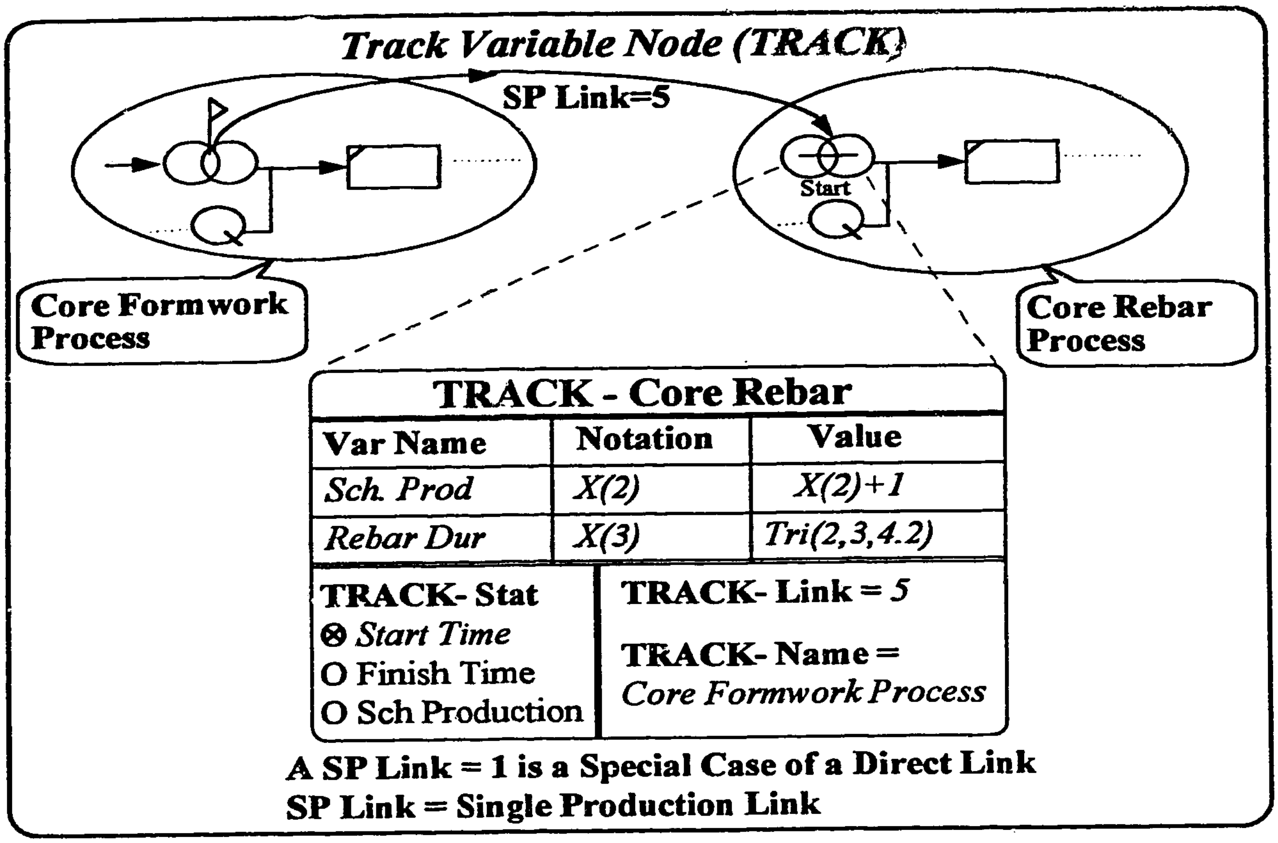


Figure 3.15 Implementation Details of the Track Variable Node in SimCon

3.3.3 Modeling Procedure & Formulation

Models are used to describe systems by symbolizing, designing, and analyzing systems. A simulation network model is used to describe information flow and decision making (i.e., entities). As an entity leaves a node, it is routed to one or more nodes and continuous to move through the network until it is terminated. Attribute values and specific global variables that are carried by entities can be changed as desired in specific simulation nodes. The procedure of modeling a given construction process as noted by Halpin and Woodhead (1976) involves four basic steps:

Flow Unit Identification: System resource flow units should be identified by a modeller for each process. Flow units can be machines, labor, materials, locations, or any other information. This is a very important step since it dictates the level of details incorporated in a model.

Flow Unit Cycles: A modeller should develop the cycle through which each entity passes. This also involves determining the full range of possible states (i.e., active and passive) that can be associated with each entity. In other words, active as well as idle states of a resource should be considered. A typical process that involves multiple cycles is a masonry operation. A highly skilled mason whose output resembles the process production is supported by unskilled laborers who assist the mason by supplying bricks, mixing mortar, and supplying mortar. In this example, entities are defined as the masons, the laborers, and the brick pallets.

Integration of Flow Unit Cycles: Every process can be composed of multiple flow unit cycles. The objective of integrating the separate cycles of the masonry operation above will be to minimize the idle time of both the skilled mason and unskilled laborers and at the same time at a maximum production.

Flow Unit Initialization: This involves determining the number and location of each entity in the simulation model in order to determine system performance.

For detailed procedures on building simulation process models as described above refer to Halpin and Woodhead (1976). In addition to the above procedure for a modeling a simulation process, a SimCon-process includes the following:

Location Identification Center: Every process can be linked to its own location breakdown center for tracking and control of the various processes. The objectives of a location breakdown center include hierarchical organization of information, allocation of resources, and progress reporting by exception.

Sequential Links Between Process: The sequential link between many construction processes is not of a 'finish to start' relationship and especially in cyclic processes. The continuous production link and single production link are used to link the various SimCon-processes together in the overall project model.

Statistical requirements: This involves determining the type and location of TRACK nodes for statistical requirements. For example, statistics might be required on the start time and finish time of the masonry operation. Similarly, a modeller might require statistics on production achieved at periodical time intervals.

The case study in Chapter 5 provides a set of SimCon-process models that apply the above concepts.

3.3.4 Analysis of Simulation Output Data

AbouRizk and Halpin (1990) state that for simulation output data to be fruitful, "*the simulator should ensure (1) proper input in the form of statistical models for work-task durations, proper allocation of resources in the system, stopping rules for ending the simulation, etc.; (2) proper analysis of the output; and (3) validation and verification of the model.*" Proper input analysis is assumed to be performed in this thesis (i.e., task durations and allocated resources were retrieved from PCL's historical database) and focus is directed at simulation experimentation and output analysis. One simulation run is sufficient in deterministic simulation models. A number of runs are required in a stochastic simulation model, however, different output can be produced with independent random seeds. Therefore, it is important that a simulator makes a number of runs with independent seeds for the random-number-generating streams to ensure that the situation is modelled and analyzed correctly.

In many cases, a simulator might be interested in statistics about a specific construction operation. Any quantile or probability of exceeding or not exceeding a given threshold value can be useful in understanding the risks involved in a construction project. For example, the 90^{th} percentile has 90% of the simulation results below that observation. A further practical analysis that is important in the decision making process is knowing the probability of exceeding a specific production or a specific completion time. The sample mean, sample variance, quantile points, and confidence intervals from simulation results can be calculated as shown in Appendix C.

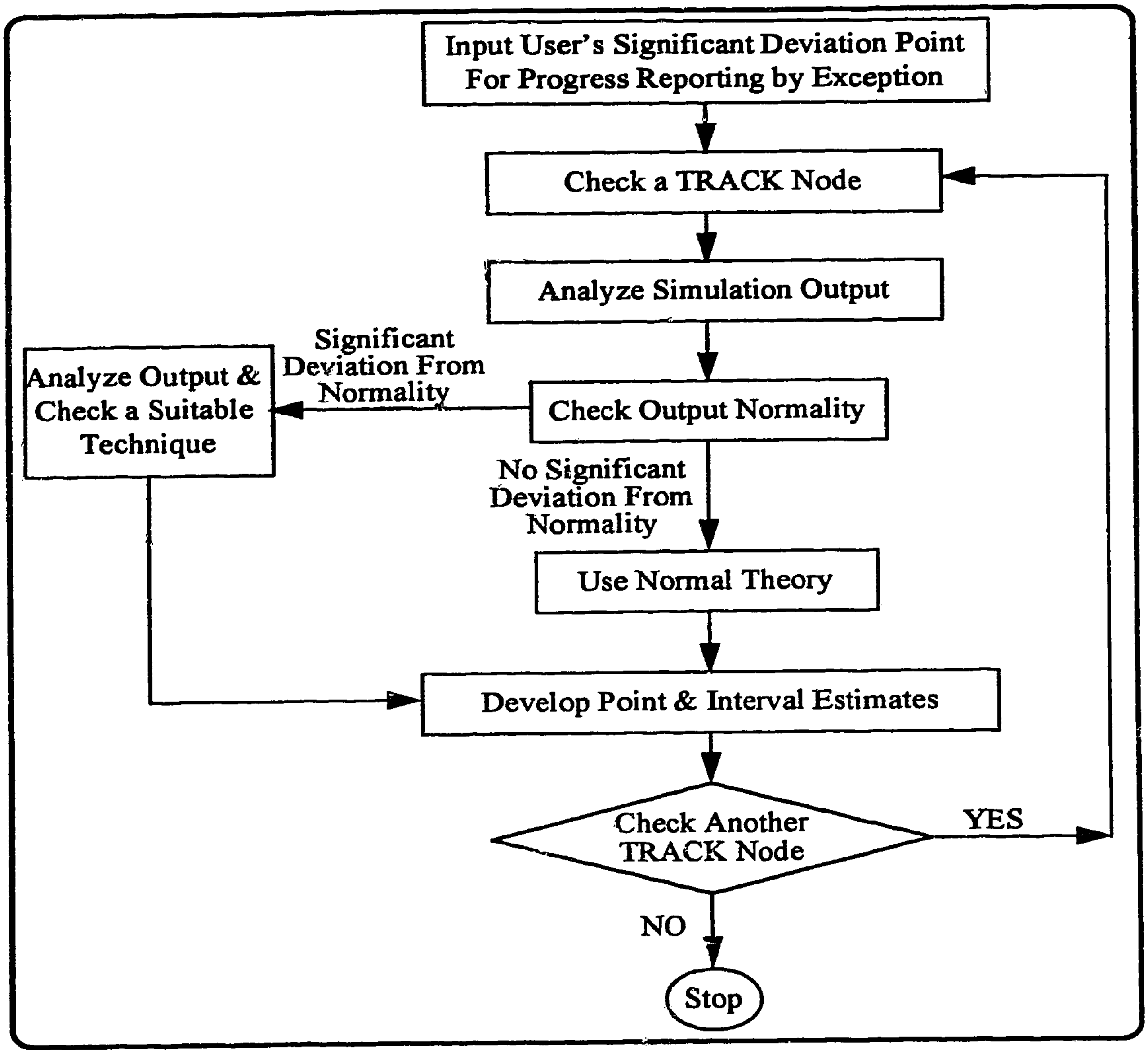


Figure 3.16 Steps Followed in Developing Output Model From Simulation Experiment in SimCon

The steps followed in output modeling in SimCon are shown in the flowchart given in Figure 3.16. In addition to estimating the mean and variance from output analysis a modeller is often interested in other statistics. The first step in output modeling in SimCon is to identify the user's significant deviation point for progress reporting by exception (i.e., identifying the expected risk). This means that a certain percentile or estimate can be required by a user below which or above which a significant deviation is considered. The user's significant deviation point can be any percentile value. For example, a value equal to the 80^{th} percentile can be used to calculate from the simulation results the 80% of the observations. Similarly, a value equal to the mean can be used to calculate from the simulation results the mean value of the observations.

The second step in output modeling, as shown in Figure 3.16, is to collect simulation output data on each TRACK node. The third step requires analysis of output data. Analysis of results from a stochastic simulation model has to consider whether or not normal distribution theory can be applied to the analysis. If the test for normality is successful (i.e., no significant deviation is found from normality) then the normal distribution of the concerned parameter becomes the basis for variance analysis. Normal output distribution were only encountered in the models in this thesis, however, Welch (1983) provides an extensive treatment of output analysis. AbouRizk and Halpin (1990) state that analysis of output parameters that deviate significantly from normality have not been encountered in simulation of construction processes based on experience with a number of MicroCYCLONE models developed over many years. Therefore, analysis of data in this thesis is considered for normally distributed output data.

The last step in output modeling, as shown in Figure 3.16, is to estimate the quantile point required in the first step. The normal theory can be used to construct the confidence interval around the single percentile and the mean if the output data are normally distributed. Percentile points and confidence intervals are calculated from a normal distribution as shown in Appendix C. The qth quantile point of the random variable X is defined as X_q equal to the minimum value x such that $F(x) \geq q$. A quantile point estimate X_q can be calculated from the mean and standard deviation. The estimate X_q is calculated by :

$$X_q = \bar{x} + Z_q S \qquad (3.1)$$

where $\bar{x}$ = mean

Z = critical value derived from standard normal distribution at the specified cutoff value q (found in statistical tables)

S = Maximum likelihood estimator of the sample standard deviation

A confidence interval around the estimator X_q as given by Wilson 1984 :

$$(\bar{x} + Z_q S) - Z_{(1-\alpha/2)}\left(\sqrt{(1+\frac{Z_q^2}{2})}\right)\frac{S}{\sqrt{n}} \leq \mu \leq \bar{x} + Z_q S) + Z_{(1-\alpha/2)}\left(\sqrt{(1+\frac{Z_q^2}{2})}\right)\frac{S}{\sqrt{n}} \qquad (3.2)$$

It should be stated that the assumption in the above equations is that the underlying distribution is normally distributed.

Output Modeling Example: The user might be interested in controlling scheduled production of formwork on a specific data date. The user's significant deviation point for progress reporting by exception is 25th percentile (low) and 75th percentile (high). Output data from the simulation model are generated and analyzed. If the test for normality is successful, the normal distribution summarizes the output results generated from a simulation model. The normal distribution for the scheduled production of formwork then becomes the basis for variance analysis. Following that the 25th and 75th percentile are calculated from the normal distribution. Project control phase in the project compares actual production of formwork to the percentile values. If production is below the 25th percentile then the process is identified with a '-ve flag' for a corrective action. If production is above the 75th percentile then the process is identified with a '+ve flag' so that performance can be recorded and lessons learned for future similar tasks. The '0 flag' means that production is in-between the low and high significant deviation points. In a similar technique the mean and standard deviation for resource utilization can be used to determine the quantile and interval estimates for variance analysis.

3.4 MECHANICS OF SIMCON

3.4.1 Planning Overview Mechanisms in SimCon

This section of Chapter 3 is directed to linking the concepts developed in the earlier sections and formulating the general procedure in controlling a project in SimCon. A project plan in SimCon is developed by constructing SimCon's hierarchy production breakdown structure that consists [illegible] ntrol centers, location breakdown centers, and construction process centers as shown in Figure 3.1.

Project control in SimCon, similar to current scheduling systems, requires comparing actual progress to project budgeted estimates, referred to in many scheduling systems as project baseline. The difference is that in SimCon progress reporting can be implemented by exception.

Information about cost performance and project progress is reported on field reports and tabulated in desired project and labor cost reports. Such reports are used to measure actual achievement and to forecast project performance through the comparison with budgeted plans and other historical records. If on comparison the actual numbers do not conform with the budgeted numbers then the source of the problem must be identified and a corrective action suggested. The cause or source of problem, such as cost overrun or schedule delay, involves determining responsible personnel or environmental causes. Following that, a corrective action can be suggested by implementing different scenarios on a computer model for best outcome.

A project control system should be composed of three tasks:

- collecting actual data (feedback) on a project's cost, schedule, resources, quality, and safety at the "right level" of detail
- analyzing collected data and comparing it to the budgeted cost, planned schedule, planned resource utilization, and quality and safety regulations
- making a decision by considering alternatives, studying probability of outcome (results), and selecting the best alternative

Progress reporting mechanisms in SimCon include production/resource-based reporting from a location breakdown center. Reporting progress by exception is necessary and especially in simulation where numerous interactions of resources can be modelled at the very detailed level. Moreover, durations of activities in many cases are much less than the updating frequency especially for repetitive processes.

Three types of reports are used for implementing the progress reporting by exception mechanism and project control in SimCon. These are: 1) production-based reports; 2) resource-based reports; and 3) productivity-based reports. A schedule plan in SimCon identifies the start and finish dates of processes and required resources. Moreover, it displays the planned production during construction. Production-based reporting can be implemented in simulation modeling to facilitate updating a simulation model and project schedule from quantity worksheets (i.e., field reports that show actual production to date). Resource-based reports track resources' performance by comparing actual hours spent to scheduled hours. Resource performance can be evaluated for the entire project up to a specific construction date. If performance is not satisfactory then a detailed analysis can be performed at the process level. Productivity-based reports are generated from production-based and resource-based reports. Productivity analysis can be performed from resource man-hours and budgeted production to track performance of labor crews in specific tasks. Productivity reports identify performance of individual processes by comparing estimated productivity to actual productivity.

3.4.1.1 Production-Based Planning

Production at the process level can be generated from a cyclic activity or a non cyclic activity. Production represents a specific output that is modelled in repetitive processes by the continuous cycling of specific tasks. In a repetitive process, production achieved to date is transformed automatically using SimCon's production counter into a usable simulation parameter to update progress achieved. Reporting on production achieved in a specific process is used to update a schedule in SimCon. The production counter property, PRO-Ratio, is used to transfer production into a simulation parameter.

In non repetitive processes a production counter node can be used with a PRO-Ratio value equal to one. A number of techniques can be used to estimate the remaining duration of processes. The generalized progress measurement system as shown in Table 3.1 and suggested by Moselhi (1993) can be used in SimCon to report progress on a non repetitive process. For example, for short duration and low cost activity, it is suggested that a zero-one hundred percent rule be used. That is the activity is zero percent complete until 'hand over', at which it becomes one hundred percent complete. This will keep progress reporting to a minimum since an activity is represented by two states: 1) completed; or 2) not completed. Progress reporting is only done once on very short duration activities with low cost to signal that an activity is completed. Production in a non repetitive process can be measured by considering each unit that passes through to be equal to total production and a process duration can be updated by using the remaining duration in scheduling. A project schedule in SimCon can be updated to reflect duration and production changes from a production-based report.

Table 3.1 Generalized Progress Measurement System

Cost	Duration		
	Very Short	**Short**	**Long**
Low	0 - 100	50 - 100	20 - 100
High	0 - 100	20 - 100 30 - 100	20 - 100

The results that are calculated from the original simulation plan are stored as budgeted estimates in SimCon's database. These estimates formulate the basis of a project baseline against which actual progress is compared. Production counters as shown in Figure 3.7 and Figure 3.8 are used to store budgeted production, actual production completed to date, and a ratio that converts actual reported production from field to a standard simulation number. For example, 200 m^3 of concrete can be represented by a production counter to be 80 cycles at 5 locations. The PRO-Ratio in this case is 0.5 (200/400). As shown in Figure 3.17 a slab pouring process is attached to Floor 2-6 LBC which is attached to Superstructure LBC. The PRO node with in the slab pouring process includes information on production ratio (PRO-Ratio =0.5), PRO-Count (80), PRO-Loc (5), and a single production link relationship with dismantling of formwork process (D_Frm - original single production link = 20, remaining single production link = 5). The production and status information of processes are shown on the right side of Figure 3.17. Status of processes is represented by C for completed, I for in-progress, and N for not-started. The unit of measure (UM) of each process represents the production units used for progress reporting in the PRO node. The original production budget represents the original total estimate of production. The planned production represents the scheduled production used for estimating the project. Scheduled production is determined based on the reporting date. Percentile points from mean and standard deviation of scheduled production are calculated as shown in Figure 3.16. Simulation results display estimated production at a specific data date. Actual production is the actual quantities noted on quantity worksheets from field reports. Variance is calculated by subtracting scheduled production from actual production. It is reported as either negative, positive, or zero. Negative variance means that the actual production is less than the lower significant deviation. Positive variance means that the actual production is greater than the higher significant deviation. Zero variance means that the actual production falls in between the lower and higher significant deviation values.

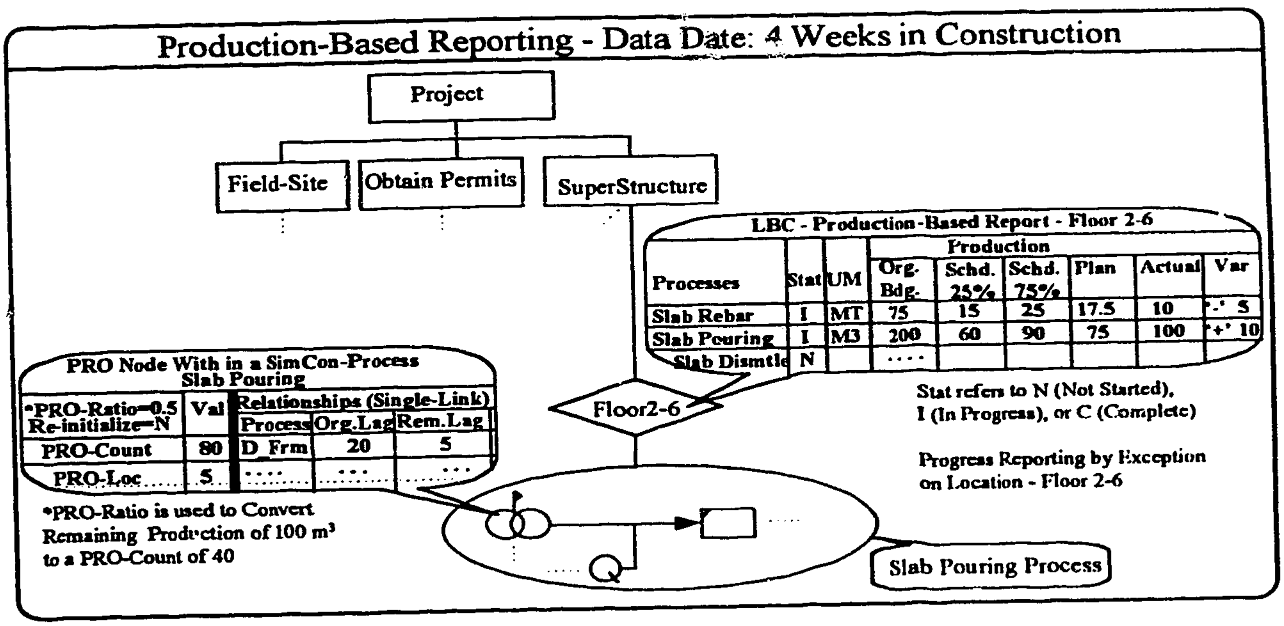


Figure 3.17 Schematic View of Production-Based Reporting in SimCon

3.4.1.2 Resource-Based Planning

Recording and tracking progress in a project is directly affected by the way information is presented to project controllers as described by Sanvido and Paulson (1992) (a controller can be a foreman, superintendent, or project manager). Sanvido developed a conceptual construction process model (CCPM) that enhances information flow, feedback systems, resource supply systems, and improving construction method and planning functions. Hierarchy operation in the field such as superintendent above foreman, and foreman above craftsman provide a project control system as depicted in Figure 3.18. In this process a controller is in charge of the resource that he uses himself. If a resource is shared by multiple areas and processes then a higher level controller is required to be in control of the resource. For example, if a tower crane is allocated to multiple locations and disciplines then a superintendent will control it. A controller must plan and coordinate the work sequence and resources at one level below.

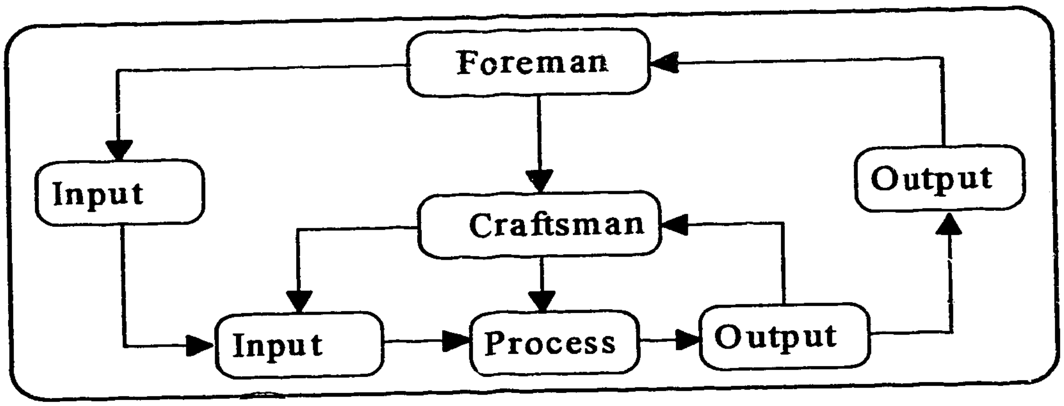


Figure 3.18 ***Schematic View of a Foreman/Craftsman Control System (Source*** **Sanvido & Paulson 1992*)***

SimCon addresses the resource-based planning and progress reporting in a similar methodology as described by Sanvido and Paulson (1992), but the hierarchy operation in the field is implemented in progress reporting. During the project planning phase, resources are allocated to various location breakdown centers. Following that, resources are modelled in a SimCon-process as outlined in flow unit identification in section 3.3.3. Reporting on resource utilization and hour usage is implemented by exception. This means that reporting is implemented on a location breakdown center and if performance is not satisfactory then a detailed analysis can be performed at the process level.

Statistical reports from simulation include percentage idle time and busy time for each resource. Resources can be either of C (contractor crew composition), E (equipment), or S (sub-trade crew composition). Resources are allocated in SimCon's LBC and then implemented in specific process modeling. Since processes are attached to locations and each location has its own resources then resource availability for various processes can be determined. For example, a project consisting of two buildings (locations) can be allocated two cranes (resources) one for each building. These resources can be accessed and shared in specific concrete processes that belong to the location structure. A schematic view of resource evaluation in SimCon is shown in Figure 3.19. Resources are allocated at specific locations as explained in section 3.2.2.

Total budgeted utilization (TBU), as shown in Figure 3.19, is internally calculated by the simulation engine. Scheduled budgeted utilization (SBU) is equal to the planned utilization of a resource up to the data date and is internally calculated by the simulation engine. The equations used in the resource-based report, as shown in Figure 3.19, are as follows:

Resource duration = (End Date) - (Start Date) .... (3.3)

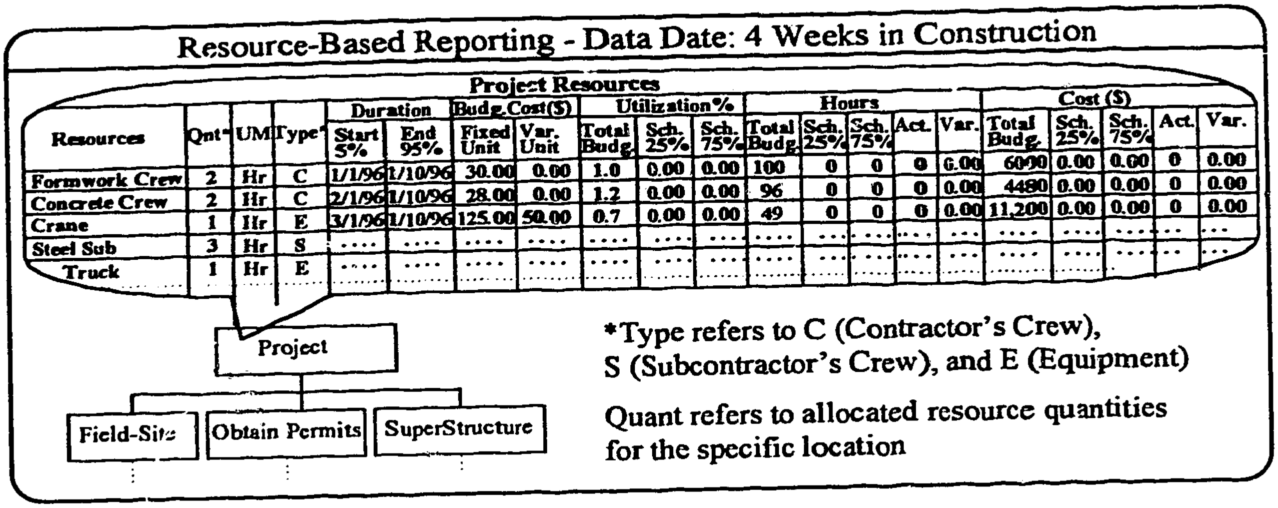
Total Budgeted Utilization = (Time in Use)/(Resource duration) .... (3.4)

Total budgeted hours = (TBU) x (Resource Duration) x (Crew Size) .... (3.5)

Scheduled budgeted hours = (SBU) x [(Data Date)-(Start Date)] x (Crew Size) ...... (3.6)

Total budgeted cost = (Fixed Unit Cost) x Resource Duration x (Crew Size) +
(Variable Unit Cost) x Total Budgeted Hours............................... (3.7)

(Data Date = The date of the last field reporting that was done)



Resources	Qnt*	UM	Type*	Duration		Budg.Cost($)		Utilization%			Hours					Cost ($)				
				Start 5%	End 95%	Fixed Unit	Var. Unit	Total Budg.	Sch. 25%	Sch. 75%	Total Budg.	Sch. 25%	Sch. 75%	Act.	Var.	Total Budg.	Sch. 25%	Sch. 75%	Act.	Var.
Formwork Crew	2	Hr	C	1/1/96	1/10/96	30.00	0.00	1.0	0.00	0.00	100	0	0	0	6.00	6090	0.00	0.00	0	0.00
Concrete Crew	2	Hr	C	2/1/96	1/10/96	28.00	0.00	1.2	0.00	0.00	96	0	0	0	0.00	4480	0.00	0.00	0	0.00
Crane	1	Hr	E	3/1/96	1/10/96	125.00	50.00	0.7	0.00	0.00	49	0	0	0	0.00	11,200	0.00	0.00	0	0.00
Steel Sub	3	Hr	S	....	....	....	....	....	....	....	....	...	...	...	...	....	....	....	..	...
Truck	1	Hr	E	....	....	....	....	....	....	....	....	...	...	...	...	....	....	....	..	...

Figure 3.19 Schematic View of Resource-Based Progress Reporting in SimCon

3.4.2 Progress Reporting Mechanisms in SimCon With a Sample Illustration From Construction

There are three main categories that are important to control in a project: 1) actual production compared to scheduled production, 2) actual resource utilization compared to scheduled resource hours, and 3) actual productivity compared to estimated productivity. The three items are directly related. Variance analysis of the three items helps to track project schedule and productivity of resources.

Tracking and control of schedule and cost progress are essential functions for the successful delivery of construction projects. Traditionally, progress reporting on construction schedules is tracked through some form of time-based reporting. Activities in a CPM schedule are allocated estimated quantities and man-hours of various resources. Some form of earned value analysis is used to determine percent complete in activities and update a schedule. This is basically inherent in the nature of defining activities in traditional methods such as CPM. In many cases the allocation of quantities to activities is static (i.e., not related directly to the project schedule) and does not show the dynamic interactions of resources and entities (i.e., any transaction type between schedule nodes). Controlling time and physical progress (i.e., production) in this manner, as independent parameters, requires more control time and does not efficiently represent the actual construction.

In repetitive modeling of activities, most physical progress can be represented by cyclic tasks. Physical progress and time correlation are more directly related and more closely resemble the real world. Production achieved through the reporting of physical progress can be directly represented in repetitive processes and hence project schedule and process duration can be more accurately updated in a lesser time.

3.4.2.1 Production-Based Progress Reporting

Production-based progress reporting is implemented by updating and controlling a project schedule from quantity worksheets as shown in Table 3.2. Status of a SimCon-process is reported as either in-progress (I), not-started (N), or completed (C). The status of a SimCon-process is used to control entity flow in processes. If a SimCon-process has a status of 'C' then entities skip it to the next process, where as, if a SimCon-process has a status of 'N' or 'I' then entities flow through. The following actions are considered in progress reporting on a SimCon-process:

- For a repetitive process with a PRO-Count >1 and occurring on one location (i.e., a cyclic process that is not repeated at different locations, PRO-Count=1 for the PRO node between processes), progress on production can be reported on a PRO-count by changing the actual production to date. A typical repetitive process having the above condition is erecting formwork for circular columns on a building main floor level where upper floors have rectangular columns. Reporting on other process variables can be done from the process level.

- For repetitive processes having a PRO-count > 1 and occurring on more than one location (i.e., a cyclic process that is repeated at various locations, PRO-count > 1 for PRO node between processes), progress on production can be reported on a PRO-count with in processes by changing the actual production to date. Progress on a PRO-count between processes is reported by changing the actual locations completed. A typical repetitive process that meets the above conditions is erecting of slab formwork on typical floors of a high rise building. Changing other process variables can be done from the process level.

- For non repetitive processes having a PRO-count = 1 and occurring on one location (i.e., a non-cyclic process that occurs at only one location, PRO-Count=1 for the PRO node between processes), there are two ways for progress reporting in SimCon: 1) progress on a PRO-node is reported as either completed or not completed; or 2) progress can be reported by using the generalized progress measurement system as shown in Table 3.1. A typical non repetitive process is the process of installing an electric generator in the basement of a building.

- For non repetitive processes having a PRO-count = 1 and that occurs on more than one location (i.e., a non-cyclic process that occurs at more than one location, PRO-count >1 for the PRO node between processes), progress on the PRO-node between processes is reported as number of locations completed. Progress in each location can be reported in two ways: 1) progress on a PRO-node is reported as either completed or not completed; or 2); progress on a each location can be reported by using the generalized progress measurement system as shown in Table 3.1. A typical non repetitive process with the above conditions is the process of installing a mechanical equipment on each floor of a building.

Technically, reporting by exception in SimCon refers to updating production estimates on PRO nodes from a location center without updating other process variables. In SimCon terminology, only one PRO node is allowed in each SimCon-process.

Table 3.2 Quantity Worksheet From Field for Production Reporting

Project Name - Data Date as 4 Weeks in Construction									
Cost Code	Description	Locations		Budget Units	UM	Units in Place		%	Projected Final
		Est	Comp			Last Est	New Est	Comp	Units
033110	Columns Erect Formwork	10	3	771	M2	0	235	30.5	771
034400	Slab/Beams Pour Concrete	10	2	1,264	M3	0	258	20.4	1264
037600	Slab Rebar	10	2	65	MT	0	12	18.5	65
037100	Cores Rebar	5	1	15	MT	0	3	20.0	15
033430	Slab Dismantle Formwork	10	0	826	M2	0	0	0.0	826

Table 3.2 shows a typical quantity work sheet that can be used for progress reporting in SimCon. Production in a SimCon-process is updated by changing dynamic variables stored in a PRO node. Production units in place are deterministic values, as

shown in Table 3.2, and report on actual production completed in a specific periodical interval. The number of estimated locations (Est) shows the number of repetitions of each process. The number of completed locations (Comp) shows the number of locations with completed construction. Budgeted units, as shown in Table 3.2, is determined from design drawing and is a deterministic value. Last estimated production (Last Est) shows the reported production from the previous update. New estimated production (New Est) shows the actual production completed this period. Projected final units at completion shows the new budgeted estimate of production at completion of a specific process.

Table 3.3 shows a production-based progress report for schedule and production control that partly demonstrates the progress reporting by exception mechanism. Starting from the left side of Table 3.3, the PRO-Ratio and PRO-Loc for each SimCon-process are displayed under the process name. The PRO-Ratio is used to convert actual physical production into a simulation parameter. The PRO-Loc is used to represent the number of typical repetitions between processes (i.e., the number of locations that a process occurs on). Status of a process (Stat) refers to I (in-progress), C (completed), or N (not started). The mean and standard deviation for the start and finish time are determined by the simulation engine based on a number of runs. The output is normally distributed in most cases as discussed earlier. The unit of measure (UM) is based on the production type of each SimCon-process. The unit cost (UC) is based on the cost of producing one unit of production. The duration of processes is determined from the mean, standard deviation, number of runs, and user-defined quantile points. The original budgeted production (O_Bdg) represent the estimated production before the project starts. The scheduled production (Sched) represents the estimated production as expected up to the current progress data date. The planned budgeted production (Plan) represents the estimated production used in estimating. The mean and standard deviation from the number of runs performed are also used to determine the user-defined quantile points. The data date is the date at which progress reporting is performed. The actual production (A_Prd) represents the actual accumulated production to date on a construction site. The variance production (V_Prd) is equal to Sched (low significance) and Sched (high significance) subtracted from Act_Prd. Using similar notations the costs are calculated by multiplying the respective production by the unit cost (UC).

Table 3.3 ***Production-Based Progress Report in SimCon - (Schedule Control)***

Data Date : 4 Weeks in Construction																			
Processes (PRO-Ratio,PRO-Loc)	Stat	Start (Hrs) Finish (Hrs)				UM	UC	Production						Cost $					
		Start 5%	Start 95%	End 5%	End 95%			OBdg	Sched 50%	Sched 95%	Plan	A_Prd	V_Prd	O_Bdg	Sh_Cst 50%	Sh_Cst 95%	Plan	A_Cst	V_Cst
FLOOR 2-6 LOCATION																			
Column Form (19.275, 10)	I	147	157	441	453	M2	0.75	771	193	193	193	154	'-'39	578	145	145	145	116	'-'29
Slab Pouring (15.8, 10)	I	187	197	489	503	M3	93	1,264	204	329	230	250	'0'	117,552	18,972	30,597	21,390	23,250	'0'
Slab Rebar (1.625, 10)	I	178	188	486	500	MT	220	65	8.64	10.4	9	12	'+'1.6	14,300	1,900	2,277	1,980	2,640	'+'363
Core Rebar (0.75, 5)	I	152	162	460	474	MT	220	15	2.14	2.14	2.14	3	'+'.85	3,300	471	471	471	660	'+'189
Slab Dsmn Frm (82.6, 10)	N	214	224	517	531	M2	0	826	0	0	0	0	'0'	0	0	0	0	0	0

The Slab Pouring process as shown on the second row of Table 3.3 states the following: The location breakdown center of the Slab Pouring process is Floor 2-6. The PRO-Ratio is equal to 15.8. The process models 10 repetitions as identified by the PRO-Loc parameter. The process is currently in progress as shown in the second column by 'I'. The estimated start and finish of the Slab Pouring process is determined as a Start (low percentile), Start (high percentile), End (low percentile), and End (high percentile). The start of the process has a 5th and 95th percentile equal to 187 and 197 hours, respectively. The end of the process has a 5th and 95th percentile equal to 489 and 503 hours, respectively. Theses percentiles are calculated from the mean and standard deviation of process estimates. Calendar day scheduling is not implemented in SimCon at this stage. The unit of measure for the Slab Pouring erection process is m^3. The unit cost of producing 1 m^3 of concrete is equal to \$93.00. The original budgeted production for the whole process is equal to 1264 m^3. The low significant scheduled production of the Slab Pouring process is equal to 204 M^3. The high significant scheduled production is equal to 329 M^3. These values are calculated from the project baseline schedule and determine the expected production as of the stated data date. Data date is the date at which production is reported and consequently the date at which scheduled production needs to be determined. The planned production as determined from an actual estimate is equal to 230 M^3. The actual production to date is equal to 250 M^3. The production variance is calculated as the actual production minus the scheduled production. There are three conditions to determine the variance: 1) actual production is greater than the high significant scheduled production; 2) actual production is less than the low significant scheduled production; 3) actual production is in-between the high and low significant scheduled production. The variance in this case is equal '0'. Scheduled production calculation is schematically shown in Figure 3.20a. Scheduled production is calculated by referring to the data date (field reporting date) as shown in Figure 3.20a. In many cases, more analysis may be required to determine the confidence interval for the scheduled production and to evaluate the variance between the actual and planned production. Figure 3.20b shows arbitrary quantile points for the scheduled production on a fixed data date. Such a plot provides the planner with a confidence interval against which actual production can be checked.

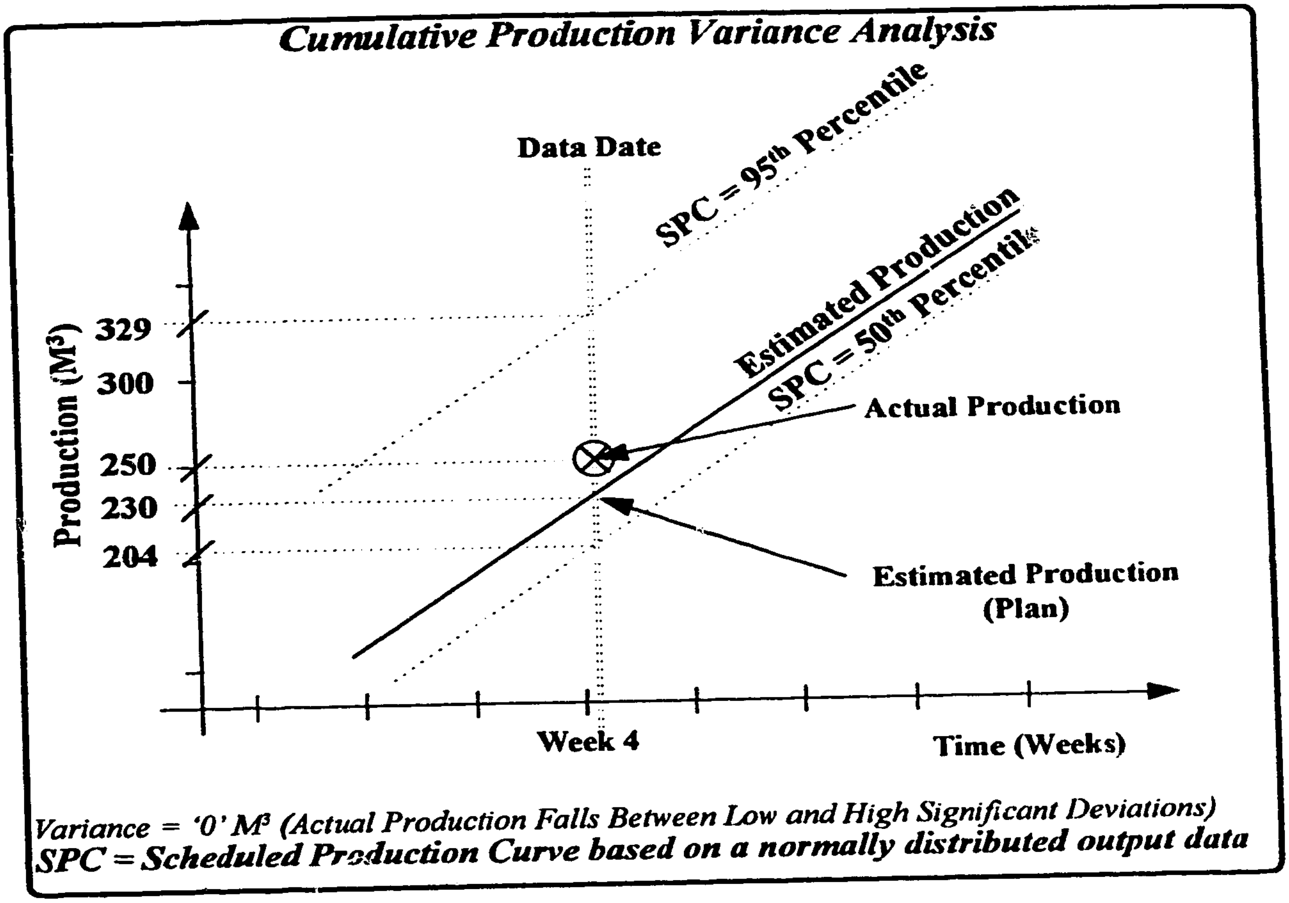


Figure 3.20a Schematic View of Variance Analysis Calculation in SimCon

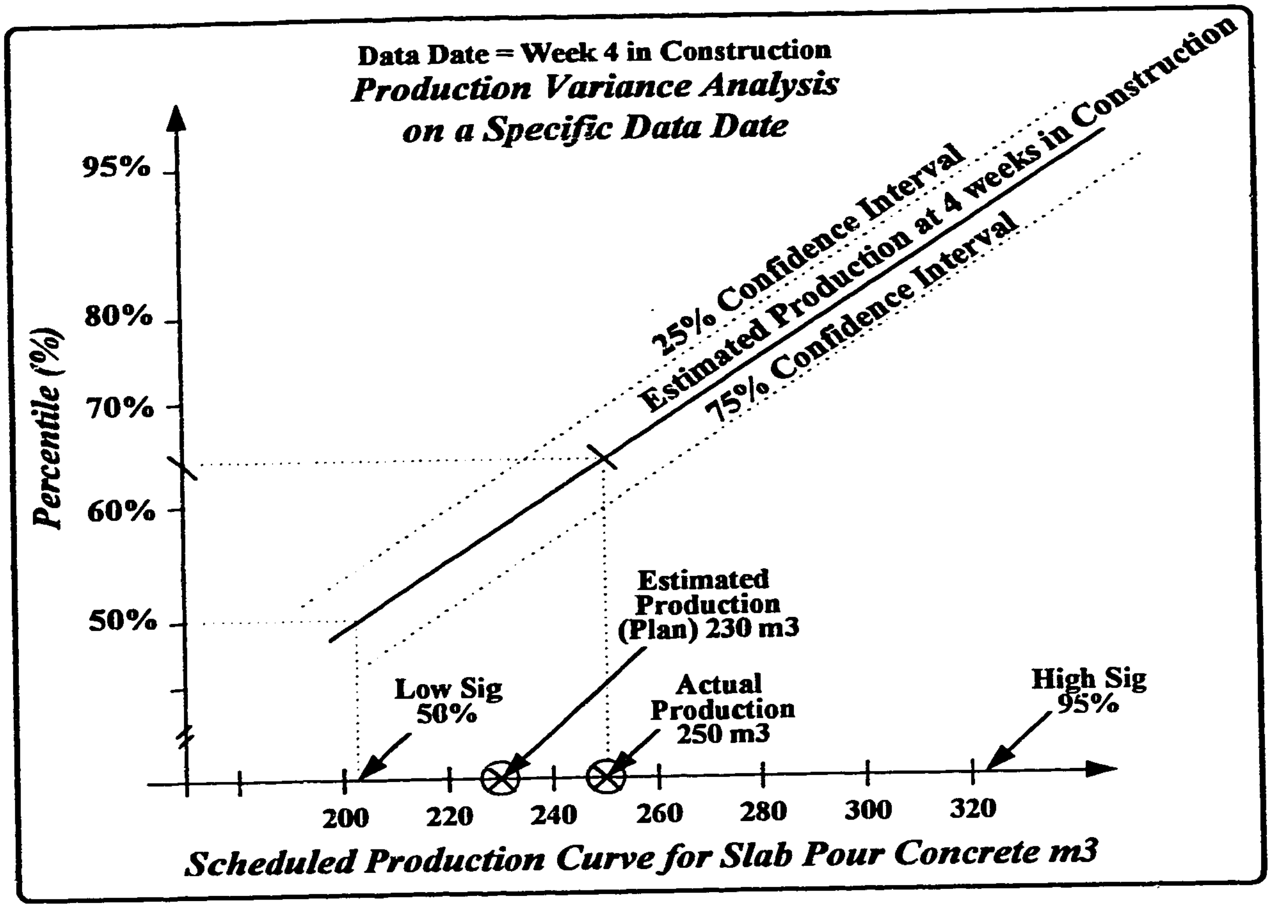


Figure 3.20b Arbitrary Quantile Points for Estimated Scheduled Production in SimCon

The cost of production of Slab Pouring process, as shown in Table 3.3, does not include resource cost. The original budgeted cost is equal to the unit cost times the budged production and is equal to $117,552.00 ($93 x 1264). The low significant (50%) scheduled cost is equal to scheduled production 50th quantile times unit cost and is equal $18,972 ($93 x 204). The high significant (95%) scheduled cost is equal to scheduled production at the 95th quantile times the unit cost and is equal $ 30,597 ($93 x 329). Actual cost is equal to cost of producing the actual production without the resource cost. The actual cost of Slab Pouring process is equal to $23,250 ($93 x 250). Cost variance is equal to '0'. This means that actual cost falls in-between than the lower and upper significant deviations for cost control.

For non repetitive processes such as slab dismantle formwork the generalized progress measurement system, as shown in Table 3.1, can be used to report progress. Slab dismantle formwork process is considered of a low cost and very short duration activity, therefore, a zero-hundred percent can be used to report progress. Hence the activity is zero percent complete until it is completed.

Production-based reports as shown in Table 3.3 have a number of advantages. Most important is progress reporting by exception and the ability to update the project schedule from quantity worksheets. A project schedule using a simulation system can include numerous nodes and activity relationships and hence require more time during progress reporting. Progress reporting by exception as shown in Table 3.3 is implemented on production basis only and does not include other details from a simulation model. Production-based reports make use of currently available quantity worksheets for field reporting and provide enough information for schedule variance analysis. Problems can be identified from variance analysis and if a more detailed analysis is needed then additional data might be required when examining a SimCon-process directly. Variance analysis is implemented on significant deviation basis. This means that a flag identifying deviation from plan is only shown if very high or very low deviations occurs, relative to user-defined quantile points.

3.4.2.2 Resource-Based Progress Reporting

Resource-based reports are updated from weekly time cards. Total resource-hours, as collected from time cards, can be used to summarize resource-hours spent on processes for general resource management and productivity control as shown in Table 3.4.

Table 3.4 Total Hours From Weekly Time Card Reports For Crane Resource

Total Hours From Weekly Time Card Reports									
Resource Type: E	Resource ID: 50100	Resource Name:			Crane				
Processes	UM	**Work Day Hours**							
		Sun	Mon	Tue	Wed	Thr	Fri	Sat	Total Hours
SUPERSTRUCTURE LOCATION									
Columns Erect Formwork	M2		2	2					4
Slab/Beams Pour Concrete	M3					3	3		6
Slab Rebar	MT				2				2
Cores Rebar	MT				1				1
Slab Dismantle Formwork	M2								
Total Hours			2	2	3	3	3		13
Total Hours To Date:	18 Hours								

Table 3.4 shows a typical weekly time card that can be used for progress reporting in SimCon. Total hours on various processes are entered manually on resource-based reports in SimCon. Time cards are to be completed for laborers, equipment, and subcontractor's resources The left side of Table 3.4 lists the processes that occur in the Superstructure Location. The 'Resource Type = E' states that this time card is for an equipment resource. The 'Resource ID = 50100' is used to distinguish various resources for internal reporting. The 'Resource Name = Crane' states the name of the resource in the time card. Actual hours spent by each resource are updated on a weekly basis as shown in Table 3.4. The accumulated resource-hours for every resource on every type of

process are added up and summarized as shown in the right side of Table 3.4. Chapter 5 includes a detailed case study showing Labor crew time cards and Sub-trade time cards.

Schedule analysis is done to determine which resource is not performing according to plan. Table 3.5 shows a resource-based progress reporting by exception example. Initial progress reporting from a location breakdown center is done on resources to determine if there are any problems. Contrary to production-based reporting (i.e., updating a PRO node from a location breakdown center), actual resource nodes and entities at the SimCon-process level are not updated. An update of information at the process level is only updated from within each SimCon-process.

The results shown in Table 3.5 allow the planner to determine if the project resources are working as scheduled. A variation in an expected resource output can be caused by resource inefficiency or any other type of delay. If a delay is caused by resource inefficiency then it can be noticed by productivity variance analysis as shown in Table 3.6 which is specific to each SimCon-process. A detailed analysis of a resource can be easily done by checking the productivity report as shown in Table 3.6.

Table 3.5 ***Resource-Based Progress Report in SimCon - Resource Control***

Data Date : 4 Weeks in Construction																								
Resources	Q	UM	Typ	Duration (Hrs)		Cost ($)		Utilization			Hours Used						Cost ($)					
				Start 5%	End 95%	Fix_U	Var_U	T_Bdg Mean	Sched 25%	Sched 75%	T_Bd Mean	Sched 25%	Sched 75%	Plan	Act	Var	Tot_Bd Mean	Sched 25%	Sched 75%	Plan	Act	Var
Crane	1	Hr	E	165	203	78.13	42.25	0.34	0	0.597	193	0	58	29	13	'0'	51,247	15,626	18,077	16,851	44,849	'0'
Formwork Crew	1	Hr	L	147	662	26.79	0.00	0.32	0.028	0.672	181	6	70	32	16	'0'	15,190	5,358	5,358	5,358	5,358	'0'
Concrete Crew	1	Hr	L	187	503	23.30	0.00	0.19	0	0.469	108	0	40	20	8	'0'	13,211	4,660	4,660	4,660	4,660	'0'
Steel-Rein-Sub	2	Hr	S	178	500	0.00	32.00	0.51	0.008	0.952	289	2	96	47	20	'0'	8,709	124	6,144	3008	1,280	'0'

The data date for the project shown in Table 3.5 is 200 hours (4 weeks x 5 days a week x 10 hours a day). The crane resource as shown on the first row of Table 3.5 states the following: The quantity (Qnt) of cranes available in the project is equal to 1. The unit of measure (UM) that is used for crane allocation is in hours. The type of resource (Typ) is 'E' and means that the resource is an equipment type.

The mean and standard deviation for the start and finish time are determined by the simulation engine based on a number of runs. The output is normally distributed in most cases as discussed earlier. The unit of measure (UM) is based on the production type of each SimCon-process. The unit cost (UC) is based on the cost of producing one unit of production. The duration of processes is determined from the mean, standard deviation, number of runs, and user-defined quantile points.

Resource duration is determined from the mean and standard deviation of the start and finish of processes (i.e., a process is determined from the allocated resource to it). Any percentile value can be determined from the mean and standard deviation based on having a normally distributed output. Availability of the resources on a construction site can be determined based on user-defined percentile points. For example, the crane resource has a 5^{th} percentile start of work at 165 hours and a 95^{th} percentile end of work at 503 hours. The knowledge of these two quantile points in time enable the planner to ensure that the allocated resources are available for the particular activity at the required time.

Implementing resource utilization in project planning provides a better evaluation for productivity improvement and the study of non-value added tasks. Equipment resources have a fixed unit cost and a variable unit cost. Utilization states the percentage of time that each resource is being used during the length of stay at the project. Actual hours used can be determined from time cards as shown in Table 3.4. Knowing that resources can be involved in more than one activity or process it is almost impossible to track resources' movement on separate activities without a detailed monitoring and analysis. Therefore, the method shown in Table 3.5 provides enough information on resource status to determine whether a more detailed analysis is required.

Further analysis of resources at the detailed level of each SimCon-process requires a more experienced practitioner with simulation terminologies. Making use of information from simulation modeling results include determining statistics in files (average length in queue, average waiting time), regular activity statistics (average & maximum utilization, entity count), average service time, and other resource statistics and histograms. Studying the availability and idleness of entities allows a modeller to further study and analyze each process and the problems under consideration. However, a resource-based report provides enough information to control resources in a project.

Table 3.6 ***Productivity-Based Report in SimCon - Productivity Control***

Data Date : 4 Weeks In Construction															
Processes	UM	Production				Man-Hours				Productivity (Man-Hrs/Unit)					
		O_Bdg	C_Bdg	Period	To Date	O_Bdg	C_Bdg	Period	To Date	O_Bdg	C_Bdg	Period	To Date	Var Index= ((To Date)-(O_Bdg))/ (To Date)	
FLOOR 2-6 LOCATION															
Columns Erect Formwork	M2	771	771	235	235	130	130	10	10	0.169	0.169	0.043	0.043	-2.93	
Slab/Beams Pour Concrete	M3	1,264	1,264	258	258	46.4	46.4	18	18	0.037	0.037	0.070	0.070	0.474	
Slab Rebar	MT	65	65	12	13	205	205	15	15	3.15	3.15	1.250	1.250	-0.152	
Cores Rebar	MT	15	15	3	3	86	86	5	5	0.974	0.974	1.67	1.67	0.417	
Slab Dismantle Formwork	M2	826	826	0	0	70.88	70.88	0	0	0.086	0.086	N/A	N/A	N/A	

Productivity-based report, as shown in Table 3.6, is produced from the production-based and resource-based reports. Production columns include original budget production (O_Bdg), current budgeted production (C_Bdg), this period production (Period), and actual to date production (To Date). The resource-hours columns include original budgeted hours (O_Bdg), current budgeted hours (C_Bdg), this period resource hours (Period), and actual to date resource hours (To Date). Productivity columns is equal to resource hours columns divided by their respective production columns. Productivity evaluation as shown by the column on the right side of Table 3.6 determines variance index which is equal to equation 3.8.

$$Variance\_Index = \frac{((Actual\_to\_Date\_\Pr oductivity) - (Original\_Budgeted\_\Pr oductivity))}{(Actual\_To\_Date\_\Pr oductivity)} \qquad 3.8$$

...

The productivity-based report, as shown in Table 3.6, provides another tool to help study the performance of processes under consideration to determine if a more detailed analysis is required of any process. A positive productivity variance index indicates that the process productivity is not as expected. A negative variance index indicates the opposite, the productivity is better than estimated. Processes can be sorted in increasing order of the variance index to point out processes that need more attention. For example, erection of column formwork process is performing better than the placing rebar slab process (i.e., variance index for column formwork = -2.93, whereas, variance index for placing rebar process is equal to -0.152), although both of them performed better than budgeted. Similarly a positive variance index means that a process is not performing as budgeted.

3.5 THE SIMCON ADVANTAGE & CHAPTER CONCLUSIONS

Progress reporting by exception as demonstrated by the production-based and resource-based reports is aimed at controlling a project from user-defined significant deviation points and at simplifying progress reporting and updating schedules in simulation systems where numerous nodes and interactions are modelled.

There are a number of advantages for using SimCon. The use of simulation for project planning and control provides advanced project management capabilities. The use of progress reporting by exception to overcome updating the detailed activity and process details in simulation minimizes the time spent in progress reporting. The use of simplified linking procedures to model complex logical relationships overcomes the difficulties in planning and progress reporting.

Effective corrective actions in a project depend on knowing "who is responsible for what ?". Tracking of project cost by cost control centers is one way that helps to know the costs and labor productivity associated with every crew. In most cases cost centers are directly related to field organizational structure. For example, a formwork foreman is responsible for all costs and labor productivity under the formwork cost center.

Control of project schedule in many cases is related to completing specific requirements on a specific location by a specific date. The use of the location breakdown center concept provides a way to track project schedule progress by location. SimCon's hierarchical production breakdown structure system offers the following advantages:

- Provides a promising evolution to a considerable future integration of construction management information
- Provides a progress reporting and feedback system within a general system simulation environment
- Overcomes the complexity of recording project progress at the extremely detailed level (i.e., progress reporting by exception)
- Provides project control from user-defined significant deviation quantile points
- Provides a short term detailed planning tool from the process level simulation model
- Provides a mechanism to represent activity relationships in a logical flow diagram based on production and incorporating these relationships in a progress reporting system.
- Provides a modeling system that implements repetitive network schedules and resource utilization and waiting times.
- Links advanced modeling techniques to formalized cost control concepts already in existence

CHAPTER 4

COMPUTER MODELLING PROTOTYPE OF SIMCON

4.1 INTRODUCTION

Pritsker (1986) defines simulation as the mathematical modeling of a system and experimentation with it on a computer. Computer graphics has become an integral part in facilitating communication (Johnson and Poorte 1988). Automating project control systems can greatly facilitate and simplify tracking of resources and construction progress. The potential use of new techniques in the construction industry are subject to three important factors (Kangari and Halpin, 1989). The three basic factors that are usually considered in the feasibility study are 1) need-based feasibility; 2) technological feasibility; and 3) economic feasibility. This chapter addresses the technological feasibility of developing the research concepts presented in Chapter 3.

Many researchers emphasize the importance of using object oriented concepts in simulation modeling (Liu and Ioannou, 1992; Roberts and Heim, 1988; Oloufa, 1993, and many others). A work breakdown structure and other hierarchical concepts enhance project modeling capabilities and are directly associated with object oriented concepts. Linking of simulation models within a hierarchical breakdown structure has also been analyzed by many researchers (Zeigler, 1987; Odeh, 1992; Luna, 1992, and Sawhney, 1994).

Computer-based design methods have traditionally used algorithmic approaches, and typically these algorithms lead to a large number of alternatives and require extensive searching before a satisfactory solution is found. Significant improvements were recently achieved by Knowledge-based system methodology in combining algorithmic and heuristic search methods. Fenves et al. (1990) presented a large exploratory system, IBDE (Integrated Building Design Environment), using blackboard architecture, that can account for the vertical integration of design activities from conceptual floor layout to construction planning. It is used for testing ideas and concepts regarding the development of integrated systems in engineering design.

The task of tracking costs and durations of large and complex projects requires an efficient reporting and feedback mechanism and especially in the risky and competitive industry of construction (Chehayeb, 1995). The needs that are considered for a project control system are the following (Chehayeb and AbouRizk, 1995):

- A production-based system for reporting progress by exception capability to keep data collection and progress reporting to a minimum
- An advanced project control model that represents the dynamic nature of resource interactions and logical sequencing
- A flexible system to maintain a very detailed schedule for short term planning.

This chapter discusses the implementation of the research concepts. The acronym SimCon used in the prototype computer system stands for Simulation-based project Control. SimCon is directed towards demonstration of the feasibility of developing the research concepts. In the remainder of this chapter, general description of the automated system is discussed, starting with internal design of SimCon, followed by implementation from a user perspective, and then future enhancements and a conclusion. The overall structure and mode of operations of SimCon are described and important features are highlighted.

4.2 INTERNAL DESIGN OF SIMCON

SimCon is a prototype program written in Microsoft™ Visual Basic language and runs under the Windows™ (Microsoft, 1993a) operating environment. SimCon utilizes object oriented concepts, event driven programming, relational database management, and a simulation language to portray information to a user as shown in Figure 4.1. The CYCLONE modeling methodology (Halpin, 1973) and the new SimCon elements introduced in Chapter 3 are used to model construction methods and resource interactions. However, SLAM II simulation language is used as the internal engine to run the simulation model. This decision was based on the widespread use of CYCLONE notations in construction and the author's knowledge and accessibility of both softwares.

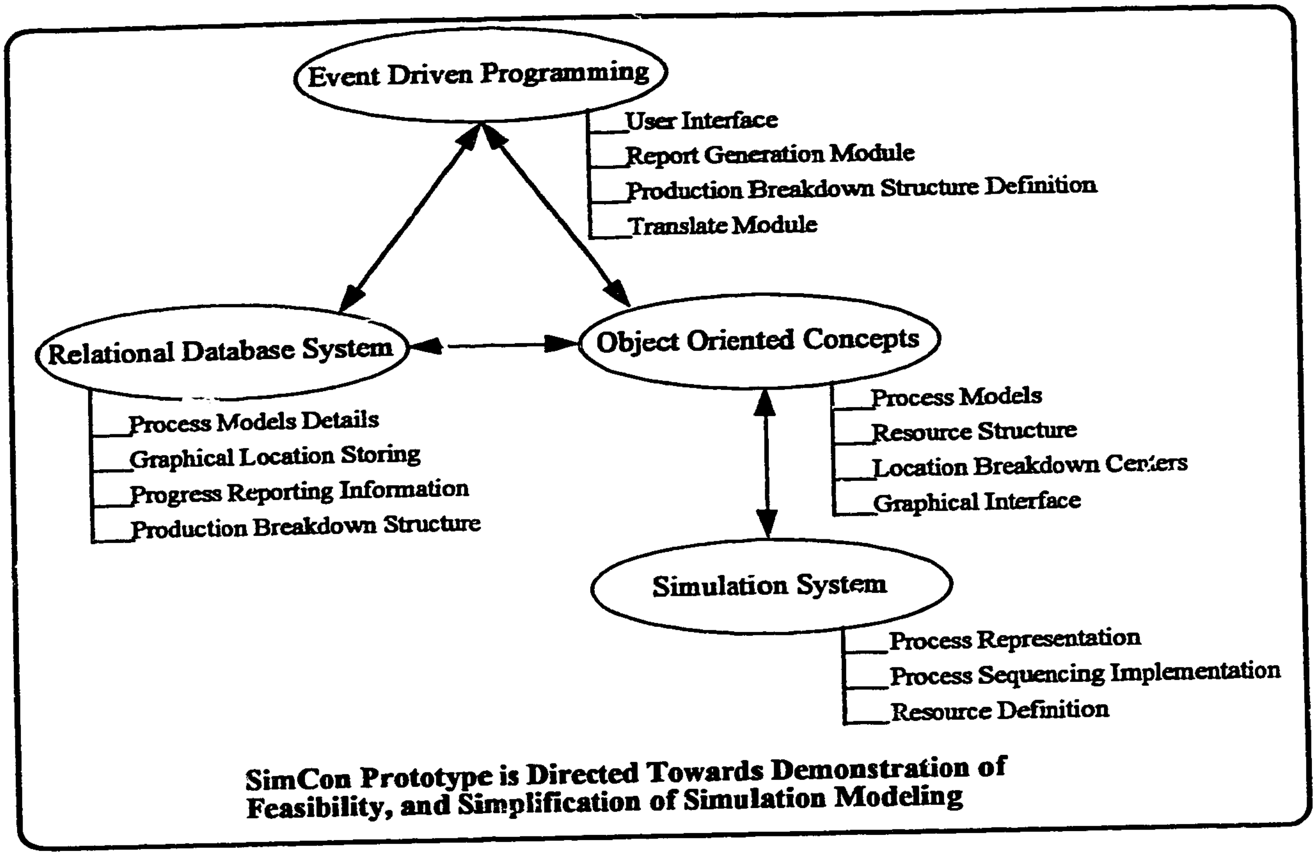


Figure 4.1 *SimCon System Configuration*

Visual C++™ (Microsoft, 1993b) with its object oriented concepts is used to graphically represent and program the simulation process nodes. SLAM II™ simulation language is utilized to simulate and schedule the construction tasks. Visual Basic™ (Microsoft, 1993a) is used as the event-driven programming language. ACCESS™ (Microsoft, 1993c) jet engine from within visual basic is used as the relational database system for storing and manipulating data with-in SimCon. The implementation procedure in the prototype system addresses proving the research concepts and not optimizing the computer system.

The keys to an effective and productive automated computer system is to provide (1) an interactive environment for the user to control the processes, (2) a powerful database that permits the user to extract segments for processing, and (3) effective sub-routines for the analysis and design of simulation processes. More important, in the construction industry accurate and efficient data exchange is vital to improving productivity. SimCon prompts the user for all relevant input data in a highly interactive way.

4.2.1 Object Oriented Features

The object oriented concepts in SimCon are utilized in the process modeling, the location breakdown center and the graphical interface. Process modeling in SimCon is implemented by selecting and linking nodes from a graphical "ToolBox" as shown in Figure 4.2. Process nodes were created as objects in Visual C++ environment and then imported into SimCon. Such objects facilitate the handling of messages, data structure, node linking requirements, and graphical interface. Appendix D-1 shows an example of the C++ code used for property definition code, event definition code, and graphic model code in modeling node objects. Every node object has a specific type and a generic description so that instances of objects can be defined and generated. This mechanism provides the programmer with the means to classify and link similar objects, capture common characteristics, and determine the set of operations and methods that can be applied on them. The attributes or data objects are stored in variables and eventually stored in the relational database to save project information.

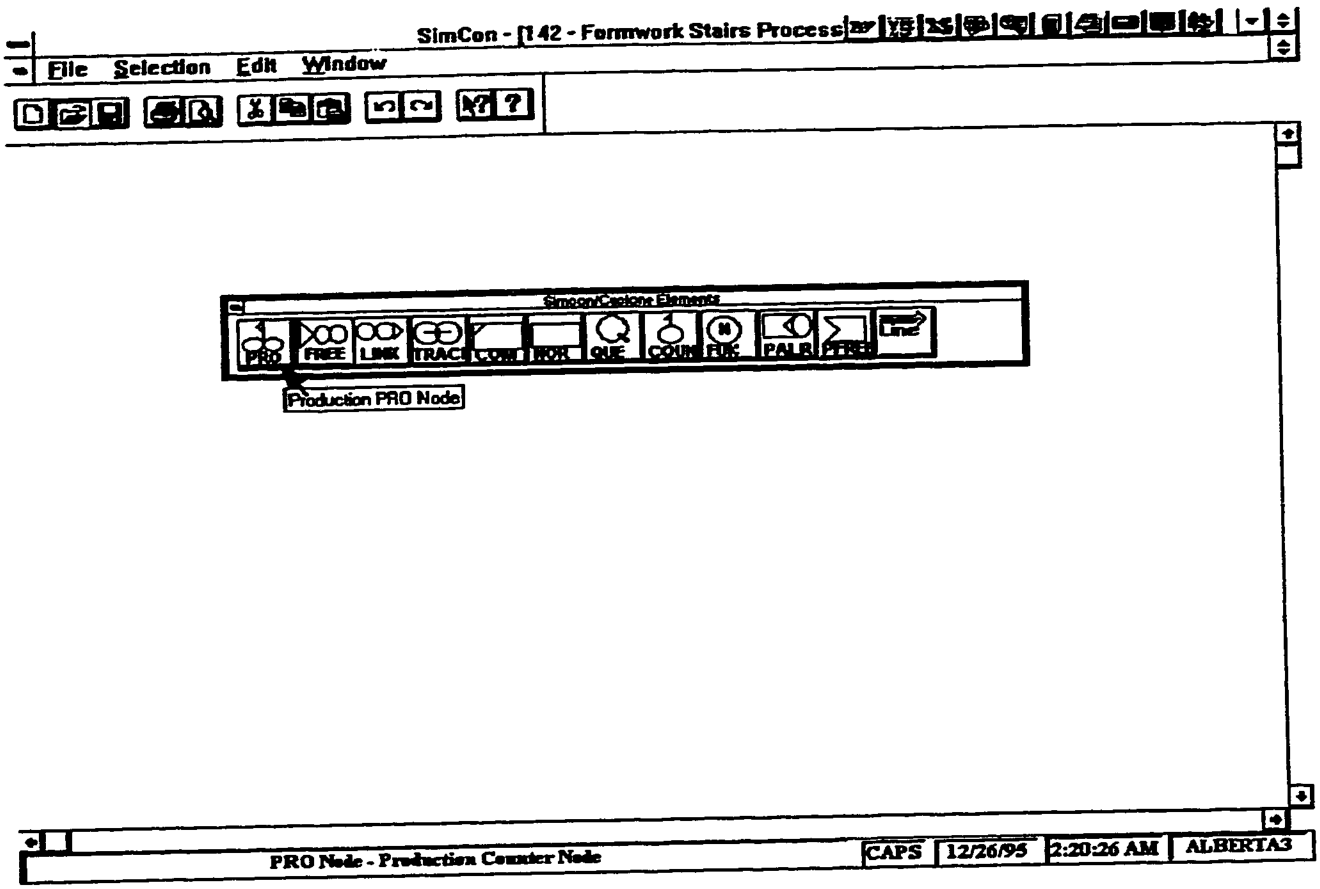


Figure 4.2 A SimCon ToolBox for Process Modelling

Object oriented concepts are used to link each location breakdown center (LBC) to its associated cost center(s) and process(s). The same location can be assigned to different cost centers by creating various instances of the assigned location. Simulation processes are also assigned to various location instances. Linking of various processes in this way makes it possible to summarize information upwards and record progress downward in the hierarchy.

Visual Basic's 'Outline Control' program is used for implementing LBC in SimCon. The object oriented concept is used by instantiating locations at various cost centers. Internally, this is implemented by adding the selected location to the cost centers hierarchy. The property of every location object is carried with its instance. An LBC is defined in SimCon as shown in Figure 4.3. The implementation of an LBC supports a location by location view of a project which in turn would allow for a refined representation of spatial variations in productivity, sequencing and duration (English and Russell, 1995).

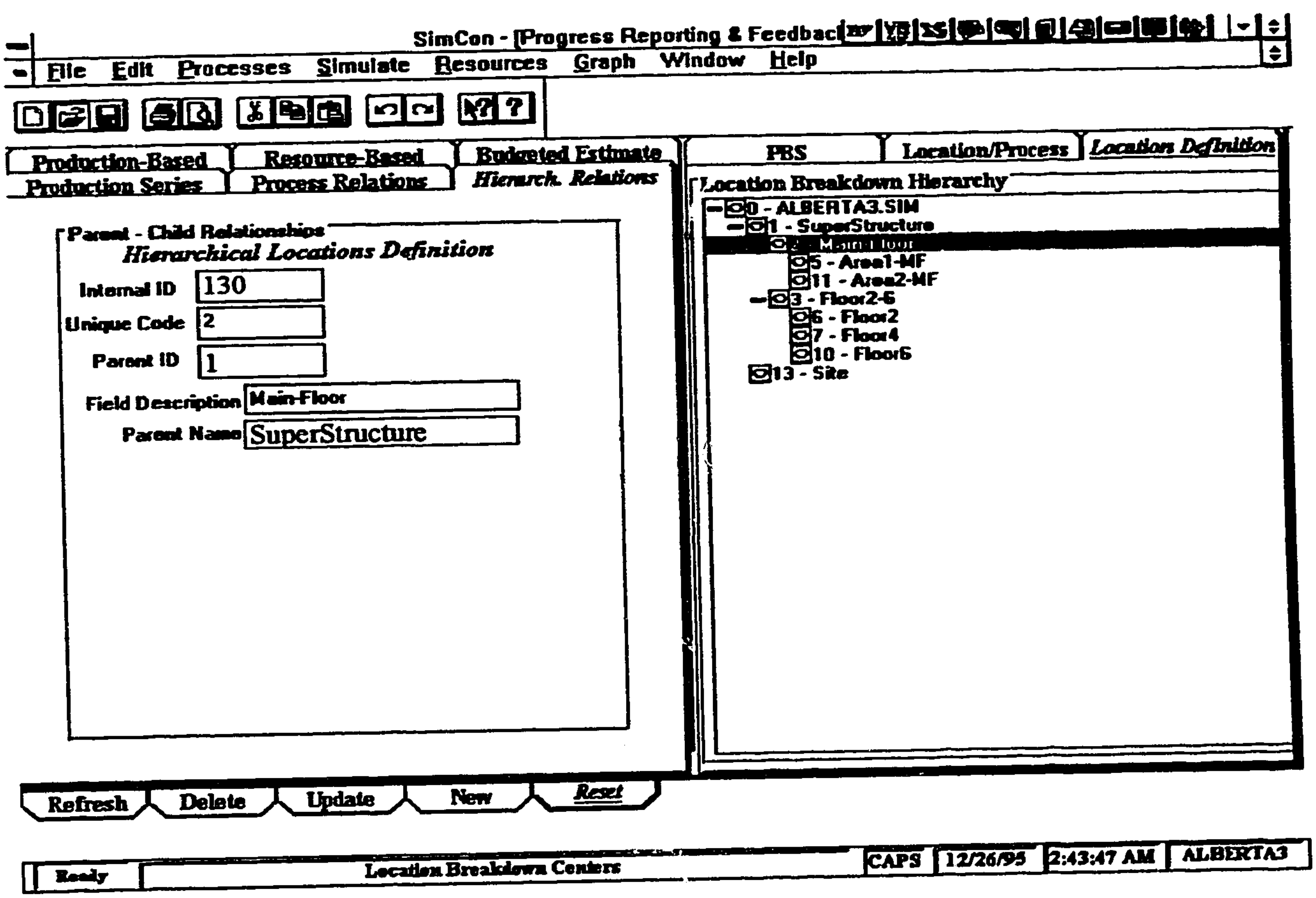


Figure 4.3 A SimCon Location Breakdown Center

Graphical interface uses the object oriented concepts to facilitate multiple process modeling as shown in Figure 4.4. The graphical interface of the process nodes are generated in Visual C++. A sample code for the generating SimCon nodes in Visual C++

is shown in Appendix D-2. Processes can be either retrieved from SimCon's library database of processes or constructed by the user using SimCon's graphical interface in the computer prototype system. A process model is developed by instantiating (creating an instance of a pre-defined object) the modeling elements provided in SimCon. The entire SimCon-process model has been implemented as an "object". Many instances of the same object can be viewed graphically at the same time by a simple "click" on a process name. Internally, and through the use of Visual Basic terminology, a process model is developed in a "Form". Every time a process model is viewed a new instance of the "Form" is created. Figure 4.5 shows the Visual Basic Code used to create and instance the existing object process. All objects that exist in a "Form" are programmed to directly link to the form's instance. Logical flow of entities in a process and other project environment constraints can be changed through a "drag and drop" mechanism in the computer graphical interface. Processes defined in SimCon's process library can be used in different projects and do not store actual values in any of the activities or resources.

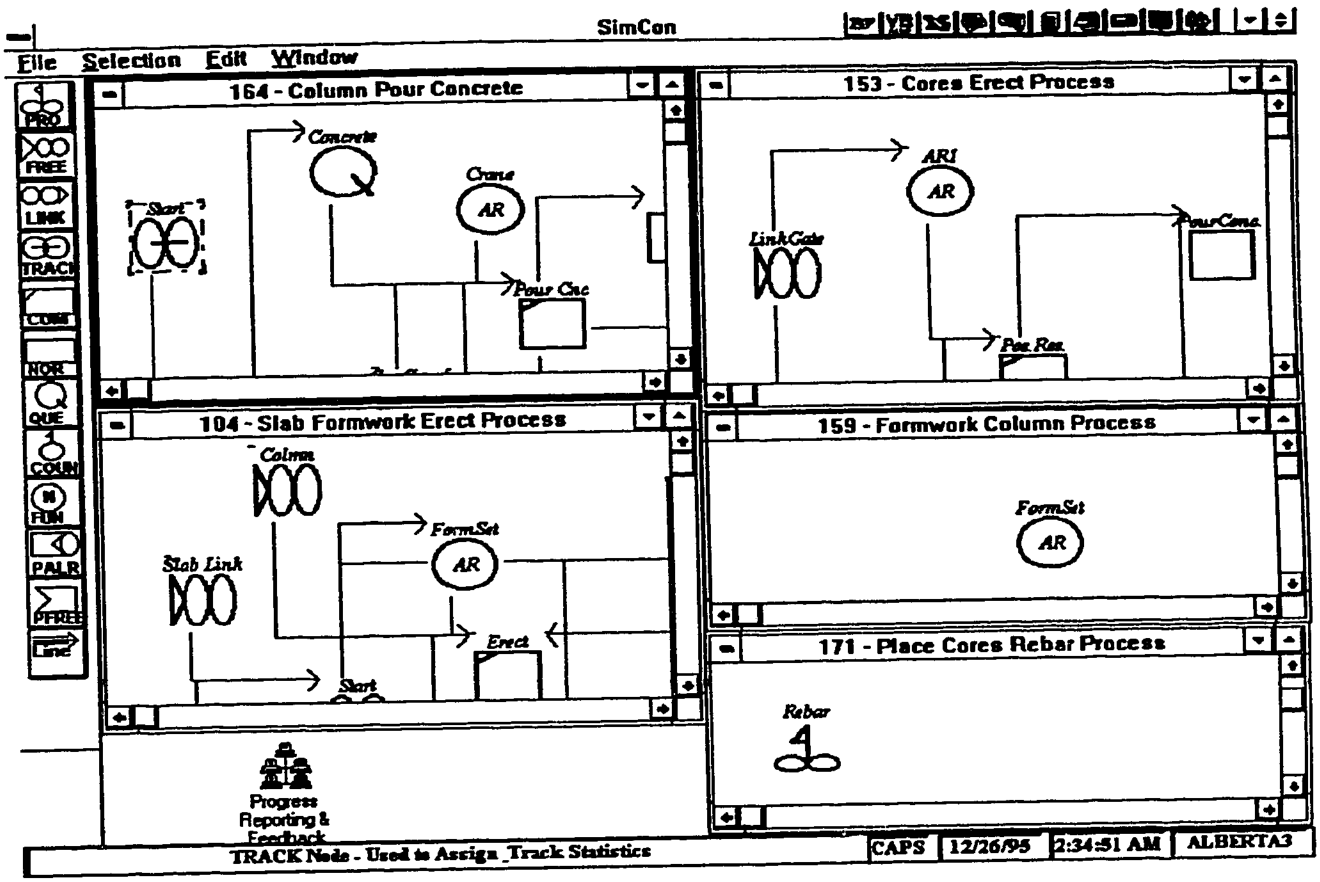


Figure 4.4 Multiple Process Modelling in SimCon's Graphical Interface

```
'///-----------------------------------------------------------------------
'///Instantiating a New Process Model
'///-----------------------------------------------------------------------
Dim SimForm As New SimConFrm
Screen.MousePointer = 11
SimForm.Caption = ProcessSelected_ID & " - " & ProcessSelected_Name
SimForm.Show
Screen.MousePointer = 1
'///-----------------------------------------------------------------------
'///     Code Explanation
'///-----------------------------------------------------------------------
'///SimConFrm is Existing Object Process Model
'///SimForm is an instance of SimConFrm
'///SimForm.Caption is the name given to the new instanced process
'///-----------------------------------------------------------------------
```

Figure 4.5 Visual Basic Sample Code for Creating Instances of Process Objects

4.2.2 Event Driven Programming

User's interaction with SimCon is implemented using an event driven program, Visual Basic. Visual Basic was found to be very suitable for developing a prototype system because it provides novice users with minimal training than that required with other windows' programs such as Visual C++. Nevertheless, few objects had to be created in Visual C++ to simplify the programming in Visual Basic. Such objects are compiled into "custom control" files and imported into Visual Basic as custom controls (i.e., special types of objects that can be used in Visual Basic programming environment). An example of a custom control is a COMBI Node in CYCLONE (COM). A COM has special characteristics, node relationships requirements, process name, successor and predecessor nodes, and graphical location. A COM is created in Visual C++ environment by defining the above object properties. When a user selects a COM for a simulation process, then the COM object is instantiated (i.e., make an instance of) and its properties are assigned values. Figure 4.6 shows a sample of the Visual Basic code used to create a node instance in a specific process file and then save this instance into the relational database.

```
'/////-------------------------------------------------------------------
'////// Creating an Instance of Node Object
'/////-------------------------------------------------------------------
Load SIMCTRL(SimCount)
SIMCTRL(SimCount).[Node Type] = MyType1
SIMCTRL(SimCount).Top = Y
SIMCTRL(SimCount).Left = X
SIMCTRL(SimCount).Visible = True
SIMCTRL(SimCount).Description = SimCount '& " - Pr"
UpdateForm!NodeDescription.Text = SimCount & " - " & ProcSel_Name
UpdateForm!NodeID.Text = SimCount
ProcessRef("NodeId") = SimCount
ProcessRef("NodeName") = Left(UpdateForm!NodeDescription.Text, 20)
'/////-------------------------------------------------------------------
'////// Saving the Created Instance Into the Relational Database
'/////-------------------------------------------------------------------
Dim Pro1 As table
Set Pro1 = OriginalDatabase.OpenTable("ProcessTable")
Pro1.Index = "NodeId"'-Parent"
Pro1.MoveFirst
Description_Caption = Pro1("NodeName")
NodeDuration = Pro1("Duration")
ParX = Pro1("OX"):  ParY = Pro1("OY")
Node_ConGen = Pro1("GenerateUnits")
Pro1("GenQue") = NodeGen:  Node_Initque = Pro1("InitQue")
NodeProb = Pro1("Prob")
Pro1.AddNew
Pro1("ParentId") = ProcessSelected_ID
Pro1("ParentName") = ProcessSelected_Name
Pro1("NodeId") = PreId
Pro1("NodeType") = PredType
Pro1("NodeName") = Description_Caption
Pro1("Duration") = NodeDuration
Pro1("ConnectionCount") = ConnectNum + 1'ConnectNum
Pro1("OX") = ParX:  Pro1("OY") = ParY
Pro1("SucId") = SucId
Pro1("SucName") = SucName
Pro1("SucType") = SIMCTRL(Index).[Node Type]
Pro1("X2") = SucX:  Pro1("Y2") = SucY
Pro1("GenerateUnits") = Node_ConGen
Pro1("InitQue") = Node_Initque
Pro1("Prob") = NodeProb
Pro1.Update
Call drawconnection
'/////-------------------------------------------------------------------
'/////SimCount is an integer variable used to track nodes by number
'/////SIMCTRL is the name of the node object
'/////-------------------------------------------------------------------
```

Figure 4.6 Visual Basic Sample Code for Creating Instances of Node Objects

4.2.3 Relational Database Programming

All the cost centers, location breakdown centers, and process nodes and relations are stored and manipulated using a relational database. The filtering and querying capability of a relational database simplifies finding and selecting records for information management. The hierarchical production breakdown structure is combined in one table in the relational database and querying for specific information can be easily implemented. For example processes can be selected from the production breakdown structure table by querying all records for a WBSType = 4 as shown in Figure 5.7. Cost centers are assigned a WBSType equal to 1 and locations are assigned a WBSType equal to 2 (a WBSType is an internal code that is used by the database to distinguish various levels in the hierarchy). Production and resource-based data are also stored in the relational database.

```
Dim OriginalDatabase As Database
Set OriginalDatabase = OpenDatabase(FilePathName$, True, False)
Dim MyDyn As dynaset
Dim CostCenters As table
Set CostCenters = OriginalDatabase.OpenTable("PBSTable")
Dim ProcessTable As table
Set ProcessTable = OriginalDatabase.OpenTable("ProTable")
Dim RecNumber As Integer
Dim QuerySel As String, Query2Sel As String

'//////-------------------------------------------------------------------
'//////   show project processes
'//////-------------------------------------------------------------------
Query2Sel = " SELECT DISTINCTROW PBSTable.CostDescription,
PBSTable.CostID, PBSTable.ParentID, PBSTable.ParName,
PBSTable.CostCode"
Query2Sel = Query2Sel & " FROM PCBSTable WHERE
((PBSTable.WBSType = 4)) ORDER BY PBSTable.ParentName;"
Set MyDyn = OriginalDatabase.CreateDynaset(Query2Sel)
ExistingProcess.Clear
ProcessCaption.Caption = "    Project Processes "
MyDyn.MoveFirst
        Do Until MyDyn.EOF
                ExistingProcess.AddItem MyDyn("CostDescription")
                MyDyn.MoveNext
        Loop
'//////-------------------------------------------------------------------
```

Figure 4.7 ***Visual Basic Procedure for Querying a Relational Database***

4.2.4 Simulation System

Graphical representation is implemented using CYCLONE notations and actual simulation is performed in SLAM II. The reason for using SLAM II as the simulation language includes the more flexibility available in modeling multiple processes in the same project as discussed later in this section. A translation module is written in Visual Basic to translate the CYCLONE process models into SLAM II network models. Every process model in SimCon is translated and saved as a separate simulation file in a SLAM II "scenario". A scenario in SLAM II is used to refer to a particular combination of a simulation model, data, and experimental controls (Pritsker et al 1989). The combination of simulation models in a specific scenario formulate a construction project. Data for a simulation scenario includes project title and modeller identification, beginning and ending times, number of runs, report types and frequency desired, initial values for status variables and initial location of entities in the model. An entity is a generic term referring to objects, information, or any transaction type as defined and described in Chapter 3. An entity arrives at process nodes, where it is stored or routed. The entity continuous to move through the network until it reaches the last process or when simulation clock is stopped. Decisions regarding an entity are based on the attribute values that it carries.

Dynamic variables included in a SimCon-process include: number and type of resources, task durations, process status (completed, in-progress, not started), and production required. These variables are assigned from outside individual processes through the use of attributes on specific activities. In this regard, a SimCon-process can mainly be constructed by assigning values to the variables of each process. These variables are manipulated by SLAM II in modeling a project.

In SimCon each process (i.e., a "form") is saved as a SLAM II simulation network model. Resources in SimCon are translated into "resource blocks" (a SLAM II terminology for defining a resource) and all are saved in one network file in SLAM II under the same scenario. The resource file name in SLAM II is called "Resource.Net". The resource file acts as a project's resource pool and interacts with other simulation models. The simulation compiled file combines all models together into one file when running the simulation program. Figure 4.8 shows a schematic view of SimCon's translation module.

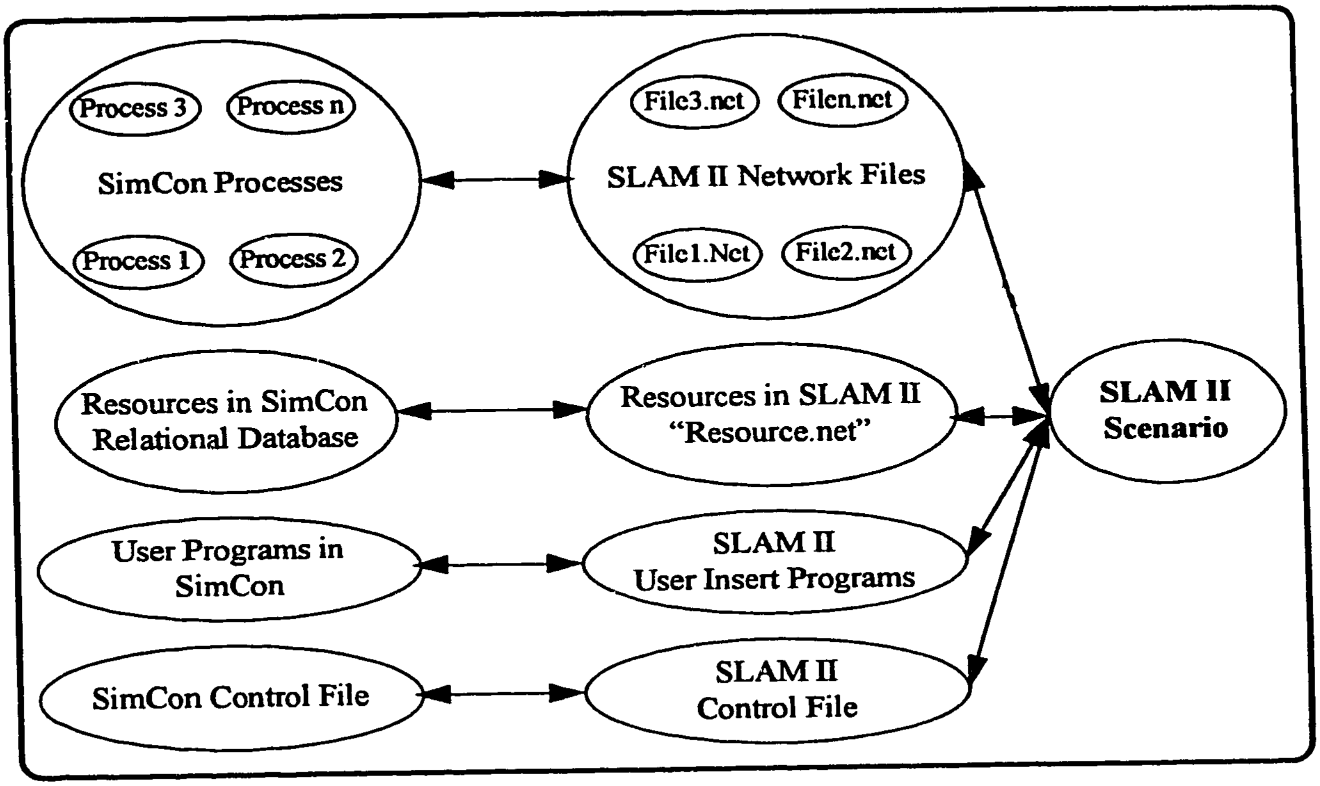


Figure 4.8 A Schematic View of SimCon's Translation Module

A PRO-Ratio in a PRO node can be calculated by dividing actual production by the number of cycles specified in a production counter. Reporting progress in a production counter is used to update progress to-date and consequently update the simulation model. For example, an earth moving operation has a production counter value (PRO-Count) equal to 16 cycles and actual measured earth is equal to 40 m^3. In this case the PRO-Ratio is equal to 2.5 (i.e., 40/16). If 15m^3 are reported to be completed then the PRO-Count value is updated to 10 cycles (i.e., 16 - 15/2.5). The details of calculating a PRO-Ratio in SimCon is shown in Figure 4.9. The programming code in Figure 4.9

shows that first step involves determining the process identification number and seeking the corresponding data from the data base. Following that the production quantity that is stored in the database is divided by the PRO-Loc and PRO-Count values to calculate the production ratio.

```
'//////-----------------------------------------------------------
'//////   Event Programming to Calculate PRO-Ratio
'//////-----------------------------------------------------------
Sub ProdBudg_Change ()
On Error GoTo Check1Er
   Dim OriginalDatabase As Database
   Set OriginalDatabase = OpenDatabase(FilePathName$, True, False)
   Dim CostCenters As table
   Set CostCenters = OriginalDatabase.OpenTable("PBSTable")
   Dim ProcessTable As table
   Set ProcessTable = OriginalDatabase.OpenTable("ProcessTable")
   Dim QuantFromPBS As Double, ParentSel As Integer
   Dim LibRef As table
'//////-----------------------------------------------------------
'//////   Determining the Process ID From Process Table
'//////-----------------------------------------------------------
      ProcessTable.Index = "NodeID"
      ProcessTable.MoveFirst
      ProcessTable.Seek "=", Val(NodeID2.Text)
      If Not ProcessTable.NoMatch Then
         ParentSel = ProcessTable("ParentID")
      Else
   MsgBox "Error!!! - Parent ID Not Found in Process Table", 48, "Error"
         Exit Sub
      End If
'//////-----------------------------------------------------------
'//////   Determining the Quantity From PBS Table
'//////-----------------------------------------------------------
      CostCenters.Index = "CostID"
      CostCenters.MoveFirst
      CostCenters.Seek "=", ParentSel
      If Not CostCenters.NoMatch Then
         QuantFromPBS = CostCenters("Quantity")
      Else
         MsgBox "Process Does not exist in PBS", 48, "Error"
      End If
 If Val(PRO-Count.Text) = 0 or Val(PRO-Loc.Text) = 0Then
   ProdRatio.Text = "N/A"
 Else
   ProdRatio.Text = QuantFromPBS / Val(PRO-Loc.Text) * val(PRO-Count)
 End If
 Exit Sub
'//////-----------------------------------------------------------
'/////Error Check Module
 Check1Er:
    MsgBox Error$
    Resume Next
 End Sub
```

Figure 4.9   Production-Ratio Calculation in SimCon

4.3 SIMCON'S IMPLEMENTATION FROM A USER'S PERSPECTIVE

A project in SimCon starts by building a model from library resources, processes, and company standard cost centers. Figure 4.10 shows a general schematic overview of SimCon's implementation procedure. A hierarchical production breakdown structure involves identifying and building a cost centers structure, a location breakdown center, and construction simulation processes. Models that are built are translated into SLAM II (Pritsker 1986). Results are retrieved from the statistical report and if no changes are required then a project baseline is defined against which progress will be measured. The project baseline defines scheduled production, scheduled cost, and scheduled resource hours. If the modeller is satisfied with the project baseline then the project is saved to a file against which actual performance can be measured. Following the start of construction, the first update of the project can start by 'progress reporting by exception' unless a detailed analysis is required. Production-based and resource-based reports are generated to check a project's progress. If construction is progressing according to plan then the schedule can be updated without going into more details. However, if delay is experienced in a specific process or if productivity is low in a resource then more details can be analyzed by collecting additional site information and performing a two-way feedback analysis on the actual construction and on the simulation model.

A two-way feedback analysis includes the following: 1) validate the simulation model to determine if it correctly represents actual construction; and 2) verify the actual delay experienced in construction by comparing it to the simulation model. In the first feedback accuracy analysis of the modeling of activities and processes in a simulation schedule is validated for use. In the second feedback analysis the actual reasons for delay or cost over run can be determined. Simulation modeling provides the capability to represent the specifics of a construction process and hence allows a detailed analysis to be performed.

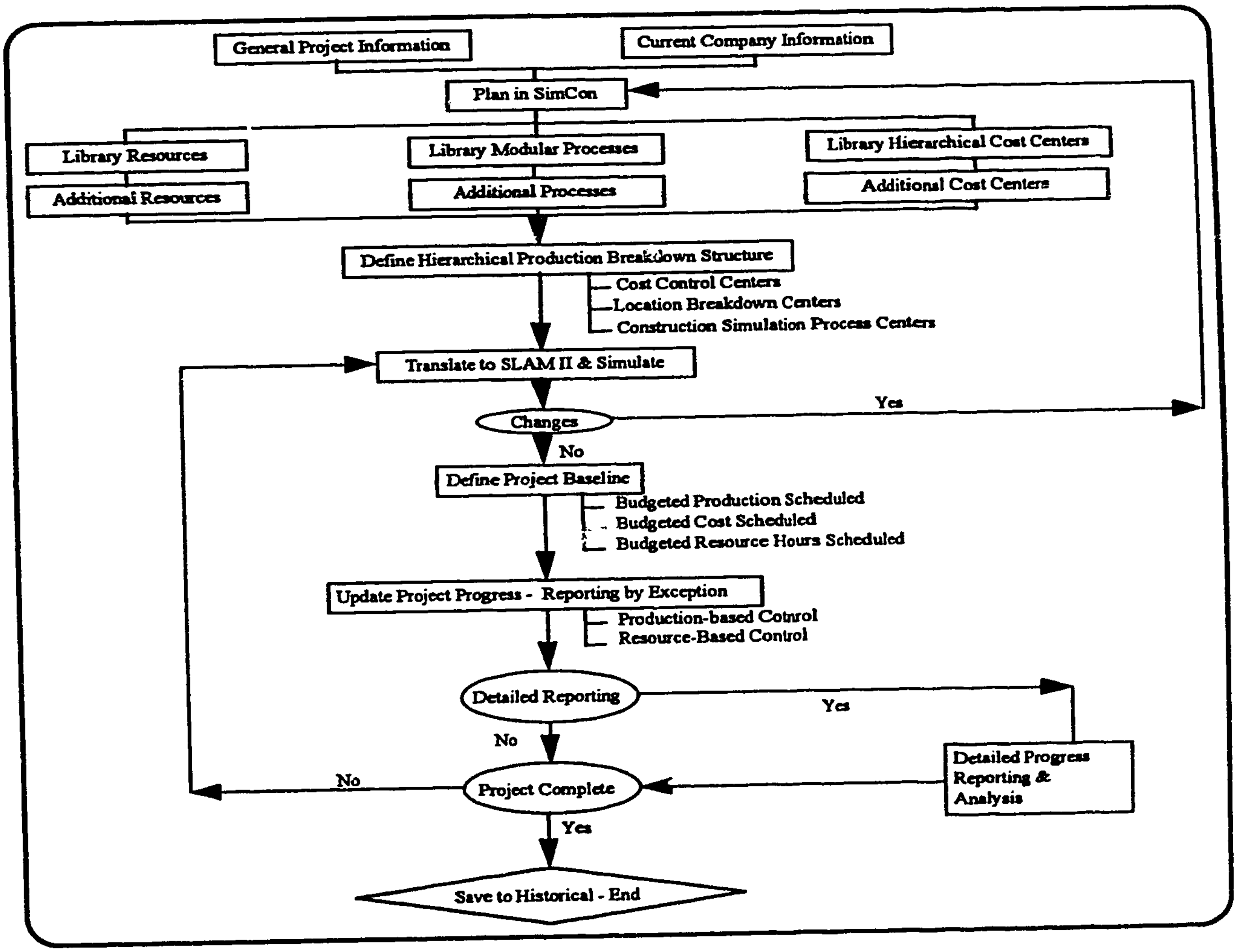


Figure 4.10 Schematic Internal View of Implementation Procedure in SimCon

4.3.1 Procedure for Developing a SimCon Project

There are a number of ways that the user can follow in constructing a project. Modeling a project in SimCon is centered around establishing the production breakdown structure. This involves building or retrieving cost control centers, location breakdown centers, and construction process centers. The suggested procedure for modeling a project in SimCon is the following:

1. Define cost control centers
2. Define location breakdown centers
3. Link specific location centers to associated cost centers
4. Define construction process centers and associate to location centers
5. Link construction process centers

4.3.2 Sample Session From SimCon

This session is intended to show the development of a project from within SimCon prototype computer system. A new project in SimCon is modelled by following the five steps noted in Section 4.3.1. Figure 4.11 shows an example of defining the cost control centers. The cost centers for controlling a project are hierarchically identified by either defining new cost centers or retrieving from existing cost center library. Cost centers are defined in SimCon by 'clicking' on the 'Hierarch. Relation' tab on the left side and on the 'PBS' tab on the right side of Figure 4.11. Following that a field description, a parent name and a unique cost code must be assigned for each new cost center. Following this, the update command as shown on the lower left corner of Figure 4.11 is clicked to add the new cost center to the existing hierarchical list.

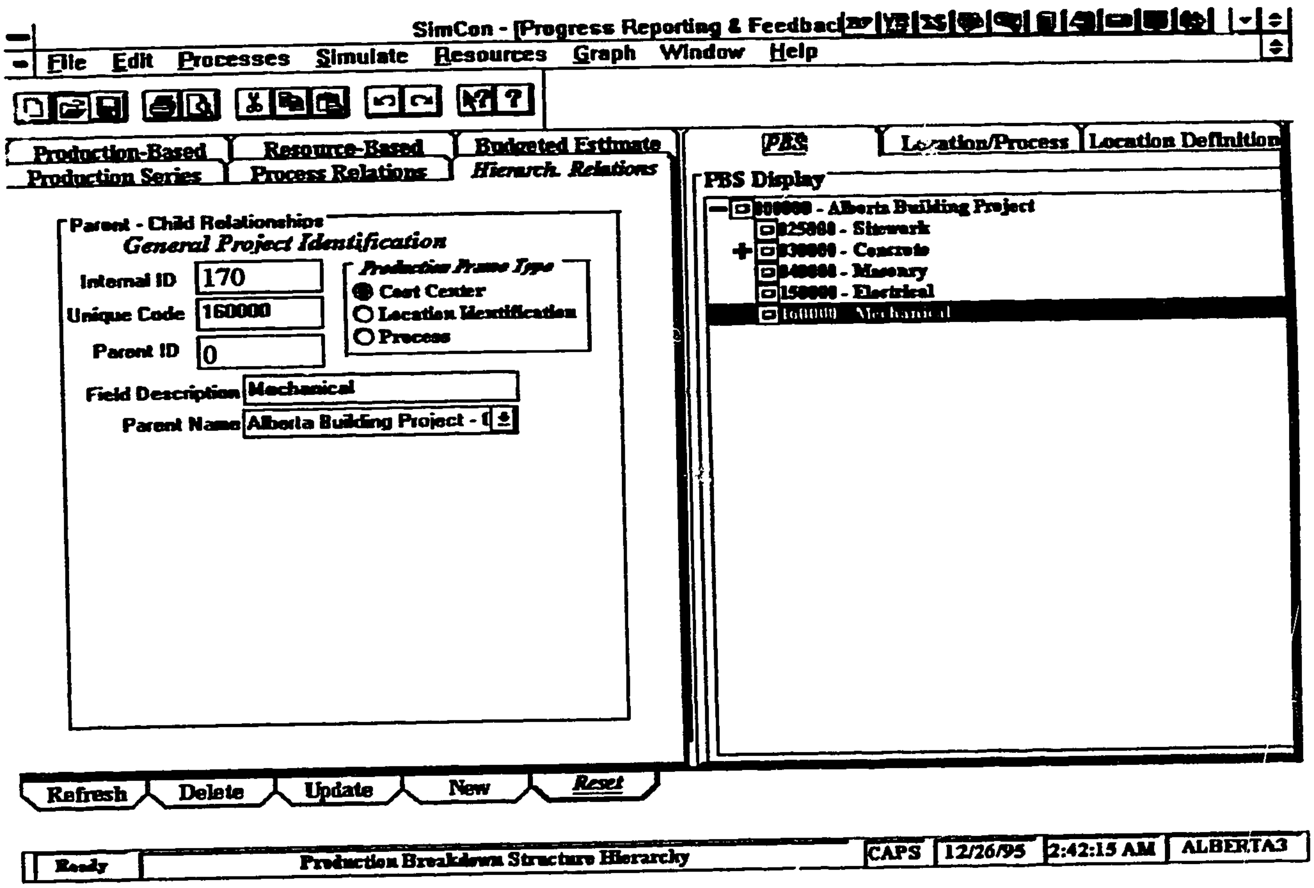


Figure 4.11 Defining Cost Control Centers in SimCon

Location breakdown centers can be defined, as shown in Figure 4.3, by selecting the 'Location definition' tab on the upper right corner and then adding a location field description in the location hierarchy. The unique code is automatically added by the computer but the user can change it to any unique number if required. LBC allows project control by location and resource allocation as discussed in Chapter 3. Figure 4.12 shows a 'Resource Form' for adding resources in SimCon. Every resource is added separately to a specific location center. The resource identification number (Resource ID) is internally added by the program. Available quantity, unit of measure, resource type, fixed unit cost, and variable unit cost are determined by the user.

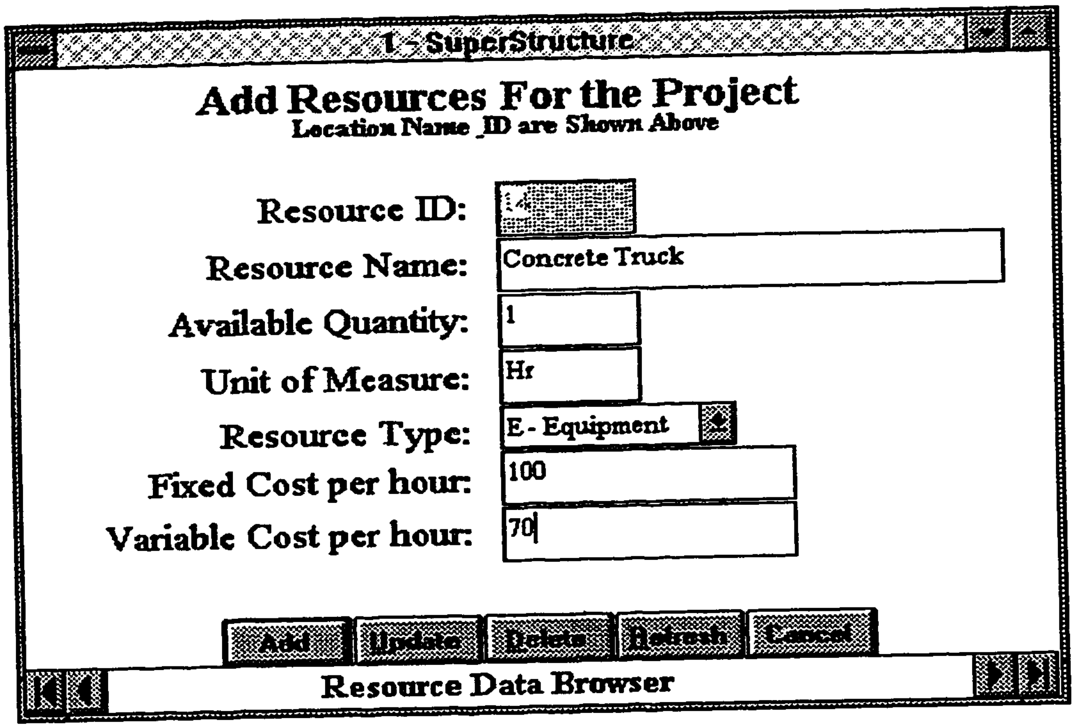


Figure 4.12 Defining a Resource in SimCon

Figure 4.13 shows process identification in SimCon. First, a location center is selected as shown in the right side of Figure 4.13. Second, a process is added as shown in the right side after selecting the 'Hierarch. Relations' tab. The user can either add a new process or select an existing one from SimCon's Library.

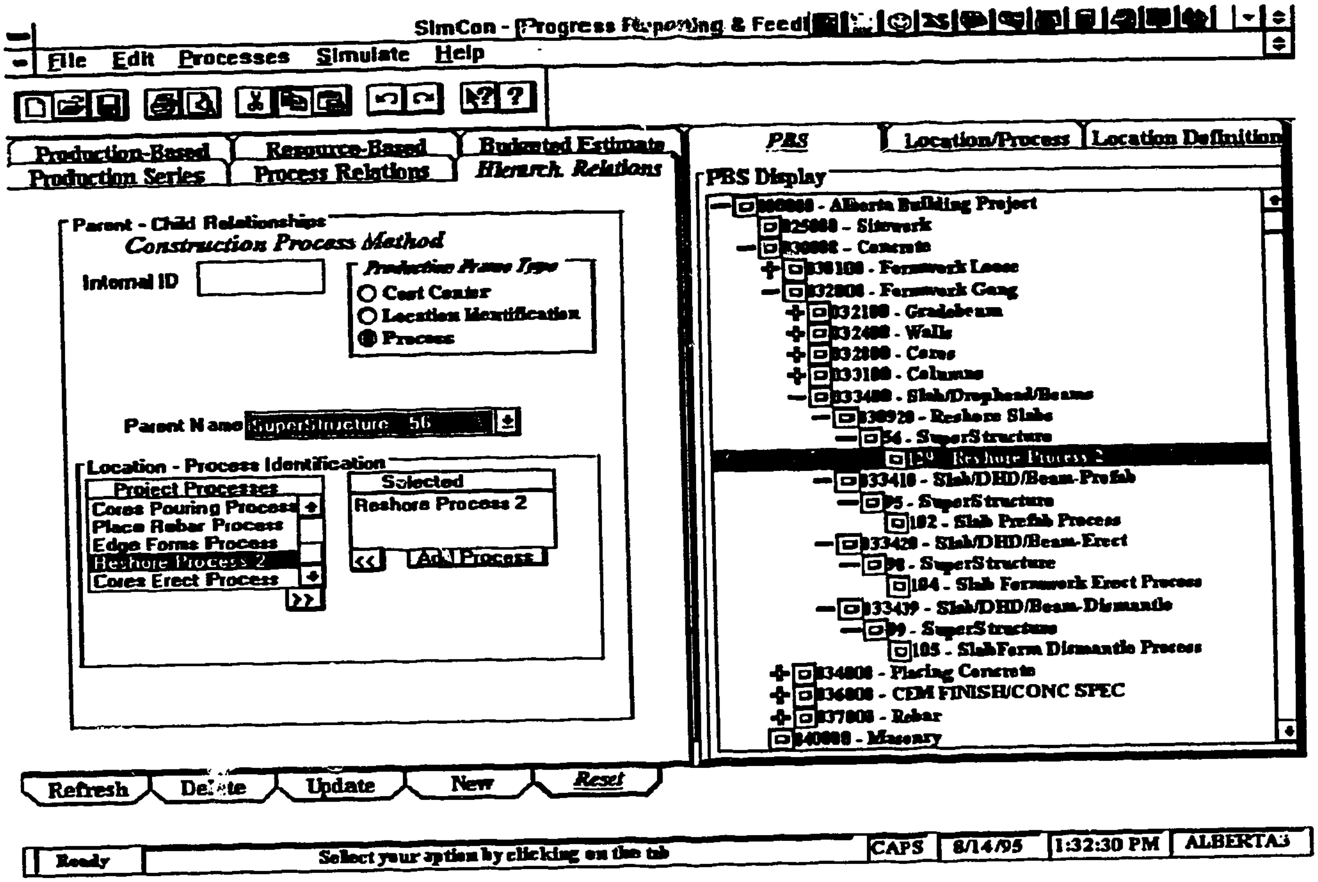


Figure 4.13 Defining a Process in SimCon's Production Breakdown Structure

After defining a process, 'double clicking' with a computer mouse on the location center will activate SimCon's graphical interface as shown in Figure 4.14. Modeling elements can be retrieved from the list of nodes on the far left side by pointing with a mouse. Every node has its respective 'form' as shown on the right side of Figure 4.14. The PRO node form, as displayed in Figure 4.14, shows the PRO-Ratio, PRO-Q, PRO-Count, PRO-Name, PRO-Link, and PRO type (i.e., within a process or occurring at various locations) parameters. The COMBI node form, as shown on the right side of Figure 4.15, shows the triangular activity duration estimates that the user can enter or change. A branch decision making dialogue box is automatically displayed when a user links nodes using the ARROW method. The probability condition has a value equal to one as shown in Figure 4.15 and states that the 'Finish' node is always following the 'Erect' node with a 100% probability. Similarly, all the other nodes have their own editing forms.

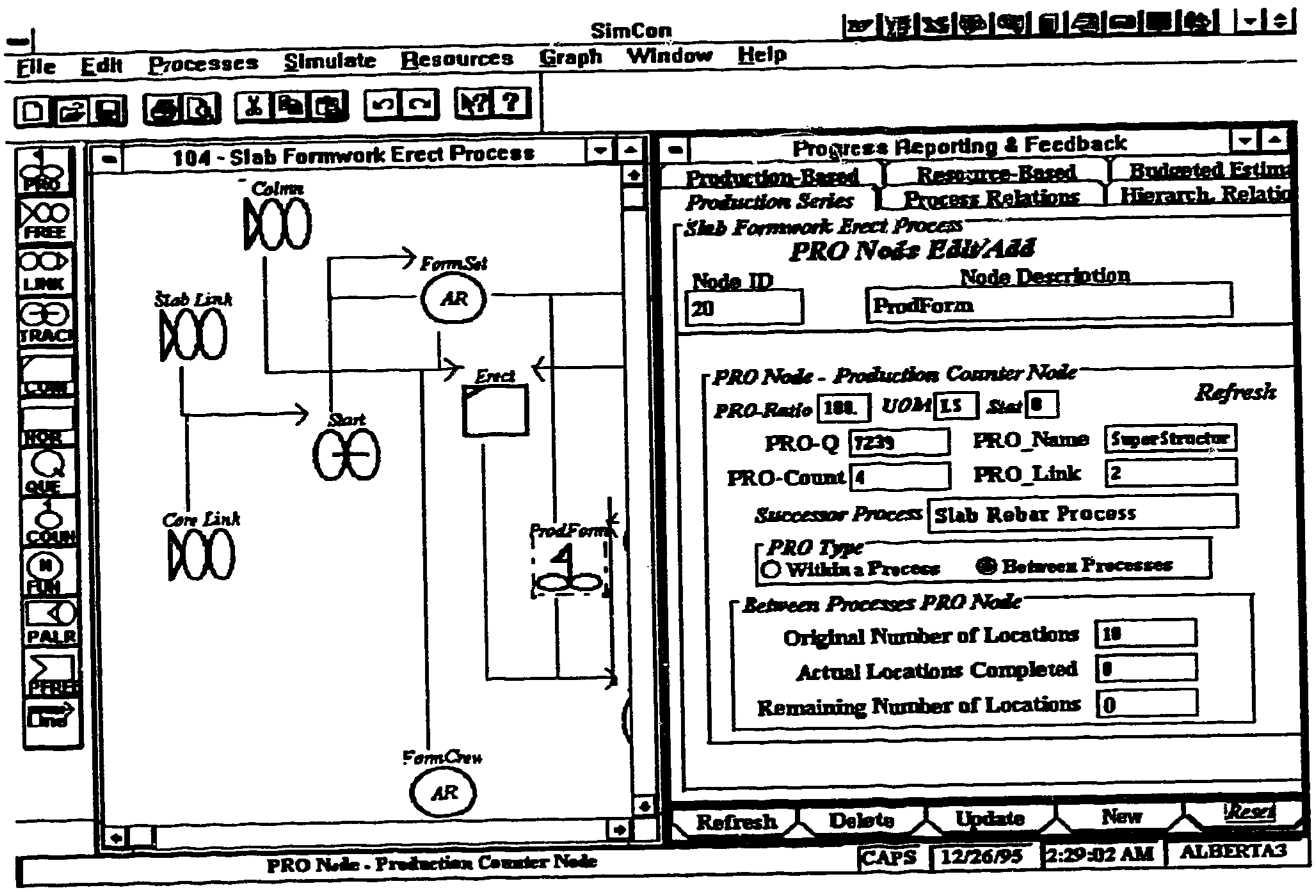


Figure 4.14 ***Process Modelling Using SimCon Graphical Interface With Details on the PRO Node***

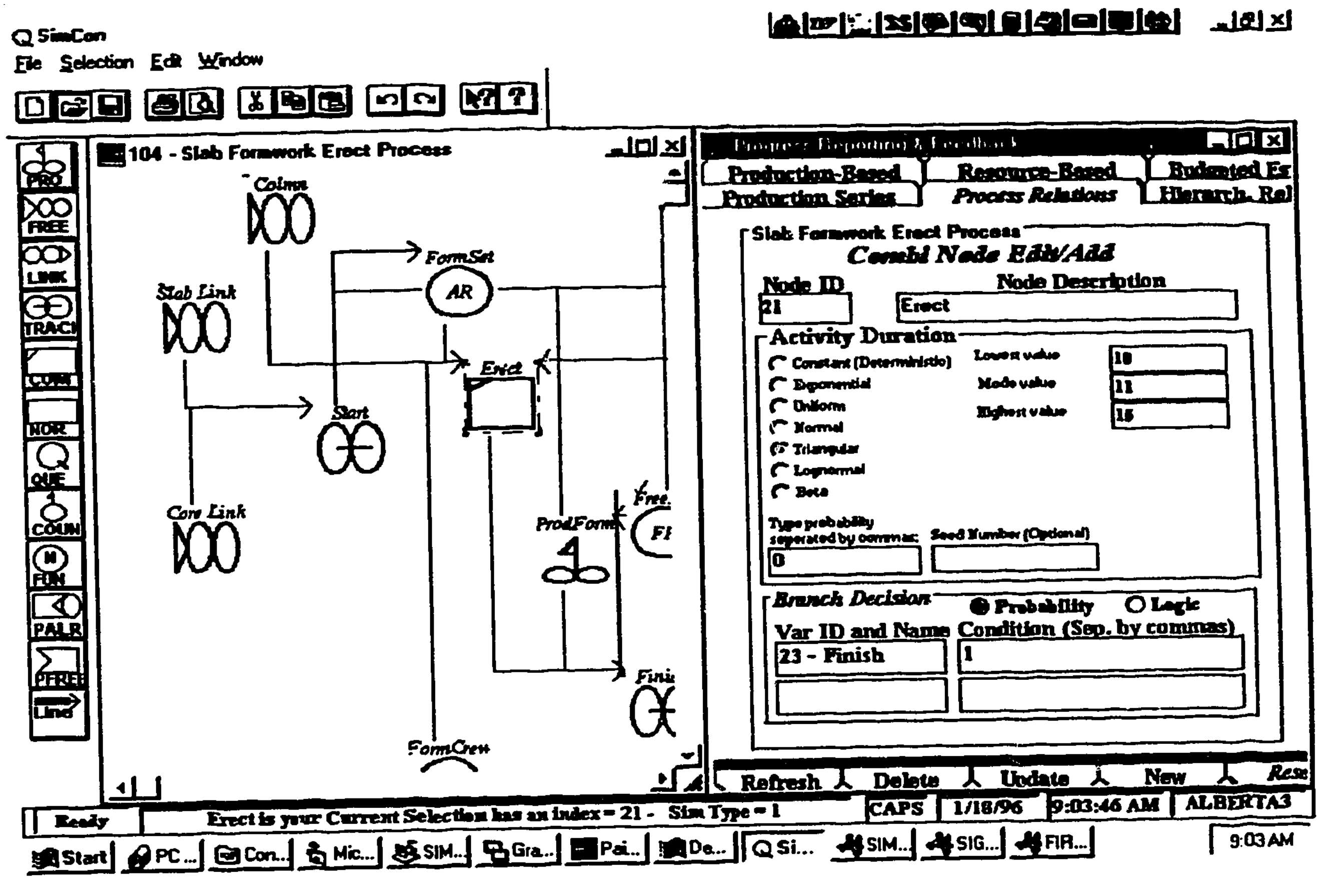


Figure 4.15 ***Process Modelling Using SimCon Graphical Interface With Details on the COMBI Node***

Following completion of the modeling of the various construction processes in SimCon, the 'Simulate' command on the 'pull-down' menu, shown on the top of Figure 4.14, allows the user to partially transfer the SimCon-process into SLAM II readable files. A translation in SimCon is implemented as shown in Figure 4.16a. Each SimCon process, as shown schematically in Figure 4.8, is translated into a separate file with a '*.net' extension. All resources from SimCon's database are translated into a SLAM II 'Resource.net' file. A control form in SimCon is also translated into SLAM II control file, 'Userfile.Con'. A typical control file includes planner's name, project name, number of runs, and simulation ending time. A standard naming convention is used to represent processes in order to provide automatic retrieval of information from SLAM II results.

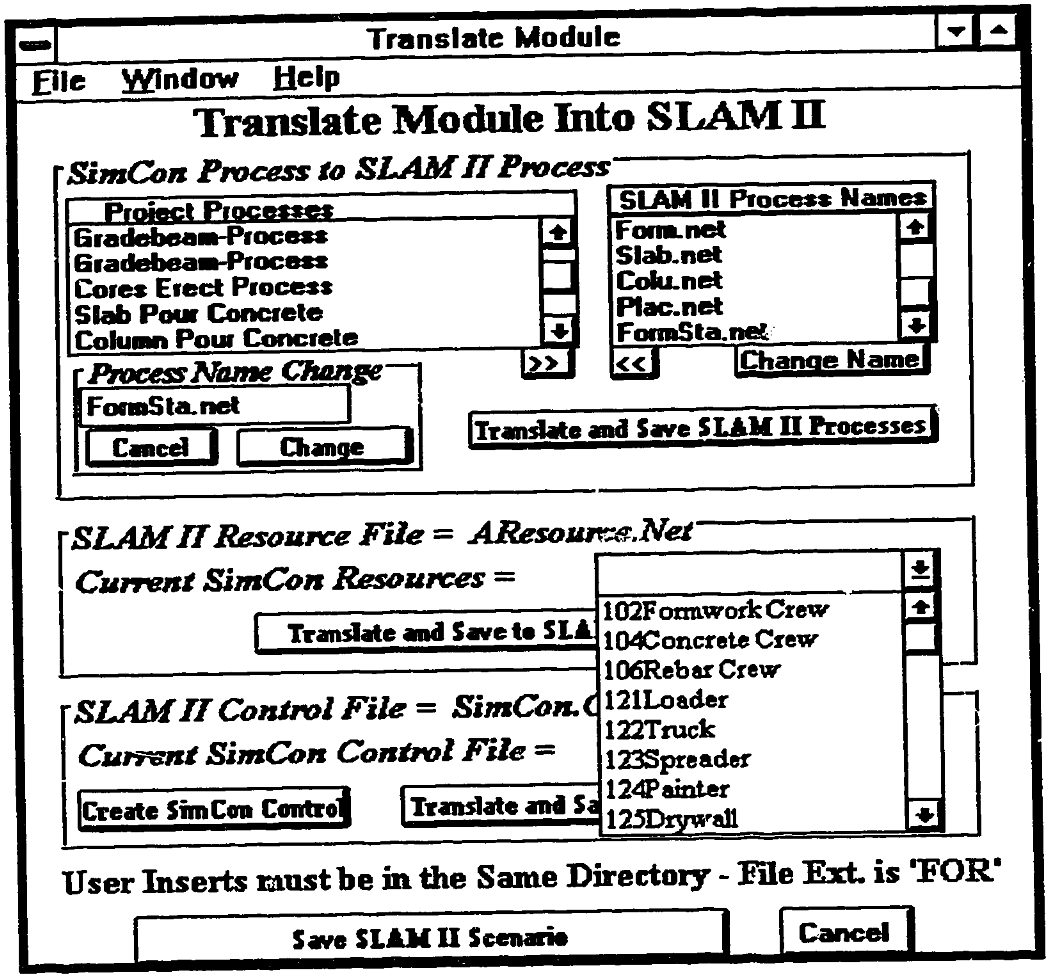


Figure 4.16a Translation Module Implementation in SimCon

```
Resource/1,RES102(2),1;
;Resource Id = 102 = Formwork Crew
Resource/2,RES104(2),2;
;Resource Id = 104 = Concrete Crew
Resource/3,RES106(3),3;
;Resource Id = 106 = Rebar Crew
Resource/9,RES126(4),9;
;Resource Id = 126 = Masonry
Resource/10,RES127(2),10;
;Resource Id = 127 = Piling
Resource/11,RES128,11;
;Resource Id = 128 = Demolition
Resource/12,RES129(3),12;
;Resource Id = 129 = Metal
;Resource Id = 103 = Column FormSet
Resource/15,RES130,15;
;Resource Id = 130 = Concrete Truck
Resource/16,RES111(2),16;
;Resource Id = 111 = Slab FormSet
Resource/17,RES112,17;
;Resource Id = 112 = Form Set
Resource/18,RES113(1),18;
Resource/21,RES101,21;
;Resource Id = 101 = Crane
```

Figure 4.16b A Typical 'Resource.Net' File that is Generated in SimCon

A typical 'Resource.Net' text file that is automatically generated in SimCon and used in SLAM II is shown in Figure 4.16b. The generated files are simulated in SLAM II simulation program.

The simulation output results generated in SLAM II are provided in a computer 'text format' as shown in Figure 4.17. The results can be provided in terms of mean and standard deviation from a various number of runs. Statistical analysis of Results from SLAM II are automatically entered into SimCon as shown in the 'pull down' menu in Figure 4.18.

1

SLAM II SUMMARY REPORT

SIMULATION PROJECT THESIS CASE STUDY BY NADER N. CHEHAYEB

DATE 23/ 5/1995 RUN NUMBER 100 OF 100

CURRENT TIME .5285E+03
STATISTICAL ARRAYS CLEARED AT TIME .0000E+00

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
FINISH TIME	5.67E+02	5.78E+01	1.02E-01	5.13E+02	6.89E+02	100
END 135 CR CNC	4.70E+02	4.07E+00	8.67E-03	4.59E+02	4.80E+02	100
BEG 135 CO CNC	1.73E+02	3.17E+00	1.83E-02	1.63E+02	1.80E+02	100
PRO 135 COR	4.50E+00	2.29E+00	5.09E-01	1.00E+00	8.00E+00	4000
BEG 153 CRE FRM	1.52E+02	2.95E+00	1.94E-02	1.45E+02	1.59E+02	100
END 153 CR FRM	4.52E+02	3.93E+00	8.71E-03	4.39E+02	4.63E+02	100
BEG 159 CL FORM	1.52E+02	2.95E+00	1.94E-02	1.45E+02	1.59E+02	100
PRO 159 FRM	2.50E+00	1.12E+00	4.47E-01	1.00E+00	4.00E+00	4000
BEG 104 SLB FRM	1.77E+02	3.07E+00	1.73E-02	1.69E+02	1.85E+02	100
PRO 104 FRM	2.50E+00	1.12E+00	4.47E-01	1.00E+00	4.00E+00	4000

RESOURCE NUMBER	RESOURCE LABEL	CURRENT CAPACITY	AVERAGE UTIL	STANDARD DEVIAT	MAXIMUM UTIL	CURRENT UTIL
1	RES101	1	.34	.473	1	0
2	RES102	1	.32	.466	1	0
3	RES103	2	.84	.880	2	0
4	RES104	1	.19	.391	1	0

Figure 4.17 A Sample of SLAM II Simulation Output as Used by SimCon

The user can select the SLAM II output results as shown in Figure 4.18. Following the selection of the output file, SimCon transfers the textual information into the production-based and resource-based reports.

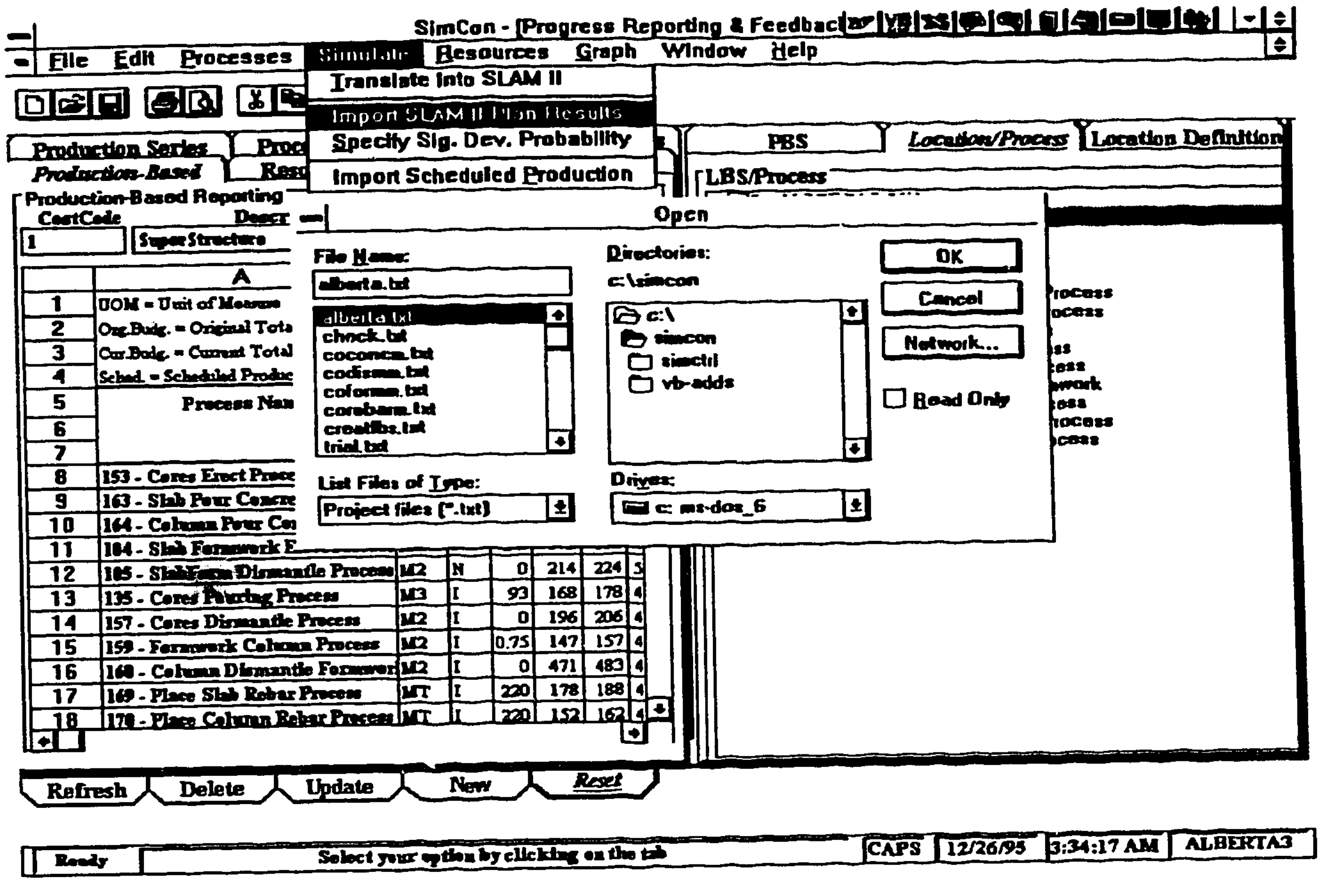


Figure 4.18 A View of the Automatic Input of SLAM II Simulation Output into SimCon

Figure 4.19 shows the user-specified significant deviation percentile data that is used in progress reporting by exception. Reporting by exception is implemented on processes that do not experience 'significant' deviations from project plan. Significant deviation is defined by the user for start and finish of processes, for production control, and for resource control. This means that a certain percentile or estimate can be specified by a user below which or above which a significant deviation is considered. The user's significant deviation point can be any percentile value. For example, a value equal to the 80^{th} percentile can be used to calculate from the simulation results the 80% of the observations. Similarly, a value equal to the mean can be used to calculate from the simulation results the mean value of the observations.

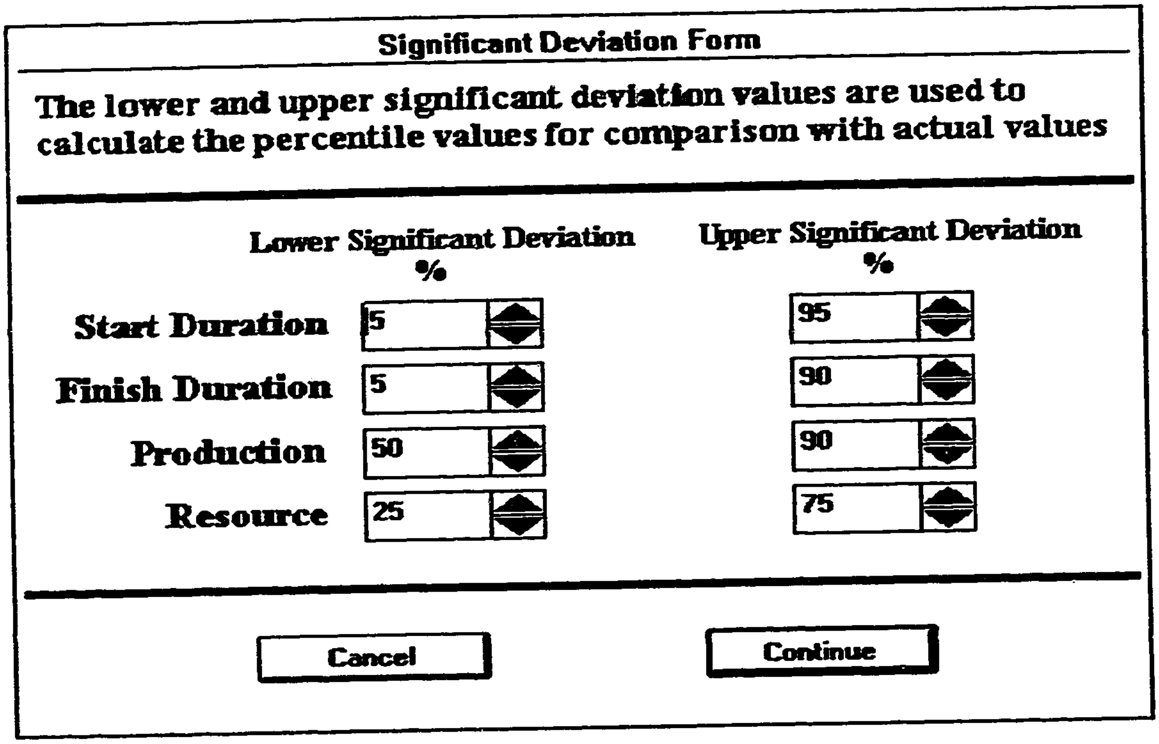


Figure 4.19 User-Specified Significant Deviation in SimCon

Pressing the 'Continue Button', as shown in Figure 4.19, calculates the various percentiles for the production-based and resource-based reports. Progress reporting can be implemented on both of Figures 4.20 and 4.21 to determine the variance for project control.

A production-based report as generated from within SimCon is shown on the left side of Figure 4.20. The list of processes that are shown are those that are defined under the 'Superstructure Location' as shown in the right side of Figure 4.20. The 5th and 95th percentile values for the start and finish of each process can be used to generate a bar chart with expected time estimates. The expected production on a specific data date can be generated in SimCon by ending the simulation run on that specific data date. User specified percentile values, as calculated from the output generated from the number of runs, is imported into the production-based report.

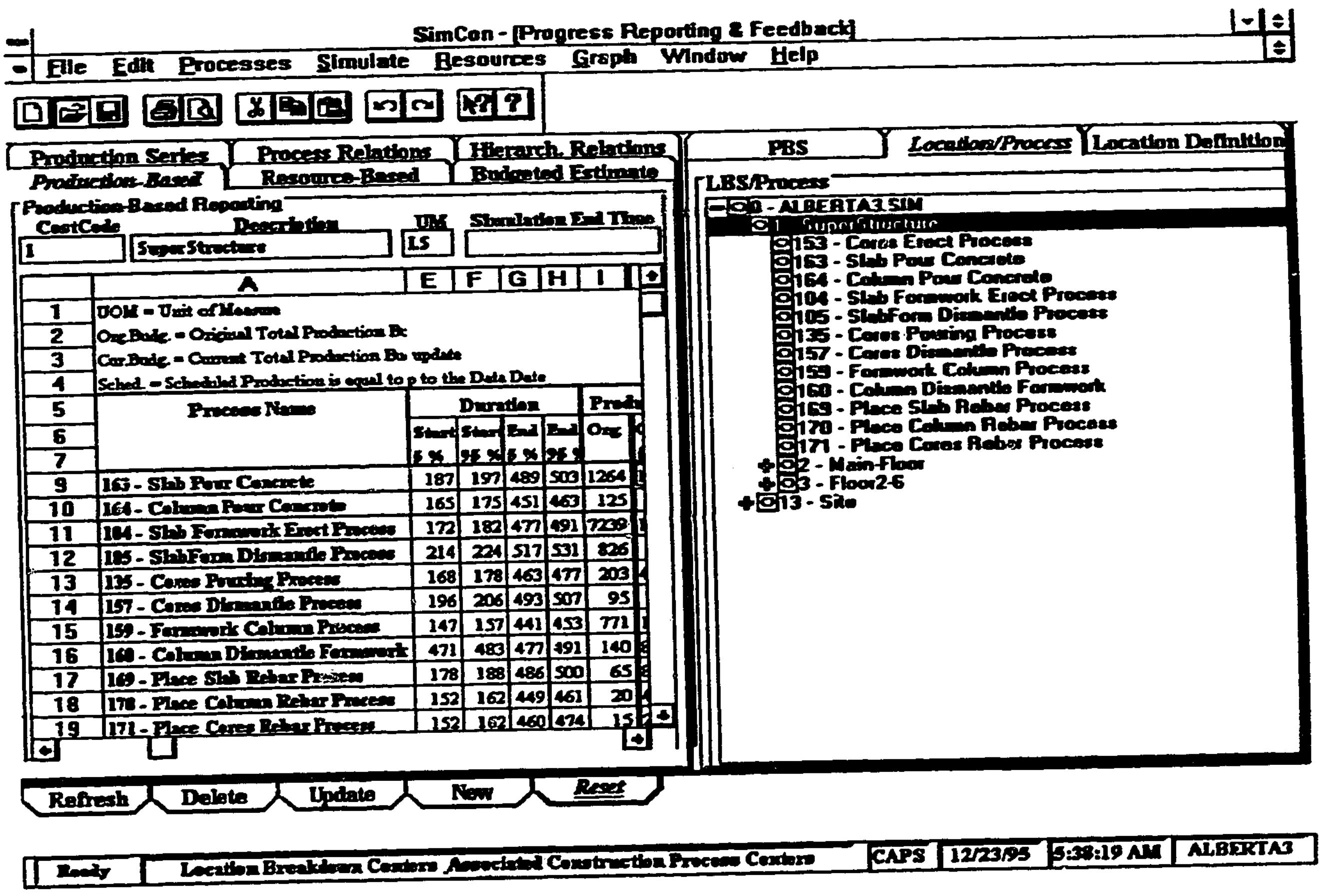


Figure 4.20 A Production-Based Report in SimCon

A resource-based report as generated from within SimCon is shown on the left side of Figure 4.21. The list of resources that are shown are those that are defined under the 'Superstructure Location' as shown in the right side of Figure 4.21. The start and finish duration of resources is automatically determined and calculated from their respective processes. The earliest start time of a resource is based on the earlier use of the resource on a specific process. Scheduled resource utilization is also determined in a similar way to that of scheduled production by ending the simulation time on the required data date. Following that, the mean and standard deviation of resource utilization is calculated and specific percentile values determined.

Production-based and resource-based reports can be printed from the 'pull-down' menu bar as shown in Figure 4.21. The production-based and resource-based reports, as shown in Figures 4.20 and 4.21, only show half of the report because of screen output limitations. However, the user in the computer program can enlarge the 'form' to full size of the computer screen. Cumulative distribution graphical output can be generated for scheduled production, scheduled resource hours, and project completion. More over, confidence intervals can be generated around the estimates as shown in the detailed case study in Chapter 5.

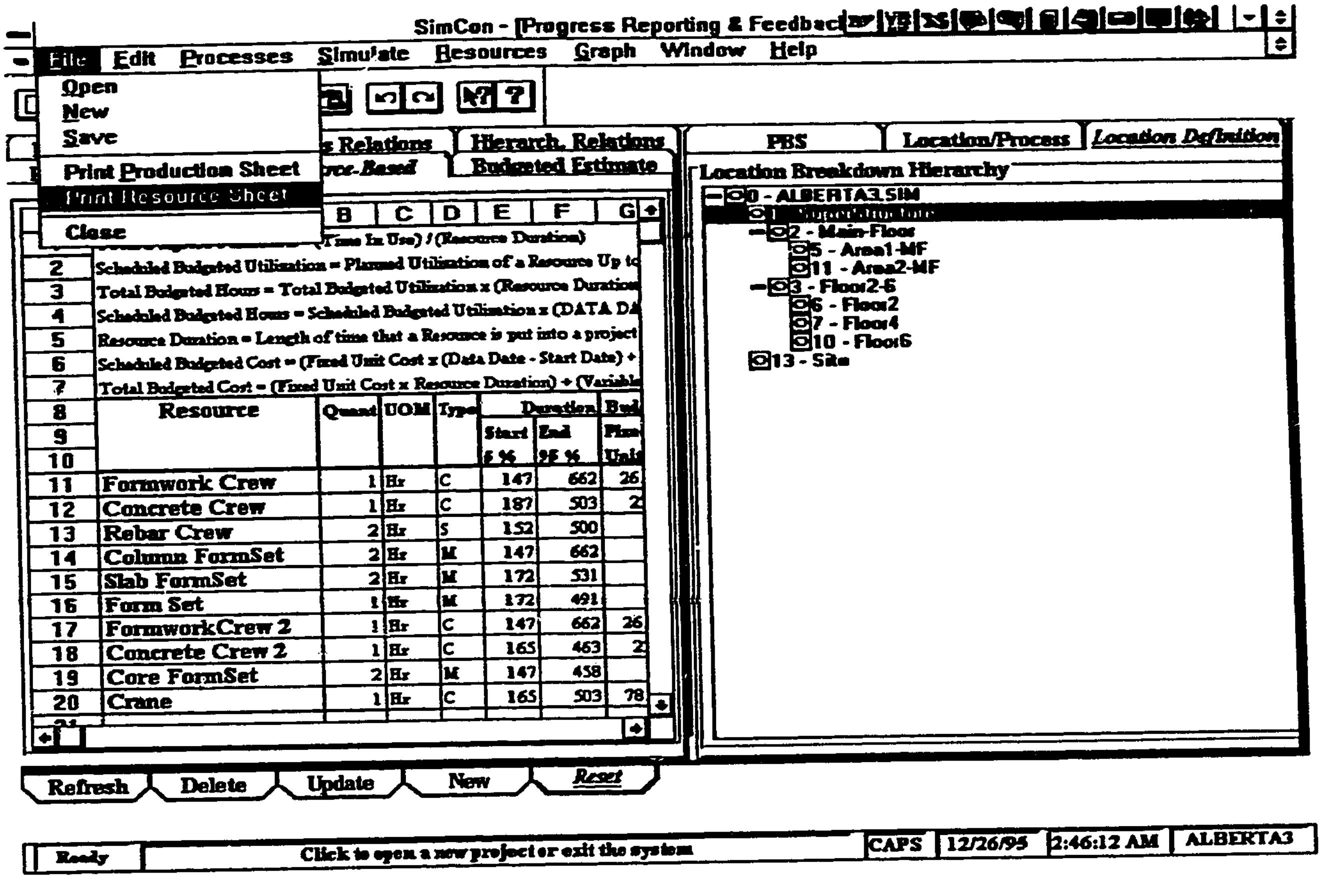


Figure 4.21 Resource-Based Report in SimCon

Results from each SimCon-process are 'rolled-up' in the production breakdown structure as shown in Figure 4.22. The user can click on any control center on the right side of Figure 4.22 to retrieve from the database and 'roll-up' the accumulated costs and man-hours of all control centers that are at a lower level. The benefits of cost centers are outlined in Chapter 3.

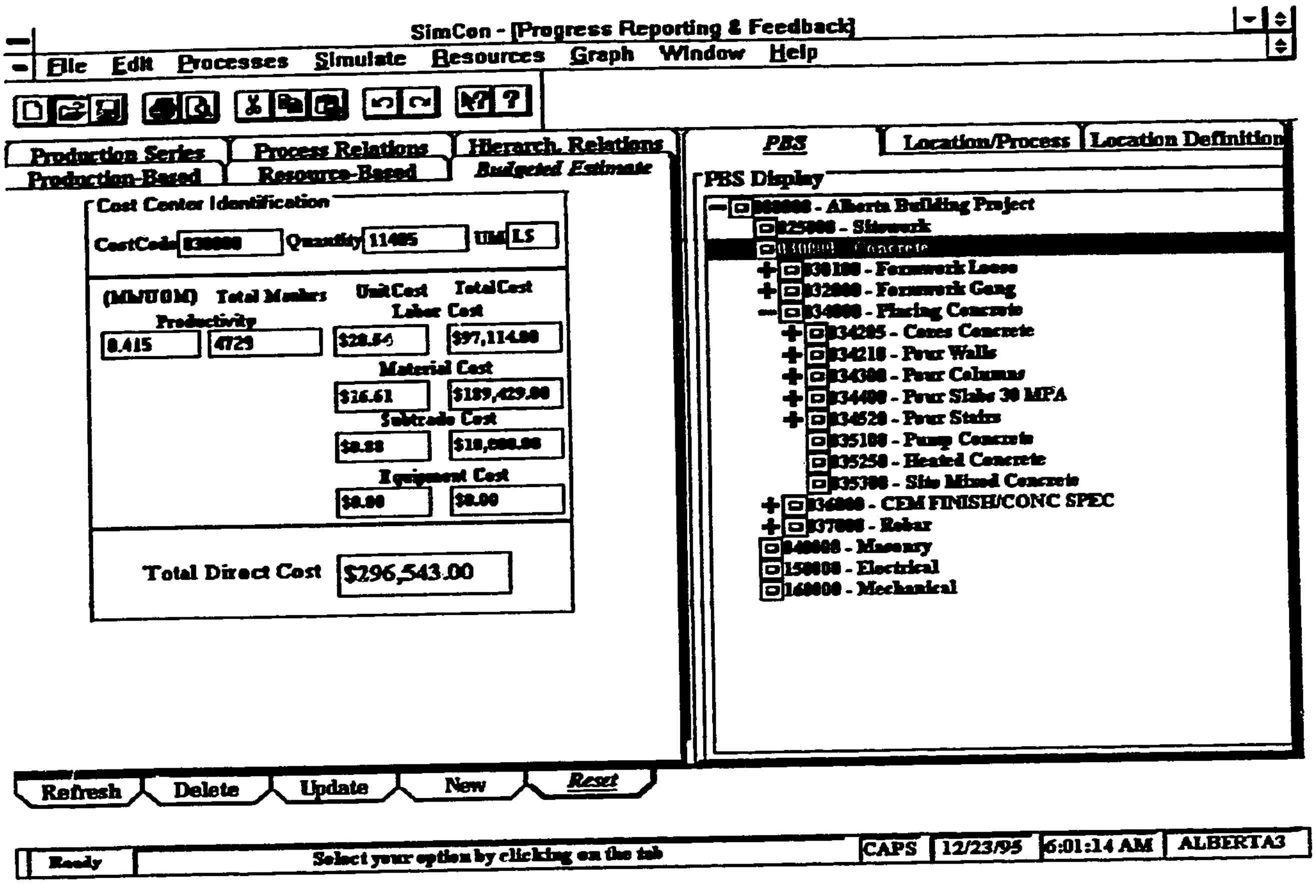


Figure 4.22 ***Budgeted Estimate Details and 'Roll-up' Mechanism in SimCon***

4.4 LIMITATIONS OF THE PROTOTYPE SYSTEM

The SimCon prototype system was developed for the following reasons:

- Demonstrate the feasibility of developing the computer system
- Demonstrate the practicality of implementing project modeling as described by the research concept
- Demonstrate the benefits of simulation-based project control

- Test and validate the SimCon concepts

In the current form, the limitations of the SimCon-prototype computer program are mainly in utilizing an external simulation engine (SLAM II) to simulate the project. The computer interface between SLAM II and SimCon-prototype is not an efficient way to build projects. Moreover, mistakes developed by users are not all detected because of the above stated objectives of SimCon.

It is suggested that an internal simulation engine be developed to simplify the linking between the program modules and limit a user's computer interaction to SimCon.

4.5 CONCLUDING REMARKS

This chapter utilized object oriented concepts, event driven programming, relational database management, and a simulation language to demonstrate the applicability of SimCon concepts in enhancing project modeling, progress reporting, and project control. The use of SimCon-prototype demonstrated the feasibility of developing the computer system, showed the benefits of simulation-based project control, and tested and validated the SimCon concepts. Chapter 5 presents more details on the use of SimCon-prototype system with a building construction case study application.

CHAPTER 5

CASE STUDY: SIMULATION OF THE ALBERTA COLLEGE BUILDING PROJECT

5.1 INTRODUCTION

In this chapter, the SimCon program is used to study and report progress on construction of the superstructure of the Alberta College Building (ACB), Edmonton, Alberta, by implementing single production links, continuous production links and progress reporting by exception concepts. Progress updating is implemented using production-based and resource-based reports from within SimCon's reporting feature. Variance analysis includes comparing an actual reported value to an estimated value. Estimated values in a stochastic simulation model are usually represented in the form of minimum, maximum, mean, and standard deviation values. The user in SimCon can specify specific percentile values or just the mean value for the variance analysis report and for other reports such as bar charts or resource planning requirements.

Construction of superstructure of the Alberta College building was selected to demonstrate the capabilities of SimCon in solving a problem of reasonable complexity. This chapter explains the implementation details of project modeling and progress reporting. Project modeling procedure is aimed at demonstrating from a user's perspective the relatively little effort of planing a project. Project planning in SimCon includes developing hierarchical production breakdown structure, identifying construction resources, constructing modular and independent processes, linking of processes, and simulation modeling. Project control in SimCon includes progress reporting by exception on significant deviations using production- and resource-based reporting.

The developed model for representing superstructure construction of ACB encompasses formwork erection processes, rebar processes, concrete processes, and formwork dismantle processes. Detailed analysis of construction elements that are modeled in SimCon for practical illustrative purposes are building slab on grade, elevator core, slab and beams, and columns.

The purpose of this chapter is to demonstrate another alternative method that provides better resource and production control. Better resource control in system simulation is achieved through the modeling of dynamic resource interactions, percent utilization and waiting time. Production control in system simulation is achieved through the cyclic and repetitive process modeling.

5.2 GENERAL DESCRIPTION OF THE ALBERTA COLLEGE BUILDING PROJECT

The Alberta College - Phase II project is located on 10050 McDonald Drive, Edmonton, Alberta, Canada. Prime consultant for the project was Wensley Spotowski Architectural Group. General contractor for the project was PCL Constructors Inc. of Edmonton. The project was constructed in 18 months (January 14, 1993 to June 30, 1994). Original contract amount was $6,496,371.00. Gross building area is 7,127 m^2 (81,270 sf) and consists of 6 floors. Slab on grade area is 1,212 m^2. The main floor includes a full service cafeteria. Levels 2, 3, 4 and 6 consist of multi-use classrooms and laboratories while level 5 includes specially constructed music studios. The reinforced concrete frame is clad with a combination of brick, stucco, and curtain-wall.

The building was constructed with minimal changes to the original contract (less than 50 change orders were issued for a total of less than $200,000). This project was modeled and tested under various work and cost breakdown structures in CPM (P3 - Primavera Project Planner Schedule) and computer simulation (SimCon & SLAM II).

The original objective from the author's work at PCL was to develop an efficient integrated cost/schedule plan for the project in P3 that will provide most control of resources and production at minimum cost and time. Various models were implemented and tested by varying the structure of cost codes, activity details, and resource details. Major requirements were having a system that will take minimum time to update, provide the required control of resources, and be relatively easy to develop and implement.

PCL uses the Masterformat of cost codes for cost control of building projects. Field reports from site include quantity work sheets and time cards that follow the standard cost code structure. The objective from such reports is to control specific crew performance and material costs. For example, a formwork crew is controlled by tracking production on formwork related activities. Similarly, a steel sub crew can be controlled by tracking production on steel placing activities.

Information about the Alberta College Building was gathered from the original estimate, barchart schedule, cost coded estimate, labor cost reports, total project cost performance reports and change order sheets. Revised activity-based estimates and activity-based cost coded budgeted estimate were implemented by the author to demonstrate the possibility of producing the standard PCL reports from within P3.

5.3 MODEL OF THE ALBERTA COLLEGE BUILDING

The emphasis of project modeling in SimCon is towards demonstration of progress reporting by exception and the flexible modeling of logical sequence of activities. The simulation model will only include slab on grade, superstructure slabs & beams, columns, and elevator core concreting operations. The concreting operation includes prefab formwork, formwork erection, placing rebars, placing concrete, curing, and dismantle of formwork. Both repetitive processes and non-repetitive processes will be used to model the construction processes in order to demonstrate the progress reporting by exception concepts within the hierarchical production breakdown structure.

5.3.1 Hierarchical Production Breakdown Structure in SimCon

This section provides a step-by-step procedure of developing the superstructure modeling in SimCon. The project is started in SimCon by defining a new project and naming it. Second, cost centers for controlling the project are hierarchically identified. This list can be either built from 'scratch' or built from existing cost center library as shown in Figure 5.1. Cost centers are defined in SimCon by defining a field description, a parent name and assigning a unique cost code. Following this, the update command as shown on the lower left corner of Figure 5.1 is clicked to add the new cost center to the existing hierarchical list.

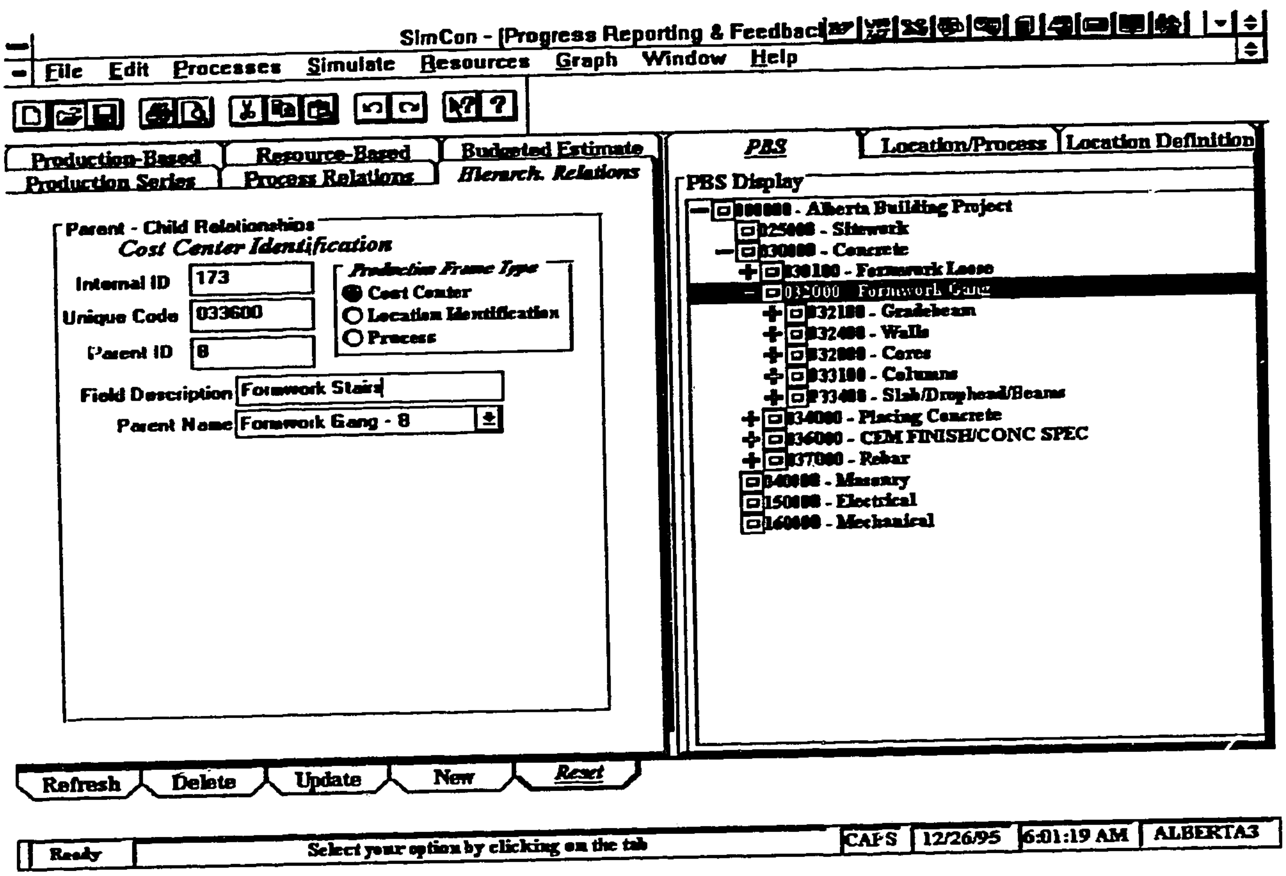


Figure 5.1 *Constructing Cost Centers for the Alberta College Building*

A location breakdown center (LBC) is defined by selecting first the 'location definition' tab on the upper right corner as shown in Figure 5.2 and then adding a location field description and its parent. The unique code is automatically added by the computer but the user can change it to any unique number if required. LBC allows project control by location and resource allocation as discussed in Chapters 3 and 4.

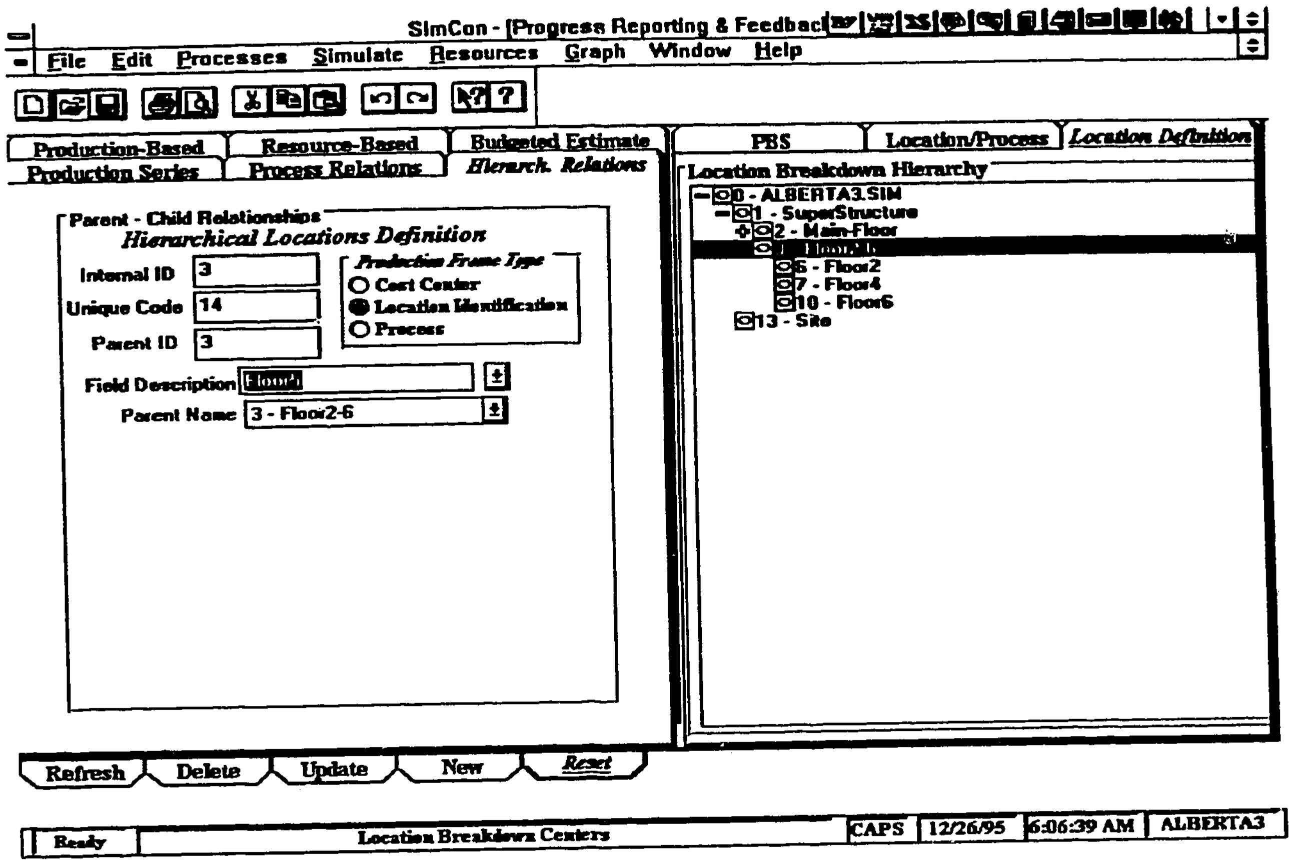


Figure 5.2 Constructing Location Breakdown Centers for the Alberta College Building

Processes can be added to the location structure by either retrieving modular processes from SimCon's library or using the graphical interface as shown in Figure 5.3 and Figure 5.4. The procedure of selecting a modular process from SimCon's library is very simple. It includes selecting the process name and location parent name. Adding a new process to a location is also done by adding the process name and the location name. The difference is that in the library process the modeling elements already exist, however, in the new process the modeling elements have to be constructed as shown in left side of Figure 5.4.

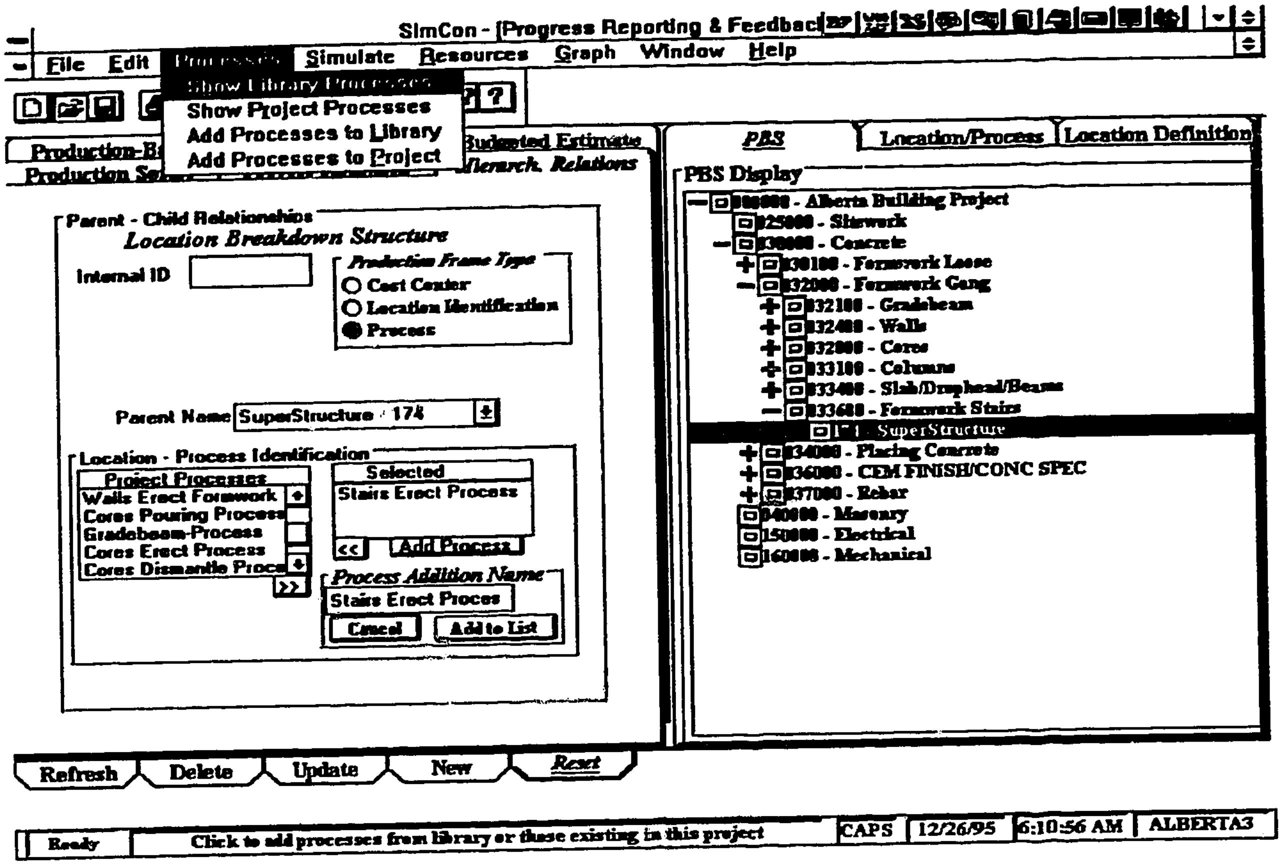


Figure 5.3 ***Constructing Processes for the Alberta College Building - Retrieving Modular Construction Processes From SimCon's Library***

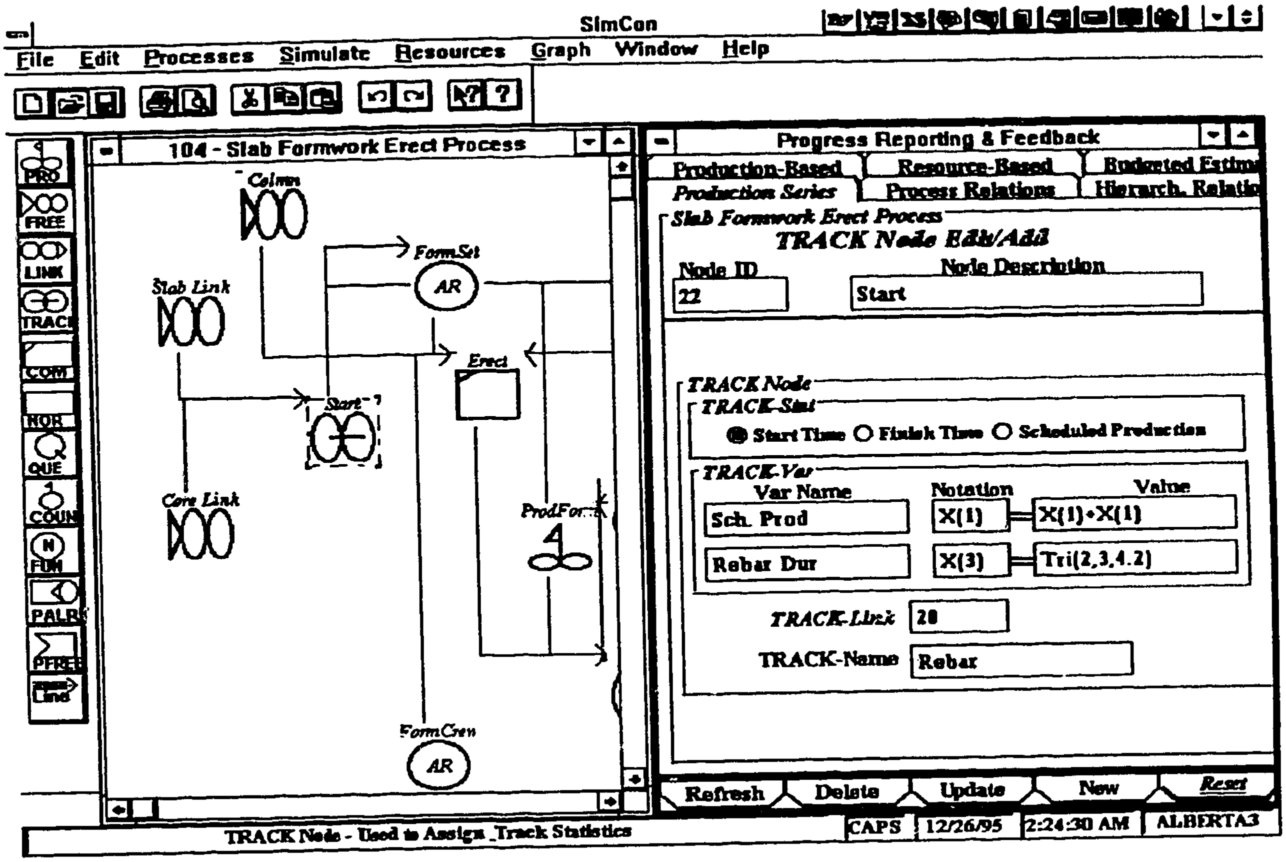


Figure 5.4 ***Constructing Processes for the Alberta College Building - Building Process Nodes from SimCon's Graphical Interface***

5.3.2 Planning: Resource Allocation & Logic Flow Diagrams

Planning is the process of representing the project scope into definable and measurable tasks/processes and establishing the logical inter-dependence among them (Halpin & Riggs, 1992). Scheduling establishes project completion time by imposing constraints on resource availability, productivity levels, and starting and finishing activity times.

Resources (material, equipment, and labor crews) are dynamically allocated in a simulation model. The network models that represent the conceptual plan are constructed independently of the resource quantity available. For example, the effect of changing the quantity of form sets on formwork crew utilization and project duration can be easily analyzed by only changing the quantity of the resource (i.e., the number of form sets). In a CPM network and using the same scenario, the logical relationships between activities have to be changed to accommodate the change in the quantity of form sets. Figure 5.5a shows two ways to model activity sequencing in CPM when two different quantities of form sets are used. Figure 5.5b shows a similar model in simulation which is independent of the quantity of resources available. Erection of formwork on a successor activity does not depend on dismantling of formwork on a previous task but on availability of formwork. This is modelled in simulation by the use of an await node to check for resource availability and a free node to free the resource and make it available. Priority rules are used to allow the user to allocate resources. For example, a priority rule would allocate a formwork crew to erection of formwork versus dismantling of formwork if both activities can start at the same time. This rule is important because if only one formwork crew is available then decision will have to be made on whether to dismantle formwork on current floor or erect formwork on next floor (assumption is that two form sets are available). Simulation modeling provides more flexibility to test various models for best outcome.

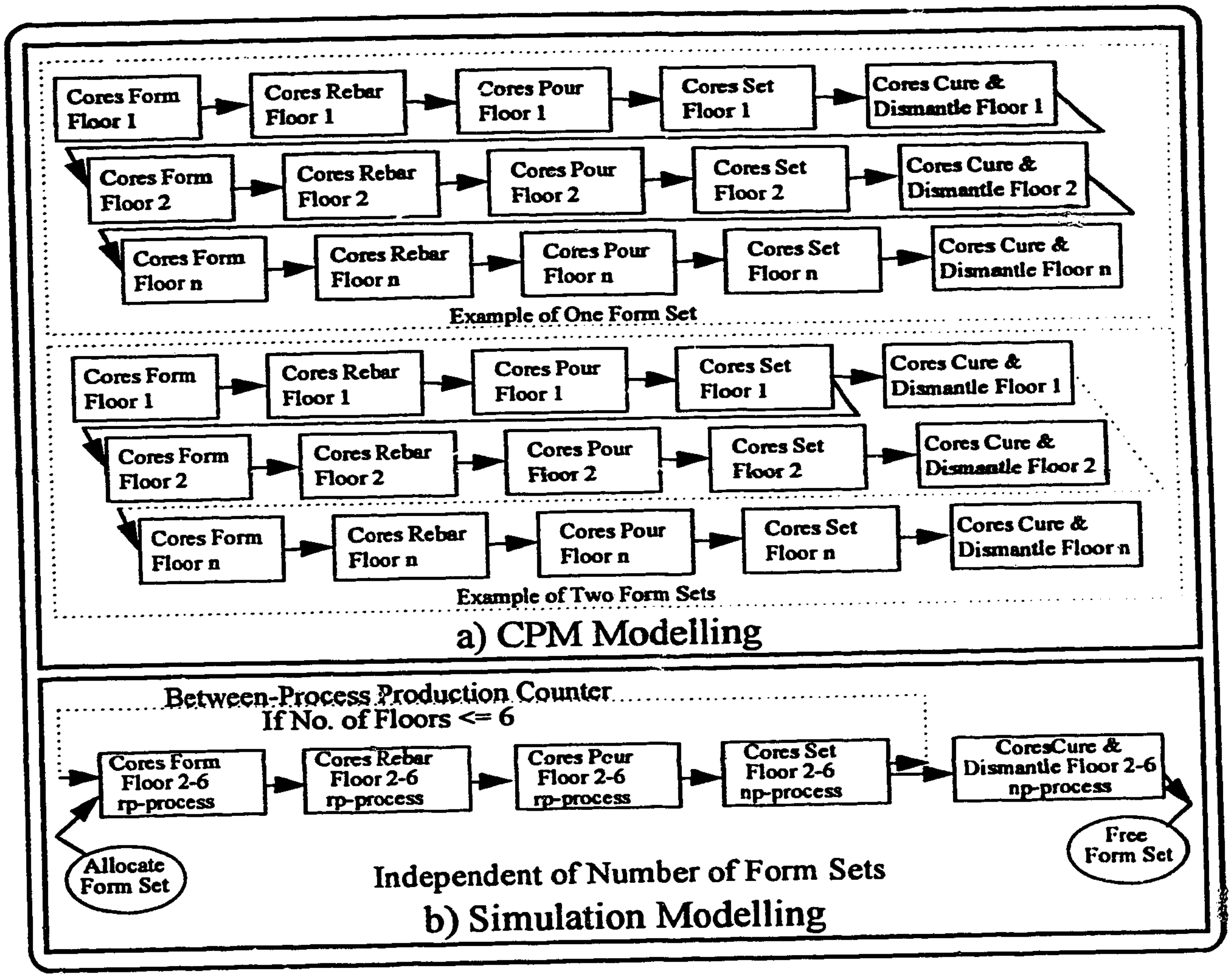


Figure 5.5 ***Comparison Between CPM and Simulation in Resource Effect on Logical Relationships; a) CPM Modelling; b) Simulation Modelling***

5.3.3 Process Sequencing for the ACB Project

The processes considered in the ACB superstructure are slab on grade (SOG), elevator core, columns, and slabs processes. The activities considered for SOG construction as shown in Figure 5.6 are the following: SOG forming; SOG rebar placing; SOG concrete placing; and SOG curing and dismantle of formwork. Following completion of SOG concrete setting, the columns' and cores' processes can start if resources are available.

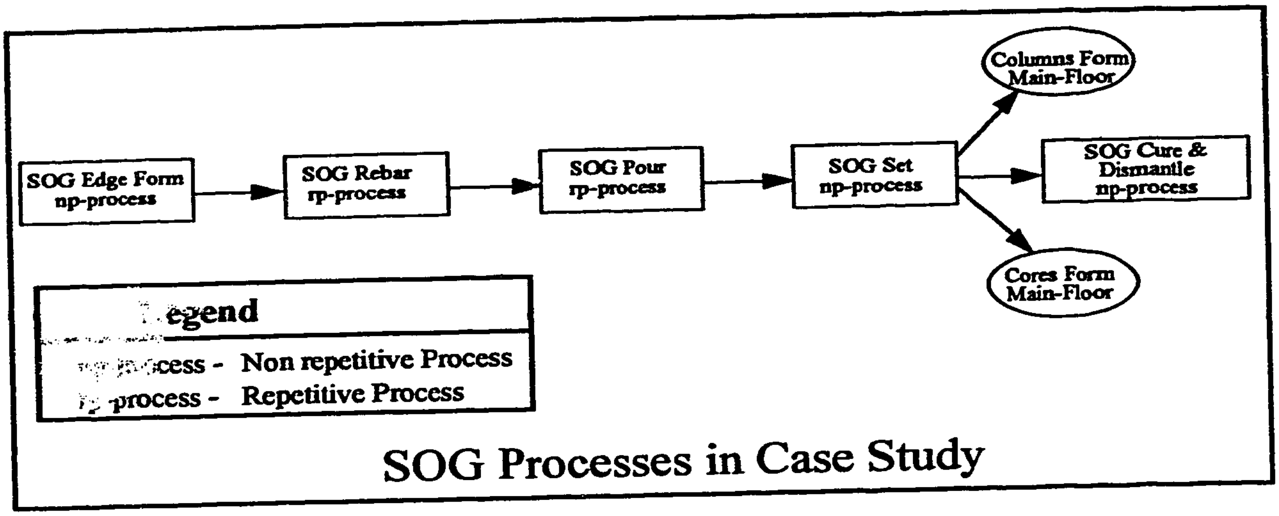


Figure 5.6 ***Network Plan for SOG Processes***

Columns' formwork process and cores' formwork process of main-floor are successors to SOG concrete setting. Main floor processes are shown in Figure 5.7 and consist of columns', cores', and slabs' processes. Slab formwork erection starts after pouring concrete for cores and columns is done. Following the curing of formwork for slabs, prefabrication of formwork for columns and cores on floors two to six begin.

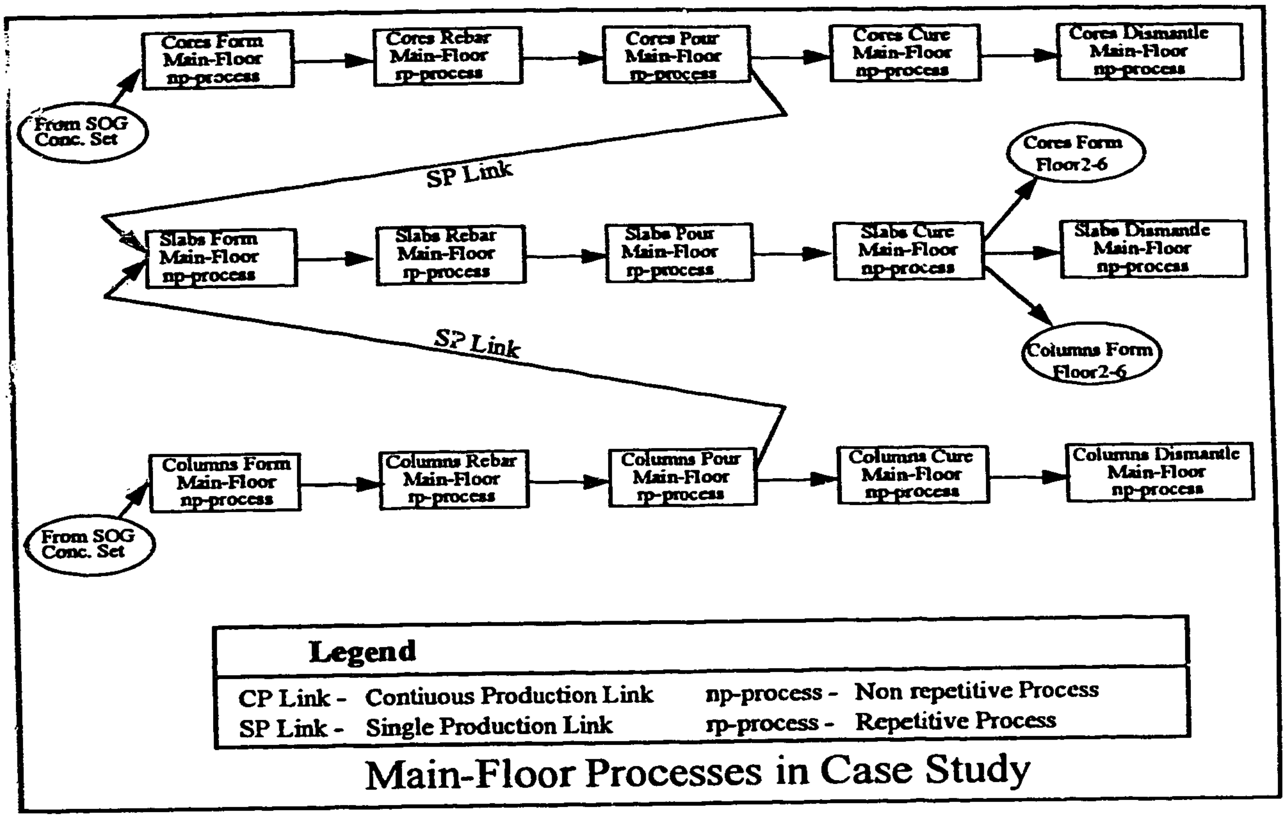


Figure 5.7 Main-Floor Sequence of Processes

The typical floor is divided into two zones during construction as shown in Figure 5.8. Each zone is about 606 m^2. Elevator core is located on Zone 2 of the building. Formwork Erection of the cores and columns on the typical floor starts after curing of slab on main floor.

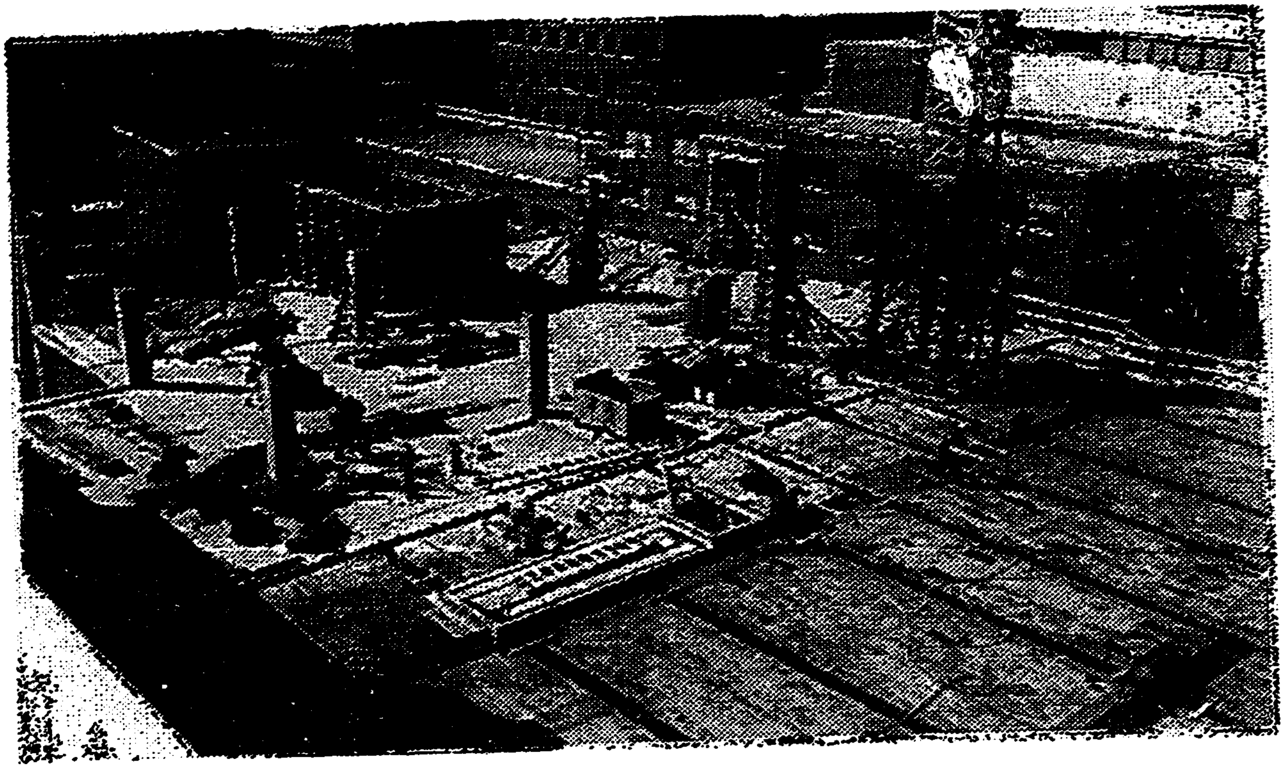


Figure 5.8 Photo Showing Two Zones of Construction on Typical Floor

The repetitive processes on the typical floor (Floor2-6) are shown in Figure 5.9a. Construction on any of the typical floors starts in zone 1 and then goes to zone 2. For example, column processes start on zone 1 and then zone 2. Following completion of columns on zone 1 and zone 2, slab processes start on zone 1 and zone 2, respectively. A continuous production link is used to represent this sequencing. The number of zones specified in the continuous production link is equal to 2. The continuous production link with a value of 2 ensures that only two runs are made on columns until a slab zone is completed if the required resources are available. Without a continuous production link then total construction of each zone would have to be done separately (i.e., slab on zone 1 follows columns on zone 1, and slab on zone 2 follows columns on zone 2).

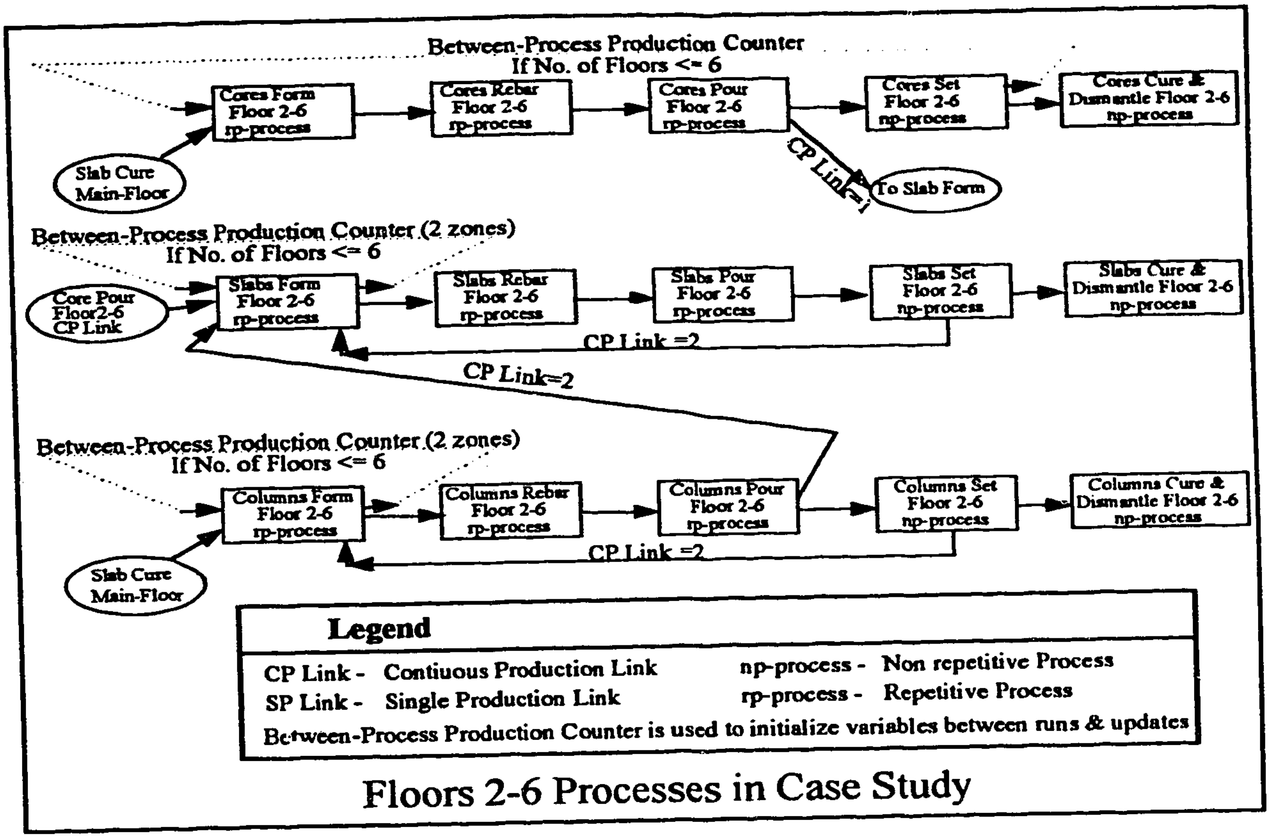


Figure 5.9a ***Floor2-6 Sequence of Processes***

Figure 5.9b shows the continuous production link implementation in SimCon. The continuous production link element is automatically built by the SimCon program after a user specifies that a continuous production link exists between two processes. For example, a user will click, using the right mouse button, on a node and selects from a popup menu a continuous production link connection. The user after that selects the process and node to link to and automatically the LINK node and the FREE node are added to both processes to confirm the user's decision.

With a continuous production link construction of columns on zone 2 can start even if slabs on zone 1 have not started. Another type of continuous production link exists between cores and slabs such that core construction is always ahead of slabs by not more than one floor. As shown in Figure 5.9a, with a continuous production link between cores and slabs, core construction can not proceed to floor n+1 until slab construction on floor n is completed.

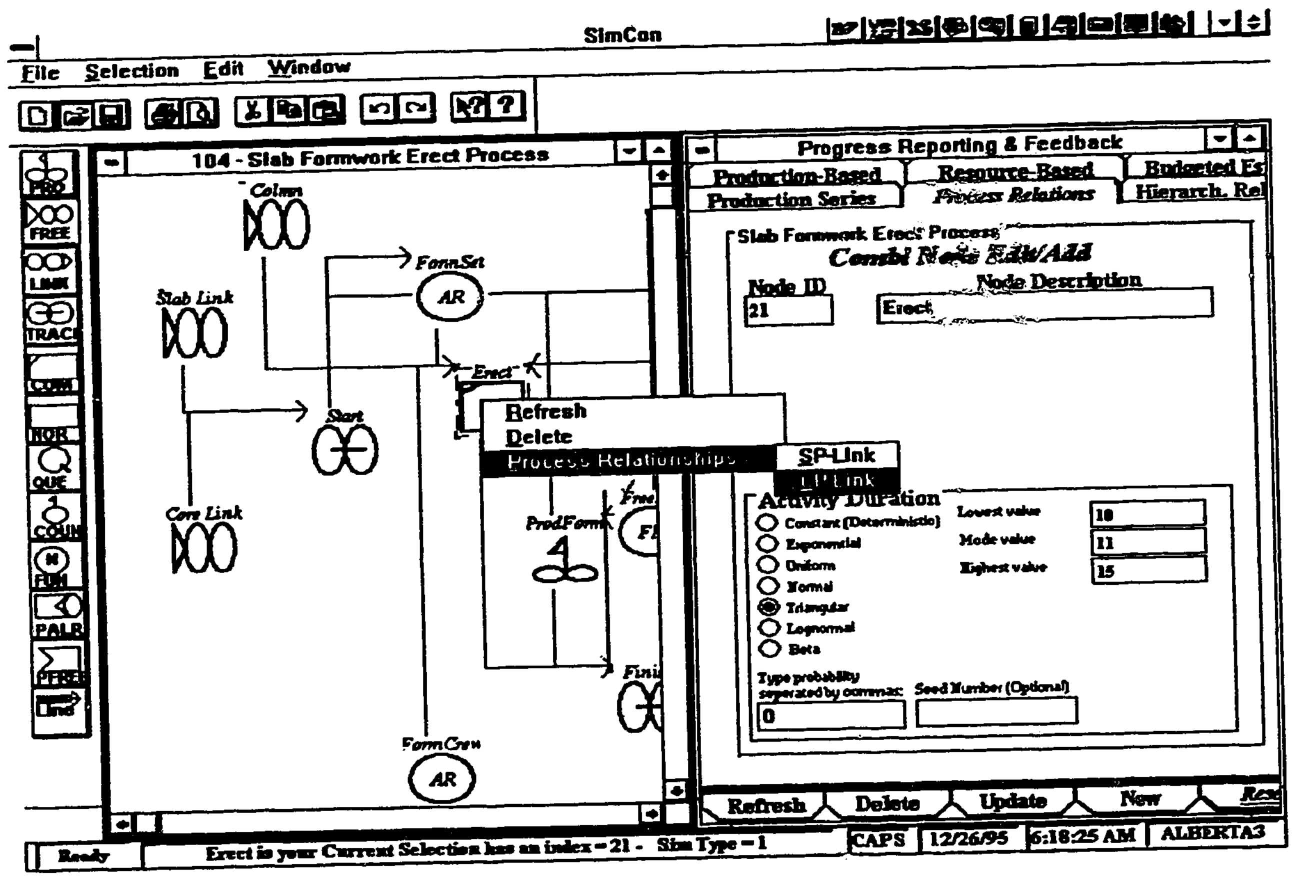


Figure 5.9b ***Continuous Production Link Implementation in SimCon***

Figure 5.10 shows a detailed representation of the continuous production link between cores' processes and slabs' processes. The SimCon representation of the model is shown in Figure 5.10a. The translate module in SimCon will create into a SLAM II network a resource block, transform a LINK node into an Await Node (SLAM II Node for Resource Allocation), and transform a FREE node into a Free Node (SLAM II Node to free a resource) as shown in Figure 5.10b.

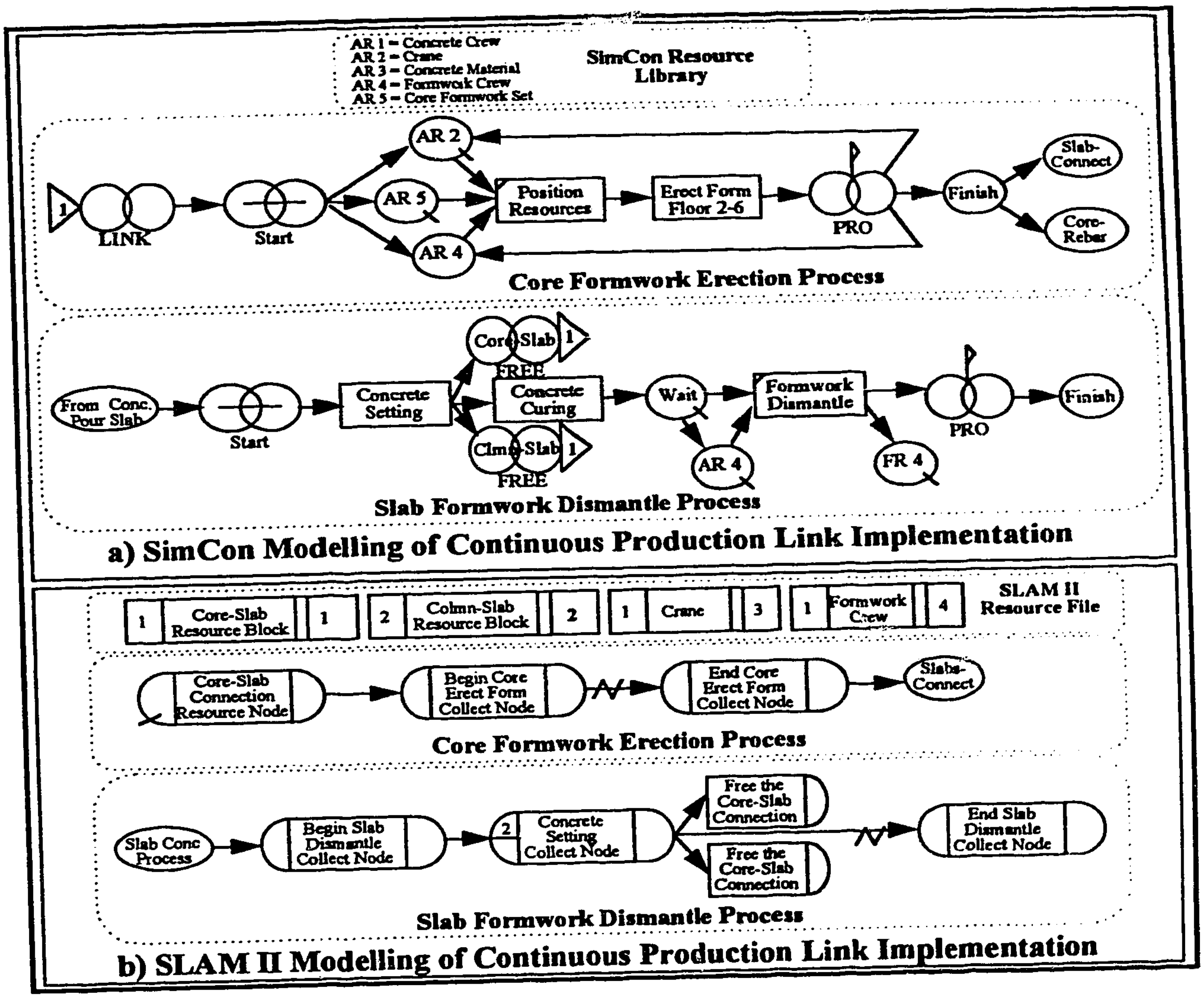


Figure 5.10 *Schematic View of SimCon and SLAM II Representations a) SimCon Modelling of Continuous Production Link b) SLAM II Modelling of Continuous Production Link Implementation.*

5.3.4 Process Models for the ACB Project

Process development in SimCon can be interactively visualized using the graphical computer prototype system as shown in Figure 5.4. The actual computer screens are not used here to show the actual processes because of screen quality and space limitations. SimCon-process models were developed for all the superstructure elements discussed above. Modular processes are stored in SimCon's library and were referenced during process modeling. Figures 5.11 through 5.15 show the typical developed slab process models for the ACB project.

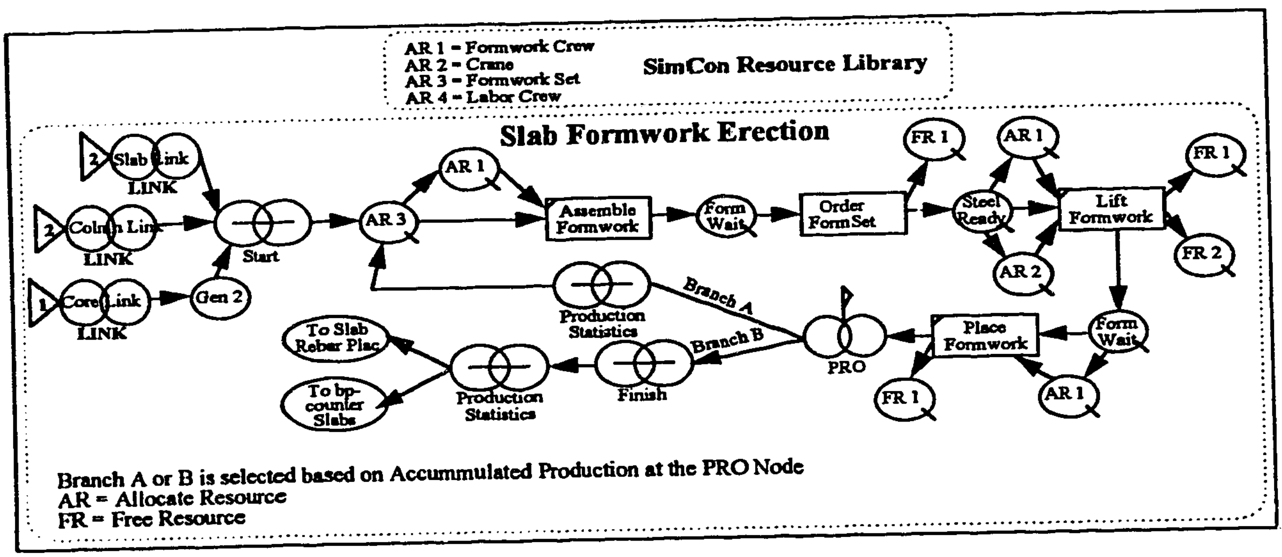


Figure 5.11 Formwork Erection Process for Repetitive Slabs Typical Floor

Figure 5.11 shows the formwork repetitive process for slabs in the typical floor. Slab formwork erection in zone 1 starts after pouring concrete columns process is completed in the same zone and after core pouring process is completed. A generate function node is used to generate 2 entities for slab erection to make up for the two zone construction in the same floor. Resources modelled in this process are a crane, formwork crew, and a formwork set. The production counter node for slabs (between processes) starts following the finish of formwork erection in the first zone. Modeling details in any of the processes is dependent on the construction method and the required control of resources. The models are built with sufficient details to prove the new concepts presented in this thesis.

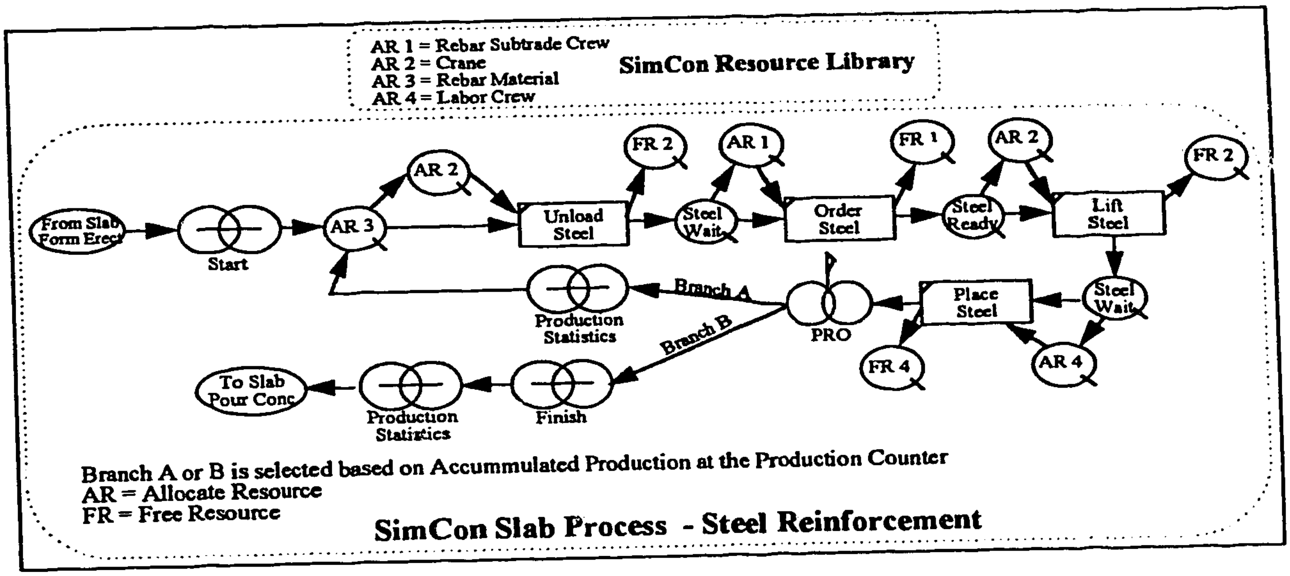


Figure 5.12 A Typical Steel Reinforcement Repetitive Process for Slabs

Figure 5.12 shows the steel reinforcement repetitive process for slabs in the typical floor. The production counter in this process controls the number of cycles completed before pouring concrete process can start. The slab rebar process and the formwork erection process can be both running at the same time in the same floor. For example, slab rebar process can be working on zone 1 while formwork erection process can be working on zone 2. This sequence is made possible by the continuous production link between slab formwork erection process and the slab concrete setting process. Representing the same cyclic sequence in a typical CPM model can be very complex requiring many more activities to model the same scenario.

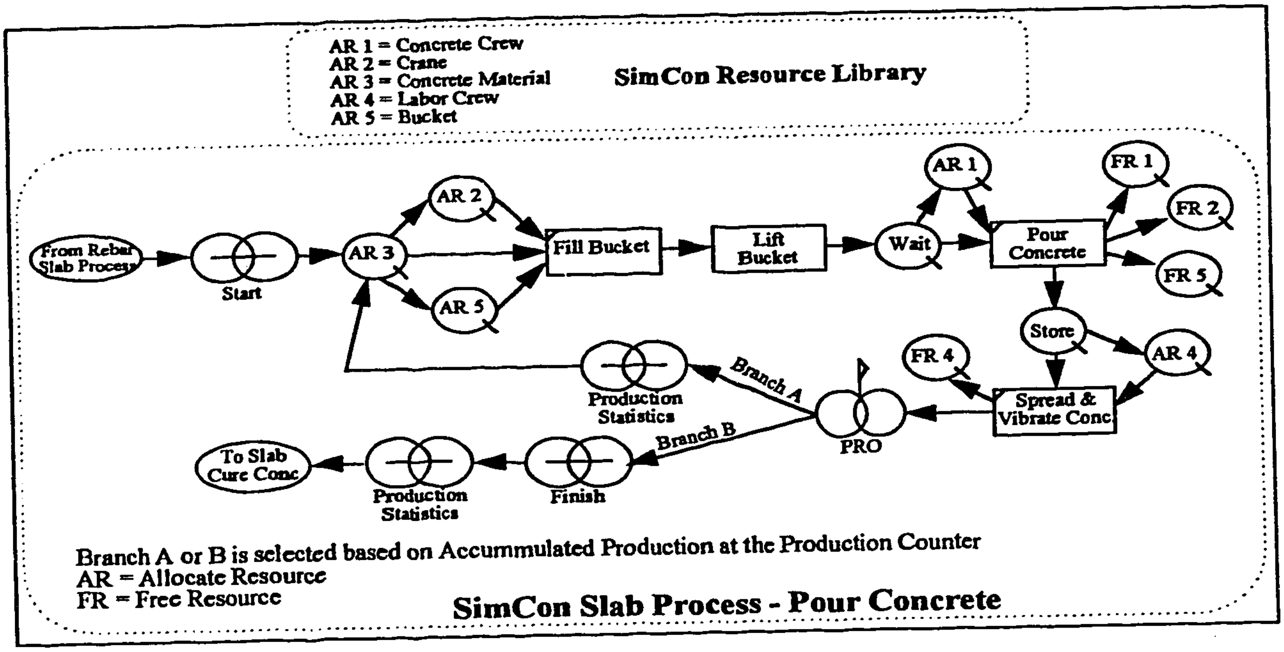


Figure 5.13 A Typical Concrete Pouring Repetitive Process for Slabs

Figure 5.13 shows a typical pouring concrete repetitive process for slabs on the typical floor. Pouring concrete in any zone starts after the rebar process in the same zone is completed. The resources modelled in this process are concrete crew, crane, concrete material, labor crew and concrete bucket. The quantity of each resource can be easily changed to study and improve process performance.

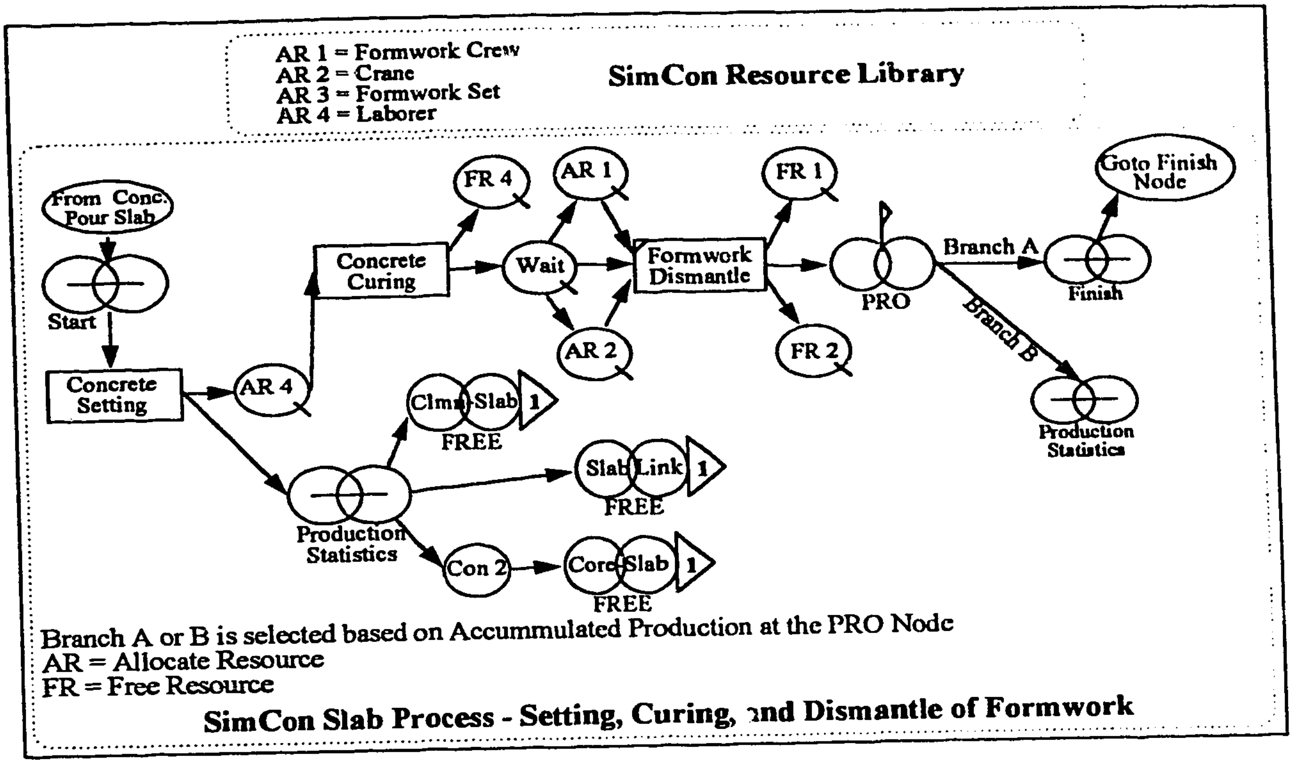


Figure 5.14 ***A Non-repetitive Process Showing Concrete Setting, Curing, and Dismantling for Slabs***

Figure 5.14 shows the concrete setting and curing and formwork dismantle non-repetitive process. One laborer is used for curing the concrete. Formwork dismantle task utilizes a crane and formwork crew resources. A production counter node is used to keep track of number of slab formwork dismantled and to determine if construction of slabs is completed. Three FREE nodes are used after the concrete setting activity. A FREE node is used to inform the column process that slab setting is complete in the specific zone. Another FREE node is used to inform core process that slab setting for one floor is complete and a FREE node is used to inform the slab formwork erection that one zone is complete. A consolidate function node is used to accumulate 2 entities before freeing the core-slab connection. An accumulation of 2 entities is implemented because two zones were used in the construction of the building as discussed earlier.

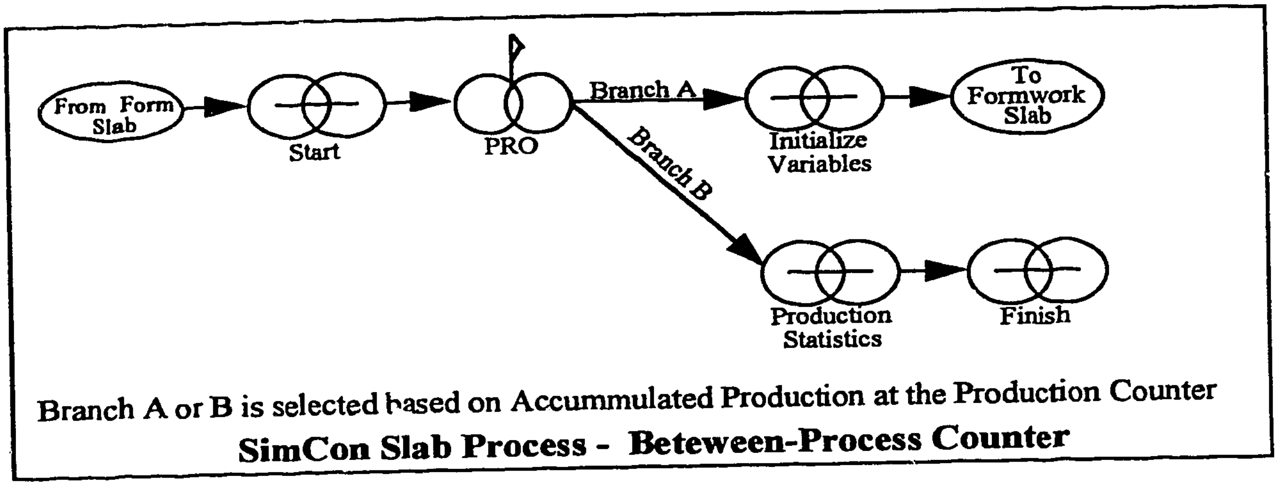


Figure 5.15 SimCon Representation of a PRO Node Between Slab Processes

Figure 5.15 shows the simple representation of the PRO node between slab processes which is used to control number of zones/locations completed and also to initialize variable used for the formwork, rebar, concrete, and dismantle processes. For example, the variables that are reinitialized in the PRO node between slab processes are the following: the number of cycles completed in a specific zone for formwork erection, rebar placing, and concrete pouring; the number of floors completed; the actual progress recorded values; and concrete hoisting duration between floors. As explained in Chapter 3, a PRO node between processes is used to initialize processes and variables between runs and updates.

The division of processes as modelled above offer a better planning and control of projects. It provides a more true representation of the repetitive nature of construction activities. For example, the representation of processes as shown in Figure 5.16a does not represent the actual construction sequence unless there is only one slab formset. This is because if there are two formsets then formwork erection on zone 2 of the same floor can start as soon as formwork erection on zone 1 is complete if there is a formset available. But the sequence of processes as shown in Figure 5.16a does not permit this to happen even if there is more than one formset because formwork erection on zone 2 can not start until formwork is dismantled in zone 1. In project planning the construction manager is usually interested in trying various scenarios to determine best solution. If a planner wants to change the number of form sets to more than one then either the logical sequence between processes has to be changed or a continuous production link is used as discussed in Chapter 3. Figure 5.16b shows the advantages of using a continuous production link in modeling the ACB project. The logical diagram flow is not affected by the number of resources that exist or the number of typical zones that are modelled.

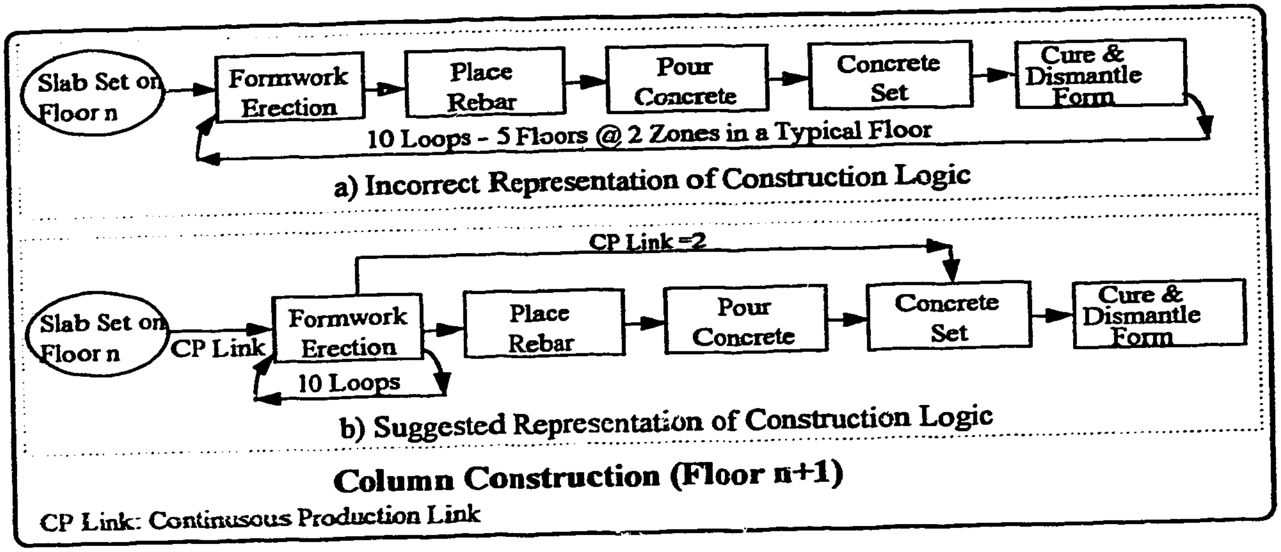


Figure 5.16 ***Schematic View for Modeling a Column / Slab Operation; a) Incorrect Way to Represent Cyclic Operations; b) Simulation Representation of Construction logic.***

Other processes showing modeling details of cores and columns can be found in Figures E1 to E10 in Appendix E. The processes are similar in modeling concepts to the slab construction and are not included in this chapter. The sequence of construction of column processes are very similar to slab construction sequence elements. The sequence of construction of core processes are also similar but are not divided into zones, since the elevator core is only located on zone 2 of the building.

5.4 SIMULATION OF THE ALBERTA COLLEGE BUILDING

The information provided in the previous sections of this chapter constitute the project modeling phase of a project. These models are translated into SLAM II models using SimCon prototype system as shown in Figure 5.17a. Every SimCon-process is translated into a separate SLAM II network file. Resources that are defined for the ACB project are also translated into one file. This mechanism provides an organized information structure for easier planning and control. The 'Control File', as shown in Figure 5.17b, provides information on the number of runs required and the name of the project to be used for output reports. Simulation end time is at the end of pr[illegible] This simulation time is the 'data date' that can be used during the control phase to update a project. At the planning phase of a project, simulation end time is stated as 'infinity' to represent entire project modeling. Following that the user can adjust specific activity connections or durations in SLAM II.

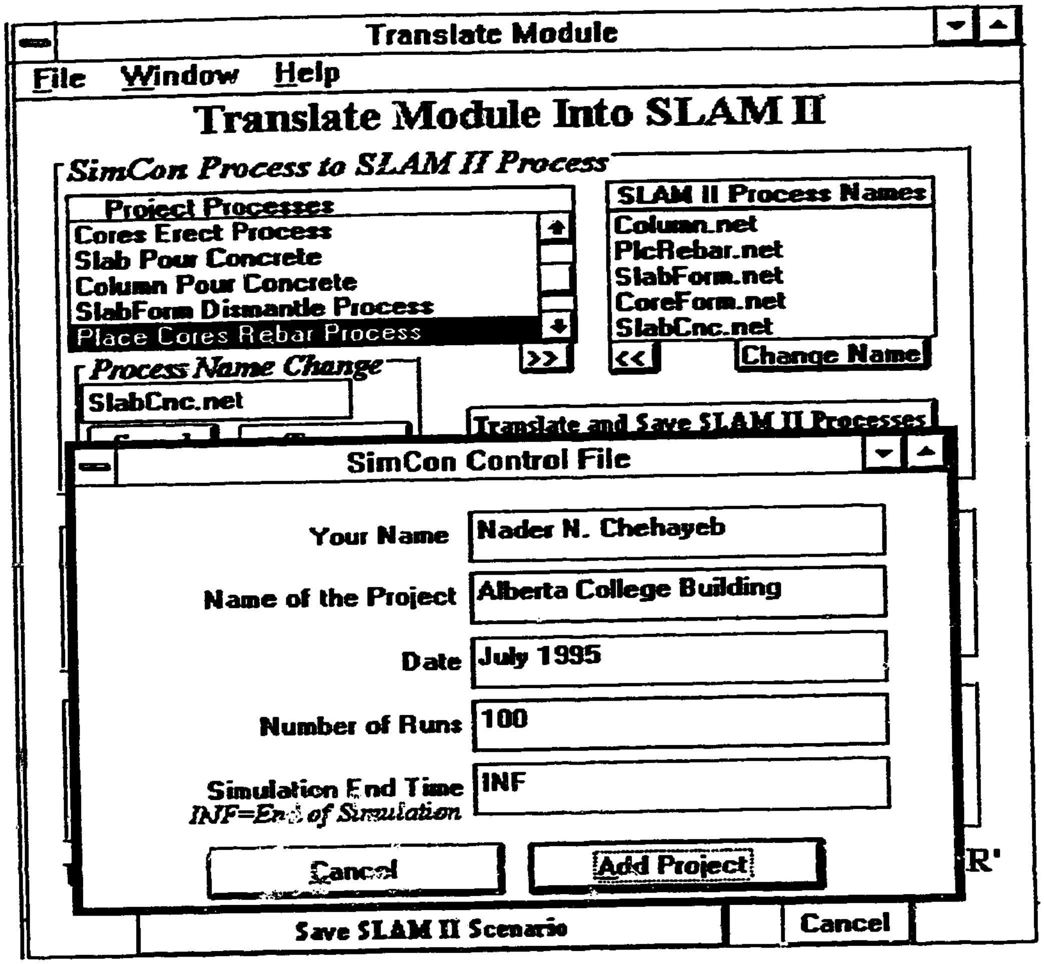


Figure 5.17a SimCon Translate Module of the ACB Project into SLAM II

```
'<<<<"SimCon.Con">>>File Name

GEN,Nader N. Chehayeb,Alberta College Building,July
1995,100,Y,Y,Y/Y,Y,Y/S,72;
LIMITS,50,95,60;
NETWORK;
INITIALIZE,,,N;
FIN;
```

Figure 5.17b Translated SimCon Control File of the ACB Project

SLAM II models in their textual representation are shown in Appendix F-1. The user after that runs the simulation program to model the ACB project. One hundred runs were executed for this case study to model the various uncertainties associated with duration estimates and resource allocation. For the purpose of this case study, triangular distribution was used to estimate activity durations for most processes. The SLAM II simulation results for the ACB superstructure are provided in a text file format as shown in Appendix F-2. This same text file is automatically imported into SimCon using the graphical interface as shown in Figure 4.18.

5.5 SIMULATION PLANNING RESULTS

The simulation results indicate a mean project completion time of about 22 weeks (873 hours) with a standard deviation of 2 weeks (83 hours) for the construction of the ACB superstructure. Schedule time as obtained from the simulation model was based on a 5 day work week and 8 hour work shifts per day. The 5th and 95th percentiles for the project completion time obtained from the model are about 18.5 weeks (736 hours) and, 25.5 weeks (1010 hours) respectively. A graphical plot showing the quantile estimates for project completion time as generated in SimCon is shown in Figure 5.18. The 95th percentile confidence interval around the respective quantile estimates is shown in Figure 5.18. The mean is estimated at the 50th percentile because the simulation output for project completion time was normally distributed.

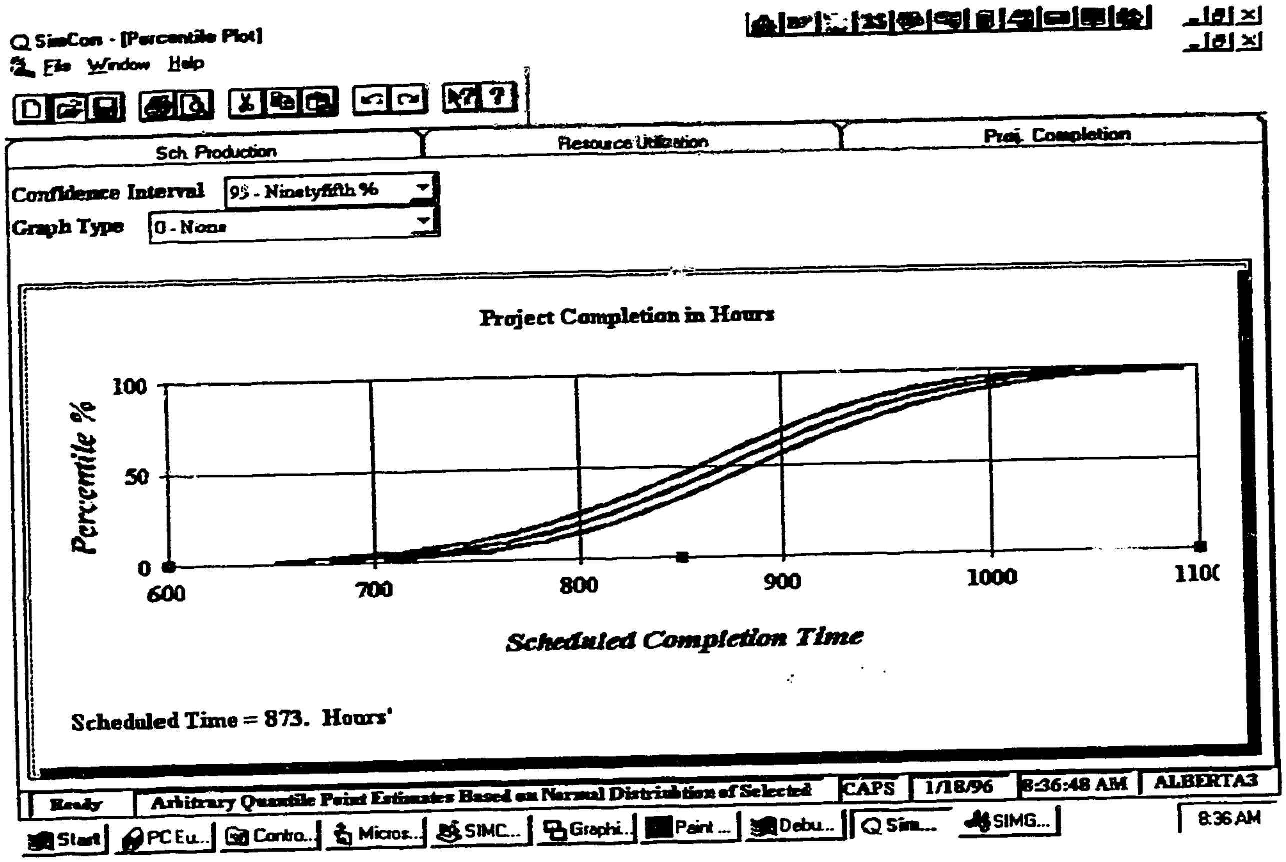


Figure 5.18 ***Cumulative Distribution of the Project Completion Time with a 95% Percent Confidence Interval From SimCon.***

To illustrate the advantages of SimCon from the planning perspective, the modeling of the ACB project required the use of 31 separate processes and 35 logic relationships connecting processes. On the other hand, 76 activities and 85 logic relationships connecting activities are required in CPM modeling. This difference becomes more evident in a high rise building. For example, in a high-rise building consisting of 30 typical floor construction then the difference is more pronounced. This will require 31 SimCon-processes and 35 logical relationships connecting processes. In CPM it will require 364 activities and 425 logic relationships connecting activities to model the project. Even though, it might take more time during the planning phase to construct the detailed representation of nodes in processes but more advantages can be seen in the advanced resource control, evaluation of non-value added tasks, and during the progress reporting phase.

5.5.1 Production-Based Planning Results

Production-based plan results are shown in Table 5.1. The 5th and 95th percentile values of the start and finish of each processes is calculated from the mean and standard deviation. These percentile values are originally set by default in SimCon and can be adjusted to show any percentile values. These values can be used to establish an estimated start and finish of each process. The scheduled production estimates show the expected production on a specific date. As shown in Table 5.1, the scheduled production is zero reflecting the fact that production has not started. Each process is represented by its internal identification number and its name. The internal identification number is used to connect the production reporting to respective processes and cost centers in the production breakdown structure hierarchy. The PRO-Ratio for each process is directly related to the original production description as shown in Table 5.1. For example, the PRO-Ratio of formwork erection of cores has a production ratio of 24.6 representing the amount of production completed after every simulation cycle. The dismantling of formwork processes are non repetitive processes and all others are repetitive processes. The 'Stat' column represents the status of each progress as either N (not started), I (in progress), or C (complete). All the processes have an N status showing that the project has not started. Definition of various variables is described in more detail in Chapter 3.

Table 5.1 ***Production-Based Plan for the Alberta College Building - One Set of Formwork & One Formwork Crew for Columns & Slabs***

UOM = Unit of Measure
Org.Budg. = Original Total Production Budget as Planned
Cur.Budg. = Current Total Production Budget after the last update
Sched. = Scheduled Production is equal to Current Budget up to the Data Date

Process Name	UM	S	UC	Duration				Production						Cost					
				Start 5 %	Start 95 %	End 5 %	End 95 %	Org	Sched 35 %	Sched 65 %	Plan	Actual	Var	Org	Sched. 35 %	Sched. 65 %	Plan	Actual	Var
(Project Not Started)																			
153 - Cores Erect Process	M2	N	0.8	168	350	627	809	492	0	0	0	0	'0'	$369	$0	$0	$0	$0	'0'
163 - Slab Pour Concrete	M3	N	93	206	388	710	892	1264	0	0	0	0	'0'	$117,552	$0	$0	$0	$0	'0'
164 - Column Pour Concre	M3	N	93	181	363	632	814	[illegible]	0	0	0	0	'0'	$11,625	$0	$0	$0	$0	'0'
184 - Slab Formwork Erect	M2	N	2.2	191	373	699	881	7239	0	0	0	0	'0'	$15,926	$0	$0	$0	$0	'0'
185 - SlabForm Dismantle	M2	N	0	233	415	739	921	826	0	0	0	0	'0'	$0	$0	$0	$0	$0	'0'
135 - Cores Pouring Proces	M3	N	93	188	370	645	827	203	0	0	0	0	'0'	$18,879	$0	$0	$0	$0	'0'
157 - Cores Dismantle Proc	M2	N	0	215	397	675	857	95	0	0	0	0	'0'	$0	$0	$0	$0	$0	'0'
159 - Formwork Column P	M2	N	0.8	168	350	622	804	771	0	0	0	0	'0'	$578	$0	$0	$0	$0	'0'
160 - Column Dismantle F	M2	N	0	471	483	659	841	140	0	0	0	0	'0'	$0	$0	$0	$0	$0	'0'
169 - Place Slab Rebar Proc	MT	N	220	197	379	708	890	65	0	0	0	0	'0'	$14,300	$0	$0	$0	$0	'0'
170 - Place Column Rebar	MT	N	220	173	355	630	812	20	0	0	0	0	'0'	$4,400	$0	$0	$0	$0	'0'
171 - Place Cores Rebar Pr	MT	N	220	173	355	642	824	15	0	0	0	0	'0'	$3,300	$0	$0	$0	$0	'0'

Production-based analysis and reporting is best performed in a repetitive modeling environment. The division of processes on production-bases as shown in Table 5.1 offers a planning and control of projects that defines how work will be accomplished over time. Moreover, it provides a way to use earned value analysis to calculate scheduled production and schedule and cost variance analysis. The advantages of using production-based reporting will be detailed during the progress reporting phase of a project. A barchart can be displayed from the start date and finish date of each process. A TRACK node, as described in Chapter 3, is used to determine statistics on start and finish time of processes. Risk analysis can be easily quantified by having the user specify the significant deviation below which or above which a project planner or manager should be notified. Such a project modeling tool offers more realistic estimates by providing quantile point estimates specifying the lowest and highest expected values as would usually be expected from an estimator. Some of the new scheduling techniques offer similar estimates for activity durations start and finish. However, with SimCon and through the application of simulation to project control these estimates can be provided for production and resource control. In addition, more information can be made available such as non-value adding tasks and resource efficiency and waiting times. Range estimates are very important for determining the higher risk activities because the variance analysis is implement by exception pointing out significant deviation only.

5.5.2 Resource-Based Planning Results

Statistical reports from simulation include percentage idle time and busy time for each resource. Resources can be either of C (contractor crew composition), E (equipment), or S (sub-trade crew composition). Resource-based plan results are shown in Table 5.2. Halpin (1993) stated that "*the management of construction is characterized by the management of resources ... the industry must become more process oriented and look for improved efficiency at the level at which resources interact.*" Non-value adding tasks can be more easily identified from a simulation output. Movement and availability of resources and the productive aspects of processes are central to construction productivity improvement.

Implementing resource utilization in project planning provides a better evaluation and decision mechanism for productivity improvement. Table 5.2 shows the resource planning results of ACB project. Equipment resources have a fixed unit cost and a variable unit cost. Utilization states the percentage of time that each resource is being used during the length of stay at the project. Resource duration as determined from the simulation results are presented as 5th percentile for the expected start and 95th percentile for the expected finish of a resource. The start and finish of a resource is automatically determined from the process to which a resource is allocated to. Any other percentile value can be determined from the mean and standard deviation as required by a user.

Table 5.2 ***Resource-Based Plan for the Alberta College Building - One Set of Formwork and One Formwork Crew for Columns & Slabs***

Total Budgeted Utilization = (Time In Use) / (Resource Duration)
Scheduled Budgeted Utilization = Planned Utilization of a Resource Up to the DATA DATE
Total Budgeted Hours = (Resource Duration) x (Crew Size) x Sched Utilization
Scheduled Budgeted Hours = (DATA DATE - Start Date) x (Crew Size) x Sched. Utilization
Resource Duration = Length of time that a Resource is put into a project (End Date - Start Date)
Scheduled Budgeted Cost = ((Fixed U Cost x (Data Date - Start Date)) x (Crew Size)) + (Var Ut Cost x Sched Bdgd Hours)
Total Budgeted Cost = ((Fixed Unit Cost x Resource Duration)) x (Crew Size)) + (Variable Unit Cost x Total Budgeted Hours)

Resource	Q	UM	Typ	Duration Start 5%	Duration End 95%	Bdg Cost Fixed Unit	Bdg Cost Varl Unit	Utilization Tot. Bdg	Utilization Sch. 25%	Utilization Sch. 75%	Hours Utilized Tot Bdg	Hours Utilized Sched 25%	Hours Utilized Sched 75%	Hours Utilized Plan	Hours Utilized Actual	Hours Utilized Var.	Cost Tot Bdg	Cost Sched. 25%	Cost Sched. 75%	Cost Plan	Cost Actual	Cost Var.
(Project Not Started)																						
FormworkCrew 1	1	Hr	C	656	656	27	0	0.33	.	.	2305	0	0	0	0	'0'	$187,101			$0		'0'
Concrete Crew 1	1	Hr	C	180	682	23	0	0.13	.	.	113	0	0	0	0	'0'	$20,341			$0		'0'
Rebar Crew	2	Hr	S	163	679	0	32	0.33	.	.	2305	0	0	0	0	'0'	$73,751			$0		'0'
Crane	1	Hr	E	177	682	78	42	0.22	.	.	384	0	0	0	0	'0'	$152,644			$0		'0'

Knowing that resources can be involved in more than one activity or process it is almost impossible to track resources' movement on separate activities without detailed monitoring and analysis. However, the method shown in Table 5.2 provides enough information on resource status to determine whether a more detailed analysis is required.

The equations and columns used in the resource-based report as shown in Table 5.2 are explained in Chapter 3. The results from Table 5.2 show that the Formwork Crew and has the highest utilization (0.33) where as the concrete crew has the lowest utilization (0.13). The Rebar Sub-trade Crew has a utilization equal to 0.165 (i.e. 0.33 divided by 2 the quantity of the resource). Based on mean duration (50^{th} percentile for normal distribution), the total actual hours of Formwork crew usage on various processes is equal to 2305 hours and of concrete crew usage 113 hours. Graphs can be produced to show scheduled resource hours versus time. In a typical CPM schedule the control reports for resources can not include accurate resource utilization information because resources are not dynamically modelled. A more thorough analysis of resources can be done by studying the detailed level of each process. The advantages of the resource-based report is more evident during progress reporting phase. Crew tracking can be performed by comparing the scheduled budgeted hours and actual hours.

Production- and resource-based reports are both used to track schedule progress in a project. Productivity evaluation on periodic intervals or on specific locations is also an important tool that is used to control and improve production on specific processes. The use of productivity reports in the ACB project is explained in the next section of this chapter.

5.5.3 Revised Model

Results from a revised model are shown in Tables 5.3 and 5.4 using the same simulation models described in Tables 5.1 and 5.2 but embellished to include two formwork crews and two formwork sets for columns and slabs. The purpose of this experiment is to show the ease and advantages of simulation modeling using some of the SimCon concepts. The idle and busy time of the two formwork crews and two concrete crews can be studied to determine if both resources are working effectively. As noticed for 'Formwork Crew 1' the utilization ratio is equal to 0.27 and that for 'Formwork Crew 2' the utilization ratio is equal to 0.17. This means that 'Formwork Crew 2' is actually going to work a little more than half the time of 'Formwork Crew 1'. On the other hand 'Concrete Crew 2' is being utilized only at a ratio of 0.01 compared to a 0.16 for 'Concrete Crew 1'. This type of resource evaluation is not possible in a CPM type schedule because in a simulation model resource priority rules can be set and decision making can be made in the dynamic nature of entity interactions.

Table 5.3 ***Revised Production Plan for ACB Project - Two Formwork Crews & Two Sets of Formwork for Columns & Slabs***

SimCon - [Progress Reporting & Feedback]

VisualTools Formula One

File Edit View Format Object Window Help

M16 0

UOM = Unit of Measure
Org.Budg. = Original Total Production Budget as Planned
Cur.Budg. = Current Total Production Budget after the last update
Sched. = Scheduled Production is equal to Current Budget up to the Data Date

Process Name	UM	S	UC	Duration				Production						Cost					
				Start 5 %	Start 95 %	End 5 %	End 95 %	Org	Sched. 50 %	Sched. 95 %	Plan	Actual	Var	Org	Sched. 50 %	Sched. 95 %	Plan	Actual	Var
(Project Not Started)																			
153 - Cores Erect Process	M2	N	0.8	157	339	457	639	492	0	0	0	0	'U'	$369	$0	$0	$0	$0	'U'
163 - Slab Pour Concrete	M3	N	93	198	378	502	682	1264	0	0	0	0	'U'	$117,552	$0	$0	$0	$0	'U'
164 - Column Pour Concre	M3	N	93	177	357	463	643	125	0	0	0	0	'U'	$11,625	$0	$0	$0	$0	'U'
184 - Slab Formwork Erect	M2	N	2.2	184	364	490	670	7239	0	0	0	0	'U'	$15,926	$0	$0	$0	$0	'U'
185 - SlabForm Dismantle	M2	N	0	225	405	530	710	826	0	0	0	0	'U'	$0	$0	$0	$0	$0	'U'
135 - Cores Pouring Proces	M3	N	93	180	360	476	656	203	0	0	0	0	'U'	$18,879	$0	$0	$0	$0	'U'
157 - Cores Dismantle Proc	M2	N	0	208	388	505	687	95	0	0	0	0	'U'	$0	$0	$0	$0	$0	'U'
159 - Formwork Column P	M2	N	0.8	157	339	453	633	771	0	0	0	0	'U'	$578	$0	$0	$0	$0	'U'
160 - Column Dismantle F	M2	N	0	471	483	491	671	140	0	0	0	0	'U'	$0	$0	$0	$0	$0	'U'
169 - Place Slab Rebar P	MT	N	220	190	370	499	679	65	0	0	0	0	'U'	$14,300	$0	$0	$0	$0	'U'
170 - Place Colu[illegible]	[illegible]	[illegible]	220	164	344	461	641	20	0	0	0	0	'U'	$4,400	$0	$0	$0	$0	'U'
171 - Place Cores[illegible]	[illegible]	N	220	163	343	472	654	15	0	0	0	0	'U'	$3,300	$0	$0	$0	$0	'U'

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Table 5.4 ***Revised Resource Plan for ACB Project - Two Formwork Crews & Two Sets of Formwork Columns & Slabs***

VisualTools Formula One - [RESOURCE]

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S11

1 Total Budgeted Utilization = (Time In Use) / (Resource Duration)
2 Scheduled Budgeted Utilization = Planned Utilization of a Resource Up to the DATA DATE
3 Total Budgeted Hours = (Resource Duration) x (Crew Size) x Sched Utilization
4 Scheduled Budgeted Hours = (DATA DATE - Start Date) x (Crew Size) x Sched. Utilization
5 Resource Duration = Length of time that a Resource is put into a project (End Date - Start Date)
6 Scheduled Budgeted Cost = ((Fixed U Cost x (Data Date - Start Date)) x (Crew Size)) + (Var Ut Cost x Sched Bdgt Hours)
7 Total Budgeted Cost = ((Fixed Unit Cost x Resource Duration)) x (Crew Size)) + (Variable Unit Cost x Total Budgeted Hours)

Resource	Q	UM	Type	Duration Start 5 %	Duration End 95 %	Bdg Cost Fixed Unit	Bdg Cost Var Unit	Utilization Tot. Bdg	Utilization Sch. 25 %	Utilization Sch. 75 %	Hours Utilized Tot Bdg	Hours Utilized Schd. 25 %	Hours Utilized Schd. 75 %	Hours Utilized Plan	Hours Utilized Actu	Hours Utilized Var.	Cost Tot Bdg	Cost Schd. 75 %	Cost Plan	Cost Actual	Cost Var.
(Project Not Started)																					
Formwork Crew 1	1	Hr	C	656	656	26.8	0	0.27	.		1432	0	0	0	0	'0'	$142,094		$0		'0'
Concrete Crew 1	1	Hr	C	180	682	23.3	0	0.16	.	.	106	0	0	0	0	'0'	$15,448		$0		'0'
Rebar Crew	2	Hr	S	163	679	0	32	0.44	.	.	2334	0	0	0	0	'0'	$74,680		$0		'0'
Formwork Crew 2	1	Hr	C	157	800	26.8	0	0.17	.	.	496	0	0	0	0	'0'	$78,152		$0		'0'
Concrete Crew 2	1	Hr	C	177	643	23.3	0	0.01	.	.	331	0	0	0	0	'0'	$7,724		$0		'0'
Crane	1	Hr	E	177	682	78.1	42.3	0.29	.	.	335	0	0	0	0	'0'	$119,847		$0		'0'

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The mean project completion time in this embellishment was 16.5 weeks (663 Hours) with a standard deviation of 2 weeks (82 Hours). The 5th percentile of completion time obtained from the model is 13 weeks (528 Hours) and the 95th percentile for completion time is 20 weeks (798 Hours). Figure 5.19 shows various percentile estimates for the estimated project completion time. Appendix F-2 shows a more detailed duration estimates at various locations in the project. A summary of the important difference between both scenarios is tabulated in Table 5.5. The project completion time was reduced by 32 % as a result of using two formwork sets. Considering the cost of the extra formwork sets and additional formwork crews, the modeller can select the best alternative.

Table 5.5 Comparison of Results Between Two Simulation Embellishments

Embellishment	Formwork Crews	Formwork Sets	Project Duration (Hours)	
			Mean	Std
1	1	1	873	83
2	2	2	663	82

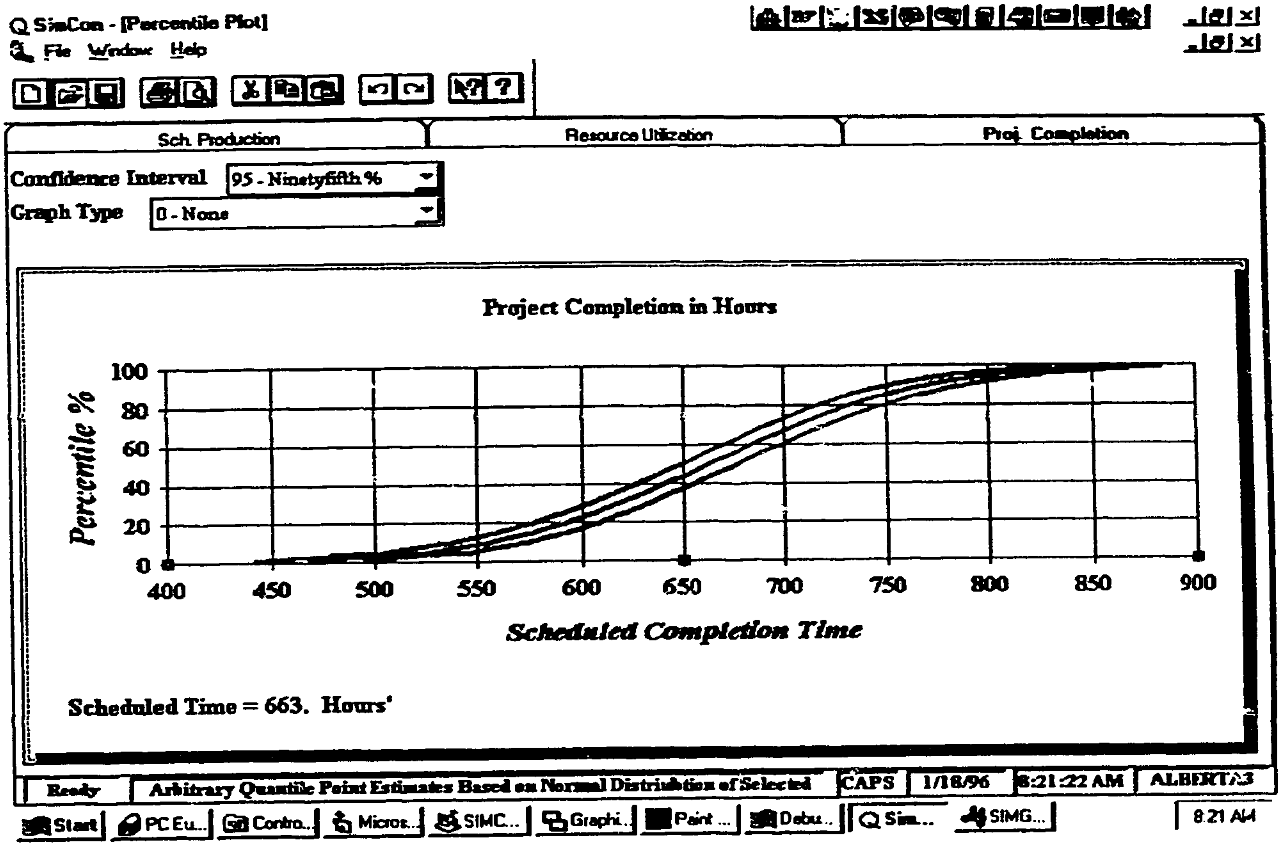


Figure 5.19 *Cumulative Distribution of the Project Completion Time with a 95% Percent Confidence Interval From SimCon.*

5.6 ACB PROGRESS REPORTING BY EXCEPTION: PRODUCTION- AND RESOURCE-BASED

Progress reporting for cost control purposes is implemented in many construction companies. Quantity worksheets are used in construction sites to collect progress information to compare estimated cost to actual cost. The use of a similar progress reporting format for schedule and cost control would greatly minimize the time spent in collecting additional information for updating schedules as discussed in Chapter 3.

In traditional control methods progress variance provides an indication of how much actual cost and schedule progress deviate from project baselines. In SimCon the control methodology is implemented by exception by comparing actual production achieved and resource-hours to scheduled project production and resource baselines. Variance analysis reports are provided by comparing actual production to significant deviation from the estimated scheduled production. This intern would reflect on cost and schedule performance. However, a better feedback in SimCon can be provided for improving a specific production in a SimCon-process and eliminating resource idle time. Moreover, less time is spent in updating unnecessary progress and focusing on processes that require improvement.

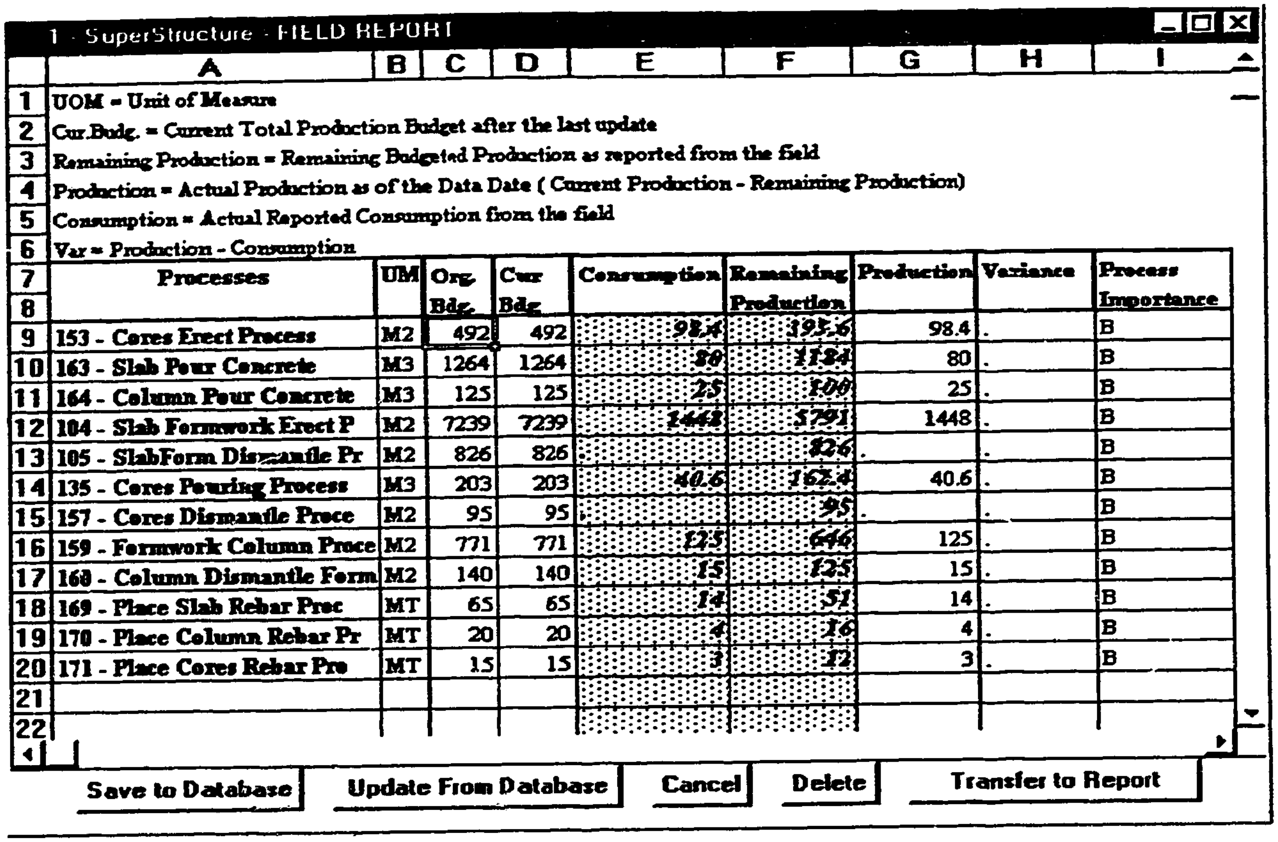
5.6.1 Production-Based Progress Reporting

Progress reporting on a specific location is implemented on the attached processes and resources. Table 5.6 shows a field report that is used for progress reporting. A very similar quantity worksheet report was used by PCL for cost control purposes in the ACB project. The same one can be used in SimCon to update a production-based schedule. The basic advantage of using the same report is to minimize the time spent on collecting additional unnecessary information. As stated in Chapter 3, if further analysis is required then additional details can be collected from the field and modelled at the process level.

Table 5.6 Quantity Worksheet Used for Production Reporting in ACB Project

Project Name - Data Date as of 94/01/14										
Cost Code	Description	Locations		Budget Units	UM	Units in Place		% Comp	Projected Final Units
		Est	Comp			Last Est	New Est		
032810	Elevator Core-Erect Formwork	5	1	492	M2	0	98.4	20	492
032830	Elevator Core-Dismantle Formwork	5	0	95	M2	0	0	0	95
033110	Columns Erect Formwork	10	2	771	M2	0	154	20	771
033130	Columns Dismantle Formwork	10	1	140	M2	0	15	11	140
033410	Slab/Beams-Erect Formwork	10	2	7,239	M2	0	1448	20	7,239
033430	Slab/Beams-Dismantle Formwork	10	0	826	M2	0	0	0	826
034205	Cores Concrete	5	1	203	M3	0	40.6	20	203
034000	Columns Concrete	10	2	125	M3	0	25	20	125
034400	Slabs Concrete	10	1	1,264	M3	0	126	10	1,264
037100	Cores Rebar*	5	1	10	MT	0	3	20	10
037200	Columns Rebar*	10	2	15	MT	0	4	20	15
037300	Slabs Rebar*	10	1	60	MT	0	12	18	60
*Actual Rebar Quantities Were Not Recorded in the ACB Project - Subcontracted Out									

Figure 5.20 shows the reporting procedure from the quantity worksheet in Table 5.6 into the SimCon program. Actual production to date as shown in Figure 5.20 calculated from the remaining production and transferred to the production-based report. The data date is entered to calculate the budgeted scheduled production from the simulation model. SLAM II modeling determines the scheduled production as of the data date. Internally, this is calculated by ending the simulation time at the data date and converting the simulation parameters into scheduled production using the production ratios specified in production counters.



	A	B	C	D	E	F	G	H	I
1	UOM = Unit of Measure								
2	Cur.Budg. = Current Total Production Budget after the last update								
3	Remaining Production = Remaining Budgeted Production as reported from the field								
4	Production = Actual Production as of the Data Date (Current Production - Remaining Production)								
5	Consumption = Actual Reported Consumption from the field								
6	Var = Production - Consumption								
7–8	Processes	UM	Org. Bdg.	Cur Bdg.	Consumption	Remaining Production	Production	Variance	Process Importance
9	153 - Cores Erect Process	M2	492	492	98.4	393.6	98.4	.	B
10	163 - Slab Pour Concrete	M3	1264	1264	80	1184	80	.	B
11	164 - Column Pour Concrete	M3	125	125	25	100	25	.	B
12	104 - Slab Formwork Erect P	M2	7239	7239	1448	5791	1448	.	B
13	105 - SlabForm Dismantle Pr	M2	826	826		826	.	.	B
14	135 - Cores Pouring Process	M3	203	203	40.6	162.4	40.6	.	B
15	157 - Cores Dismantle Proce	M2	95	95		95	.	.	B
16	159 - Formwork Column Proce	M2	771	771	125	646	125	.	B
17	160 - Column Dismantle Form	M2	140	140	15	125	15	.	B
18	169 - Place Slab Rebar Proc	MT	65	65	14	51	14	.	B
19	170 - Place Column Rebar Pr	MT	20	20	4	16	4	.	B
20	171 - Place Cores Rebar Pro	MT	15	15	3	12	3	.	B
21									
22									

Figure 5.20 ***Production-Based Progress Reporting in SimCon***

Production on cyclic activities is updated by changing dynamic variables stored in a production counter node (PRO node). A PRO node as shown in Figure 5.11 for slab formwork erection has a production ratio equal to 1.0. Actual production reported in the field of 80 m^3 is converted into a simulation counter by dividing ((80/(8x10))=1.0; 10 locations (2 zones per floor) and 8 simulation cycles)). The simulation counter is updated internally by SimCon to reflect the actual production achieved.

Table 5.7 shows a progress reporting by exception example. Initial progress reporting is done on a production-basis to determine if there are any problems. Variance analysis is performed to determine which process requires more attention. Slab concrete pouring process showed a variance from scheduled production of '-'81 m^3. This value falls below the 50th percentile (161 m^3) and hence a '-' sign is shown in front of the variance result. The 95th percentile is equal to 318 m^3. The planned production from the actual estimate is equal to 161 m^3. In this case the planner decided to flag any production below the estimate by setting the low significant percentile equal to the 50th percentile and flag only those above the 95th percentile. If actual production is more than 318 m^3 then a positive sign is shown so that performance can be recorded and lessons learnt to maintain performance and for use in future projects. However, in this case, a detailed analysis of Slab concrete pouring process can be done to check the exact causes of production delay and to improve performance. This can be done by first determining whether the cause of delay is internal (inefficient resource production or logical sequencing) or because of some external factors (constrained by a predecessor activity, weather, equipment breakdown, strike, etc.). The solution would depend on the cause of delay whether it was an internal or external cause. Similarly, slab formwork erection shows a variance from scheduled cost of '-'159 dollars. The additional cost can be investigated for corrective actions.

In addition to identifying performance of individual processes, there are three main advantages of the production-based report, as shown in Table 5.7. These are:

1. Variance analysis is performed on significant deviations.
2. A production-based report and project schedule are updated from quantity worksheets without the need for additional information if there are no significant deviations.

3. The simulation model developed using SimCon is continuously updated with minimum effort.

Table 5.7 ***Production-Based Progress Report for the ACB Project - Two Formwork Crews & Two Sets of Columns & Slabs Formwork (Schedule Control)***

SimCon - [Progress Reporting & Feedback]

Visual Tools Formula One

File Edit View Format Object Window Help

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UOM = Unit of Measure

Org.Budg. = Original Total Production Budget as Planned

Cur.Budg. = Current Total Production Budget after the last update

Sched. = Scheduled Production is equal to Current Budget up to the Data Date

Process Name (Project is 200. Hours in Progress)	UM	S	UC	Duration				Production						Cost					
				Start 5 %	Start 95 %	End 5 %	End 95 %	Org	Sched 50 %	Sched 95 %	Plan	Actual	Var	Org	Sched. 50 %	Sched. 95 %	Plan	Actual	Var
153 - Cores Erect Process	M2	I	0.8	157	339	457	639	492	109.5	173	109	*98.4*	'-'11	$369	$82	$146	$82	$74	'-'8
163 - Slab Pour Concrete	M3	I	93	198	378	502	682	1264	161.2	317.9	161	*80*	'-'81	$117,552	$14,988	$15,145	$14,988	$7,440	'-'7548
164 - Column Pour Concre	M3	I	93	177	357	463	643	125	47.19	81.27	47.2	*25*	'-'22	$11,625	$4,388	$4,423	$4,388	$2,325	'-'2063
104 - Slab Formwork Erect	M2	I	2.2	184	364	490	670	7239	1520	2616	1520	*1448*	'-'72	$15,926	$3,344	$4,440	$3,344	$3,186	'-'159
105 - SlabForm Dismantle	M2	N	0	225	405	530	710	826	0	0	0	*0*	'0'	$0	$0	$0	$0	$0	'0'
135 - Cores Pouring Proces	M3	I	93	180	360	476	656	203	38.37	66.08	38.4	*40.6*	'0'	$18,879	$3,568	$3,596	$3,568	$3,776	'+'180
157 - Cores Dismantle Pro	M2	N	0	208	388	505	687	95	15.96	27.46	16	*0*	'-'16	$0	$0	$12	$0	$0	'0'
159 - Formwork Column P	M2	I	0.8	157	339	453	633	771	171.5	271.1	172	*125*	'-'47	$578	$129	$228	$129	$94	'-'35
160 - Column Dismantle F	M2	I	0	471	483	491	671	140	8.82	28.1	8.82	*15*	'0'	$0	$0	$19	$0	$0	'0'
169 - Place Slab Rebar Pro	MT	I	220	190	370	499	679	65	7.243	12.68	7.24	*14*	'+'1	$14,300	$1,593	$1,599	$1,593	$3,080	'+'1481
170 - Place Column Rebar	MT	I	220	164	344	461	641	20	3.914	6.471	3.91	*4*	'0'	$4,400	$861	$864	$861	$880	'+'16
171 - Place Cores Rebar Pr	MT	I	220	163	343	472	654	15	1.826	3.045	1.83	*3*	'0'	$3,300	$402	$403	$402	$660	'+'257

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Analysis of a SimCon-process at the detailed level requires a knowledgeable planner in simulation analysis. At this stage of SimCon, analysis at the very detailed level requires a simulation analyst who can understand the various simulation terminologies. However, production-based reporting can be done at various time and location intervals allowing a more focused analysis. For example, in the ACB project a production-based report can be produced on Floor 2. This can be easily done by running simulation until the PRO node between the slab processes is equal to 2. Simulation would stop by dismantling of slab formwork on Floor 2. Such reports can be used to determine cost and resource requirements to finish a specific milestone (in this case it was finishing Floor 2 construction). Durations of processes at the end of various locations is shown in Appendix F-2. Barcharts and other schedule types can be produced from SimCon results using currently available computer softwares.

5.6.2 Resource-Based Progress Reporting

Reporting on resource utilization and hour usage is implemented by exception. This has two meanings: 1) if performance is not satisfactory then a detailed analysis can be performed at the process level; and 2) variance analysis reports point out resources that deviate significantly from estimates. A specific resource performance can be evaluated for the entire project or up to a specific date in the project. Resource-based progress reports identify resource performance to compare scheduled to actual resource hours.

Time cards were used in the ACB project to collect resource-hours spent on processes for general resource management and specific productivity control. The accumulated resource-hours from every resource on every type of process are added up and summarized as shown in Tables 5.8, 5.9, and 5.10. In the ACB project time cards were used for PCL's labor force only. No other time cards were used for equipment or sub-trade. Time usage of the crane and other sub-trades on various processes were approximated to illustrate the research concepts. The actual hours from weekly time cards are manually entered in SimCon to automatically produce the various reports.

Table 5.8 Total Hours From Weekly Time Card Reports For Crane Resource

Total Hours From Weekly Time Card Reports									
Resource Type: E	Resource ID: 50100	Resource Name:	Crane						
Processes	UM	Work Day Hours							
		Sun	Mon	Tue	Wed	Thr	Fri	Sat	Total Hours
FLOOR 2-6 LOCATION									
Column Formwork	M2		2			1			3
Core Formwork	M2		3						3
Slab Formwork	M2			2		1	2		5
Column Pouring	M3								
Core Pouring	M3								
Slab Pouring	M3						3		3
Column Rebar	MT								
Core Rebar	MT								
Slab Rebar	MT								
Clmn Dsmntle Form	M2								
Core Dsmntle Form	M2								
Slab Dsmntle Form	M2								
Total Hours			5	2		2	5		14
Total Hours To Date:	65 Hours								

Table 5.9 Total Hours From Weekly Time Card Reports For Concrete Crew

Total Hours From Weekly Time Card Reports									
Resource Type: C	Resource ID: 10100		Resource Name:		Concrete Crew 1				
Processes	UM	Work Day Hours							
		Sun	Mon	Tue	Wed	Thr	Fri	Sat	Total Hours
FLOOR 2-6 LOCATION									
Column Formwork	M2								
Core Formwork	M2								
Slab Formwork	M2								
Column Pouring	M3								
Core Pouring	M3								
Slab Pouring	M3						10		10
Column Rebar	MT								
Core Rebar	MT								
Slab Rebar	MT								
Clmn Dsmntle Form	M2								
Core Dsmntle Form	M2								
Slab Dsmntle Form	M2								
Total Hours									10
Total Hours To Date:	46 Hours								

Table 5.10 Total Hours From Weekly Time Card Reports For Steel Sub-trade

Total Hours From Weekly Time Card Reports									
Resource Type: S	Resource ID: 90100		Resource Name:		Sub-trade Steel Crew				
Processes	UM	Work Day Hours							
		Sun	Mon	Tue	Wed	Thr	Fri	Sat	Total Hours
FLOOR 2-6 LOCATION									
Column Formwork	M2								
Core Formwork	M2								
Slab Formwork	M2								
Column Pouring	M3								
Core Pouring	M3								
Slab Pouring	M3								
Column Rebar	MT			10					10
Core Rebar	MT				50				50
Slab Rebar	MT					30	40		70
Clmn Dsmntle Form	M2								
Core Dsmntle Form	M2								
Slab Dsmntle Form	M2								
Total Hours				10	50	30	40		130
Total Hours To Date:	620 Hours								

The actual hours spent by various resources are initially summarized in time cards as shown in Tables 5.8, 5.9, and 5.10. The total accumulated crane-hours by the crane resource is equal to 65 hours. Similarly, the total accumulated man-hours by the concrete crew and steel sub-trade crew is equal to 46 and 620 hours, respectively.

Figure 5.21 shows the reporting procedure from time cards into the SimCon program. Actual hours spent by every resource is accumulated and reported as shown in the left side of Figure 5.21. The data date is entered to calculate the budgeted scheduled production. SLAM II modeling determines the scheduled production as of the data date. Internally, this is calculated by ending the simulation time at the date and calculating scheduled resource utilization.

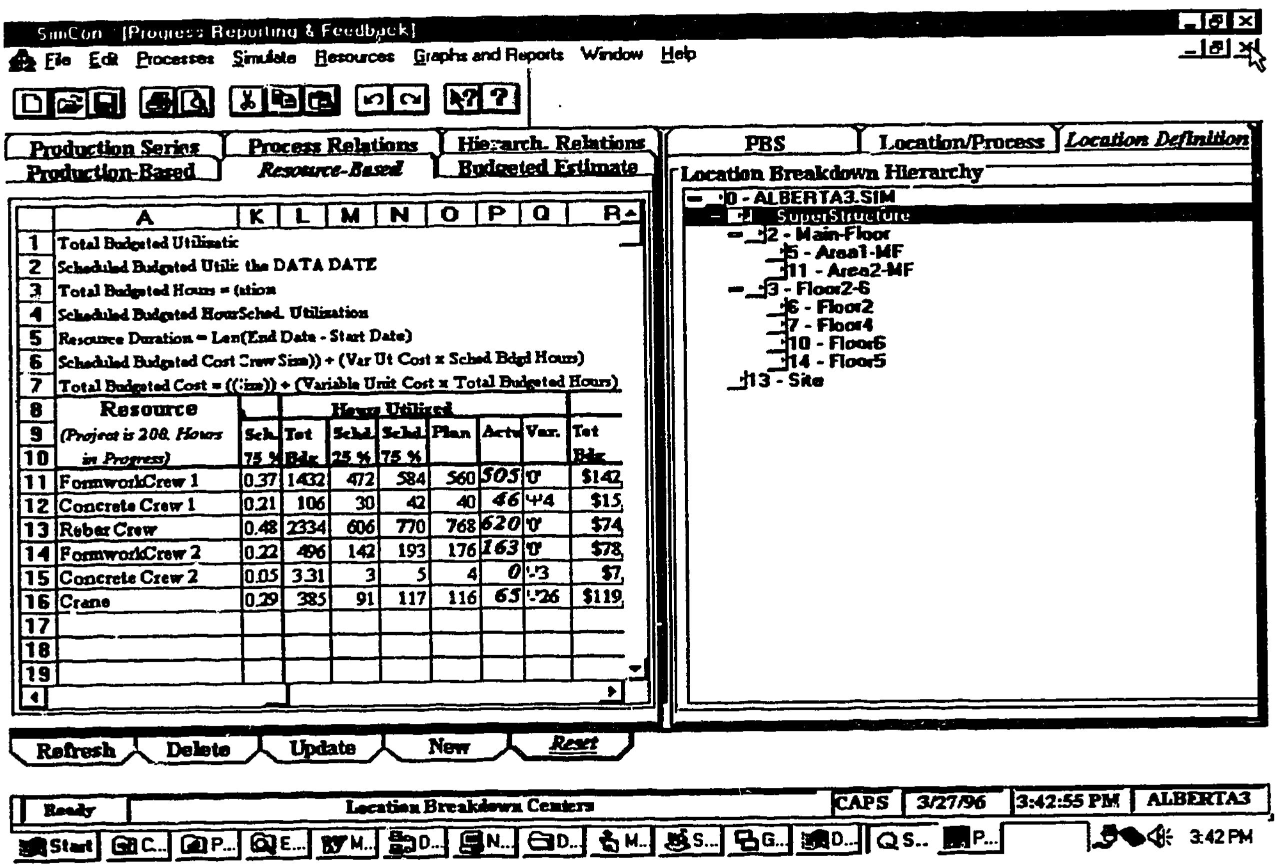

Figure 5.21 ***Resource-Based Progress Reporting in SimCon***

Table 5.11 shows a resource-based progress reporting by exception for the ACB project. Initial progress reporting over all processes is done to determine if there are any problems with resource performance. Schedule analysis is done to determine which resource is not performing according to schedule as shown in Table 5.11. Concrete crew resource showed a variance of 4 utilized hours from the 75^{th} percentile scheduled hours. A variation in the expected resource output can be caused by resource inefficiency or any other type of delay. If the delay is caused by resource inefficiency then it can be noticed by productivity variance analysis as shown in Table 5.12 which shows specific processes for productivity evaluation.

Table 5.11 ***Resource-Based Progress Report for the ACB Project - Two Formwork Crews & Two Sets of Column and Slab Formwork - (Resource Control)***

1. Total Budgeted Utilization = (Time In Use) / (Resource Duration)
2. Scheduled Budgeted Utilization = Planned Utilization of a Resource Up to the DATA DATE
3. Total Budgeted Hours = (Resource Duration) x (Crew Size) x Sched Utilization
4. Scheduled Budgeted Hours = (DATA DATE - Start Date) x (Crew Size) x Sched. Utilization
5. Resource Duration = Length of time that a Resource is put into a project (End Date - Start Date)
6. Scheduled Budgeted Cost = ((Fixed U Cost x (Data Date - Start Date)) x (Crew Size)) + (Var Ut Cost x Sched Bdgt Hours)
7. Total Budgeted Cost = ((Fixed Unit Cost x Resource Duration)) x (Crew Size)) + (Variable Unit Cost x Total Budgeted Hours)

Resource (Project is 200 Hours in Progress)	Q	Unit	Type	Duration Start 5%	Duration End 95%	Bdg Cost Fixed Unit	Bdg Cost Variable Unit	Utilization Tot. Bdg	Utilization Sch. 25%	Utilization Sch. 75%	Hours Utilized Tot Bdg	Hours Utilized Sched 25%	Hours Utilized Sched 75%	Hours Utilized Plan	Hours Utilized Actual	Hours Utilized Var.	Cost Tot Bdg	Cost Sched. 25%	Cost Sched. 75%	Cost Plan	Cost Actual	Cost Var.
FormworkCrew 1	1	Hr	C	656	656	27	0	0.33	0.3	0.37	1750	472	584	528	505	'0	$142,094	$5,358	$5,358	$5,358	$5,358	'0
Concrete Crew 1	1	Hr	C	180	682	23	0	0.18	0.15	0.21	119	30	42	36	46	'+4	$15,448	$4,660	$4,660	$4,660	$4,660	'0
Rebar Crew	2	Hr	S	163	679	0	32	0.43	0.38	0.48	2281	606	770	688	620	'0	$72,983	$19,405	$24,627	$22,016	$19,840	'0
FormworkCrew 2	1	Hr	C	157	800	27	0	0.19	0.16	0.22	554	142	193	167	163	'0	$78,152	$5,358	$5,358	$5,358	$5,358	'0
Concrete Crew 2	1	Hr	C	177	643	23	0	0.04	0.03	0.05	13.3	3	5	4	0	'-3	$7,724	$4,660	$4,660	$4,660	$4,660	'0
Crane	1	Hr	E	177	682	78	42	0.26	0.23	0.29	345	91	117	104	65	'-26	$118,166	$19,462	$20,578	$20,020	$18,372	'-1090

A detailed analysis of a resource can be easily done by checking the productivity report as shown in Table 5.12. The concrete processes are checked to determine which process caused the variance in the concrete crew performance. Slab pouring processes showed a variance index of 0.36. The other concrete pouring processes had a negative variance index meaning that they performed better than budgeted. The positive variance index in the slab concrete pouring process means that productivity is also low and conclusion can be made that this process was the reason for low resource productivity as noticed in Table 5.11.

Table 5.12 Productivity-Based Report For ACB Project Control (Productivity Control)

SimCon - [Progress Reporting & Feedback]

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1 - SuperStructure

UOM = Unit of Measure
Org.Budg. = Original Total Production Budget as Planned
Cur.Budg. = Current Total Production Budget after the last update
Sched. = Scheduled Production is equal to Current Budget up to the Data Date
Productivity = Production / Man-Hours
Var Index = ((To Date Productivity) - (Cur. Bdg. Productivity)/(To Date Productivity))

Processes		UM	Production Org Bdg.	Production Cur Bdg.	Production Period	Production ToDate	Man-Hours Org Bdg.	Man-Hours Cur Bdg.	Man-Hours Period	Man-Hours ToDate	Productivity (Man-Hours/Unit) Org Bdg.	Productivity Cur Bdg.	Productivity Period	Productivity ToDate	Var Index
153 -	Cores Erect Process	M2	492	492	98.4	98.4	419	419	74	74	0.852	0.852	0.752	0.752	-0.133
163 -	Slab Pour Concrete	M3	1264	1264	80	80	708	708	70	70	0.56	0.56	0.875	0.875	0.36
164 -	Column Pour Concret	M3	125	125	25	25	127	127	22	22	1.016	1.016	0.88	0.88	-0.155
184 -	Slab Formwork Erect	M2	7239	7239	1448	1448	6607	6607	1220	1220	0.913	0.913	0.843	0.843	-0.084
185 -	SlabForm Dismantle P	M2	826	826	0	0	157	157	0	0	0.19	0.19	0	0	0
135 -	Cores Pouring Proces	M3	203	203	40.6	[illegible]	106	106	20	20	0.522	0.522	0.493	0.493	-0.06
157 -	Cores Dismantle Proc	M2	95	95	0	0	24	24	0	0	0.253	0.253	0	0	0
159 -	Formwork Column Pr	M2	771	771	125	125	926	926	161	161	1.201	1.201	1.288	1.288	0.068
168 -	Column Dismantle Fo	M2	140	140	15	15	42	42	7	7	0.3	0.3	0.467	0.467	0.357
169 -	Place Slab Rebar Pro	MT	65	65	14	14	4100	4100	1200	1200	63.077	63.077	85.714	85.714	0.264
178 -	Place Column Rebar P	MT	20	20	4	4	600	600	200	200	30	30	50	50	0.4
171 -	Place Cores Rebar Pr	MT	15	15	3	3	551	551	100	100	36.733	36.733	33.333	33.333	-0.102

Save to Database | Update From Database | Cancel | Delete - Start From Existing Processes

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5.6.3 Graphical Quantile Point Estimates of Selected Processes & Resources

Statistics on each SimCon-process, start and finish duration, production, and resource utilization, are collected. These results provide a low, high, mean, and standard deviation estimates of each parameter. In addition to the standard variance analysis provided in the previous sections, risk analysis in SimCon allows the modeller to evaluate the actual results in comparison to percentile values generated from the underlying distributions.

In many cases, a simulator might be interested in other statistics about a specific construction operation. Any quantile or probability of exceeding or not exceeding a given threshold value can be useful in understanding the risks involved in a construction project. For example, the 90th percentile has 90% of the simulation results below that observation. A further practical analysis that is important in the decision making process is knowing the probability of exceeding a specific production or a specific completion time. Appendix C provides some equations and analysis that can be used for statistical purposes.

For example, in the ACB project a range of percentile values for the scheduled production of the slab concrete pouring process can be provided instead of the mean production or selected percentile estimates as shown in Figure 5.22. The actual production after 5 weeks (200 Hours) is equal to 80 m^3. This result falls on the 20th percentile, meaning that performance is below average. The significant deviation for production as stated by the user is equal to 161 m^3 (50th percentile) and 318 m^3 (95th percentile). The actual estimated production used for planning is equal to 161 m^3. The 95% confidence interval can be developed by substituting the values obtained from each quantile point estimate into Eq. 3.2. The variance in the production of Slab Pouring Concrete Process as calculated and shown in the right side of Figure 5.22 is equal to 81 (161 - 80).

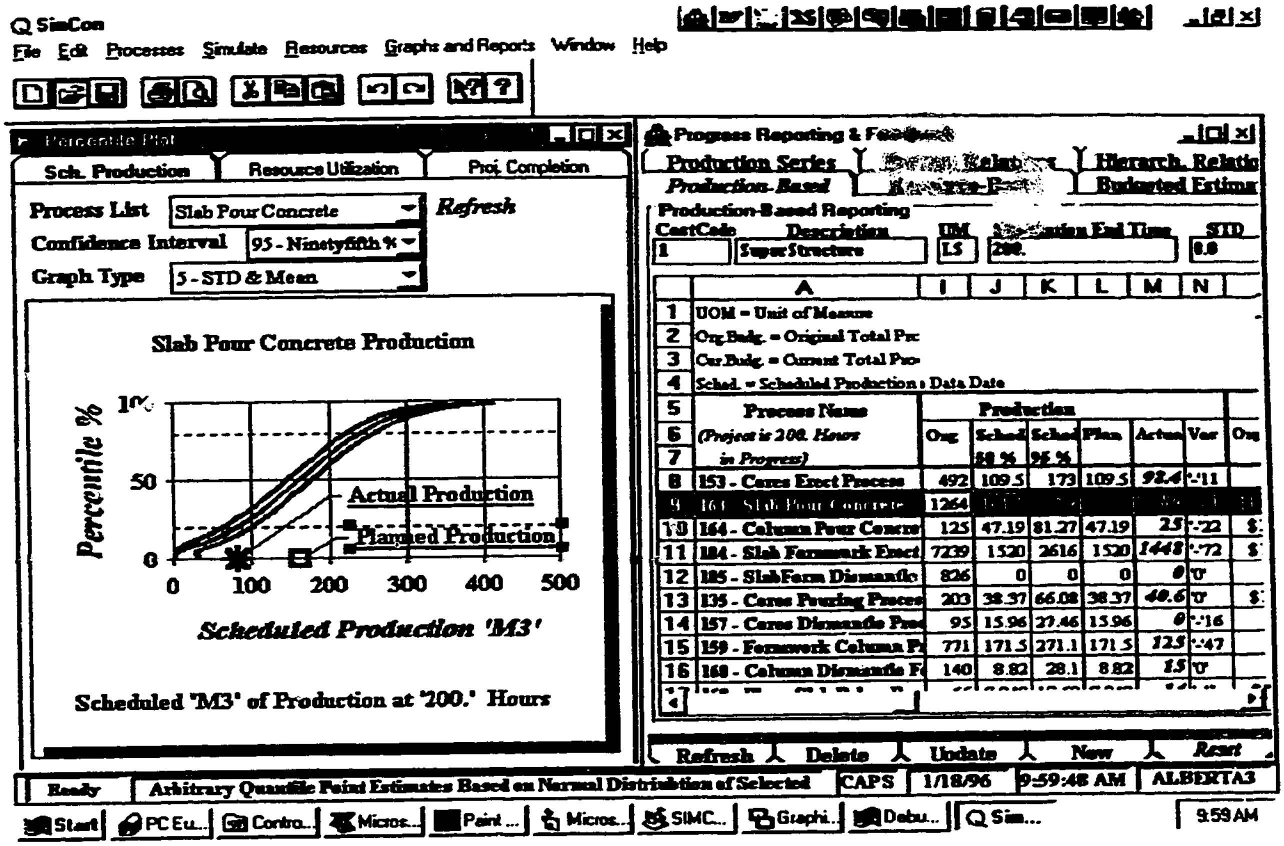

Figure 5.22 ***Cumulative Distribution of Slab Concrete Pouring Process with 95th Percentile Confidence Interval From SimCon***

Various quantile estimates for scheduled resource hours can also be determined and plotted to help a planner evaluate the risks involved in knowing the scheduled utilized hours of work. Figure 5.23 shows the scheduled utilized hourly quantile point estimates for the 'Concrete Crew 1' resource at 200 hours in the project. The actual utilized hours recorded is equal to 46 hours as shown in the right side of Figure 5.23. The 25th and 75th percentile estimates are equal to 30 and 42 hours, respectively. The estimated plan hours for the 'Concrete Crew 1' is equal to 36 hours. The actual hours falls at approximately the 87th percentile. This allows the planner to evaluate the risks involved to improve the resource performance in future work.

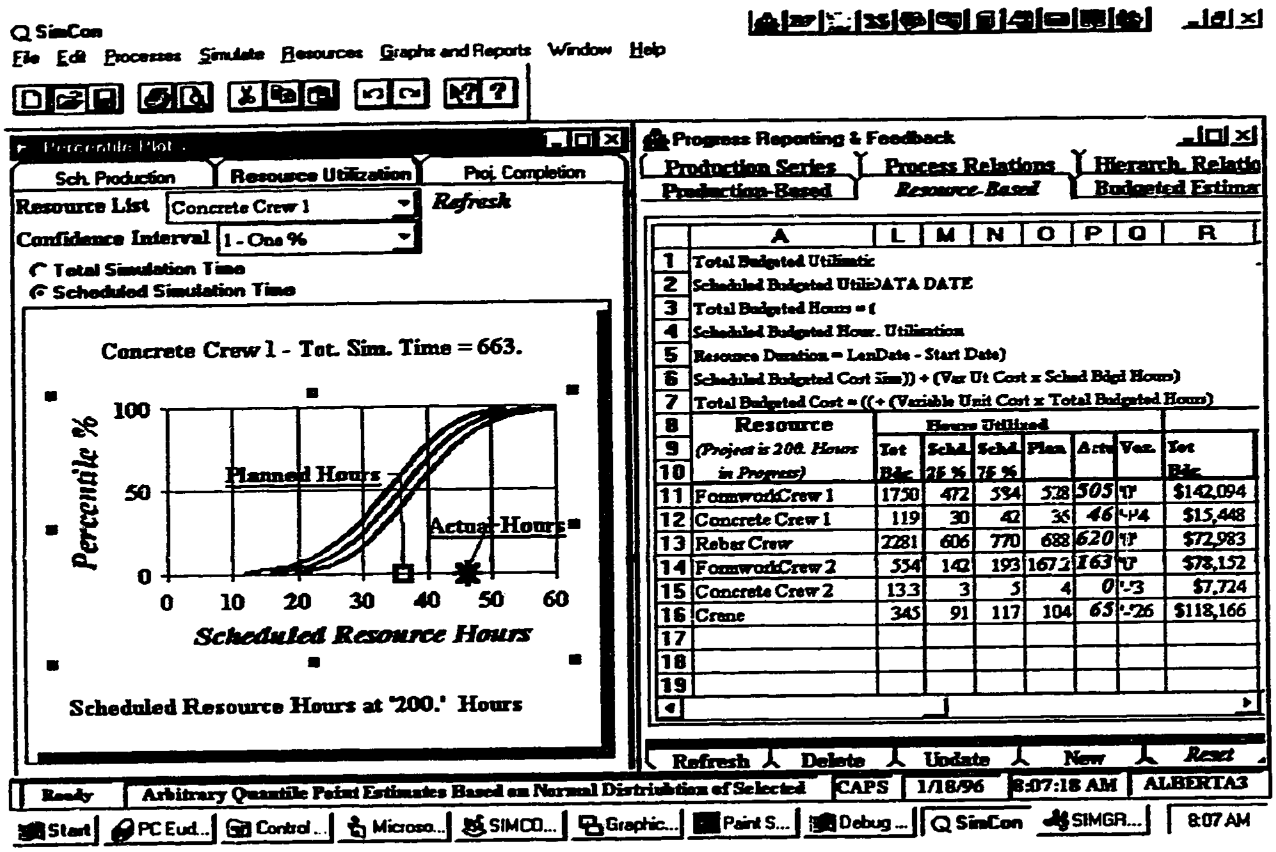

Figure 5.23 ***Graphical Quantile Point Estimates for the Scheduled Work of the Concrete Crew Resource***

In comparison, the 'Formwork Crew 1' resource had a '0' variance meaning that the actual utilized hours is in-between the lowest and highest significant deviation points. The actual utilized hours is equal to 505 hours as shown in Figure 5.24. The 25th and 75th percentile estimates are equal to 472 hours and 584 hours, respectively. The estimated plan hours for the 'Formwork Crew 1' is equal to 528 hours.

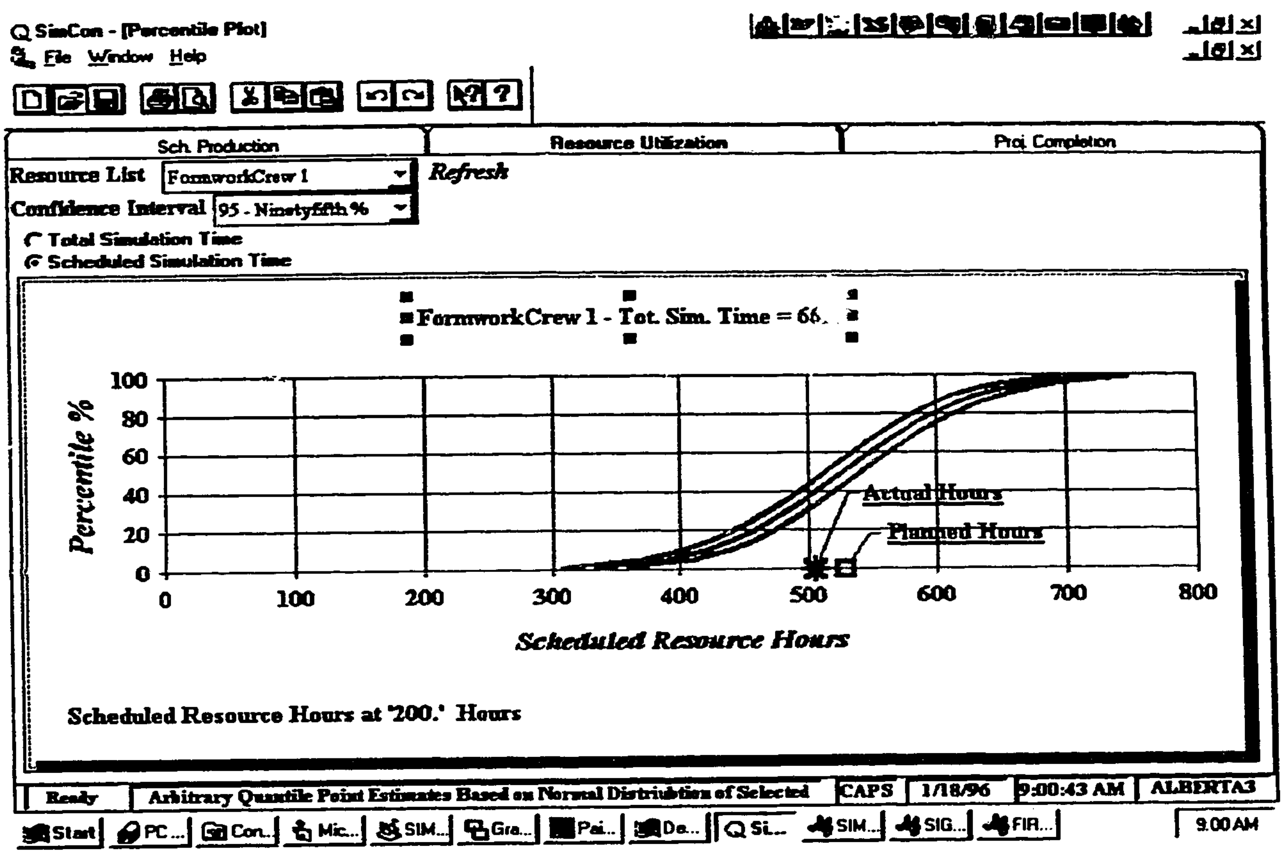

Figure 5.24 ***Cumulative Distribution of Scheduled Utilized Hours for the Formwork Crew Resource with a 95% Confidence Interval***

5.7 CHAPTER CONCLUSIONS: SUMMARY OF SIMCON ADVANTAGES VS. TRADITIONAL SCHEDULING METHODS

The advantages of SimCon are threefold: 1) the use of simulation for project planning and control; 2) the use of progress reporting by exception to overcome updating the detailed activity and process details in simulation and provide reporting on significant deviations; 3) the use of simplified linking procedures to model complex logical relationships. The above three concepts are all modelled in the ACB project case study.

Without the SimCon concepts modeling of the ACB project as shown in this chapter would not have been possible.

The use of simulation in the ACB project was advantageous for the following reasons: 1) repetitive nature of processes; 2) resource utilization and waiting time; 3) more true representation of the actual construction processes. In the ACB project minimal number of activities were required to model the repetitive nature of construction processes as shown in Figures 5.6 - 5.8. In CPM many more activities would be needed to model the same sequence of events as discussed earlier. Resource utilization and waiting time provides the planner with a better tool to efficiently analyze resource and activity performance. Possible bottlenecks and sources of delays can be more readily identified at the detailed level of a simulation model. It was possible to improve the utilization of the concrete crews (crew 1 and crew 2) idle time by setting priority rules to control the allocation of crews to various processes. Similarly, the continuous production links introduced in the ACB project allowed the modeller to change the number of formsets without the need to change the model logic. A number of alternatives can be tested for best outcome. In a CPM schedule this type of analysis is not possible because resources are not dynamically modelled.

The use of progress reporting by exception to overcome updating at the very detailed level of a simulation model provides a promising solution to making use of simulation for project control. In addition, variance analysis reports can be generated in SimCon that outline tasks and resources that deviate significantly from user-defined estimates. The significant estimated values are calculated from percentile points defined by the user for lowest and highest deviations. Production-based reports make use of currently available field reports and provide enough information for schedule variance analysis. Expected production by the simulation model is compared to actual production to verify project progress. Resource-based reports provide an overall comparison between budgeted resource utilization and actual resource usage. Productivity reports (man-hours/unit production) combine the results from production-based and resource-based reports to compare budgeted productivity to actual productivity for specific processes. A positive variance in both a production-based report and a productivity-report can mean that the cause of delay is due to low productivity on a specific process. The repetitive nature of construction activities can be modelled in simulation and hence the concept of production reporting can be applied.

CHAPTER 6

CONCLUSIONS

6.1 SUMMARY OF RESEARCH

A new modeling tool for progress reporting and project control of a construction project is presented and described in this thesis. SimCon, the acronym used for SIMulation-based project CONtrol, provides a better project control tool for improving production by applying an advanced scheduling tool, minimizing progress reporting, and simplifying the linking procedure of cyclic processes. The research concept was possible to implement through a production breakdown structure that includes in its hierarchy cost control centers, location centers, and construction process centers.

There are a number of advantages for using simulation for project control. Simulation modeling improves the decision-making of upper level construction management by providing a mechanism to evaluate non-value added tasks and resource utilization. Traditional scheduling control tools lack the required interactions with the lower level management where the dynamic nature of a construction process and its complex interrelated components interact; basically, the level at which resources interact.

The problem with applying simulation modeling is the tremendous data support required for progress reporting. This research work attempts to overcome this handicap by integrating project components in a hierarchical production breakdown structure to facilitate progress reporting by exception.

Using the SimCon methodology, cost centers are first identified in a project. Following that, location breakdown centers are defined and attached to respective cost centers. Resources are then defined in the location hierarchy. The construction process centers are defined at various locations and linked to each other using the new continuous and single production links. These steps constitute modeling a scheduling project. Following that, progress reporting by exception can be implemented at various location centers. This includes reporting progress on production achieved in production-based reports and actual utilized hours in resource-based reports. Variance analysis reports outline tasks and resources that deviate significantly from estimated values. As a result concentrating the effort of project control can be maintained on tasks and resources that require more attention.

6.1.1 Why a Production Breakdown Structure?

- ***Cost centers***: A hierarchical cost code structure is used for estimating, planning, progress reporting and feedback, and for maintaining historical records for future projects. A modeling scheme that builds on cost centers will help to bridge the gap between current cost control techniques and new modeling techniques.

- ***Location breakdown center***: A location breakdown center is used to link construction methods and project schedule to associated cost centers. It further provides a mechanism to group together cost centers and construction methods in the same location, and to report on schedule progress in a project by location.

- *Construction process center*: A construction process center models production and time and is used to represent the logical constraints between activities in a network schedule. Repetitive cycles, randomness and probabilistic estimates, network branch decision making, and dynamic resource utilization, interaction and waiting time can be modelled.

6.1.2 Why Progress Reporting Using a Simulation Model?

- Evolution to considerable future integration of construction management information
- Production and resource-based simulation model provide the capability to report progress at a higher level
- Overcome the complexity of recording project progress at the extremely detailed level (i.e., progress reporting by exception)
- Provide a scheduling system that will take less time to update while maintaining the required details for short term interval planning and advanced project control (resource utilization)
- The use of the new simple continuous and single production links simplifies to a user the construction sequencing methodology and provides a better estimate on progress by a more true representation of activity relationships

- Identify non-value added tasks and provide better corrective actions
- Provide simulation risk analysis for better project management
- Variance analysis on significant deviation basis from user-defined quantile estimates

6.2 SIMCON APPLICABILITY

SimCon is intended for use in the industrial and academic fields. While the specific examples used in this dissertation pertain to building construction planning and control, the conceptual design of the model is generic and can be equally applied to heavy earth-moving construction as shown in Appendix H. Different organizational levels in management are addressed in SimCon's hierarchy concept. Resource interactions and specific construction methods are implemented at the process level. Progress information by locations and cost control centers are identified at the higher level in the production breakdown structure. SimCon is also a good educational tool because it forces the modeller to think of the many planning and control issues that have to be dealt with in actual construction.

6.3 CONTRIBUTIONS TO KNOWLEDGE

The research contributes to knowledge in the following ways:

- Provides a new technique for representing project information in a form that allows project control within a simulation model.

- Provides new mechanisms to integrate project-level information and specific process-level details.
- Provides new simulation constructs to implement progress reporting by exception and overcome reporting progress at the very detailed level of a schedule.
- Provides mechanisms to simplify cyclic process inter-relationships in a project level simulation model
- Provides variance analysis report on significant deviation estimates
- Demonstrates the functionality and feasibility of simulation-based project control through SimCon, the computer prototype system.

6.4 RECOMMENDATIONS FOR FUTURE RESEARCH DIRECTIONS

The computer prototype system, SimCon, implements the concepts discussed in this thesis. SimCon was directed at demonstrating the feasibility of a simulation-based project control and at simplifying simulation modeling through the ideas presented in this research. Recommendations for future research work is directed towards a computer integrated platform, additional scheduling techniques (resource allocation, calendar day, user interface (i.e. graphical and input), automated report generation, and simulation optimization.

Computer Integrated Platform: The main improvement in the computer prototype system can be realized in developing an integrated platform that combines event driven programming, database management, object oriented programming, and simulation language in one system. In SimCon, SLAM II, which is used as the simulation engine, does not allow access to its code to fully integrate into a complete automated simulation package. An objected-oriented simulation program integrated within SimCon is necessary before practitioners in the construction industry can use it.

Additional Scheduling Techniques: Scheduling limitations in SimCon's prototype system include 1) resource allocation and scheduling techniques, 2) calendar day scheduling techniques, and 3) progress measurement techniques. Additional resource allocation and scheduling techniques are required for resource preemption. For example a resource allocated to a COMBI node can not be interrupted so that it can be claimed by higher priority activities. This limitation can be overcome by the use of a PREEMPT (Pritsker et al., 1989) node. An additional scheduling technique available in literature can also be used to implement calendar day scheduling. Generalized progress measurement system was only implemented for very short duration processes. Enhancements can be made to implement progress measurement for short and long duration. This can be implemented by allowing reporting on percentage completion of a process's production.

User Interface: Data input and the graphical user interface can be further enhanced to provide a more 'user friendly' interface. Data input interface can be improved to include automated data reporting from site and other control systems (i.e., accounting, field reports, procurement, etc.). The graphical interface can be enhanced by allowing the user to view the full relationships between processes (currently SimCon allows the user to see each process separately without inter relationships with other processes). Moreover, errors induced by a modeller are not detected in the current prototype system.

Automated Report Generation: The report generation module in SimCon currently produces production-based, resource-based, and productivity reports. Additional reports should be directed for various organizational levels. For example, the practical translated details of simulation statistics at the process level would be of interest to foremen and superintendents. Other summary level reports would be of interest to project and district managers. An integrated expert system for the report generation would present intelligent feedback on processes that require more attention.

Simulation Optimization: An integrated simulation engine can greatly assist in improving the simulation process performance by automating certain procedures to achieve best outcome.

Future research work should address in more detail the issues of project estimating using a simulation system. After that the same simulation system used for estimating becomes the project plan and eventually used for project control. Moreover, any new system should take into consideration the level of modeling complexity and the existing sophistication of the construction industry. The focus of this research was on applying advanced project control techniques and minimizing the time spent on progress reporting at the very detailed level of a hierarchical breakdown structure and providing control reports that outline tasks and resources that deviate significantly from the plan.

APPENDIX A: BIBLIOGRAPHY

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APPENDIX B: DEFINITIONS & NOTATIONS

Polymorphism: Polymorphism is an attribute of object-oriented programming. It defines the fact that the same message can be passed to different objects and still respond by different actions. This advantage is greatly helpful. For example, sending a progress report on an activity can be sent to an object and be implemented differently by the control system than by accounting or scheduling systems.

Encapsulation: Encapsulation is an internal programming feature in object-oriented programming. It defines the way objects access and manipulate information. For example, if information is to be updated on an object then there is no need to add a procedure or subroutine, but rather through an object which enhances the readability and accessibility of the program code.

Inheritance: Inheritance is an object-oriented tool for organizing, building, and using reusable objects. Changes in parent objects properties (functions and special attributes) are captured by children.

Project-Level: A project-level as defined in this thesis is made up of a combination of individual cost centers and summarizes information from lower levels in the production breakdown structure.

Process-Level: A process-level as defined in this thesis is the lowest level in the production breakdown structure. A process-level contains CYCLONE and SimCon elements that drive the simulation scheduling.

SimCon-Process: A production-based simulation process that is constructed to include one specific type of production with a certain unit of measure. This will allow progress reporting to be done from a higher hierarchical level.

Progress Reporting by Exception: The methodology of reporting progress on one single parameter in a SimCon-process from a location breakdown center in a production breakdown structure.

Production-Based Report: Production-based report is a control report generated in SimCon from a location center to compare actual production to scheduled production.

Resource-Based Report: Resource-based report is a control report generated in SimCon from a location center to compare actual resource hours to schedule hours.

Productivity-Based Report: Productivity-based report is combined from production-based and resource-based reports to help study the performance of specific processes to determine if a more detailed analysis is required.

The following symbols are used in this study.

SimCon	SIMulation-based Construction Project CONtrol
PRO Node	A SimCon node that is used to keep track of hierarchical production
PRO-Q	A PRO node parameter that represents total production required
PRO-Count	A PRO node parameter that represents the internal count by a simulation process
PRO-Ratio	A PRO node parameter that represents the ratio between PRO-Q and PRO-Count
PRO-Link	A PRO node parameter that represents the number of cycles required to release the first entity to next process
PRO-Name	A PRO node parameter that identifies the name of the location breakdown center that is linked to the specific process.
LINK Node	A SimCon node that is used to continuously link processes
LINK-N	A LINK node parameter that determines the buffer zone between a predecessor process and a successor process
LINK-P	A LINK node parameter that specifies the name of the predecessor process
LINK-D	A LINK node parameter that specifies the name of the predecessor node in the LINK-P name
FREE Node	A SimCon node that is used in conjunction with a LINK node to link activities
FREE-P	A FREE node parameter that specifies the name of the Successor process
FREE-D	A FREE node parameter that specifies the name of the Successor node in the FREE-P name
ASSIGN Node	A SimCon node that is used to assign variables and track certain statistics.
ASSIGN-Stat	An ASSIGN node parameter that determines the statistic type to collect information on; start time, finish time, or production.
ASSIGN-Var	An ASSIGN node parameter that is used by simulation modellers to prescribe values to defined variables
ASSIGN-Link	An ASSIGN node parameter that is used to determine the production required from the predecessor process to start the current process
ASSIGN-Name	An ASSIGN node parameter that is used to determine the name of the predecessor process
CP Link	Continuous Production Link as specified by LINK & FREE nodes
SP Link	Single Production Link as specified by PRO and ASSIGN nodes
CPM	Critical Path Method
WBS	Work Breakdown Structure
CBS	Cost Breakdown Structure
PBS	Production Breakdown Structure; Cost Centers, Location Centers, and Process Centers
PCL	A major general contractor in North America

APPENDIX C: CAPTURING REQUIRED STATISTICS

Results from a stochastic simulation model can be provided in terms of low, high, mean, and standard deviation values based on a certain fixed number of runs. In many cases, a simulator might be interested in other statistics about a specific construction operation. Any quantile or probability of exceeding or not exceeding a given threshold value can be useful in understanding the risks involved in a construction project. For example, the 90^{th} percentile has 90% of the simulation results below that observation. A further practical analysis that is important in the decision making process is knowing the probability of exceeding a specific production or a specific completion time. Probabilistic time analysis in simulation modeling is similar to PERT type analysis. However, the mathematical analysis of probabilistic production-based results requires planning of locating nodes to collect statistics for output. This becomes more important when determining scheduled production at periodical time intervals as will be explained in a later section.

Results from every simulation run are used to calculated the sample mean and sample variance as calculated in equations C.1 and C.2. The confidence interval around the calculated mean in equation C.1 can be determined from equation C.3. It should be stated that the assumption in this case is that the underlying distribution is normally distributed. Output analysis can become fairly complicated if the sample can not be assumed to be normally distributed. The statistic t = (X-u)/(S/SQR(n)) follows a t distribution with n-1 degrees of freedom. The q^{th} quantile is calculated by the approximation of the binomial distribution to the normal distribution for large sample sizes. The estimator of the q^{th} quantile (X_q) is given in equation C.4. The parameter z_q is derived from the normal statistical table. The probability that an output parameter does not exceed a particular fixed value is calculated using equation C.5 where $\phi(z)$ is the cumulative probability density for a standard normal distribution and $\bar{x}$ is the sample mean and S is the sample variance.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad \text{(C.1)}$$

$$S^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 \qquad \text{(C.2)}$$

$$\bar{x} - t_{\alpha/2}(n-1)\frac{S}{\sqrt{n}} \le \mu \le \bar{x} + t_{1-\alpha/2}(n-1)\frac{S}{\sqrt{n}} \qquad \text{(C.3)}$$

$$X_q = \bar{x} + z_q S \qquad \text{(C.4)}$$

$$\Phi(x - \bar{x} / S) \qquad \text{(C.5)}$$

The user determines the statistic percentile estimates (SPS) required for project control. This statistic confidence is used for comparison purposes between scheduled progress and actual progress for the variance analysis reports. The SPS value can be any percentile value. For example, an SPS value equal to the 80^{th} percentile would be used to calculate from the simulation results the 80% of the observations. Similarly, an SPS value equal to the mean can be used to calculate from the simulation results the mean value of the observations. The calculated result is compared to actual progress value to determine the schedule and production variance.

APPENDIX D: VISUAL C++ CODE IN SIMCON

APPENDIX D-1: VISUAL C++ CODE FOR OBJECT DEFINITIONS

```
//-----------------------------------------------------------------
// Resource Information
//-----------------------------------------------------------------
// Toolbox bitmap resource IDs numbers.
//-----------------------------------------------------------------
#define IDBMP_SIMCTRL          8000
#define IDBMP_SIMCTRLDOWN      8001
#define IDBMP_SIMCTRLMONO      8003
#define IDBMP_SIMCTRLEGA       8006

//-----------------------------------------------------------------
// Update these fields for each build.
//-----------------------------------------------------------------
#define VBX_VERSION              3,00,0,00
#define VBX_VERSION_STR          3.00.000\0

#ifndef RC_INVOKED
//-----------------------------------------------------------------
// Control Procedure
//-----------------------------------------------------------------
LONG FAR PASCAL _export SIMCTRLCtlProc(HCTL, HWND, USHORT, USHORT,
LONG);


// Custom Properties
#define OFFSETIN(struc,field)       ((USHORT)&(((struc *)0)->field))

enum {Queue,
            Combi,
            Normal,
            Consolidate,
            Output,
            Input,
            Arn,
            Frn,
            Counter,
            ProdEvent,
```

```
                ProdGate,
                ProdVar,
                ProdCounter
        };

typedef struct SIMCTRLstruct
   {
                short   NodeType;
                HSZ             Description;
                HFONT        hfont;
                BOOL Modular;
                BOOL Lowest;
                short   numleft;
                short   numtop;
                short   numright;
                short   numbottom;
                BOOL selected;
   } SIMCTRLSTRUCT;

typedef SIMCTRLSTRUCT FAR * LPSIMCTRL;

#define SIMCTRLDEREF(hctl)        ((LPSIMCTRL)VBDerefControl(hctl))

char nodetypedesc[] =           0 - Queue\0\
                                        1 - Combi\0\
                                        2 - Normal\0\
                                        3 - Consolidate\0\
                                        4 - Input Port\0\
                                        5 - Output Port\0\
                                        6 - Allocate Resource\0\
                                        7 - Free Resource\0\
                                        8 - Counter\0\
                                        9 - Production Event\0\
                                        10- Production Gate\0\
                                        11- Production Variable\0\
                                        12- Production Counter\0\
                                        ;

PROPINFO PPROPINFO_CUS_NODETYPE=
{
        Node Type,
        DT_ENUM|PF_fGetData|PF_fPreHwnd|PF_fSetMsg|PF_fSetData,
        OFFSETIN(SIMCTRLSTRUCT,NodeType),
        0,
```

```
        0,
        nodetypedesc,
        12,
};

PROPINFO PPROPINFO_CUS_DESCRIPTION=
{
        Description,
        DT_HSZ|PF_fGetData|PF_fSetData|PF_fSetMsg|PF_fSaveData,
        OFFSETIN (SIMCTRLSTRUCT,Description)
};

PROPINFO PPROPINFO_CUS_MODULAR=
{
        Modular,
        DT_BOOL|PF_fGetData|PF_fSetMsg|PF_fSetData,
        OFFSETIN (SIMCTRLSTRUCT,Modular)
};

PROPINFO PPROPINFO_CUS_LOWEST=
{
        Lowest,
        DT_BOOL|PF_fGetData|PF_fSetMsg|PF_fSetData,
        OFFSETIN (SIMCTRLSTRUCT,Lowest)
};

PROPINFO PPROPINFO_CUS_NUMLEFT=
{
        numleft,
        DT_SHORT|PF_fGetData|PF_fSetData,
        OFFSETIN (SIMCTRLSTRUCT,Lowest)
};

PROPINFO PPROPINFO_CUS_NUMTOP=
{
        numtop,
        DT_SHORT|PF_fGetData|PF_fSetData,
        OFFSETIN (SIMCTRLSTRUCT,Lowest)
};

PROPINFO PPROPINFO_CUS_NUMRIGHT=
{
        numright,
        DT_SHORT|PF_fGetData|PF_fSetData,
```

```
        OFFSETIN (SIMCTRLSTRUCT,Lowest)
};

PROPINFO PPROPINFO_CUS_NUMBOTTOM=
{
        numbottom,
        DT_SHORT|PF_fGetData|PF_fSetData,
        OFFSETIN (SIMCTRLSTRUCT,Lowest)
};

PROPINFO PPROPINFO_CUS_SELECTED=
{
        Selected,
        DT_BOOL|PF_fGetData|PF_fSetMsg|PF_fSetData,
        OFFSETIN (SIMCTRLSTRUCT,selected)
};


//---------------------------------------------------------------------
// Property list
//---------------------------------------------------------------------
// Define the consecutive indicies for the properties
//---------------------------------------------------------------------
#define IPROP_SIMCTRL_CTLNAME                        0
#define IPROP_SIMCTRL_INDEX                          1
#define IPROP_SIMCTRL_BACKCOLOR                      2
#define IPROP_SIMCTRL_LEFT                           3
#define IPROP_SIMCTRL_TOP                            4
#define IPROP_SIMCTRL_WIDTH                          5
#define IPROP_SIMCTRL_HEIGHT                         6
#define IPROP_SIMCTRL_VISIBLE                        7
#define IPROP_SIMCTRL_PARENT                         8
#define IPROP_SIMCTRL_HWND                           9
#define IPROP_SIMCTRL_NODETYPE                       10
#define IPROP_SIMCTRL_DESCRIPTION           11
#define IPROP_SIMCTRL_FONTNAME                       12
#define IPROP_SIMCTRL_FONTBOLD                       13
#define IPROP_SIMCTRL_FONTITALIC            14
#define IPROP_SIMCTRL_FONTSTRIKE            15
#define IPROP_SIMCTRL_FONTUNDER                      16
#define IPROP_SIMCTRL_FONTSIZE                       17
#define IPROP_SIMCTRL_MODULAR                        18
#define IPROP_SIMCTRL_LOWEST                         19
#define IPROP_SIMCTRL_NUMLEFT                        20
```

```
#define IPROP_SIMCTRL_NUMTOP                    21
#define IPROP_SIMCTRL_NUMRIGHT                  22
#define IPROP_SIMCTRL_NUMBOTTOM                 23
#define IPROP_SIMCTRL_SELECTED                  24

PPROPINFO SIMCTRL_Properties[] =
   {
   PPROPINFO_STD_CTLNAME,
   PPROPINFO_STD_INDEX,
   PPROPINFO_STD_BACKCOLOR,
   PPROPINFO_STD_LEFT,
   PPROPINFO_STD_TOP,
   PPROPINFO_STD_WIDTH,
   PPROPINFO_STD_HEIGHT,
   PPROPINFO_STD_VISIBLE,
   PPROPINFO_STD_PARENT,
   PPROPINFO_STD_HWND,
   &PPROPINFO_CUS_NODETYPE,
        &PPROPINFO_CUS_DESCRIPTION,
        PPROPINFO_STD_FONTNAME,
        PPROPINFO_STD_FONTBOLD,
        PPROPINFO_STD_FONTITALIC,
        PPROPINFO_STD_FONTSTRIKE,
        PPROPINFO_STD_FONTUNDER,
        PPROPINFO_STD_FONTSIZE,
        &PPROPINFO_CUS_MODULAR,
        &PPROPINFO_CUS_LOWEST,
        &PPROPINFO_CUS_NUMLEFT,
        &PPROPINFO_CUS_NUMTOP,
        &PPROPINFO_CUS_NUMRIGHT,
        &PPROPINFO_CUS_NUMBOTTOM,
        &PPROPINFO_CUS_SELECTED,
    NULL
    };

//---------------------------------------------------------------------
// Event list
//---------------------------------------------------------------------
// Define the consecutive indicies for the events
//---------------------------------------------------------------------
#define IEVENT_SIMCTRL_MOUSEDOWN                0
#define IEVENT_SIMCTRL_MOUSEMOVE                1
#define IEVENT_SIMCTRL_MOUSEUP                  2
#define IEVENT_SIMCTRL_DBLCLICK                 3
```

```
PEVENTINFO SIMCTRL_Events[] =
   {
   PEVENTINFO_STD_MOUSEDOWN,
   PEVENTINFO_STD_MOUSEMOVE,
   PEVENTINFO_STD_MOUSEUP,
   PEVENTINFO_STD_DBLCLICK,
   NULL
   };

//----------------------------------------------------------------------
// Model struct
//----------------------------------------------------------------------
// Define the control model (using the event and property structures).
//----------------------------------------------------------------------
MODEL modelSIMCTRL =
   {
   (unsigned)VB_VERSION,                 // VB version being used
   0,                                            // MODEL flags
   (PCTLPROC)SIMCTRLCtlProc,             // Control procedure
   CS_VREDRAW | CS_HREDRAW,                  // Class style
       0,                                               // Default Windows
style
   sizeof(SIMCTRLSTRUCT),                    // Size of SIMCTRL structure
   IDBMP_SIMCTRL,                                // Palette bitmap ID
   SIMCTRL,                                  // Default control name
   SIMCTRL,                                  // Visual Basic class name
   NULL,                                         // Parent class name
   SIMCTRL_Properties,                       // Property information table
   SIMCTRL_Events,                           // Event information table
   IPROP_SIMCTRL_LEFT,                       // Default property
   IEVENT_SIMCTRL_MOUSEDOWN,                 // Default event
   -1                                        // Property representing value of ctl
   };

#endif // RC_INVOKED

//----------------------------------------------------------------------
```

APPENDIX D-2 VISUAL C++ CODE FOR GRAPHICAL OBJECT

```
#include <windows.h>
#include vbapi.h
#include SIMCTRL.h

//-----------------------------------------------------------------
// Global Variables
//-----------------------------------------------------------------
HANDLE hmodDLL;

void display(HCTL hctl,HWND hwnd,HDC hdc)
{
        RECT rect,drawrect,descrect;
        HPEN newpen=NULL;
        HPEN oldpen=NULL;
        HPEN dashed_pen=NULL;
        LPSIMCTRL lpnode=NULL;
        HFONT hfontold=NULL;
        HBRUSH hbr=NULL;
        HBRUSH hbr_black=NULL;
        HBRUSH hbrOld=NULL;
        COLORREF /*oldcolor,*/Gray,Black,Selected;

        Gray=RGB(192,192,192);
        Black=RGB(0,0,0);
        Selected=RGB(0,80,120);

        hbr=CreateSolidBrush(Gray);
        hbr_black=CreateSolidBrush(Black);
        dashed_pen=CreatePen(PS_DASHDOT,1,Selected);
        newpen=CreatePen(PS_SOLID,2,Black);

        GetClientRect(hwnd,&rect);

        drawrect=rect;
        drawrect.top=(int)(drawrect.top+drawrect.bottom*1/5)+3;
        drawrect.bottom-=5;
        drawrect.left+=4;
        drawrect.right-=4;

        descrect=rect;
        descrect.bottom=drawrect.top-3;
```

```
	oldpen=SelectObject(hdc,newpen);
	lpnode=SIMCTRLDEREF(hctl);
	hfontold=SelectObject(hdc,lpnode->hfont ? lpnode-
>hfont:GetStockObject(SYSTEM_FONT));

	if (lpnode->selected) {
		//oldcolor=GetBkColor(hdc);
		//SetBkColor(hdc,Gray);
		HPEN old_pen;
		hbrOld=SelectObject(hdc,hbr_black);
		//SetBkColor(hdc,oldcolor);
		Rectangle(hdc,rect.left,rect.top,rect.left+3,rect.top+5);
		Rectangle(hdc,rect.right,rect.top,rect.right-3,rect.top+5);
		Rectangle(hdc,rect.left,rect.bottom,rect.left+3,rect.bottom-5);
		Rectangle(hdc,rect.right,rect.bottom,rect.right-3,rect.bottom-5);
		SelectObject(hdc,hbrOld);
		old_pen=SelectObject(hdc,dashed_pen);
		Rectangle(hdc,rect.left+1,rect.top+2,rect.right-1,rect.bottom-2);
		SelectObject(hdc,old_pen);
	}

	switch (lpnode->NodeType) {
		case Queue: {
			Ellipse(hdc, drawrect.left, drawrect.top, drawrect.right,
drawrect.bottom);
			MoveTo(hdc,(int)(drawrect.right*0.7),(int)(drawrect.bottom*0.7));
			LineTo(hdc,drawrect.right-3,drawrect.bottom-1);
		}
		break;
		case Combi: {

	Rectangle(hdc,drawrect.left,drawrect.top,drawrect.right,drawrect.bottom);
			MoveTo(hdc,drawrect.left,(int)(drawrect.top+drawrect.bottom)/3);
			LineTo(hdc,(int)((drawrect.left+drawrect.right)/3),drawrect.top);
		}
		break;

		case Normal: {
				Rectangle(hdc, drawrect.left, drawrect.top, drawrect.right,
drawrect.bottom);
			}
			break;
```

```
		case Consolidate: {
			Ellipse(hdc, drawrect.left, drawrect.top, drawrect.right,
drawrect.bottom);
		}
		break;
		case Output: {
			Ellipse(hdc, drawrect.left, drawrect.top,
drawrect.right,drawrect.bottom);
			DrawText(hdc, OUT, -1, &drawrect, DT_CENTER |
DT_VCENTER | DT_SINGLELINE);
		}
		break;
		case Input: {
			Ellipse(hdc, drawrect.left, drawrect.top, drawrect.right,
drawrect.bottom);

	//MoveTo(hdc,(int)(drawrect.right*0.7),(int)(drawrect.bottom*0.7));
			//LineTo(hdc,drawrect.right,drawrect.bottom);
			DrawText(hdc, IN, -1, &drawrect, DT_CENTER | DT_VCENTER
| DT_SINGLELINE);
		}
		break;
		case Arn: {
			Ellipse(hdc, drawrect.left, drawrect.top, drawrect.right,
drawrect.bottom);
			DrawText(hdc, AR, -1, &drawrect, DT_CENTER |
DT_VCENTER | DT_SINGLELINE);
		}
		break;
		case Frn: {
		   Ellipse(hdc, drawrect.left, drawrect.top, drawrect.right,
drawrect.bottom);
			DrawText(hdc, FR, -1, &drawrect, DT_CENTER |
DT_VCENTER | DT_SINGLELINE);
		}
		break;
		case Counter: {
			int xmiddle,ymiddle,yquarter;

			xmiddle=(int)(drawrect.left+(drawrect.right-drawrect.left)/2);
			ymiddle=(int)(drawrect.top+(drawrect.bottom-drawrect.top)/2);
			yquarter=(int)(drawrect.top+0.25*(drawrect.bottom-
drawrect.top));
```

```
            Ellipse(hdc,drawrect.left+7,ymiddle,drawrect.right-7, drawrect.bottom);
                    MoveTo(hdc,xmiddle,ymiddle);
                    LineTo(hdc,xmiddle,drawrect.top);
                    LineTo(hdc,drawrect.right,yquarter);
                    LineTo(hdc,xmiddle,yquarter);
            }
            break;
            case ProdEvent: {
                    int xpart,ypart;
                    POINT pt;
                    RECT circle_rect;

                    xpart=(int)((drawrect.right-drawrect.left)/5);
                    ypart=(int)((drawrect.bottom-drawrect.top)/2);


                    pt.x=drawrect.left;
                    pt.y=drawrect.top;
                    MoveTo(hdc,pt.x,pt.y);
                    pt.x+=xpart;
                    pt.y+=ypart;
                    LineTo(hdc,pt.x,pt.y);
                    pt.x-=xpart;
                    pt.y+=ypart;
                    LineTo(hdc,pt.x,pt.y);
                    pt.y-=2*ypart;
                    LineTo(hdc,pt.x,pt.y);
                    circle_rect.left=drawrect.left+xpart;
                    circle_rect.top=drawrect.top;
                    circle_rect.right=circle_rect.left+2*xpart;
                    circle_rect.bottom=drawrect.bottom;
                    Ellipse(hdc,circle_rect.left, circle_rect.top, circle_rect.right,
circle_rect.bottom);
                    circle_rect.left=drawrect.left+3*xpart;
                    circle_rect.top=drawrect.top;
                    circle_rect.right=circle_rect.left+2*xpart;
                    circle_rect.bottom=drawrect.bottom;
                    Ellipse(hdc,circle_rect.left, circle_rect.top, circle_rect.right,
circle_rect.bottom);
            }
            break;
            case ProdGate: {
        RECT myrect;
```

```
        POINT pt;
        int xmiddle=(int)(rect.right/2);

                        Ellipse(hdc, drawrect.left, drawrect.top, xmiddle,drawrect.bottom);
                        Ellipse(hdc, xmiddle, drawrect.top,
drawrect.right,drawrect.bottom);
                        pt.x=drawrect.left+(int)(xmiddle/2);
                        pt.y=(int)( (drawrect.top+drawrect.bottom)/2);
                        MoveTo(hdc,pt.x,pt.y);
                        pt.x+=(int)((drawrect.right-drawrect.left)/2);
                        LineTo(hdc,pt.x,pt.y);
}
break;
case ProdVar: {
                        int xpart=(int)((drawrect.right-drawrect.left)/5);
                        int ypart=(int)((drawrect.bottom-drawrect.top)/2);
                        POINT pt;
                        RECT circle_rect;

                        pt.x=drawrect.right-xpart-2;
                        pt.y=drawrect.top;
                        MoveTo(hdc,pt.x,pt.y);
                        pt.x+=xpart;
                        pt.y+=ypart;
                        LineTo(hdc,pt.x,pt.y);
                        pt.x-=xpart;
                        pt.y+=ypart;
                        LineTo(hdc,pt.x,pt.y);
                        pt.y-=2*ypart;
                        LineTo(hdc,pt.x,pt.y);
                        circle_rect.left=drawrect.left;
                        circle_rect.top=drawrect.top;
                        circle_rect.right=circle_rect.left+2*xpart;
                        circle_rect.bottom=drawrect.bottom;
                        Ellipse(hdc,circle_rect.left, circle_rect.top, circle_rect.right,
circle_rect.bottom);
                        circle_rect.left=drawrect.left+2*xpart;
                        circle_rect.top=drawrect.top;
                        circle_rect.right=circle_rect.left+2*xpart;
                        circle_rect.bottom=drawrect.bottom;
                        Ellipse(hdc,circle_rect.left, circle_rect.top, circle_rect.right,
circle_rect.bottom);
                }
                break;
```

```
            case ProdCounter: {
        RECT crect;
        POINT pt;
        int xpart,ypart;

        xpart=(int)((drawrect.right-drawrect.left)/4);
                        ypart=(int)((drawrect.bottom-drawrect.top)/3);

                        crect=drawrect;
                        crect.top=drawrect.bottom-ypart;
                        crect.right=crect.left+2*xpart;
                        Ellipse(hdc, crect.left, crect.top, crect.right,crect.bottom);
                        crect.left+=2*xpart;
                        crect.right+=2*xpart;
                        Ellipse(hdc, crect.left, crect.top, crect.right,crect.bottom);
                        pt.x=crect.left;
                        pt.y=drawrect.bottom-(int)( ypart/2);
                        MoveTo(hdc,pt.x,pt.y);
                        pt.y-=(int) (2.5*ypart);
                        LineTo(hdc,pt.x,pt.y);
                        pt.x-=xpart;
                        pt.y+=ypart;
                        LineTo(hdc,pt.x,pt.y);
                        pt.x+=xpart;
                        LineTo(hdc,pt.x,pt.y);
            }
            break;
        }
        lpnode=SIMCTRLDEREF(hctl);
        DrawText(hdc,(LPSTR)VBDerefHsz(lpnode->Description),-
1,&descrect,DT_VCENTER|DT_CENTER|DT_SINGLELINE);

        DeleteObject(hbr);
        DeleteObject(hbr_black);
        SelectObject(hdc,hfontold);
        SelectObject(hdc,oldpen);
        DeleteObject(newpen);
        DeleteObject(dashed_pen);
}


//-----------------------------------------------------------------
// default message handling
```

```
//-------------------------------------------------------------
LONG FAR PASCAL _export SIMCTRLCtlProc
(
   HCTL   hctl,
   HWND   hwnd,
   USHORT msg,
   USHORT wp,
   LONG   lp
)
{
   switch(msg) {
        case WM_SETFONT:
                SIMCTRLDEREF(hctl)->hfont=(HFONT)wp;
                return 0;

        case WM_GETFONT: {
                LPSIMCTRL lpnode=SIMCTRLDEREF(hctl);
                return lpnode->hfont;
        }
        case WM_NCCREATE: {
                LPSIMCTRL lpSim=SIMCTRLDEREF(hctl);
                lpSim->NodeType=Queue;
        }
        break;

        case WM_PAINT:

                if (wp)
                        display(hctl,hwnd,(HDC)wp);
                else {
                        PAINTSTRUCT ps;
                        BeginPaint(hwnd,&ps);
                        display(hctl,hwnd,ps.hdc);
                        EndPaint(hwnd,&ps);
                }

        break;

        case WM_SIZE: InvalidateRect(hwnd,NULL,TRUE);return 0;

        case WM_NCDESTROY: {
                LPSIMCTRL lpnode=SIMCTRLDEREF(hctl);
                if (lpnode->Description) {
                        VBDestroyHsz(lpnode->Description);
```

```
            }
            break;
        }
        case VBM_SETPROPERTY:
            switch(wp) {
                case IPROP_SIMCTRL_NODETYPE:
                    if (lp>-1 && lp<11) {
                        InvalidateRect(hwnd,NULL,TRUE);
                    }
                    return 0;
                //case IPROP_SIMCTRL_DESCRIPTION:

                //case IPROP_SIMCTRL_MODULAR:

                default:{
                    InvalidateRect(hwnd,NULL,TRUE);
                }
            }
        break;
    }
        return VBDefControlProc(hctl, hwnd, msg, wp, lp);
}


//----------------------------------------------------------------------
// Initialize library. This routine is called when the first client loads
// the DLL.
//----------------------------------------------------------------------
int FAR PASCAL LibMain
(
    HANDLE hModule,
    WORD   wDataSeg,
    WORD   cbHeapSize,
    LPSTR  lpszCmdLine
)
{
    // Avoid warnings on unused (but required) formal parameters
    wDataSeg    = wDataSeg;
    cbHeapSize  = cbHeapSize;
    lpszCmdLine = lpszCmdLine;

    hmodDLL = hModule;

    return 1;
```

```
}


//------------------------------------------------------------------
// Register custom control. This routine is called by VB when the custom
// control DLL is loaded for use.
//------------------------------------------------------------------
BOOL FAR PASCAL _export VBINITCC
(
  USHORT usVersion,
  BOOL   fRuntime
)
{
  // Avoid warnings on unused (but required) formal parameters
  fRuntime  = fRuntime;
  usVersion = usVersion;

  // Register control(s)
  return VBRegisterModel(hmodDLL, &modelSIMCTRL);
}


//------------------------------------------------------------------
// WEP
//------------------------------------------------------------------

int FAR PASCAL WEP(int fSystemExit);

#pragma alloc_text(WEP_TEXT,WEP)

int FAR PASCAL WEP
(
  int fSystemExit
)
{
  // Avoid warnings on unused (but required) formal parameters
   fSystemExit = fSystemExit;

  return 1;
```

APPENDIX E: ACB COLUMNS AND CORES PROCESSES

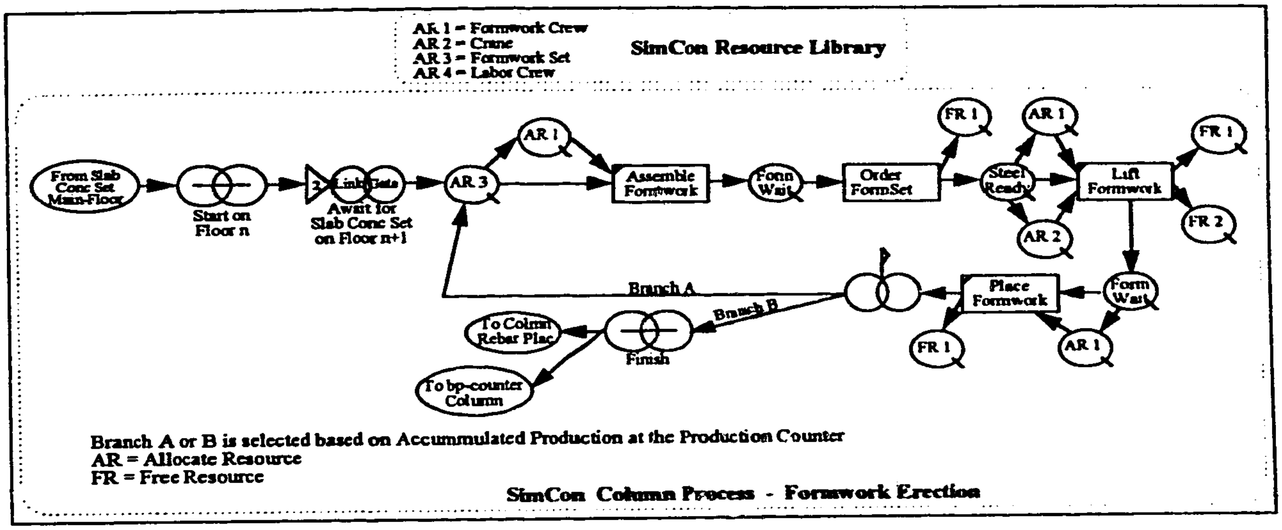

Figure Appendix E.1: ***Column Formwork Erection Process***

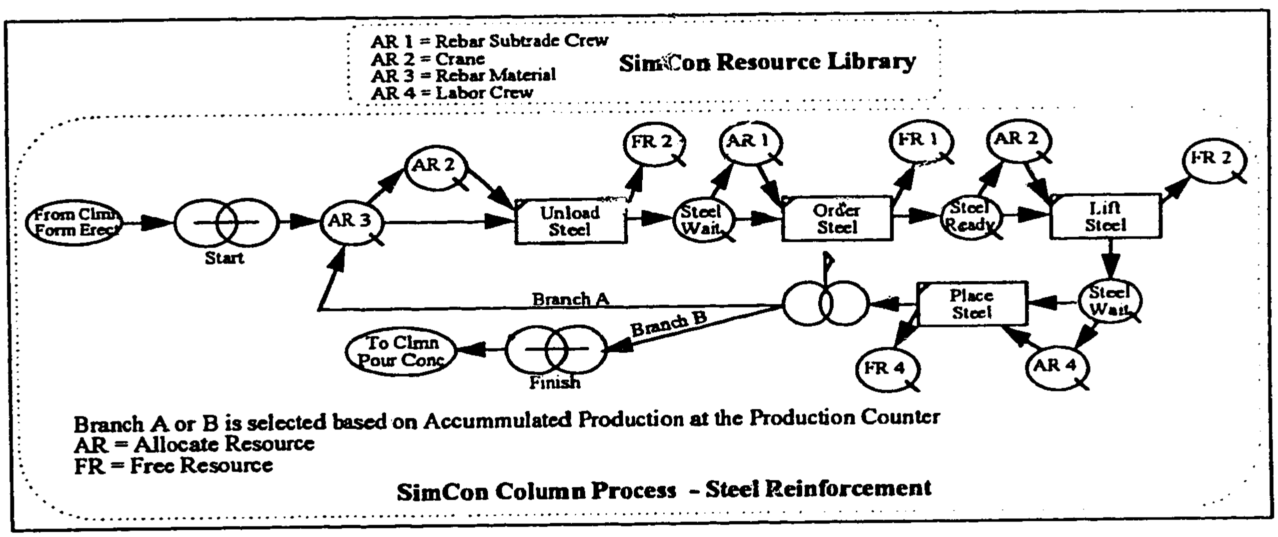

Figure Appendix E.2: ***Column Steel Reinforcement Process***

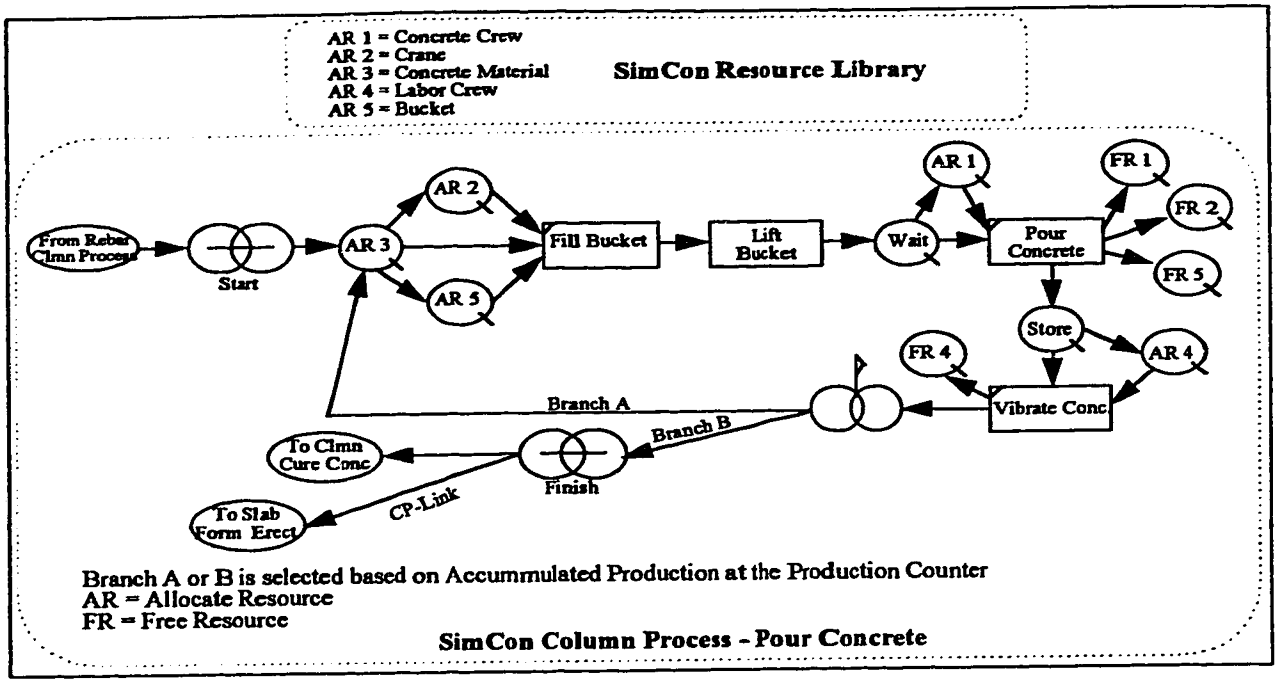

Figure Appendix E.3: ***Column Pour Concrete Process***

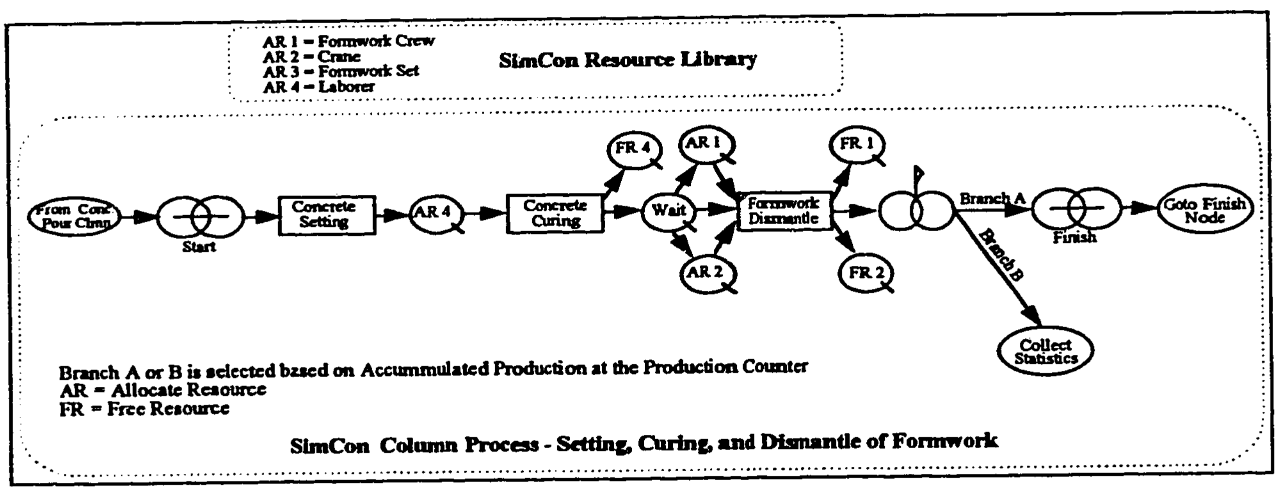

Figure Appendix E.4: ***Column Formwork Dismantle Process***

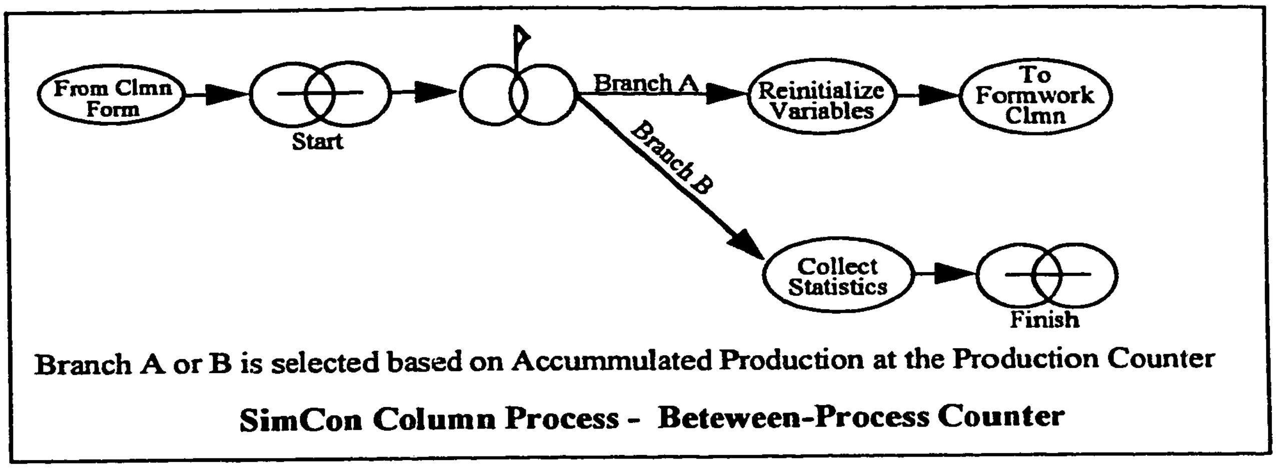

Figure Appendix E.5: ***Column Between Process PRO Node***

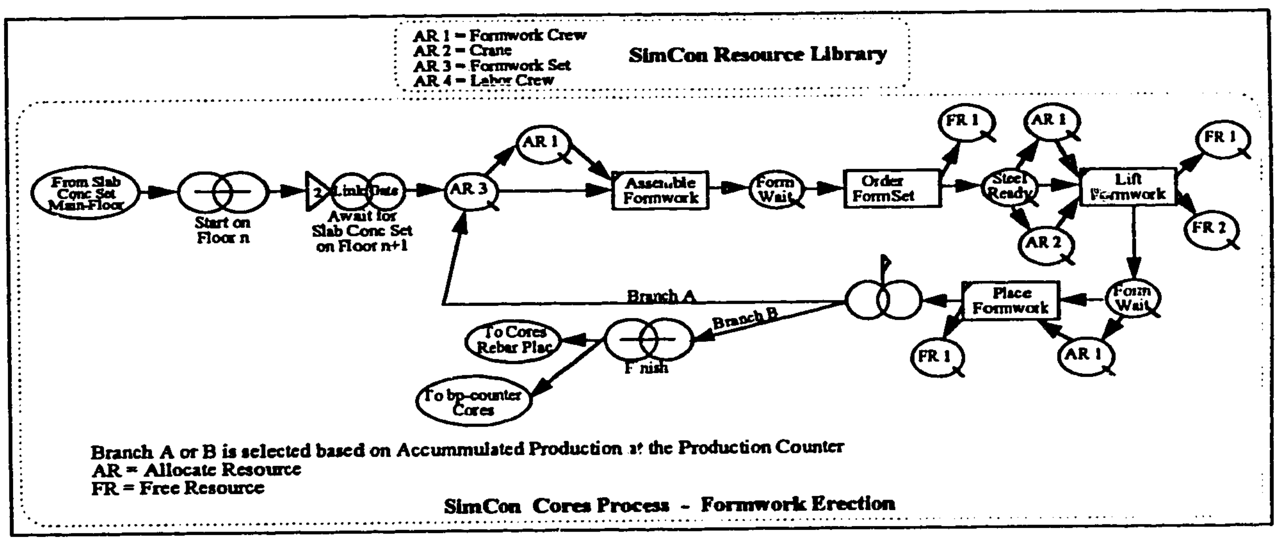

Figure Appendix E.6: ***Cores Formwork Erection Process***

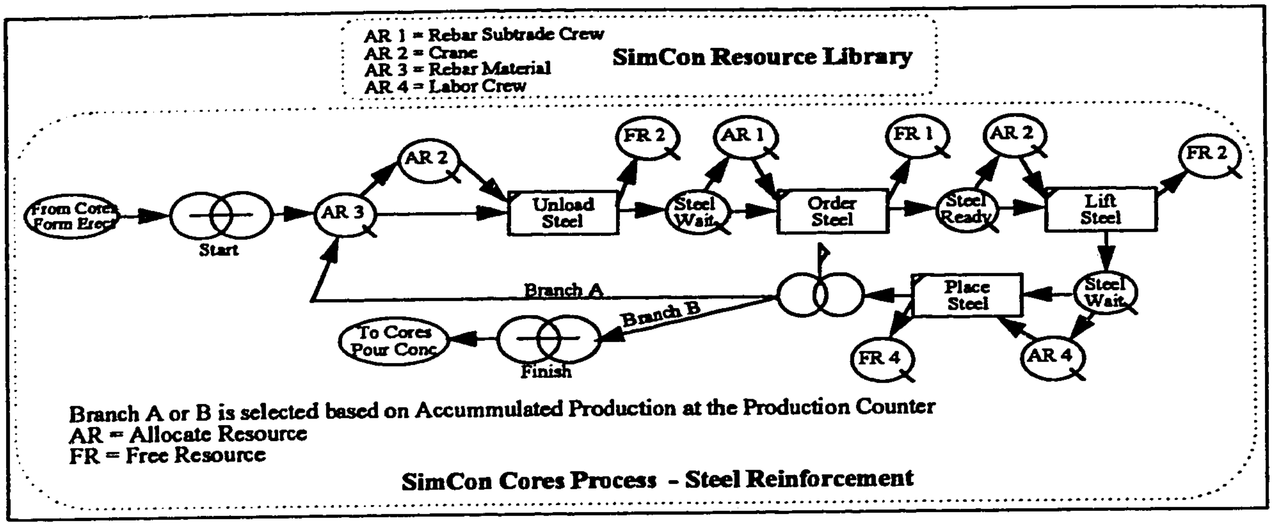

Figure Appendix E.7: Cores Steel Reinforcement Process

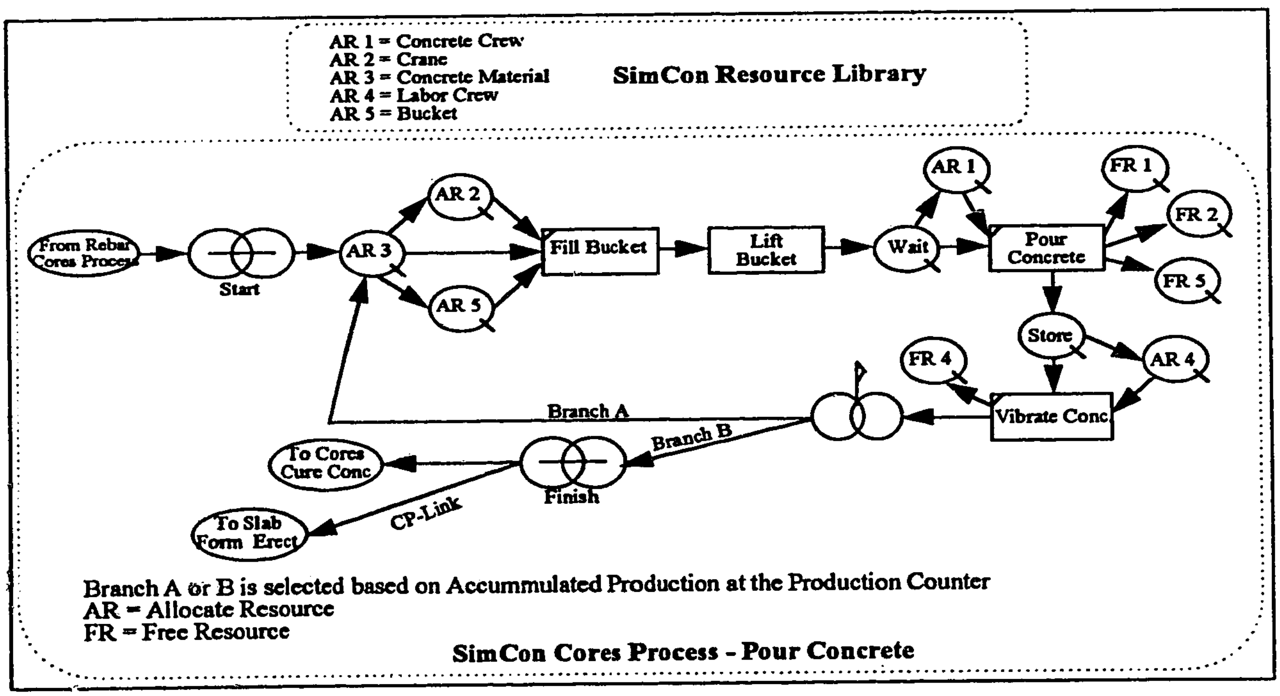

Figure Appendix E.8: Cores Pour Concrete Process

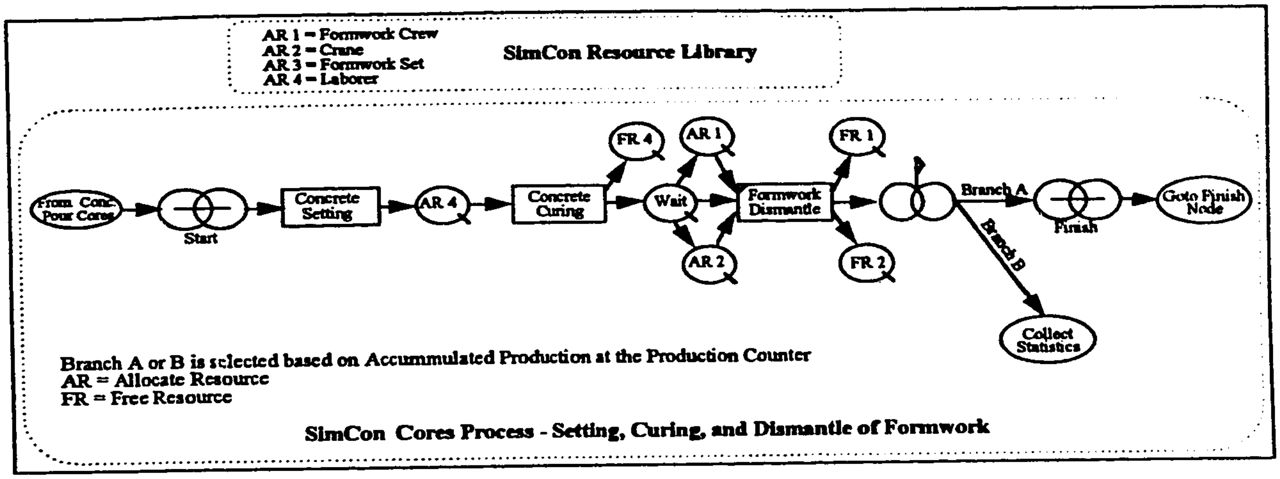

Figure Appendix E.9: *Cores Formwork Dismantle Process*

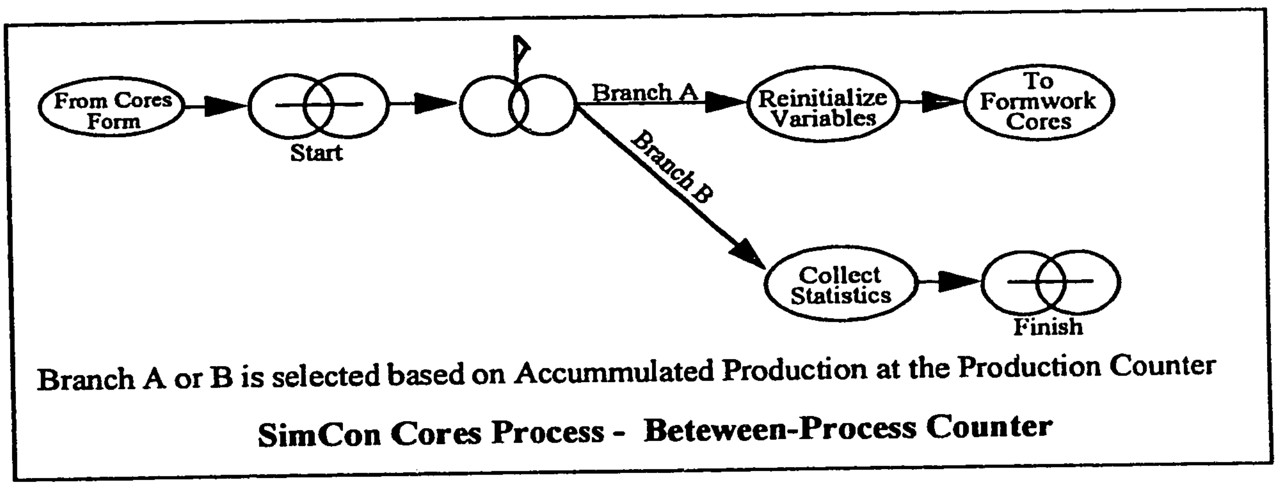

Figure Appendix E.10: *Cores Between Process PRO Node*

APPENDIX F: SLAM II MODELS

APPENDIX F-1: TEXTUAL FORMAT

```
1
GEN,NADER N. CHEHAYEB,THESIS CASE STUDY,23/5/1995,100,Y,Y,Y/Y,Y,Y/S,72;
LIMITS,21,95,60;
NETWORK;
;FILE ARESOUR3.NET, NODE LABEL SEED AAZZ
    RESOURCE/1,RES101,10;
    RESOURCE/2,RES102,5,6,7,1,4;
    RESOURCE/3,RES103(2),5;
    RESOURCE/4,RES104,2;
    RESOURCE/5,RES105(400),2;
    RESOURCE/6,RES106(2),3;
    RESOURCE/7,RES107(300),3;
    RESOURCE/8,COLSLAB(2),8;
    RESOURCE/9,CORESLAB,9;
    RESOURCE/10,RES110(2),6;
    RESOURCE/11,RES111(2),1;
    RESOURCE/12,RES112,7;
    RESOURCE/13,RES113,5,6,7,1,4;
    RESOURCE/14,RES114,2;
;FILE BPCOLM.NET, NODE LABEL SEED BPCO
;FILE BPCORES.NET, NODE LABEL SEED ZAAA
;FILE BPSLABS.NET, NODE LABEL SEED SLBP
;FILE COCONCF.NET, NODE LABEL SEED FCFC
;FILE COCONCM.NET, NODE LABEL SEED UCAQ
;FILE CODISMF.NET, NODE LABEL SEED CDAA
;FILE CODISMM.NET, NODE LABEL SEED CODM
;FILE COFORMF.NET, NODE LABEL SEED WXOR
;FILE COFORMM.NET, NODE LABEL SEED COFM
;FILE COLCONC.NET, NODE LABEL SEED IQZP
;FILE COLCONCF.NET, NODE LABEL SEED CFNM
;FILE COLDISMF.NET, NODE LABEL SEED NALS
;FILE COLDISMM.NET, NODE LABEL SEED CLDI
;FILE COLFORMF.NET, NODE LABEL SEED EACQ
;FILE COLFORMM.NET, NODE LABEL SEED PCLA
;FILE COLREBAF.NET, NODE LABEL SEED RCFZ
;FILE COLREBAR.NET, NODE LABEL SEED VCAR
;FILE COREBARF.NET, NODE LABEL SEED CORF
;FILE COREBARM.NET, NODE LABEL SEED CORM
;FILE SLCONCF.NET, NODE LABEL SEED SABZ
;FILE SLCONCM.NET, NODE LABEL SEED SLXQ
;FILE SLDISMF.NET, NODE LABEL SEED SDQP
;FILE SLDISMM.NET, NODE LABEL SEED SLMC
;FILE SLFORMF.NET, NODE LABEL SEED ALYZ
;FILE SLFORMM.NET, NODE LABEL SEED ASLA
;FILE SLREBARF.NET, NODE LABEL SEED SLRF
;FILE SLREBARM.NET, NODE LABEL SEED SLRM
```

```
;FILE SOGCONC2.NET, NODE LABEL SEED SGCO
;FILE SOGDISMT.NET, NODE LABEL SEED SODI
;FILE SOGERECT.NET, NODE LABEL SEED SOFO
;FILE SOGREBAR.NET, NODE LABEL SEED SORE
;FILE ARESOUR3.NET, NODE LABEL SEED AAZZ
;
;For all Carpentry Work
;
;Crane=101
;
;Crane for Formwork, Concrete, & Steel
;
;slab f set=111
;
;formwcrew=102
;
;form set=112
;
;clmnfset=103
;
;core f set=110
;
;concrete crew=104
;
;formcrew2=113
;
;concrete=105
;
;steel sub=106
;
;concrete crew 2=114
;
;steel=107
;
;2 Zones in One Floor Representation
;
;Continuous Production Link Gate - Resource Simulation Control
;
SOG1  TERMINATE;
;
FIN   COLCT,TNOW,ENTRIES;
      ACTIVITY;
      ACCUMULATE,3,3,,1;
      ACTIVITY,,.05;
      ACTIVITY,,.1,ABAN;
      ACTIVITY,,.65,ABAM;
      ACTIVITY,,.1,ABAO;
      ACTIVITY,,.1,ABAP;
      GOON;
      ACTIVITY,80;
```

```
ABAM COLCT,TNOW,FINISH TIME,10/710/6;
    ACTIVITY;
ABAQ GOON;
    ACTIVITY;
    ACTIVITY,,,ABAB;
    ACTIVITY,,,ABAC;
    ACTIVITY,,,ABAD;
    ACTIVITY,,,ABAE;
    ACTIVITY,,,ABAF;
    ACTIVITY,,,ABAG;
    ACTIVITY,,,ABAH;
    ACTIVITY,,,ABAI;
    ACTIVITY,,,ABAJ;
    ACTIVITY,,,ABAK;
    ACTIVITY,,,ABAL;
    COLCT,XX(20),PRO 153 CORE FRM,,1;
    ACTIVITY;
ABAA TERMINATE,12;
ABAB COLCT,XX(21),PRO 171 CORE RBR,,1;
    ACTIVITY,,,ABAA;
ABAC COLCT,XX(19),PRO 135 CORE CNC,,1;
    ACTIVITY,,,ABAA;
ABAD COLCT,XX(77),PRO 157 COR DSMT,,1;
    ACTIVITY,,,ABAA;
ABAE COLCT,XX(32),PRO 159 COLM FRM,,1;
    ACTIVITY,,,ABAA;
ABAF COLCT,XX(18),PRO 170 COL RBR,,1;
    ACTIVITY,,,ABAA;
ABAG COLCT,XX(29),PRO 164 COLM CNC,,1;
    ACTIVITY,,,ABAA;
ABAH COLCT,XX(71),PRO 160 COL DSMT,,1;
    ACTIVITY,,,ABAA;
ABAI COLCT,XX(87),PRO 104 SLB FRM,,1;
    ACTIVITY,,,ABAA;
ABAJ COLCT,XX(30),PRO 169 SLB RBR,,1;
    ACTIVITY,,,ABAA;
ABAK COLCT,XX(31),PRO 163 SLB CNC,,1;
    ACTIVITY,,,ABAA;
ABAL COLCT,XX(83),PRO 105 SLB DSM,,1;
    ACTIVITY,,,ABAA;
ABAN GOON;
    ACTIVITY,40,,ABAM;
ABAO GOON;
    ACTIVITY,120,,ABAM;
ABAP GOON;
    ACTIVITY,160,,ABAM;
;
    CREATE,,200,,1,1;
    ACTIVITY,,,ABAQ;
;FILE BPCOLM.NET, NODE LABEL SEED BPCO
```

```
;
BPCLM COLCT,XX(45),XX45 COLUM;
     ACTIVITY;
ASSIGN,ATRIB(90)=ATRIB(90)+1,ATRIB(70)=0,ATRIB(71)=0,ATRIB(72)=0,XX(45)=
     XX(45)+1,XX(51)=0,ATRIB(39)=TRIAG(100,114,125),ATRIB(40)=TRIAG(200,250,
     300),ATRIB(41)=TRIAG(0.5,0.72,0.95),ATRIB(42)=TRIAG(30,70,90),1;
     ACTIVITY;
     COLCT,XX(45),COLMN FLOOR COMP,,1;
     ACTIVITY,,XX(45).LT.XX(44),CLFF;
     ACTIVITY,,XX(45).GE.XX(44);
     COLCT,XX(45),END COL  FL SOG1;
     ACTIVITY,,,SOG1;
;FILE BPCORES.NET, NODE LABEL SEED ZAAA
;
BPCOR COLCT,XX(11),XX11 CORES;
     ACTIVITY;
ASSIGN,ATRIB(91)=ATRIB(91)+1,XX(12)=XX(12)+1,XX(9)=8,ATRIB(78)=0,ATRIB(
     77)=0,ATRIB(76)=0,ATRIB(17)=TRIAG(100,114,125),ATRIB(18)=TRIAG(200,250,
     300),ATRIB(19)=TRIAG(0.1,0.12,0.15),ATRIB(20)=TRIAG(30,70,90),1;
     ACTIVITY;
     COLCT,XX(12),CORE FLOOR COMP,,1;
     ACTIVITY,,XX(12).LT.XX(11),COFF;
     ACTIVITY,,XX(12).GE.XX(11);
     COLCT,XX(12),END CORE FL SOG1;
     ACTIVITY,,,SOG1;
;FILE BPSLABS.NET, NODE LABEL SEED SLBP
;
BPSLB COLCT,XX(17),XX17 SLABS;
     ACTIVITY;
     COLCT,XX(88),XX88 CHECK SLABS;
     ACTIVITY;
ASSIGN,ATRIB(92)=ATRIB(92)+1,XX(88)=XX(88)+1,XX(15)=8,ATRIB(73)=0,ATRIB(
     74)=0,ATRIB(75)=0,ATRIB(29)=TRIAG(100,114,125),ATRIB(30)=TRIAG(200,250,
     300),ATRIB(32)=TRIAG(30,70,90),ATRIB(31)=TRIAG(0.6,0.72,0.95),1;
     ACTIVITY;
     COLCT,XX(88),SLAB FLOOR COMP,,1;
     ACTIVITY,,XX(88).LT.XX(17),SLFF;
     ACTIVITY,,XX(88).GE.XX(17);
     COLCT,XX(88),END SLB FL SOG1;
     ACTIVITY,,,SOG1;
;FILE COCONCF.NET, NODE LABEL SEED FCFC
;
;Pour Concrete For Cores Floor2-6
;
COCF  GOON,1;
     ACTIVITY,,XX(11).EQ.0;
     ACTIVITY,,XX(11).GT.0,FCFG;
```

```
      GOON;
      ACTIVITY,,,COAA;
COAA  ASSIGN,XX(75)=XX(75)+1;
      ACTIVITY;
      COLCT,XX(75),XX75 CORE CONC,,1;
      ACTIVITY;
      GOON,1;
      ACTIVITY,,XX(75).GE.XX(11),FCFH;
      ACTIVITY,,XX(75).LT.XX(11),FCFI;
FCFH  COLCT,TNOW,END 135 CR CNC,10/390/28;
      ACTIVITY,,,CPSC;
      ACTIVITY,,,CPSC;
      ACTIVITY,,,CODF;
FCFI  GOON;
      ACTIVITY,,,CODF;
      ACTIVITY,,,CPSC;
      ACTIVITY,,,CPSC;
FCFG  GOON,1;
      ACTIVITY,,XX(11)-ATRIB(91).GT.1;
      ACTIVITY,,XX(11)-ATRIB(91).LE.1,FCFF;
COBS  COLCT,FIRST,BEG 135 CO CNC,10/172/2,1;
      ACTIVITY;
FCFE  ASSIGN,ATRIB(19)=TRIAG(.1,.35,.6);
      ACTIVITY;
FCFD  AWAIT(2),ALLOC(1);
      ACTIVITY;
      AWAIT(10),RES101;
      ACTIVITY/19,ATRIB(19),,;COREF-POUR;
      FREE,RES101;
      ACTIVITY;
      EVENT,2;
      ACTIVITY;
ASSIGN,ATRIB(19)=TRIAG(.1,.35,.6),ATRIB(78)=ATRIB(78)+1,XX(19)=XX(19)+1,1;
      ACTIVITY,,ATRIB(78).GT.XX(9),COAA;
      ACTIVITY,,ATRIB(78).LE.XX(9);
      COLCT,ATRIB(78),PRO TRY 135  COR,,1;
      ACTIVITY,,,FCFD;
FCFF  COLCT,FIRST,BEG  F CNC 135,10/154/2,1;
      ACTIVITY,,,FCFE;
;
;CP-Link =  CP between Slab and Core
;FILE COCONCM.NET, NODE LABEL SEED UCAQ
;
;Pour Concrete For Cores Main Floor
;
COCM  GOON,1;
      ACTIVITY,,XX(6).EQ.0;
      ACTIVITY,,XX(6).GT.0,UCAT;
      GOON;
```

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     ACTIVITY,,,COAC;
UCAT COLCT,FIRST,BEG CORE MN CONC,10/74/1,1;
     ACTIVITY;
     ASSIGN,ATRIB(15)=TRIAG(.3,.4,.5);
     ACTIVITY;
UCAR AWAIT(2),ALLOC(1);
     ACTIVITY;
     AWAIT(10),RES101,
     ACTIVITY/15,ATRIB(15),,;COREM-POUR;
     FREE,RES101;
     ACTIVITY;
     EVENT,2;
     ACTIVITY;
     ASSIGN,ATRIB(15)=TRIAG(.3,.4,.5),XX(7)=XX(7)+1,1;
     ACTIVITY,,XX(7).GT.XX(6);
     ACTIVITY,,XX(7).LE.XX(6),UCAS;
     COLCT,TNOW,END CORE MN CONC,10/77/1,1;
     ACTIVITY,,,COAC;
UCAS COLCT,XX(7),SCHPRO COR M CON,,1;
     ACTIVITY,,,UCAR;
;
COAC GOON;
     ACTIVITY,,,SLFM;
     ACTIVITY,,,CODM;
;FILE CODISMF.NET, NODE LABEL SEED CDAA
;
;Dismantle Formwork for Cores Floor2-6 - A Non Repetitive Process (NP)
;
;Atrib(20)=Duration of Dismantle of Formwork for Cores (hours)
;
CODF ASSIGN,XX(77)=XX(77)+1,ATRIB(20)=TRIAG(3, 7, 9),1;
     ACTIVITY,,ATRIB(20).LE.0,FIN;
     ACTIVITY,,ATRIB(20).GT.0;
     GOON,1;
     ACTIVITY/23,XX(8),,;CURING TIME;
     GOON,1;
     ACTIVITY,,XX(11)-ATRIB(91).GT.1;
     ACTIVITY,,XX(11)-ATRIB(91).LE.1,CDAC;
     COLCT,FIRST,BEG 157 CRE DISM,10/200/2;
     ACTIVITY;
CDAB AWAIT(4),ALLOC(12),,1;
     ACTIVITY/20,ATRIB(20),,;COREF-DISMANTLE;
     COLCT,XX(77),XX77 COUNT;
     ACTIVITY;
     FREE,RES110,1;
     ACTIVITY;
     EVENT,1,1;
     ACTIVITY,,XX(77).LT.XX(11),SOG1;
     ACTIVITY,,XX(77).GE.XX(11);
     COLCT,TNOW,END 157 CRE DISM,10/640/3,1;
```

```
     ACTIVITY,,,FIN;
CDAC COLCT,FIRST,BEG CR DM LS 157,10/154/2,1;
     ACTIVITY,,,CDAB;
;
;Between-Process Cores- Form, Rebar, Conc, Dismntle
;FILE CODISMM.NET, NODE LABEL SEED CODM
;
;Dismantle Formwork for Cores Main Floor - A Non Repetitive Process (NP)
;
;Atrib(16)=Duration of Dismantle of Formwork for Cores (hours)
;
CODM ASSIGN,ATRIB(16)=TRIAG(4, 5, 6),1;
     ACTIVITY,,ATRIB(16).LE.0,SOG1;
     ACTIVITY,,ATRIB(16).GT.0;
     GOON;
     ACTIVITY/22,XX(8),,;CURING TIME;
     COLCT,FIRST,CORE BEG DISM MN,10/100/1;
     ACTIVITY;
     AWAIT(4),ALLOC(12),,1;
     ACTIVITY/16,ATRIB(16),,;CORESM-DISMANTLE;
     EVENT,1,1;
     ACTIVITY;
     FREE,RES110,1;
     ACTIVITY;
     COLCT,TNOW,CORE END DISM MN,10/113/1.5,1;
     ACTIVITY,,,SOG1;
;FILE COFORMF.NET, NODE LABEL SEED WXOR
;
;Cores Erection Formwork Operation Prefab - Floor 2-6 - (NP) Process
;
;ATrib(17) = Duration of Erection of Formwork for One Floor
;
COFF ASSIGN,XX(64)=XX(64)+1,ATRIB(17)=TRIAG(.7,1,1.2),1;
     ACTIVITY,,XX(11).EQ.0,CRYA;
     ACTIVITY,,XX(11).GT.0;
     GOON,1;
     ACTIVITY,,XX(11)-ATRIB(91).GT.1;
     ACTIVITY,,XX(11)-ATRIB(91).LE.1,WXPA;
     COLCT,FIRST,BEG 153 CRE FRM,10/154/2,1;
     ACTIVITY,,ATRIB(17).GT.0;
WXOZ AWAIT(9),CORESLAB;
     ACTIVITY;
     AWAIT(6),ALLOC(6);
     ACTIVITY;
     AWAIT(10),RES101;
     ACTIVITY;
WXOX GOON;
     ACTIVITY/17,ATRIB(17),,;CORES-F-ERECT;
     ASSIGN,ATRIB(17)=TRIAG(.3, 1,1.6),ATRIB(76)=ATRIB(76)+1,XX(20)=XX(20)+1,1;
     ACTIVITY,,ATRIB(76).GT.XX(52);
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    ACTIVITY,,ATRIB(76).LE.XX(52),WXOY;
    FREE,RES101;
    ACTIVITY;
    EVENT,1;
    ACTIVITY,,,CRYA;
WXOY  COLCT,ATRIB(76),PRO TRY 153 F FM,,1;
    ACTIVITY,,,WXOX;
WXPA  COLCT,FIRST,BEG ST FRM 153,10/154/2,1;
    ACTIVITY,,,WXOZ;
;
CRYA  COLCT,XX(64),XX64 CORE FORM,,1;
    ACTIVITY;
    GOON,1;
    ACTIVITY,,XX(64).LT.XX(11);
    ACTIVITY,,XX(64).GE.XX(11),WXPB;
    GOON;
    ACTIVITY,,,CORF;
    ACTIVITY,,,BPCOR;
WXPB  COLCT,TNOW,END 153 CR FRM,10/600/2;
    ACTIVITY,,,CORF;
    ACTIVITY,,,BPCOR;
;FILE COFORMM.NET, NODE LABEL SEED COFM
;
;Cores Erection Formwork Operation Prefab - Main Floor  - (NP) Process
;
COFM  ASSIGN,ATRIB(13)=TRIAG(12,14,16),1;
    ACTIVITY;
    COLCT,FIRST,BEG CORE FRM MN,10/45/.5,1;
    ACTIVITY,,ATRIB(13).EQ.0,CORM;
    ACTIVITY,,ATRIB(13).GT.0;
    AWAIT(6),ALLOC(9);
    ACTIVITY/13,ATRIB(13),,;CORES-M-ERECT;
    EVENT,1;
    ACTIVITY;
    COLCT,TNOW,END CORE FRM MN,10/58/.5;
    ACTIVITY,,,CORM;
;FILE COLCONC.NET, NODE LABEL SEED IQZP
;
;Pour Concrete For Columns - RP Process - Main-Floor
;
CLCM  GOON,1;
    ACTIVITY,,XX(36).EQ.0;
    ACTIVITY,,XX(36).GT.0,IQZV;
    GOON;
    ACTIVITY,,,COAD;
IQZV  COLCT,FIRST,BEG COL CONC,10/79/1,1;
    ACTIVITY;
    ASSIGN,ATRIB(36)=TRIAG(1,1.2,1.5);
    ACTIVITY;
IQZT  AWAIT(2),ALLOC(1);
```

```
     ACTIVITY;
     AWAIT(10),RES101;
     ACTIVITY/36,ATRIB(36),,;COLM-POUR;
     EVENT,2;
     ACTIVITY;
     FREE,RES101;
     ACTIVITY;
     ASSIGN,ATRIB(36)=TRIAG(1,1.2,1.5),XX(37)=XX(37)+1,1;
     ACTIVITY,,XX(37).GT.XX(36);
     ACTIVITY,,XX(37).LE.XX(36),IQZU;
     COLCT,TNOW,END COL CONC,10/91/1,1;
     ACTIVITY,,,COAD;
IQZU  COLCT,XX(37),SCHPRO COL CON,,1;
     ACTIVITY,,,IQZT;
;
COAD  GOON;
     ACTIVITY,,,SLFM;
     ACTIVITY,,,CLDM;
;FILE COLCONCF.NET, NODE LABEL SEED CFNM
;
;Pour Concrete For Columns - RP Process - Floor 2-6
;
CLCF  GOON,1;
     ACTIVITY,,XX(44).EQ.0;
     ACTIVITY,,XX(44).GT.0,CFNP;
     GOON;
     ACTIVITY,,,CLAE;
CFNP  GOON,1;
     ACTIVITY,,XX(44)-ATRIB(90).LE.2;
     ACTIVITY,,XX(44)-ATRIB(90).GT.2,CLBS;
     COLCT,FIRST,BEG CL CN LT 164,10/154/2,1;
     ACTIVITY;
CFNO  COLCT,TNOW,TNOW COL BG C FL,,1;
     ACTIVITY;
     ASSIGN,ATRIB(71)=0,ATRIB(41)=TRIAG(.1,.2,.3);
     ACTIVITY;
CFNN  AWAIT(2),ALLOC(1);
     ACTIVITY;
     AWAIT(10),RES101;
     ACTIVITY/41,ATRIB(41),,;COLM-POUR;
     EVENT,2;
     ACTIVITY;
     FREE,RES101;
     ACTIVITY;
ASSIGN,XX(29)=XX(29)+1,ATRIB(41)=TRIAG(.05,.2,.4),ATRIB(71)=ATRIB(71)+1,1;
     ACTIVITY,,ATRIB(71).GT.XX(41),CLAE;
     ACTIVITY,,ATRIB(71).LE.XX(41);
     COLCT,ATRIB(71),PRO TRY 164 COL;
     ACTIVITY,,,CFNN;
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CLBS  COLCT,FIRST,BEG 164 COL CNC,10/165/2,1;
      ACTIVITY,,,CFNO;
;
;CP-Link =  CP between Slab and CoLumns
;
CLAE  ASSIGN,XX(69)=XX(69)+1;
      ACTIVITY;
      COLCT,XX(69),XX69 COL FL CONC;
      ACTIVITY;
      GOON,1;
      ACTIVITY,,XX(69).LT.XX(44);
      ACTIVITY,,XX(69).GE.XX(44),CFNQ;
      GOON;
      ACTIVITY,,,CLDF;
      ACTIVITY,,,CPSL;
CFNQ  COLCT,TNOW,END 164 COL CONC,10/600/2.5;
      ACTIVITY,,,CPSL;
      ACTIVITY,,,CLDF;
;FILE COLDISMF.NET, NODE LABEL SEED NALS
;
;Dismantle Formwork for Columns - A Non Repetitive Process (NP) -Floor 2-6
;
;Atrib(42)=Duration of Dismantle of Formwork for Columns (hours)
;
CLDF  ASSIGN,ATRIB(42)=TRIAG(1.5, 3.5, 4.5),1;
      ACTIVITY,,XX(44).LE.0,FIN;
      ACTIVITY,,XX(44).GT.0;
      GOON,1;
      ACTIVITY/43,XX(8),,;CURING TIME;
      GOON,1;
      ACTIVITY,,XX(44)-ATRIB(90).LE.2;
      ACTIVITY,,XX(44)-ATRIB(90).GT.2,NALU;
      COLCT,FIRST,BEG CL DM LT 160,10/154/2,1;
      ACTIVITY;
NALT  AWAIT(4),ALLOC(12),,1;
      ACTIVITY/42,ATRIB(42),,;COLM-DISM;
      FREE,RES103,1;
      ACTIVITY;
      ASSIGN,XX(71)=XX(71)+1;
      ACTIVITY;
      COLCT,XX(71),XX71 COUNT;
      ACTIVITY;
      EVENT,1,1;
      ACTIVITY,,XX(71).LT.XX(44),SOG1;
      ACTIVITY,,XX(71).GE.XX(44);
      COLCT,TNOW,END 160 COL DSFM,11/631/2,1;
      ACTIVITY,,,FIN;
NALU  COLCT,FIRST,BEG 60 CL DSFM,10/190/2;
      ACTIVITY,,,NALT;
;FILE COLDISMM.NET, NODE LABEL SEED CLDI
```

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;
;Dismantle Formwork for SOG - A Non Repetitive Process (NP)
;
;Atrib(12)=Duration of Dismantle of Formwork for Columns (hours)Main-Floor
;
CLDM  ASSIGN,ATRIB(37)=TRIAG(3, 4, 5),1;
     ACTIVITY,,ATRIB(37).LE.0,CLAA;
     ACTIVITY,,ATRIB(37).GT.0;
     GOON,1;
     ACTIVITY/38,XX(8),,;CURING TIME;
     COLCT,TNOW,COL BEG DIS FORM,10/114/1;
     ACTIVITY,,,CLAA;
     ACTIVITY;
     AWAIT(4),ALLOC(12),,1;
     ACTIVITY/37,ATRIB(37),,;COLM-DISM;
     EVENT,1,1;
     ACTIVITY;
     FREE,RES103,1;
     ACTIVITY;
     COLCT,TNOW,COL END DIS FORM,11/119/1,1;
     ACTIVITY,,,SOG1;
;
CLAA  GOON;
     ACTIVITY,,,SOG1;
;FILE COLFORMF.NET, NODE LABEL SEED EACQ
;
;Erect Formwork for Columns Floor2-6  - A Non Repetitive Process (NP)
;
;Atrib(39)=Duration of Erection of Formwork for Columns  (hours)
;
CLFF  ASSIGN,ATRIB(72)=0,ATRIB(39)=TRIAG(.4,.5,.6),1;
     ACTIVITY;
     AWAIT(8),COLSLAB,,1;
     ACTIVITY,,XX(44).EQ.0,CRXA;
     ACTIVITY,,XX(44).GT.0;
     GOON,1;
     ACTIVITY,,XX(44)-ATRIB(90).GT.2;
     ACTIVITY,,XX(44)-ATRIB(90).LE.2,EACU;
     COLCT,FIRST,BEG 159 CL FORM,10/154/2,1;
     ACTIVITY;
EACT  AWAIT(5),ALLOC(5);
     ACTIVITY;
     AWAIT(10),RES101;
     ACTIVITY/39,ATRIB(39),,;COLM-ERECT;
EACR  GOON;
     ACTIVITY;
     ASSIGN,XX(32)=XX(32)+1,ATRIB(39)=TRIAG(.2,.5,.8),ATRIB(72)=ATRIB(72)+1,1;
     ACTIVITY,,ATRIB(72).GT.XX(50);
     ACTIVITY,,ATRIB(72).LE.XX(50),EACS;
     FREE,RES101;
```

```
    ACTIVITY;
    EVENT,1;
    ACTIVITY,,,CRXA;
EACS COLCT,ATRIB(72),PRO TRY 159 FRM,,1;
    ACTIVITY,,,EACR;
EACU COLCT,FIRST,BEG FM LS CL 159,10/154/2,1;
    ACTIVITY,,,EACT;
;
CRXA COLCT,XX(62),XX62 COL FORM,,1;
    ACTIVITY;
    ASSIGN,XX(62)=XX(62)+1;
    ACTIVITY;
    GOON,1;
    ACTIVITY,,XX(62).LT.XX(44);
    ACTIVITY,,XX(62).GE.XX(44),EACV;
    GOON;
    ACTIVITY,,,CLRF;
    ACTIVITY,,,BPCLM;
EACV COLCT,TNOW,END 159 CL FORM,10/590/3;
    ACTIVITY,,,CLRF;
    ACTIVITY,,,BPCLM;
;FILE COLFORMM.NET, NODE LABEL SEED PCLA
;
;Erect Formwork for Columns Main-Floor - A Non Repetitive Process (NP)
;
;Atrib(39)=Duration of Erection of Formwork for Columns (hours)
;
CLFM ASSIGN,ATRIB(34)=TRIAG(10,14,17),1;
    ACTIVITY,,ATRIB(34).EQ.0,CLRM;
    ACTIVITY,,ATRIB(34).GT.0;
    COLCT,TNOW,COL MN BEG FORM,10/45/.5,1;
    ACTIVITY;
    AWAIT(5),ALLOC(7);
    ACTIVITY/34,ATRIB(34),,;COLM-ERECT;
    EVENT,1;
    ACTIVITY;
    COLCT,TNOW,COL MN END FORM,10/70/1,1;
    ACTIVITY,,,CLRM;
;FILE COLREBAF.NET, NODE LABEL SEED RCFZ
;
;Atrib(47)=Duration of Placing of Rebar for Columns - (RP) Process
;
;Place Rebar for Columns Floor2-6
;
CLRF GOON,1;
    ACTIVITY;
    COLCT,TNOW,TNOW COL FL REB1,,1;
    ACTIVITY;
    ASSIGN,XX(39)=7,ATRIB(70)=0,ATRIB(40)=TRIAG(.8,1,1.2),1;
    ACTIVITY,,XX(44).EQ.0,CRAA;
```

```
       ACTIVITY,,XX(44).GT.0;
       GOON,1;
       ACTIVITY,,XX(44)-ATRIB(90).LE.2;
       ACTIVITY,,XX(44)-ATRIB(90).GT.2,RCGB;
       COLCT,FIRST,BEG CL RB LS 170,10/154/2,1;
       ACTIVITY;
 RCGA  AWAIT(3),ALLOC(4),,1;
       ACTIVITY/40,ATRIB(40),,;COLM-REBAR;
       FREE,RES106,1;
       ACTIVITY;
ASSIGN,XX(18)=XX(18)+1,ATRIB(40)=TRIAG(.6,1,1.4),ATRIB(70)=ATRIB(70)+1,1;
       ACTIVITY,,ATRIB(70).GT.XX(39),CRAA;
       ACTIVITY,,ATRIB(70).LE.XX(39);
       COLCT,ATRIB(70),PRO TRY 170 RBR,,1;
       ACTIVITY,,,RCGA;
 RCGB  COLCT,FIRST,BEG 170 COL RBR,10/159/2;
       ACTIVITY,,,RCGA;
;
 CRAA  ASSIGN,XX(68)=XX(68)+1,1;
       ACTIVITY;
       COLCT,ATRIB(70),ATR70 CL FL RBR,,1;
       ACTIVITY;
       COLCT,XX(39),XX39 CL FL RBR,,1;
       ACTIVITY;
       COLCT,XX(68),XX68 COL FL REB2,,1;
       ACTIVITY;
       GOON,1;
       ACTIVITY,,XX(68).LT.XX(44),CLCF;
       ACTIVITY,,XX(68).GE.XX(44);
       COLCT,TNOW,END 170 COL RBR,10/603/2,1;
       ACTIVITY,,,CLCF;
;FILE COLREBAR.NET, NODE LABEL SEED VCAR
;
;Atrib(34)=Duration of Placing of Rebar for columns  - (RP) Process
;
;Place Rebar for columns - Main-Floor
;
 CLRM  GOON,1;
       ACTIVITY;
       ASSIGN,ATRIB(35)=TRIAG(1,1.33,1.5),1;
       ACTIVITY,,XX(34).EQ.0,CLCM;
       ACTIVITY,,XX(34).GT.0;
       COLCT,TNOW,BEG COL MN REBAR,10/70/1;
       ACTIVITY;
 VCAS  AWAIT(3),ALLOC(4),,1;
       ACTIVITY/35,ATRIB(35),,;COLM-REBAR;
       FREE,RES106,1;
       ACTIVITY;
       ASSIGN,ATRIB(35)=TRIAG(1,1.33,1.5),XX(35)=XX(35)+1,1;
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     ACTIVITY,,XX(35).GT.XX(34);
     ACTIVITY,,XX(35).LE.XX(34),VCAT;
     COLCT,TNOW,END COL MN REBAR,10/78/1,1;
     ACTIVITY,,,CLCM;
VCAT COLCT,XX(35),SCHPRO CL MN RBR,10/0/1,1;
     ACTIVITY,,,VCAS;
;FILE COREBARF.NET, NODE LABEL SEED CORF
;
;Place Rebar for Cores Floor 2-6
;
CORF GOON,1;
     ACTIVITY;
     ASSIGN,ATRIB(18)=TRIAG(2,3,4),1;
     ACTIVITY,,XX(11).EQ.0,CRQA;
     ACTIVITY,,XX(11).GT.0;
     GOON,1;
     ACTIVITY,,XX(11)-ATRIB(91).GT.1;
     ACTIVITY,,XX(11)-ATRIB(91).LE.1,CORJ;
     COLCT,FIRST,BEG 171 CR RBR,10/158/2,1;
     ACTIVITY;
CORI AWAIT(3),ALLOC(4),,1;
     ACTIVITY/18,ATRIB(18),,;COREF-REBAR;
     FREE,RES106,1;
     ACTIVITY;
     ASSIGN,XX(21)=XX(21)+1,ATRIB(18)=TRIAG(2,3,4),ATRIB(77)=ATRIB(77)+1,1;
     ACTIVITY,,ATRIB(77).GT.XX(58),CRQA;
     ACTIVITY,,ATRIB(77).LE.XX(58);
     COLCT,ATRIB(77),PRO TRY 171 RBR,,1;
     ACTIVITY,,,CORI;
CORJ COLCT,FIRST,BEG ST CR RB 171,10/154/2,1;
     ACTIVITY,,,CORI;
;
CRQA ASSIGN,XX(73)=XX(73)+1,1;
     ACTIVITY;
     COLCT,XX(73),XX73 CORE REBAR,,1;
     ACTIVITY;
     GOON,1;
     ACTIVITY,,XX(73).LT.XX(11),COCF;
     ACTIVITY,,XX(73).GE.XX(11);
     COLCT,TNOW,END 171 CRE RBR,11/615/2,1;
     ACTIVITY,,,COCF;
;FILE COREBARM.NET, NODE LABEL SEED CORM
;
;Place Rebar for Cores Main Floor
;
CORM GOON,1;
     ACTIVITY;
     ASSIGN,ATRIB(14)=TRIAG(15,17,18),1;
     ACTIVITY,,ATRIB(14).EQ.0,COCM;
     ACTIVITY,,ATRIB(14).GT.0;
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     COLCT,TNOW,BEG CORE RBAR MN,10/58/1,1;
     ACTIVITY;
     AWAIT(3),ALLOC(4),,1;
     ACTIVITY/14,ATRIB(14);
     FREE,RES106,1;
     ACTIVITY;
     COLCT,TNOW,END CORE RBAR MN,10/75/.8;
     ACTIVITY,,,COCM;
;FILE SLCONCF.NET, NODE LABEL SEED SABZ
;
;Pour Concrete For Slabs Floor2-6
;
SLCF GOON,1;
     ACTIVITY,,XX(17).EQ.0;
     ACTIVITY,,XX(17).GT.0,SACD;
     GOON;
     ACTIVITY,,,SLAA;
SACD GOON,1;
     ACTIVITY,,XX(17)-ATRIB(92).GT.2;
     ACTIVITY,,XX(17)-ATRIB(92).LE.2,SACC;
SLBS COLCT,FIRST,BEG 163 SLB CNC,10/190/2,1;
     ACTIVITY;
SACB ASSIGN,ATRIB(75)=0,ATRIB(31)=TRIAG(.2,.3,.45);
     ACTIVITY;
SACA AWAIT(2),ALLOC(1);
     ACTIVITY;
     AWAIT(10),RES101;
     ACTIVITY/31,ATRIB(31),,;SLAB-F-POUR;
     EVENT,2;
     ACTIVITY;
     FREE,RES101;
     ACTIVITY;
ASSIGN,XX(31)=XX(31)+1,ATRIB(31)=TRIAG(.2,.3,.45),ATRIB(75)=ATRIB(75)+1,1;
     ACTIVITY,,ATRIB(75).GT.XX(15),SLAA;
     ACTIVITY,,ATRIB(75).LE.XX(15);
     COLCT,ATRIB(75),PRO TRY 163 CNC,,1;
     ACTIVITY,,,SACA;
SACC COLCT,FIRST,BEG SLBC LST 163,10/154/2,1;
     ACTIVITY,,,SACB;
;
SLAA ASSIGN,XX(81)=XX(81)+1;
     ACTIVITY;
     COLCT,XX(81),XX81 SLB FL CONC,,1;
     ACTIVITY;
     GOON,1;
     ACTIVITY,,XX(81).LT.XX(17),SLDF;
     ACTIVITY,,XX(81).GE.XX(17);
     COLCT,TNOW,END 163 SLB CONC,11/680/2,1;
     ACTIVITY,,,SLDF;
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```
;FILE SLCONCM.NET, NODE LABEL SEED SLXQ
;
;Pour Concrete For Slabs Main Floor
;
SLCM  GOON,1;
      ACTIVITY,,XX(13).EQ.0;
      ACTIVITY,,XX(13).GT.0,SLXT;
      GOON;
      ACTIVITY,,,SLDM;
SLXT  COLCT,FIRST,BEG SLAB MN CONC,10/123/1.6,1;
      ACTIVITY;
      ASSIGN,ATRIB(26)=TRIAG(.6,.8,1);
      ACTIVITY;
SLXR  AWAIT(2),ALLOC(1);
      ACTIVITY;
      AWAIT(10),RES101;
      ACTIVITY/26,ATRIB(26),,;SLAB-M-POUR;
      EVENT,2;
      ACTIVITY;
      FREE,RES101;
      ACTIVITY;
      ASSIGN,ATRIB(26)=TRIAG(.6,.8,1),XX(14)=XX(14)+1,1;
      ACTIVITY,,XX(14).GT.XX(13);
      ACTIVITY,,XX(14).LE.XX(13),SLXS;
      COLCT,TNOW,END SLAB MN CONC,10/130/1.6,1;
      ACTIVITY,,,SLDM;
SLXS  COLCT,XX(14),SCHPRO SLB M CON,10/0/1;
      ACTIVITY,,,SLXR;
;FILE SLDISMF.NET, NODE LABEL SEED SDQP
;
;Dismantle Formwork for Slabs Floor2-6 - A Non Repetitive Process (NP)
;
;Atrib(32)=Duration of Dismantle of Formwork for Cores (hours)
;
SLDF  ASSIGN,ATRIB(32)=TRIAG(3.5, 4, 4.5),1;
      ACTIVITY,,ATRIB(32).LE.0,FIN;
      ACTIVITY,,ATRIB(32).GT.0;
      GOON,1;
      ACTIVITY/33,XX(8),,;CURING TIME;
      GOON,1;
      ACTIVITY,,XX(17)-ATRIB(92).GT.2;
      ACTIVITY,,XX(17)-ATRIB(92).LE.2,SDQU;
      COLCT,FIRST,BEG 105 SLAB DSM,10/217/2;
      ACTIVITY;
      ACTIVITY,,,SDQS;
SDQT  GOON;
      ACTIVITY;
      ACTIVITY,,,SDQR;
      FREE,COLSLAB,1;
      ACTIVITY;
```

```
     COLCT,TNOW,COLSLAB ONLY,,1;
     ACTIVITY;
SDQQ GOON,1;
     ACTIVITY,,,SOG1;
SDQR BATCH,1,2;
     ACTIVITY;
     FREE,CORESLAB,1;
     ACTIVITY;
     COLCT,TNOW,CORESLAB ONLY,,1;
     ACTIVITY,,,SDQQ;
SDQS AWAIT(4),ALLOC(12),,1;
     ACTIVITY/32,ATRIB(32),,;SLAB-F-DISMANTLE;
     FREE,RES111,1;
     ACTIVITY;
     ASSIGN,XX(83)=XX(83)+1;
     ACTIVITY;
     COLCT,XX(83),XX83 SLB DSM F,,1;
     ACTIVITY;
     EVENT,1,1;
     ACTIVITY,,XX(83).LT.XX(17),SOG1;
     ACTIVITY,,XX(83).GE.XX(17);
     COLCT,TNOW,END 105 SLAB DSM,10/705/2.8,1;
     ACTIVITY,,,FIN;
SDQU COLCT,FIRST,BEG SLM LST 105,10/154/2;
     ACTIVITY,,,SDQT;
     ACTIVITY,,,SDQS;
;FILE SLDISMM.NET, NODE LABEL SEED SLMC
;
;Dismantle Formwork for Slab Main Floor - A Non Repetitive Process (NP)
;
;Atrib(16)=Duration of Dismantle of Formwork for Slab (hours)
;
SLDM ASSIGN,ATRIB(27)=TRIAG(6, 8, 9),1;
     ACTIVITY,,ATRIB(27).LE.0,SOG1;
     ACTIVITY,,ATRIB(27).GT.0;
     GOON,1;
     ACTIVITY/28,XX(8),,;CURING TIME;
     COLCT,FIRST,SLAB BEG DISM MN,10/154/1.6;
     ACTIVITY,,,COFF;
     ACTIVITY,,,SLFF;
     ACTIVITY,,,CLFF;
     ACTIVITY;
     AWAIT(4),ALLOC(12),,1;
     ACTIVITY/27,ATRIB(27),,;SLAB-M-DISMANTLE;
     EVENT,1,1;
     ACTIVITY;
     FREE,RES111,1;
     ACTIVITY;
     COLCT,TNOW,SLAB END DISM MN,10/167/1.6,1;
     ACTIVITY,,,SOG1;
```

```
;FILE SLFORMF.NET, NODE LABEL SEED ALYZ
;
;Slab Erection Formwork Operation Prefab - Floor 2-6  - (NP) Process
;
;ATrib(29) = Duration of Erection of Formwork for One Floor
;
;Slab-Core-Column-Assemble node
;
CPSL  COLCT,TNOW,ELEM FROM COLMN;
      ACTIVITY;
ALZB  QUEUE(19),,,,ALZA ;
ALZA  SELECT,ASM/HIGH(92),LIT,,ALZB,ALZC,ALZD;
      ACTIVITY(1);
      QUEUE(21),,,;
      ACTIVITY(1);
      GOON,1;
      ACTIVITY,,XX(17)-ATRIB(92).GT.2;
      ACTIVITY,,XX(17)-ATRIB(92).LE.2,ALZH;
      COLCT,FIRST,BEG 104 SLB FRM,10/176/2,1;
      ACTIVITY;
ALZG  ASSIGN,ATRIB(73)=0,1;
      ACTIVITY;
      AWAIT(1),ALLOC(2),,1;
      ACTIVITY;
      AWAIT(10),RES101,,1;
      ACTIVITY;
ALZE  GOON;
      ACTIVITY/29,ATRIB(29),,;SLAB-F-ERECT;
ASSIGN,ATRIB(73)=ATRIB(73)+1,ATRIB(29)=TRIAG(1,1.5,1.8),XX(87)=XX(87)+1,1;
      ACTIVITY,,ATRIB(73).GT.XX(56);
      ACTIVITY,,ATRIB(73).LE.XX(56),ALZF;
      FREE,RES101,1;
      ACTIVITY;
      EVENT,1;
      ACTIVITY,,,CRZA;
ALZF  COLCT,ATRIB(73),PRO TRY 104 FRM,,1;
      ACTIVITY,,,ALZE;
ALZH  COLCT,FIRST,BEG SB FM LT 104,10/154/2,1;
      ACTIVITY,,,ALZG;
;
CPSC  COLCT,TNOW,ELEM FROM CORE;
      ACTIVITY;
ALZC  QUEUE(18),,,,ALZA ;
;
SLFF  ASSIGN,ATRIB(29)=TRIAG(1,1.5,1.8),1;
      ACTIVITY,,XX(17).EQ.0,SLRF;
      ACTIVITY,,XX(17).GT.0,SLOD;
SLOD  COLCT,TNOW,TNOW AT SLFF 3,,1;
      ACTIVITY;
```

```
ALZD  QUEUE(20),,,,ALZA ;
;
CRZA  ASSIGN,XX(66)=XX(66)+1;
      ACTIVITY;
      GOON,1;
      ACTIVITY,,XX(66).LT.XX(17);
      ACTIVITY,,XX(66).GE.XX(17),ALZI;
      COLCT,XX(66),XX66 SLAB FRM FL;
      ACTIVITY,,,SLRF;
      ACTIVITY,,,BPSLB;
ALZI  COLCT,TNOW,END 104 SLB FRM,11/668/2;
      ACTIVITY,,,SLRF;
      ACTIVITY,,,BPSLB;
;FILE SLFORMM.NET, NODE LABEL SEED ASLA
;
;Slab Erection Formwork Operation Prefab - Main Floor  - (NP) Process
;
SLFM  ACCUMULATE,2,2;
      ACTIVITY;
      ASSIGN,ATRIB(24)=TRIAG(15,20,22),1;
      ACTIVITY;
      COLCT,FIRST,BEG SLAB FRM MN,10/90/1,1;
      ACTIVITY,,ATRIB(24).EQ.0,SLRM;
      ACTIVITY,,ATRIB(24).GT.0;
      AWAIT(1),ALLOC(8),,1;
      ACTIVITY/24,ATRIB(24),,;SLAB-M-ERECT;
      EVENT,1;
      ACTIVITY;
      COLCT,TNOW,END SLAB FRM MN,11/105/1.5,1;
      ACTIVITY,,,SLRM;
;FILE SLREBARF.NET, NODE LABEL SEED SLRF
;
;Place Rebar for Slabs Floor 2-6
;
SLRF  GOON,1;
      ACTIVITY;
      ASSIGN,ATRIB(74)=0,ATRIB(30)=TRIAG(1.5,1.8,2),1;
      ACTIVITY,,XX(17).EQ.0,CRWA;
      ACTIVITY,,XX(17).GT.0;
      GOON,1;
      ACTIVITY,,XX(17)-ATRIB(92).GT.2;
      ACTIVITY,,XX(17)-ATRIB(92).LE.2,SLRH;
      COLCT,FIRST,BEG 169 SLB RBAR,10/180/2,1;
      ACTIVITY;
SLRG  AWAIT(3),ALLOC(4),,1;
      ACTIVITY/30,ATRIB(30),,;SLAB-F-REBAR;
      FREE,RES106,1;
      ACTIVITY;
ASSIGN,XX(30)=XX(30)+1,ATRIB(30)=TRIAG(1.5,1.8,2),ATRIB(74)=ATRIB(74)+1,1;
```

```
     ACTIVITY,,ATRIB(74).GT.XX(54),CRWA;SLREB-GT;
     ACTIVITY,,ATRIB(74).LE.XX(54),;SLREBAR-LE;
     COLCT,ATRIB(74),PRO TRY 169 RBR,,1;
     ACTIVITY,,,SLRG;
SLRH COLCT,FIRST,BEG SL RB LT 169,10/154/2,1;
     ACTIVITY,,,SLRG;
;
CRWA ASSIGN,XX(79)=XX(79)+1,1;
     ACTIVITY;
     COLCT,XX(79),XX79 SLAB RBR FL,,1;
     ACTIVITY;
     GOON,1;
     ACTIVITY,,XX(79).LT.XX(17),SLCF;
     ACTIVITY,,XX(79).GE.XX(17);
     COLCT,TNOW,END 169 SLAB RBR,10/675/3,1;
     ACTIVITY,,,SLCF;
;FILE SLREBARM.NET, NODE LABEL SEED SLRM
;
;Place Rebar for Slab - Main Floor
;
SLRM GOON;
     ACTIVITY;
     ASSIGN,ATRIB(25)=TRIAG(10,19,21),1;
     ACTIVITY,,ATRIB(25).EQ.0,SLCM;
     ACTIVITY,,ATRIB(25).GT.0;
     COLCT,TNOW,BEG SLAB RBAR MN,10/107/1.5,1;
     ACTIVITY;
     AWAIT(3),ALLOC(4),,1;
     ACTIVITY/25,ATRIB(25),,;SLAB-M-REBAR;
     FREE,RES106,1;
     ACTIVITY;
     COLCT,TNOW,END SLAB RBAR MN,10/123/1.6;
     ACTIVITY,,,SLCM;
;FILE SOGCONC2.NET, NODE LABEL SEED SGCO
;
;Pour Concrete For SOG - RP Process
;
SOGC GOON,1;
     ACTIVITY,,XX(4).EQ.0;
     ACTIVITY,,XX(4).GT.0,SGCR;
     GOON;
     ACTIVITY,,,SOGD;
SGCR COLCT,FIRST,BEG SOG CONC,10/15/.4,1;
     ACTIVITY;
     ASSIGN,ATRIB(10)=TRIAG(.5,.8,.9);
     ACTIVITY;
SGCP AWAIT(2),ALLOC(1);
     ACTIVITY;
     AWAIT(10),RES101;
     ACTIVITY/10,ATRIB(10),,;SOG-POUR;
```

```
   EVENT,2;
   ACTIVITY;
   FREE,RES101;
   ACTIVITY;
   ASSIGN,ATRIB(10)=TRIAG(.5,.8,.9),XX(5)=XX(5)+1,1;
   ACTIVITY,,XX(5).GT.XX(4);
   ACTIVITY,,XX(5).LE.XX(4),SGCQ;
   COLCT,TNOW,END SOG CONC,10/21/.5,1;
   ACTIVITY,,,SOGD;
SGCQ COLCT,XX(5),SCHPRO SOG CON,10/0/1,1;
   ACTIVITY,,,SGCP;
;FILE SOGDISMT.NET, NODE LABEL SEED SODI
;
;Dismantle Formwork for SOG - A Non Repetitive Process (NP)
;
;Atrib(12)=Duration of Dismantle of Formwork for SOG (hours)
;
SOGD ASSIGN,ATRIB(12)=TRIAG(5, 7, 9),1;
   ACTIVITY,,ATRIB(12).LE.0,SOAA;
   ACTIVITY,,ATRIB(12).GT.0;
   GOON,1;
   ACTIVITY/21,XX(8),,;CURING TIME;
   COLCT,TNOW,SOG BEG DIS FORM,10/45/.4;
   ACTIVITY,,,SOAA;
   ACTIVITY;
   AWAIT(4),ALLOC(12),,1;
   ACTIVITY/12,ATRIB(12),,;SOG-DISMANTLE;
   EVENT,1,1;
   ACTIVITY;
   FREE,RES112,1;
   ACTIVITY;
   COLCT,TNOW,SOG END DIS FORM,10/76/1.1,1;
   ACTIVITY,,,SOG1;
;
SOAA GOON;
   ACTIVITY,,,COFM;
   ACTIVITY,,,CLFM;
;FILE SOGERECT.NET, NODE LABEL SEED SOFO
;
;Erect Formwork for SOG - A Non Repetitive Process (NP)
;
;Atrib(2)=Duration of Erection of Formwork for SOG (hours)
;
SOGF CREATE,,,1,1,1;
   ACTIVITY;
   ASSIGN,ATRIB(2)=TRIAG(10,11,12),1;
   ACTIVITY,,ATRIB(2).LE.0,SOGR;
   ACTIVITY,,ATRIB(2).GT.0;
   COLCT,TNOW,SOG BEG FORM,10/0/10,1;
   ACTIVITY;
```

```
     AWAIT(7),ALLOC(10);
     ACTIVITY/2,ATRIB(2),,;SOG-ERECT;
     EVENT,1;
     ACTIVITY;
     COLCT,TNOW,SOG END FORM,10/9/1.1;
     ACTIVITY,,,SOGR;
;FILE SOGREBAR.NET, NODE LABEL SEED SORE
;
;Atrib(3)=Duration of Placing of Rebar for SOG  - (RP) Process
;
;Place Rebar for SOG
;
SOGR  GOON,1;
     ACTIVITY;
     ASSIGN,ATRIB(3)=TRIAG(.25,.31,.41),1;
     ACTIVITY,,ATRIB(3).EQ.0,SOGC;
     ACTIVITY,,ATRIB(3).GT.0;
     COLCT,TNOW,BEGIN SOG REBAR,10/9/1.1;
     ACTIVITY;
SORF  AWAIT(3),ALLOC(4),,1;
     ACTIVITY/3,ATRIB(3),,;SOG-REBAR;
     FREE,RES106;
     ACTIVITY;
     ASSIGN,ATRIB(3)=TRIAG(.25,.31,.41),XX(3)=XX(3)+1,1;
     ACTIVITY,,XX(3).GT.XX(2);
     ACTIVITY,,XX(3).LE.XX(2),SORG;
     COLCT,TNOW,END SOG REBAR,10/15/.5,1;
     ACTIVITY,,,SOGC;
SORG  COLCT,XX(3),SCH PRO SOG RBAR,10/0/1,1;
     ACTIVITY,,,SORF;
     END;
MONTR,TRACE,,1,TNOW;
TIMST,XX(20),CORE FORM ERECT;
TIMST,XX(21),CORE REBAR PLC;
TIMST,XX(19),CORE CONCRETE;
TIMST,XX(32),COLUMN FORM PRO;
TIMST,XX(18),COLUMN REBAR PRO;
TIMST,XX(29),COLMN CNCRT PR;
TIMST,XX(87),SLAB FORM PROD;
TIMST,XX(30),SLAB REBAR PRO;
TIMST,XX(31),SLAB CNCRTE PRO;
INITIALIZE,,,N;
INTLC,XX(58)=4,XX(50)=4,XX(52)=4,XX(54)=4,XX(56)=4,XX(11)=5,XX(17)=10,XX(44)=10,
XX(8)=24,XX(39)=7,XX(41)=8,XX(34)=6.1,XX(36)=8.1,XX(15)=8,XX(13)=8,XX(8)=24,XX(
9)=8,XX(2)=16,XX(6)=8,XX(4)=8.1;
MONTR,TRACE,,1,XX(12),XX(18),XX(45),XX(11),XX(17),XX(44);
FIN;
```

ARRAY STORAGE REPORT

DIMENSION OF NSET/QSET(NNSET):	150000
WORDS ALLOCATED TO FILING SYSTEM:	5940
WORDS ALLOCATED TO VARIABLES:	9071
WORDS AVAILABLE FOR PLOTS/TABLES:	134989

EXECUTION WILL BE ATTEMPTED

APPENDIX F-2: SLAM II RESULTS

Table Appendix F.1: Expected Construction Finish Time by Location Centers

Location	Finish Time			
	low	high	mean	std
Sub-Structure	7.94	8.71	8.4	0.17
Main-Floor	19.25	21.5	20.5	0.47
Floor 2	27.38	49.13	34.00	7.15
Floor 3	36.25	58.38	42.88	7.24
Floor 4	44.38	66.5	51.5	7.26
Floor 5	55	77.13	61.75	7.29
Floor 6	64.13	86.13	70.88	7.21

Table Appendix F.2: Expected Construction Durations of Processes Sorted by Location Centers

Process	Start (Days)				Finish (Days)			
	Low	High	Mean	Std	Low	High	Mean	Std
Sub Structure								
SOG Formwork	-	-	-	-	1.25	1.49	1.38	0.05
SOG Place Steel	1.25	1.49	1.38	0.05	1.9	2.18	2.08	0.05
SOG Pour Concrete	1.9	2.18	2.08	0.05	2.73	3.06	2.9	0.06
SOG Cure & Dismantle	5.73	6.06	5.9	0.06	7.94	8.71	8.4	0.17
Main-Floor								
Columns Formwork	5.73	6.06	5.9	0.06	7.15	8.06	7.56	0.2
Columns Rebar	7.15	8.06	7.56	0.2	8.29	9.18	8.68	0.21
Columns Pour Concrete	8.29	9.18	8.68	0.21	9.69	10.85	10.16	0.27
Columns Cure & Dismantle	12.63	13.88	13.13	0.27	13.13	14.38	13.63	0.28
Cores Formwork	5.73	6.06	5.9	0.06	7.41	7.89	7.65	0.11
Cores Rebar	7.41	7.89	7.65	0.11	9.44	10.09	9.74	0.15
Cores Pour Concrete	9.44	10.09	9.74	0.15	10.15	11.08	10.53	0.21
Cores Cure & Dismantle	13.13	14.13	13.5	0.21	13.75	14.75	14.13	0.21
Slab Formwork	10.15	11.08	10.53	0.21	12.34	13.5	12.88	0.27
Slab Rebar	12.34	13.5	12.88	0.27	13.88	16	15	0.46
Slab Pour Concrete	13.88	16	15	0.46	14.75	17	15.88	0.47
Slab Cure & Dismantle	17.75	20	18.88	0.47	19.25	21.5	20.5	0.47
Floor 2								
Columns Formwork	17.75	20	18.88	0.47	18.5	20.63	19.63	0.47
Columns Rebar	18.38	20.63	19.63	0.47	20.13	22.5	21.38	0.48
Columns Pour Concrete	20	22.38	21.25	0.47	20.63	24	21.88	0.56
Columns Cure & Dismantle	23.25	26.25	24.63	0.49	24	27.5	25.25	0.56
Cores Formwork	17.75	20	18.88	0.47	18.38	20.5	19.5	0.47
Cores Rebar	18.38	20.5	19.5	0.47	20.38	22.63	21.63	0.48
Cores Pour Concrete	20.38	22.63	21.63	0.48	20.88	23.13	22.13	0.47
Cores Cure & Dismantle	23.88	26.13	25.13	0.47	24.75	27	25.88	0.48
Slab Formwork	20.88	23.25	22.13	0.47	22.38	24.63	23.5	0.49
Slab Rebar	21.63	24	22.88	0.48	23.5	25.75	24.63	0.49
Slab Pour Concrete	22.75	25	24	0.48	23.88	26.13	25	0.5
Slab Cure & Dismantle	[illegible]	28.38	27.25	0.48	27.38	29.63	28.5	0.5
Floor 3								
Columns Formwork	25	27	26.02	0.41	27	29.13	28.13	0.41
Columns Rebar	27	29.12	28.12	0.41	28	30.13	29.13	0.41
Columns Pour Concrete	28.25	31.5	29.37	0.41	28.25	30.38	29.38	0.42
Columns Cure & Dismantle	31	33	32	0.42	31.75	33.88	32.88	0.43
Cores Formwork	18.5	20.5	19.5	0.39	27.75	29.75	28.75	0.41
Cores Rebar	27.75	29.75	28.75	0.41	29.50	31.63	30.63	0.43
Cores Pour Concrete	20.63	22.63	21.63	0.4	21	32	[illegible]	4.45
Cores Cure & Dismantle	29	35	31.62	4.45	33.25	35.88	34.88	0.48
Slab Formwork	30.62	32.62	31.75	0.43	31.25	33.38	32.5	0.44
Slab Rebar	31.25	33.37	32.5	0.44	32.38	34.5	33.5	0.44
Slab Pour Concrete	32.12	33.75	32.87	0.43	32.75	34.88	33.88	0.44
Slab Cure & Dismantle	35	37	36.25	0.43	36.25	[illegible]	37.38	0.45

Process	Start (Days)				Finish (Days)			
	Low	High	Mean	Std	Low	High	Mean	Std
Floor 4								
Columns Formwork	31.75	33.88	32.88	0.43	35.25	37.75	36.75	0.49
Columns Rebar	35.25	37.75	36.75	0.49	36.25	38.88	37.88	0.50
Columns Pour Concrete	36.25	38.88	37.88	0.50	36.5	39.13	38	0.50
Columns Cure & Dismantle	41	43.63	42.4	0.52	40	42.63	41.5	0.52
Cores Formwork	33.25	35.88	34.88	0.48	35.88	38.5	37.38	0.49
Cores Rebar	35.88	38.5	37.38	0.49	37.5	40.25	39.25	0.51
Cores Pour Concrete	37.5	40.25	39.25	0.51	29.38	40.63	35.25	0.45
Cores Cure & Dismantle	30.38	41.63	36.35	0.45	41.75	44.5	43.5	0.50
Slab Formwork	36.25	38.38	37.38	0.45	39.38	42.13	41.13	0.51
Slab Rebar	39.38	42.13	41.13	0.51	40.5	43.38	42.25	0.51
Slab Pour Concrete	40.5	43.38	42.25	0.51	40.88	43.63	42.63	0.51
Slab Cure & Dismantle	41.88	44.63	43.63	0.51	44.38	47.13	46.13	0.50
Floor 5								
Columns Formwork	44.37	47.12	45.75	0.54	45.37	47.87	46.62	0.55
Columns Rebar	44.5	47.12	45.75	0.54	46.25	48.87	47.62	0.55
Columns Pour Concrete	45.5	48.12	46.75	0.54	46.5	49.12	47.87	0.55
Columns Cure & Dismantle	49.12	51.75	50.5	0.55	49.87	52.62	51.37	0.56
Cores Formwork	36.87	39.25	38.12	0.52	45.87	48.37	47.25	0.55
Cores Rebar	45.87	48.37	47.25	0.55	47.75	50.12	49.12	0.55
Cores Pour Concrete	47.75	50.12	49.42	0.55	30.12	50.5	40.37	7.52
Cores Cure & Dismantle	51.25	53.5	52.5	0.52	52	54.62	53.37	0.55
Slab Formwork	48.25	50.5	49.5	0.54	50	52.37	51.37	0.56
Slab Rebar	49.12	51.5	50.5	0.55	51.12	53.5	52.5	0.55
Slab Pour Concrete	50.12	52.62	51.62	0.56	51.5	53.75	52.87	0.56
Slab Cure & Dismantle	53.5	56	54.87	0.56	55	57.38	56.37	0.57
Floor 6								
Columns Formwork	53.63	56.25	54.88	0.46	54.38	57.25	55.88	0.48
Columns Rebar	53.63	56.25	55.00	0.46	55.50	58.25	56.88	0.49
Columns Pour Concrete	54.63	57.25	56.00	0.47	55.63	58.50	57.13	0.49
Columns Cure & Dismantle	58.13	61.13	59.63	0.49	59.25	62.00	60.50	0.50
Cores Formwork	46.25	48.38	47.25	0.44	54.88	57.88	56.50	0.49
Cores Rebar	54.88	57.88	56.50	0.49	57.00	59.63	58.25	0.51
Cores Pour Concrete	57.00	59.63	58.45	0.51	39.38	60.00	49.50	7.51
Cores Cure & Dismantle	60.38	63.00	61.75	0.51	61.25	63.88	62.50	0.53
Slab Formwork	57.38	60.00	58.75	0.51	59.13	61.75	60.50	0.52
Slab Rebar	58.25	60.88	59.63	0.51	60.25	62.88	61.63	0.52
Slab Pour Concrete	59.38	62.00	60.75	0.51	60.63	63.25	62.00	0.52
Slab Cure & Dismantle	62.75	65.38	64.00	0.51	64.13	66.75	65.50	0.51

APPENDIX G: PAVEMENT EXAMPLE USING SIMCON

Sequencing activities in a paving example consisting of 10 sections includes repetitive sequencing of similar operations as shown in Figure Appendix G.1. Representing this sequence in a CPM network can be very time consuming as shown in Figure Appendix G.1. Moreover, data collection and progress reporting can become very costly and inefficient in such a schedule.

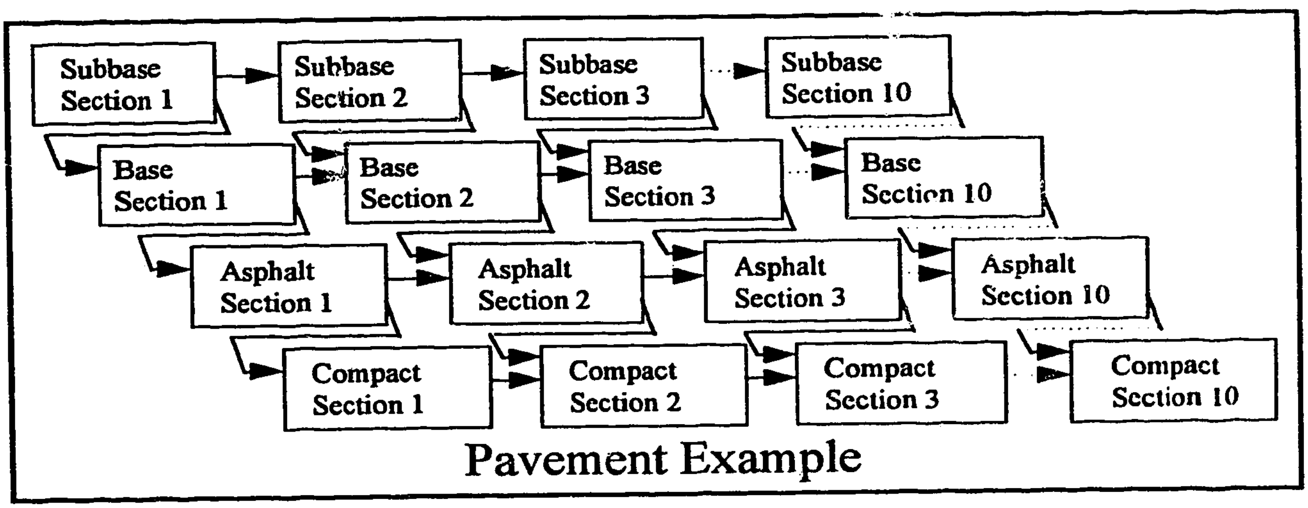

Figure Appendix G.1 Activity Sequencing in a Typical CPM Schedule for Pavement Example

Simulation offers an advantage by the modeling of repetitive activities. The repetitive tasks of a paving operation is modelled by four cyclic processes that have a continuous production link relationship as shown in Figure Appendix G.2. Entities move through the Sub-base process until the number of sections are completed. Continuous construction is maintained by allowing Sub-base process to go for three sections before it is restricted as described by the CP-Link = 3.

The use of simulation is limited by the complexities involved in the construction of a simulation model. The use of continuous links and single links simplifies to a user the construction sequencing methodology as demonstrated in Figure Appendix G.2. Every rectangle shown in Figure Appendix G.2 represents a simulation process consisting of CYCLONE and SimCon nodes. The continuous link is established in simulation terminology by requiring base process to have an entity arrive from placing asphalt process before it can start. The continuous link is deleted once the preceding process is completed or when a specific production is achieved as required by a user. The programming implementation details of a continuous link and a single link are explained in Chapter 4.

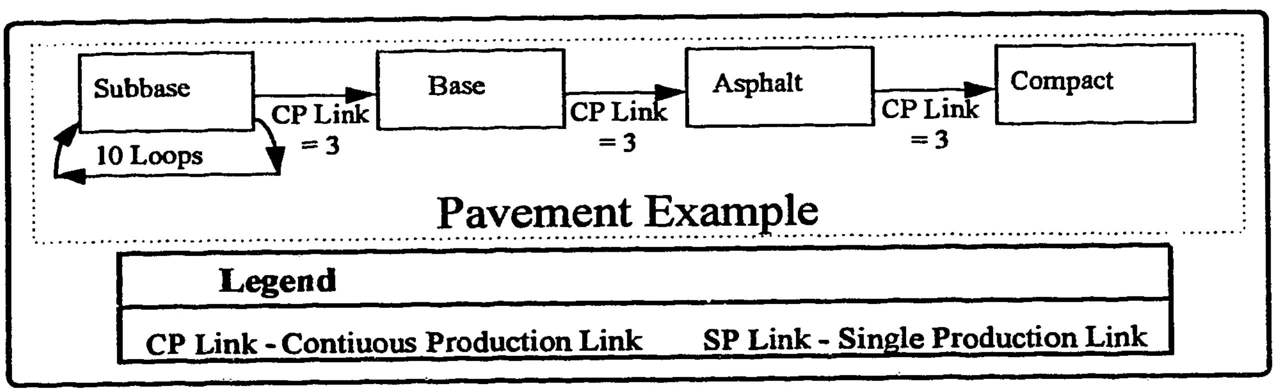

Figure Appendix G.2 Demonstration of Continuous Link in SimCon

Linking of simulation processes can become very complex by certain logical constraints. For example the repetitive processes of a paving operation should not be represented as shown in Figure Appendix G.3a if the excavator, in such a scenario, is required to be working on the next section even if compaction of the current section is not completed. Representing such sequencing as shown in Figure Appendix G.3b requires an experienced simulation analyst and considerable time to model a project to make sure that placing sub-base is not done before excavating and leveling. As demonstrated in Figure Appendix G.3b placing sub-base process is continuously following excavate and level process. The continuous link makes sure that sub-base process starts after a specified production in excavation and that it does not exceed a certain limit to maintain the sequence of production in both processes. In this regard a continuous link helps to represent the logical relationships between activities more realistically.

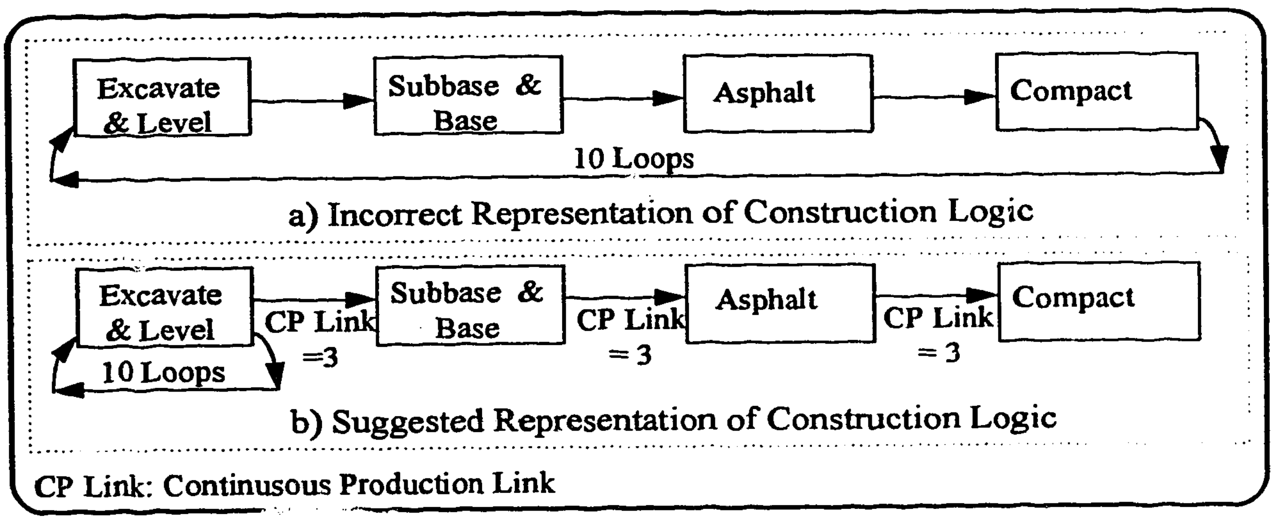

Figure Appendix G.3 Schematic View for Modeling a Paving Operation; a) Incorrect Way to Represent Cyclic Operations; b) Suggested Representation of Construction logic.

VITA

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