

**DECISION SUPPORT SYSTEM
FOR
CONSTRUCTION CYCLE DESIGN**

by
GORDON KI-WAI LAW

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DEPARTMENT OF CIVIL ENGINEERING

The University of British Columbia
2075 Wesbrook Place
Vancouver, Canada
V6T 1W5

Date: APRIL 1987

ABSTRACT

The objective of this thesis is to develop a conceptual design of a computerized environment for detailed design of construction activities associated with projects characterized by significant repetition.

High-rise building construction is used as the example of repetitive construction projects. The construction cycle design of a typical floor structure is studied to gain an understanding of the difficulty and complexity involved in the activity design process. Modeling techniques currently used in construction planning, modeling techniques developed in the field of operations research, and assembly line balancing techniques used in industrial engineering are reviewed to determine their applicability for detailed construction cycle design.

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Using the concept of decision support systems developed in the fields of management science and knowledge engineering for solving ill-structured and ill-defined problems, a conceptual design of a decision support system for construction cycle design is developed.

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1. INTRODUCTION

Construction projects are traditionally developed by owners or users who are concerned about the functional and aesthetical aspects of the facilities and rarely consider the difficulties in producing the desired end products. The construction industry must develop construction methods and technologies that can efficiently, economically and safely produce the desired physical facilities.

Most construction projects are of relatively short duration and little scope is offered for economies of scale through mass production. Therefore, general contracting firms and subcontractors concentrate their activities within limited areas in order to master the skills and technologies associated with their specialization and to reduce unit costs to an extent that they can stay in business. Expertise in their specialized areas is developed by learning through practice; in-depth analysis of construction activities is rarely considered except when a construction activity is new and has significant impact on overall project cost and completion time, when problems develop during construction and threaten completion of the project, or when the activity is to be repeated a significant number of times (say greater than twelve to fifteen times).

1.1 TRADITIONAL APPROACH TO CONSTRUCTION PLANNING

Current construction planning methods being used, such as the critical path method, provide higher management with information on construction deadlines and resource requirements of projects. Such information also provides goals and objectives towards which field management personnel are expected to work, although they are not provided with a tactical plan, such as a detailed short cycle schedule, to achieve them.

Field management personnel, who are concerned with the methods of accomplishment required to meet goals imposed by higher management, must focus their efforts at the production level of the construction process. Their immediate concerns are the commitment of resources, the method and sequence of construction operations and the elimination of delays and idle resources. They are interested in a much more detailed breakdown of construction activities as a mean of revealing potential delays and imbalances affecting the rate of construction. A more detailed analysis of construction activities also provides them with information useful for tracking and controlling valuable resources.

Day-to-day operational plans of construction activities are rarely considered and studied in detail and in a systematic manner. Rather, they are either implicit in the adoption and modification of past methods or developed by site managers and construction superintendents in the field

during construction of the facilities. Detailed descriptions of day-to-day construction operations reside in the minds of key site personnel. It is generally accepted that site managers and construction superintendents will have enough experience and skills to achieve the goals set for the project in an efficient manner. However, the management training environment through which site management personnel are expected to acquire these skills is extremely uneven and tied to tradition and historical precedents. The rapid advance in construction technologies often reduces the usefulness of past experience.

1.2 REPETITIVE CONSTRUCTION AND CONSTRUCTION PLANNING

Repetitive construction projects, which include mass housing development, high-rise building, highway, bridge and tunnel projects, are characterized by standardized design for a large number of typical sections. The high degree of repetition in these project types allow savings in cost and time achieved through highly detailed construction planning to be multiplied; problems that result from poor planning will, however, propagate and magnify as a project progresses. For example, in the production of a thirty story building, savings in the construction of a typical floor will be multiplied thirty times; idle time of resources resulting from poor planning will also be multiplied thirty times.

1.3 NEED FOR ACTIVITY DESIGN TOOLS FOR FIELD MANAGEMENT

Existing planning models which originated for management at the organizational and project levels fail to meet the detailed needs of management at the construction site. This problem is well recognized by practitioners in the construction industry and has been addressed by authors in the construction literature. Peer [98] stated that:

"None of the network methods includes in its algorithm and calculation any consideration for solving the practical organization problems of the production process on site." [98]

Dabbas and Halpin [27] further stated that:

"Methodologies and systems which address problems at the level of field decision making and control are less abundant. In particular, systems for analyzing construction operations at the technological level have not received as much attention as higher level systems." [27]

The traditional approach to construction planning does little to encourage innovations in the design of construction activities in order to benefit from advances in construction technologies. Also, this approach deals with problems only when they actually arise during the construction process when it is often either too late or too costly to make changes.

To encourage the detailed design of construction activities before resources are actually committed and to deal with problems before they arise in the field, a planning system which caters to the needs of site management personnel must be developed. Such a system should be able to provide information useful for tracking and controlling valuable resources, should be easy to use and should be able to respond to the dynamic environment of the construction site.

1.4 RESEARCH OBJECTIVE AND APPROACH

The objective of this thesis is to develop a conceptual design of a computerized environment for detailed design of construction activities with emphasis on activities associated with projects characterized by significant repetition. The activity design environment would assist construction management personnel to systematically analyze and design construction activities resulting in tactical plans to achieve goals set for a construction project. The environment would also allow construction management personnel to apply personal judgment, intuition and creativity in the activity design process.

In chapter two, the terminology used throughout the thesis is presented.

In chapter three, the construction cycle planning problem in high-rise construction projects is described to

gain an understanding of the difficulties and complexity involved in designing a construction activity.

In chapter four, existing models for construction planning described in the literature are reviewed and studied to determine their applicability for detailed activity design.

In chapter five, the assembly line balancing technique described in the industrial engineering literature is studied to determine whether it can be adapted for design of construction activities.

In chapter six, a brief overview of the process of decision making is described. Then, the process of activity design is described by flow charts and five modules: problem recognition, problem definition, solution formulation, solution analysis, and design improvement and enrichment. Finally, a conceptual design of an activity design environment is described in terms of computer input/output formats and interaction between the computer and the decision maker.

Chapter seven presents thesis conclusions and recommendations for future research.

2. TERMINOLOGIES

One of the first problems encountered in the study of construction planning is the lack of a consistent terminology with which to describe construction processes. In this chapter, the terminology used for describing the construction process at the production level of the project management hierarchy will be introduced and will be used consistently in this thesis. Terminology associated with two approaches to work breakdown structures used in the activity design environment will also be described.

2.1 HIERARCHICAL LEVELS IN CONSTRUCTION MANAGEMENT

In the management of construction projects, a hierarchical structure exists because of the differences in the concerns of management personnel at head office and at the construction site. The hierarchy can be roughly divided into three levels: organizational, project and production.

At the organizational level, management is concerned with the legal and business structure of a firm, the various functional areas of management, and the interaction between head office and field management personnel performing these functions. It is also concerned with the a project's total

cost, duration, and cash flow in relation to the portfolio of other projects.

At the project level, management is concerned with project definition, contractual and legal obligations, and breakdown of the project into activities for time, cost and resource control.

Management at the production level, which is described as site/field management in chapter one, is concerned with the selection of efficient construction methods and technologies, the commitment of resources and the day-to-day progress of construction at the site. Construction planning at the production level can involve three levels of detail:

(1) Activity

An activity is a time and resource consuming element of a project. It is normally defined for the purpose of time and cost control by a planner/scheduler, estimator, or cost engineer. It is usually related to the construction of a division of the physical facility by a sequence of operations. An activity is unique and must be completed once. An example of an activity is the completion of the floor structure of a thirty story high-rise building.

(2) Operation

A construction operation represents a collection of work tasks related to each other technologically. It is closely related to the construction method and can

be repetitive in nature. The duration of an operation is measured in hours or days. An example of an operation is the forming of a section of a floor slab using say a tower crane, 2 general labourers, 10 carpenters and 1 foremen.

(3) **Work Task**

A work task is the basic descriptive unit of the construction process. If a work task is broken down into components, human factor considerations or detailed equipment motions are involved. A work task should be a readily identifiable component of a construction operation. Its description must be so clear that any member of a construction crew can readily grasp and visualize what is involved in the work task. Work tasks are therefore the basic building blocks of operations. An example of a work task is installing a support bracket of a section of slab formwork.

Another term that will be used in this thesis is **assignment** which is a collection of work tasks or operations specifically assigned to a crew member or a crew.

Of the hierarchical levels described, only the production level is pertinent to the activity design problem. Discussions in this thesis will concentrate at the production level.

2.2 TERMINOLOGY FOR INFORMATION REPRESENTATION

Information representation is one of the most important elements in any problem solving environment. In the activity design environment, which will be developed in this thesis, the physical facility being constructed has to be broken down into smaller units. The terminology employed in representing this information must be consistent to ensure proper communication between the computer and management personnel. Systematic work breakdown structures described in the construction management literature, can provide the terminology needed to represent the above information.

In the paper "Work Breakdown Structures in Construction", Ponce-Campos and Ricci [64] described a work breakdown structure (WBS) as:

"a systematic approach to subdividing an effort into its components and/or end product." [64]

In other words, a work breakdown structure is a systematic approach to represent the manner in which a physical facility and its components are constructed.

The approaches to work breakdown structure in physical assemblies and in work categories will be adopted. The terminology described below will be used in discussions of the activity design environment.

2.2.1 WBS IN PHYSICAL "ASSEMBLIES"

The first task in any problem solving process is defining the problem in a clear and precise manner. In a construction project, the problem definition process involves defining the dimensions of the physical facility in detail. The following terminology will be used for problem definition in the activity design environment being developed.

Total-Assembly: denotes the physical facility to be delivered at completion of the project as defined by the total scope of work in the contract documents.

Assembly Group: denotes a grouping of physical assemblies with similar functions and represents a significant portion of a building or structure; e,g superstructure, substructure, south-wing, north-wing.

Assembly: denotes a meaningful subdivision of an assembly group; e.g. a floor elevation, a sub-grade elevation.

Sub-Assembly: denotes a horizontal division of an assembly group or an assembly; e.g. the north-wing of the superstructure, bay 13 of a floor elevation.

Assembly (subassembly) Component: denotes one of the components of an assembly (subassembly); e.g. slab, columns, walls, and cores are components of a floor elevation assembly.

2.2.2 WBS IN WORK/COMPONENT "CATEGORIES"

Construction operations are labour intensive processes. Solution formulation involves defining the operations or work which are to be performed to construct the physical facility. Operations can be categorized by the trade performing the work or the physical components on which work is being performed. The following terminology will be used in the solution formulation process in the activity design environment being developed.

Category Group: denotes a grouping of components by disciplines or trades; e.g. civil/site, concrete, metal.

Category: denotes a grouping of components by functions under the same category group; e.g. under the category-group of concrete, we can have supported slabs, grade slabs, cores, columns, footings, and walls.

Category Component: denotes the material or sub-component that make up an identifiable project

component; e.g. in the concrete component we can have form-work, rebar, concrete, and misc. metals.

Category Sub-Component: denotes a process in each work category component; e.g. [form-work] is composed of [form-work installation] and [form-work dismantling] processes.

3. CYCLE PLANNING IN REPETITIVE CONSTRUCTION PROJECTS

In order to understand the process involved in designing a construction activity, in this chapter the decision making process involved in designing typical construction cycles in high-rise construction projects will be used as an example to illustrate the complexity of the activity design problem. The typical construction cycle in a high-rise building construction project is often simply identified as a single activity in the project network; for example, the activity of form and pour the fifth floor. The design of a construction cycle can therefore be identified with the design of a construction activity. Thus, the terms activity design and construction cycle design will be used interchangeably in this thesis.

The typical construction cycle in a high-rise building construction project will first be described and the problems and objective of construction cycle design are discussed. Then, the design parameters and variables will be studied. Finally, statements will be made regarding the goal of the construction cycle planning problem and the need of a construction cycle design environment.

3.1 THE TYPICAL CONSTRUCTION CYCLE

The construction of a high-rise building consists of construction of the substructure and superstructure. Construction of the superstructure often accounts for a major portion of the total project duration. The construction of the superstructure can be roughly divided into the following groups of activities: (1) structural, (2) electrical, (3) mechanical, and (4) building finishes. The structural activities form the most significant group of activities as other activities cannot proceed unless the structural components are complete. The structural activities are characterized by a sequence of operations which are carried out to produce a typical floor structure. The sequence of operations are repeated a number of times until the building structure is completed. Because of the cyclic nature of the repeated sequence of operations, they are collectively called the "typical cycle".

Since the floor structures must be completed before the other activities mentioned above can begin, the structural activities often appear as "critical" in the project network. The rate at which a typical floor structure is produced therefore governs how fast the other activities can progress. This fact has been well recognized and most general contractors perform the structural activities with their own work-force; the other groups of activities which involve intermittent use of special trades are often subcontracted to contractors specialized in those particular

areas. Since the structural activities form the critical group of activities the following discussions will concentrate on the structural activities.

3.2 THE CONSTRUCTION CYCLE PLANNING PROBLEM

Once the project is awarded to a construction firm, the project manager, construction manager, site superintendent, and sometimes the site foremen will meet to discuss how the building is to be constructed. The major concern is meeting the project criteria in the most effective manner in terms of time, money, labour, materials, and equipment utilization. The "time" objective is therefore met at the expense of the "cost" of the committed resources. In order to use the committed resource effectively, the field management personnel must choose the most appropriate construction technologies and methods. In the traditional approach to construction planning, the construction cycle for a floor structure often appears in the project network as a single activity; for example, the activity of form and pour floor slab with a duration of five days. Even though the construction methods and technologies are discussed in project meetings, because of the lack of a proper construction planning system, they are often mentioned only in general terms, and are rarely analyzed and documented in a systematic manner. Problems with the chosen construction

methods and technologies are dealt with only as they appear during the construction process.

3.2.1 DESIGN PARAMETERS AND DECISION VARIABLES

To illustrate the decision process and understand the complexity involved in designing a construction activity, some of the parameters and decision variables in the design of the construction cycle of a typical floor structure in a high-rise building project will be discussed.

(1) Cycle Time

In order to meet the target date for delivery of the finished product, management must make a decision regarding the time required to construct a typical floor, i.e. cycle time. This decision often evolves into a time-cost trade-off problem: a reduced cycle time can be achieved at the expense of more expensive equipment, a larger labour pool and increased overtime cost. However, cycle time can also be shortened by proper operation planning to reduce idle time of labour and equipment and through selection of effective equipment and forming technology.

The cycle time for a floor structure will influence and is influenced by the selection of forming and material handling technologies, material, equipment and labour usage and sequencing of operations.

(2) Forming Technologies

Formwork cost represents one of the major and most variable portion of the cost in the structure cycle. It normally accounts for 33% to 55% of the total concrete placement cost (Fintel [25]); the cost of the rigidly specified concrete and reinforcing steel normally do not vary to any significant extent. Cost of concrete placement depends on the proper sequencing of operations, effective use of over-time, efficient work space division and allocation and selection of appropriate material handling equipment, all of which are related to the forming system selected and how the system is implemented.

Conventional built-in-place formwork is used normally only in highly complicated non-reusable forming or the opposite extreme of simple, undemanding formwork. In low-rise building construction projects where expensive lifting equipment is not feasible, an entire story may be formed and later disassembled and passed up to the next floor through shafts or outside the building after the concrete has acquired the minimum strength.

Reusable formwork is used in large repetitive projects such as high-rise building projects. The economy of the formwork will depend on: (1) the first cost of formwork, either rental or custom built, (2) cost of non-reusable parts, (3) number of reuses, (4)

cost of erecting and stripping, and (5) cost of cleaning, repairing, and modifications. The ganging of forming sections and the choice of shoring system (horizontal or vertical) must also be studied in terms of their implications of their cost, time, and labour requirements and impacts on other operations.

(3) **Materials Transportation**

Experience in high-rise construction projects has indicated that proper scheduling of major lifting equipment such as the tower crane is crucial to the time and cost performance of a project. The choice of lifting equipment depends on the site conditions and the purposes for which they are intended. For most high-rise building projects, their locations in busy commercial areas prohibit the use of mobile crane; consequently, tower cranes are most often used. Being an expensive piece of equipment, only one is normally used except in projects with large plan areas and the required reach necessitates the use of two or more tower cranes. Capacities of the lifting equipment will be governed by the maximum reach and weight required to be lifted. Conversely, the capacity of the crane may limit the size of formwork sections that can be transported.

The lifting equipment will be used for the transport of heavy forming sections, prefabricated concrete or reinforcing steel components, and placement

of concrete when a crane and bucket system is chosen. Most of these operations are critical in the structure cycle. Thus careful planning and study of the equipment schedule is required to avoid delay or interruption of operations.

(4) Concrete Placement

Next to formwork, concrete placement is the most costly item and is labour intensive. The choice of placement method has a significant impact on the economy and quality of the concrete placed. The efficiency of the operation is often measured in terms of the rate of placement in volume of concrete placed per unit time.

The most frequently used systems of concrete placement are pumping, crane and bucket, and material hoists. For large projects, integrated systems of material hoists, conveyor belts, and motorized buggies might be used.

The use of high-early strength concrete can reduce the curing time and thus allows the forms and shores to be reused more often. Use of super-plasticizers will significantly reduce the time required for placement and finishing. In fact, decisions pertaining to the selection of concrete additives and non-destructive testing to determine strength can be central to the design of the structural cycle.

(5) Prefabrication of Components

Prefabrication of structure components, such as concrete stairways, column reinforcing steel cages, and use of welded reinforcing steel mesh, often allows the corresponding operations to be carried out in more efficient manners by allowing them to proceed in parallel rather than sequentially. Prefabricated components, however, need to be transported to the work location and thus have to compete with other operations for use of lifting equipment; moreover, prefabricated components and on-site prefabrication processes occupy site areas needed for material storage and other purposes.

(6) Breakdown and Sequence of Operations

Decisions made on forming, material transportation, and concrete placement technologies determine to some extent the list of operations required to be carried out. The decision maker can choose to break down the floor structure into smaller sections and decide the sequence in which they are to be constructed. He can decide to form the whole floor and then place the concrete or he can decide to form half a floor, place the concrete, and then form and place the rest of the floor; similar decisions can be made for other operations such as construction of the elevator cores.

Decisions on how the floor structure is to be broken down and constructed determine the number of sets of forms required. Careful sequencing of the corresponding operations is necessary to ensure smooth transitions between operations and to minimize idle time for labour and equipment resources.

(7) Scheduling of Sub-Trades

Operations performed by sub-trades, though not studied in detail by general contractors, are distinct operations which take up time and space during the construction process. Sub-trades must be scheduled to come on site only when the partly-finished product is ready for their particular operations. Conflicts between sub-trades arising from limited work space and need for the same lifting equipment must be avoided as they impose delay costs to the sub-trades and subsequently to the general contractor.

(8) Number of Crews, Crew Sizes, and Crew Mix

Decisions on forming, material handling, and concrete placement technologies, prefabrication of components, and the breakdown of the floor structure together define the set of operations and tasks involved in construction of the floor structure. The tasks involved in each operation subsequently define the labour types, and the sizes and mixes of each crew required.

The production rate required to achieve the desired cycle time will, up to certain limits, be proportional to the crew size. Multiple crews can be used to speed up the construction operations, but at the expense of more sets of forms and more crowded work space. Extra shifts and/or over-time can also be used to shorten cycle time but not without the associated costs.

(9) Use of Resources and Crew Assignment

Given the pool of resources, the decision maker must determine the schedules for each major piece of equipment and work assignments for each crew and each individual member of a crew so as to achieve the expected productivity rate with maximum efficiency. If the desired production rate cannot be achieved with the given pool of resources, changes in the size of the resource pool and/or in the construction technology must be contemplated.

Operations that use shared resources must be scheduled to minimize queuing delays. Decisions have to be made on the priorities given to various operations when conflicts of equipment usage arise. For the case of limited work space, the work schedule of each crew must be carefully developed to avoid over-crowding.

(10) Identifying Critical Operations and Processes

Once the construction operations have been defined and assigned to various crews and equipment, operations that are critical and will potentially disturb the smooth progress of the construction process must be identified. Any expected problems should be analyzed and studied and the corresponding correction plans developed, if time and cost allow, before they actually happen in the field.

3.2.2 NEED FOR AN ACTIVITY DESIGN ENVIRONMENT

From the above discussions, we can identified the following characteristics of the construction cycle design problem:

- (1) multiple objectives: time, cost, and effectiveness and efficiency of committed resources;
- (2) trade-offs between multiple objectives such as time and cost within product quality constraints;
- (3) a large number of variables, such as choice of technologies, choice of construction methods and sequence of operations, and the commitment and use of resources, that together determine the effectiveness of the subsequent production schedule;
- (4) a large number of possible values for each variable and a large number of feasible variable value combinations.

The ultimate objective of the construction cycle design process is to maximize profits through the selection of a time and cost effective solution. This require the evaluation of all possible design alternatives. However, because the linkages between them are not precisely known and because of the inability to define all of the decision variables in quantitative term, we do not have a closed form production function that link all the design variables and the design objective. An optimal solution cannot be obtained by a deterministic mathematical process. The problem must be solved by management personnel who understand the design objective and the complex linkages between the design variables, and by applying experience, personal judgment and intuition in the solution design process.

Although a deterministic mathematical procedure is not available to determine the best design alternative, it is possible to create an environment in which the construction management personnel can readily explore the design alternatives and generate an action plan to be used in the field. The conceptual design of an activity design environment will be described in chapter six, after the review of modeling techniques being used in construction planning and industrial engineering in chapters four and five.

4. EXISTING MODELS FOR CONSTRUCTION PLANNING

In order to develop a construction cycle planning framework, the existing models used in construction planning will first be reviewed to determine their applicability for detailed construction cycle design.

4.1 DETERMINISTIC MODELS

4.1.1 BAR CHARTS

The bar (or Gantt) chart was developed by Henry L. Gantt (1861-1919) for industrial production management in the early 1900's. The basic intentions are: (1) to set down the steps (influenced by technical restrictions), stages, or phases of work that must be followed in order to bring a project to fruition, and (2) to enable the planner to monitor and track status of the project. Since its introduction, the bar chart has received wide acceptance from management in many disciplines for graphically portraying project plans and work progress. The basic modeling concept of the bar chart is the representation of a project work item (activity) with a time scaled bar whose length represents the planned duration of the work item. It

can be located in calendar time to indicate the schedule for starting, execution and completion of the project work item it represents. The scaled length of the bar is also used as a graphical base on which to plot actual performance toward completion of the work item. Ingenious use of the bar chart provides management with useful project information on overall scheduling, use of resources and productivity.

The major advantage of the bar chart model is that it is simple and easy to understand and update, and thus has been widely used by construction personnel at all levels in the management hierarchy. However, the model fails to show details of the technologies involved in the construction operations and the inter-relations of project work items. The nature of the inter-relations among work items have to be deduced by users. Used by itself, the bar chart is inadequate for solving the complex problems that construction management personnel often face today. In general, construction projects are now analyzed using more sophisticated models and the output is displayed in bar chart format for easy understanding by field personnel.

Melin and Whitetaker [83] devised a graphic representation, the fenced bar charts (figure 4.1), which retains the simplicity of the bar chart model but shows the network logic found in precedence or arrow diagrams. Other techniques including the line-of-balance and multiple activity chart have their origin in the bar chart modeling rationale.

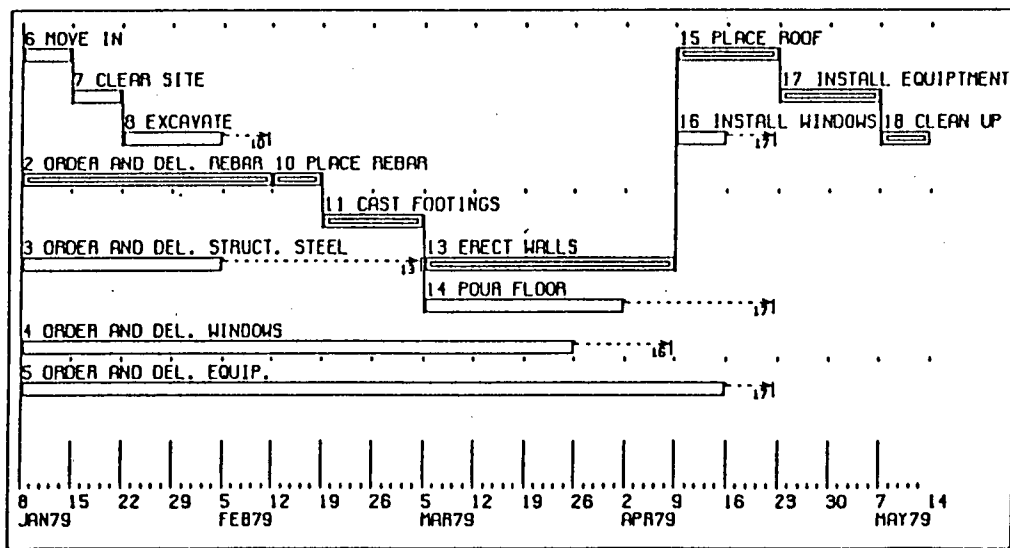


Figure 4.1: Fenced bar chart of a warehouse project

Source: Melin and Whitetaker [83], p. 501

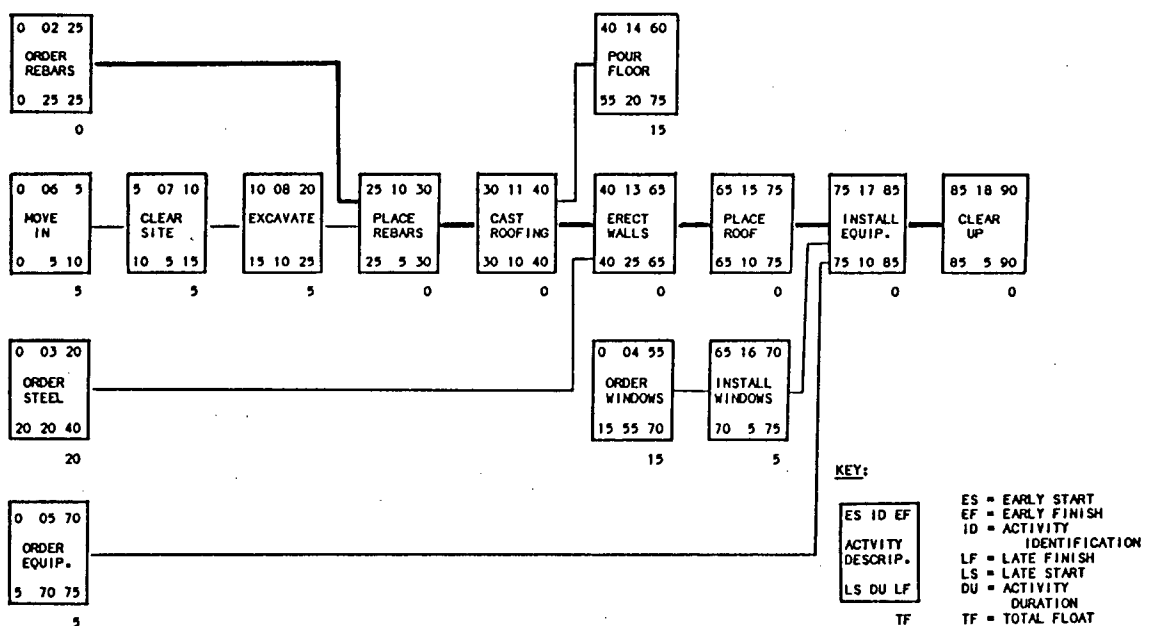


Figure 4.2: Precedence diagram of a warehouse project

Source: Melin and Whitetaker [83], p. 500

4.1.2 CRITICAL PATH METHOD (CPM)

The critical path method, originated in 1957 by James E. Kelly of UNIVAC and Morgan R. Walker of duPont, represents a project plan by a network model that depicts the logic of the construction plan. Two types of graphs, the precedence (activity on node, figure 4.2) and the arrow (activity on arrow) diagrams have been used, with the former now being preferred. The network model uses labeling techniques to assign a variety of attributes to the model such that a wide spectrum of problems can be treated graphically.

Preparing a CPM network usually involves the following steps:

1. List the activities (or work items).
2. Establish the durations of and the resources required for each activity.
3. Develop the network logic, i.e. precedence relations.
4. Find the critical path and non-critical paths.
5. On a time frame, develop resource usage histograms for each type of resource for the whole project.
6. Level resources within acceptable limits for the project.
7. Re-schedule start times of activities to suit resource leveling.
8. Iterate through 3 to 7 until a "satisfactory" solution is achieved.

The major advantages of the critical path method are as follows:

1. Logic restraints are clearly shown on the diagram whereas assumptions were necessary when bar charts were used for control.
2. It stimulates more detailed planning by the contractor which usually results in better coordination, fewer delays, fewer claims and earlier project completion.
3. It permits evaluation of the impacts of anticipated and actual changes of project conditions on the contractor's work.
4. It can be used to provide progress and payment data.
5. Updating permits refinement of occupancy dates, needed delivery dates for owner furnished items and the final completion dates.
6. An additional advantage of the critical path method is the easy access to numerous computer software packages developed for use in the construction industry. Several of these packages integrate the project scheduling function with material procurement, cost control and accounting functions.

Despite the numerous advantages of the critical path method, it has not been welcomed by many construction personnel because of its relative complexity. The network diagram and its modeling rules cannot be easily understood by untrained personnel. Updating of the project network is

also tedious for large projects. Even when much of the redrafting and computational work is performed with the assistance of computers, the vast amount of computer printout generated is not welcomed and is often not easily comprehensible by site personnel. Birrell [11] criticized the critical path method for not being able to represent the more realistic "heuristic" process of construction planning.

4.1.3 LINE-OF-BALANCE (LOB)

The line of balance (LOB) is a scheduling technique developed by the U.S. Navy in the early 1900s. It was first applied to industrial manufacturing and production control where the objective was to evaluate the flow rates of finished products in a production line. Three diagrams are used in the LOB technique:

- (1) The **production diagram**, as shown in figure 4.3(a), represents the inter-relations of the assembly operations for a single unit of the finished product. It is the representation of the technological constraints on the operations and shows the operations required to produce a single unit, such as a typical floor structure of a high-rise building project.
- (2) The **objective diagram**, as shown in figure 4.3(b), is used to plot the planned number of units produced versus time. For a mass housing development project,

the objective diagram may show the expected number of housing units produced in each week or month.

- (3) The **progress diagram**, as shown in figure 4.3(c), indicates the numbers of units for each of the subassemblies which should be completed by specific dates. It takes the form of a vertical bar graph; each bar represents an operation shown in the production diagram; the length of a bar indicates the actual number of units of the corresponding subassembly produced to date. Actual progress is compared to the "line of balance" (or balance line), a line produced from the production and objective diagrams. It corresponds to the level of progress needed for each operation at the particular date to achieve the objective.

The line of balance method focuses on monitoring the current status of an activity relative to its scheduled status so that corrective action can be initiated where and when required.

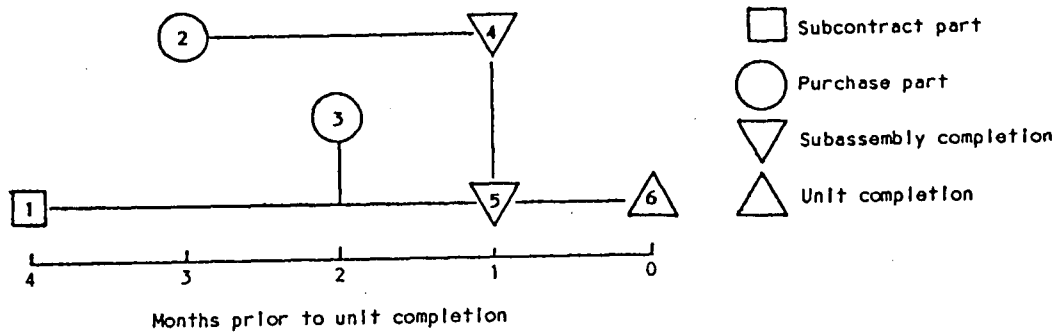


Figure 4.3(a): Production diagram

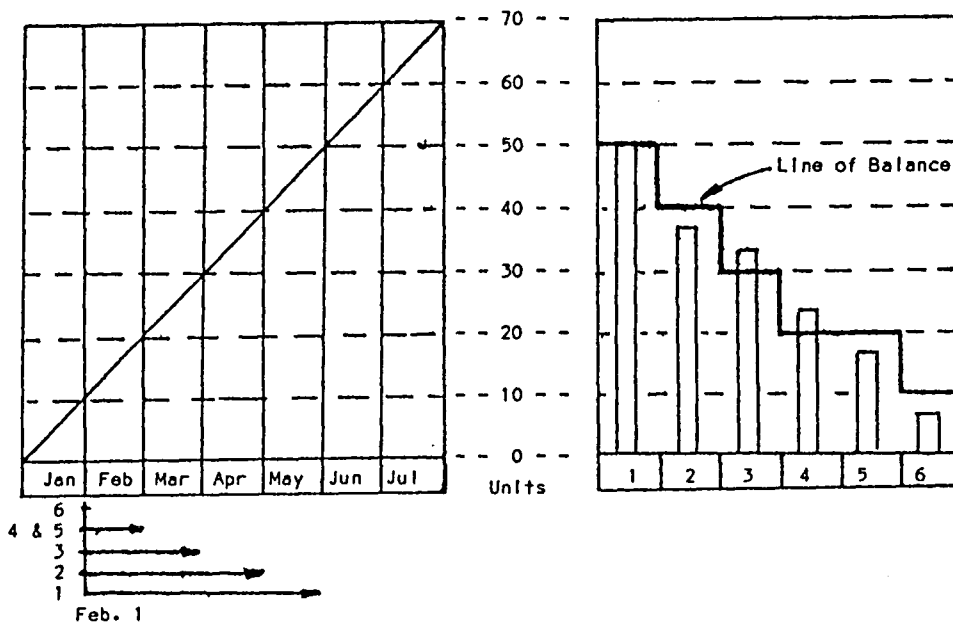


Fig 4.3(b): Objective diagram Fig 4.3(c): Progress diagram

Figure 4.3: Line-of-Balance modeling technique

Source: Johnston [57], p. 250

4.1.4 TIME SPACE SCHEDULING METHOD (TSM)

The time space scheduling method described by Stradal and Cacha [123], has been labeled by other authors also as "linear scheduling method (LSM)" (Johnston [57]), "linear planning chart" (Russell [114]), "vertical production method (VPM)" (O'Brien [93]), and "flow line method" (Cormican [23]). This scheduling technique has some relationship to the LOB technique. TSM emphasizes a diagram similar to the objective diagram for planning purposes while LOB places emphasis on the balance line of the progress diagram. The label "Time Space Scheduling Method" is chosen because the scheduling technique shows clearly the locations or "space" where each corresponding activity take place in a given "time".

The TSM diagram graphs time versus location where location is essentially a measure of progress. Location can be measured in many ways. In high-rise building projects the measure is floors whereas in mass housing development projects the appropriate unit is housing units. Time can be measured in terms of hours, days, weeks, or months, as is appropriate to the project time and level of detail desired in the schedule.

Stradal and Cacha [123] has described the use of TSM diagrams for studying the effect of double shifts and change in production rates of construction operations on the number of formwork sets required. O'Brien [93] has used TSM diagrams to study the floor cycle of a high-rise building;

the availability of scaffolding for bricklayers and close-in requirement for sheetrock contractors were studied and rates of progress of different trades were synchronized to produce a satisfactory schedule.

The most significant advantage of TSM is the simplicity with which it can convey a detailed working schedule. Further, the responsibilities of individual crews can also be separated and represented by their corresponding progress lines.

Authors who advocate the use of TSM stress the importance of "balanced" production lines such that idle time for valuable resources is minimized. At the activity level, the Time-Space diagram indicates the "desired" rates of progress for various activities (see figure 4.4(a)). This model indicates the "desired" end result but how to achieve it is left to the management. One disadvantage of the TSM, similar to that of the bar chart model, is the difficulty of identifying logic relationships between activities. Another disadvantage of TSM is that it can become complicated and confusing to untrained personnel when the number of activities is large, the sequence of activities is complex and when production rates vary from location to location (see figure 4.4(b)).

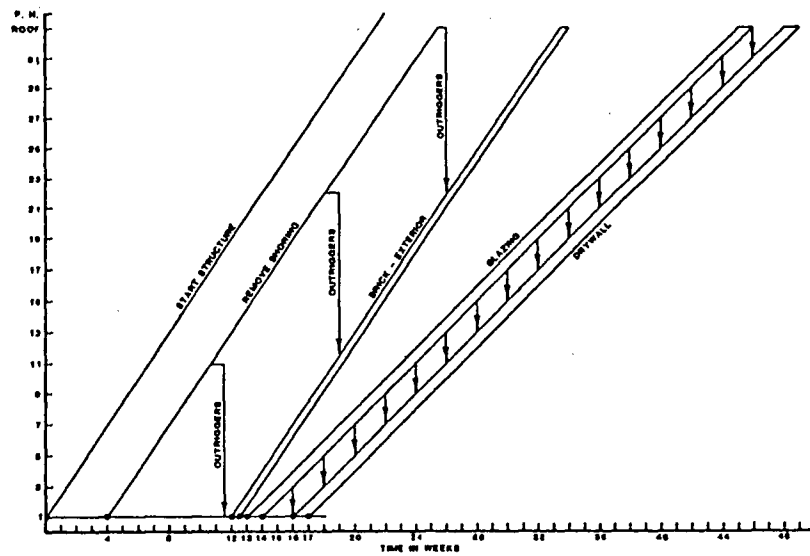


Figure 4.4(a): A simple Time-Space diagram

Source: O'Brien [93], p. 115

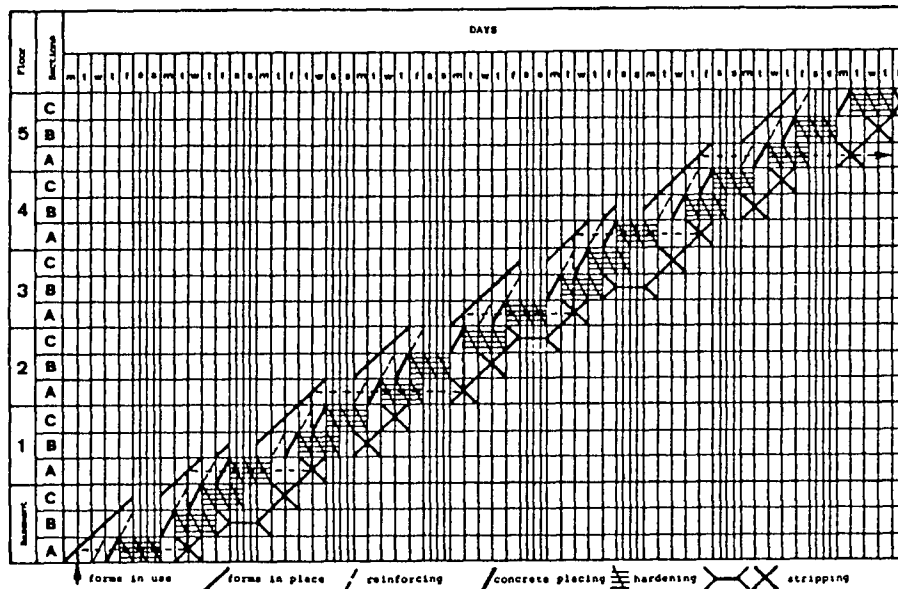


Figure 4.4(b): A more complex Time-Space diagram

Source: Stradal and Cacha [123], p. 454

Figure 4.4: Time-Space diagrams

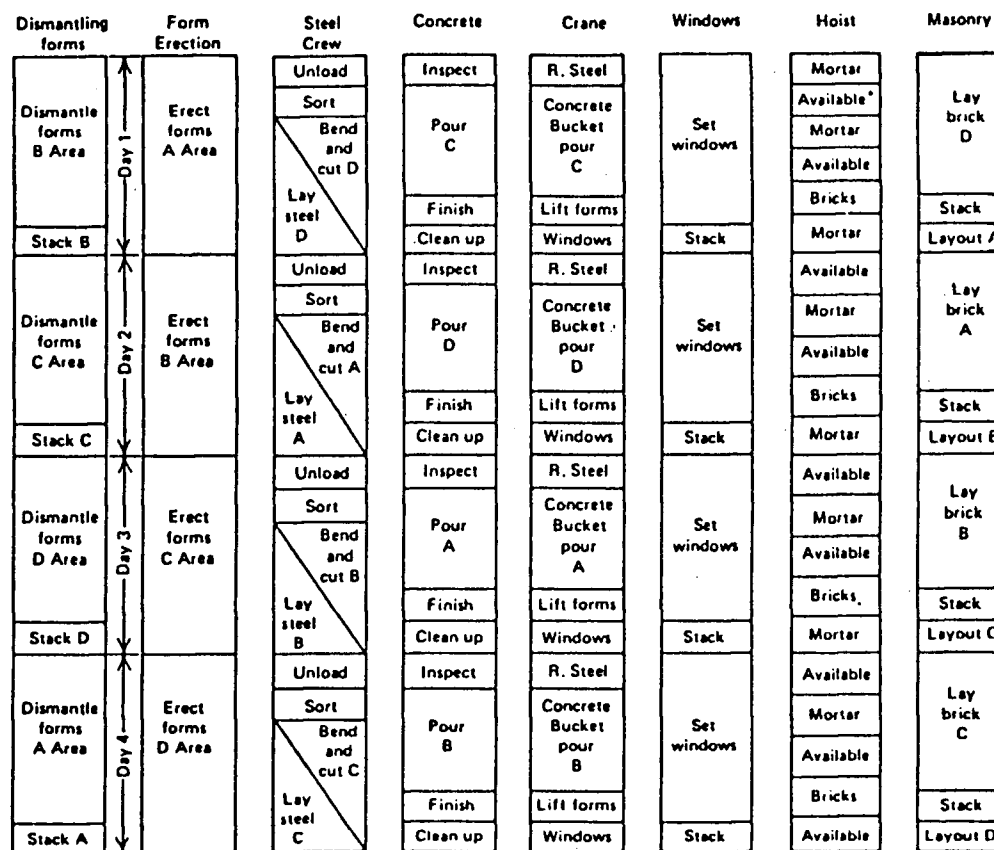
4.1.5 MULTIPLE ACTIVITY AND CREW BALANCE CHARTS

Halpin and Woodhead [43] described the Multiple Activity Chart (figure 4.5) used to coordinate activities with crew allocations and to schedule delivery and material handling systems. It consists of a series of vertical bars. A vertical bar is used for each crew, hoist, or crane unit involved. Each vertical bar portrays the work assignment and schedule for a labour crew or a major piece of equipment. The work assignments for each crew or equipment are arranged such that they occur in a common length or building cycle. The bars are then analyzed to see if there is conflict of locations or in use of shared equipment.

Crew Balance Charts are similar to multiple activity charts except the former model focuses on the internal operation of a particular crew and each bar is used to represent individual crew member work assignments and sequences. Crew balance charts can also be used for work improvement purposes. By changing the size of the work crew and rearranging work assignments to crew members, unnecessary overload and idle time can be minimized to produce the most efficient crew size.

These models are only conceptual models of the real system and include no quantitative or analytical techniques to assist management to determine the set of work assignments to various crews. They are helpful in the evaluation of operation sequencing and the total labour contribution of each working trade. They provide a clear

statement of work assignments and sequences not available from other models.



* Available for other tasks.

Figure 4.5: Multiple activity chart for a building cycle

Source: Halpin and Woodhead [43], p 37

4.2 PROBABILISTIC MODELS

4.2.1 UNCERTAINTIES IN THE CONSTRUCTION ENVIRONMENT

Probabilistic models have been used for construction planning because of the dynamic construction environment. Uncertainties in both external and internal elements of a project influence the accuracy of estimates for activity durations. Ahuja and Nandakumar [2] identified the following list of stochastic elements that affect the accuracy of activity duration estimates:

- | | |
|------------------------------|--------------------------------|
| 1. learning curve | 11. foundation conditions |
| 2. weather | 12. design schedule |
| 3. space congestion | 13. drawing approval schedule |
| 4. crew absenteeism | 14. inspection schedule |
| 5. regulatory requirements | 15. ineffective supervision |
| 6. design changes and rework | 16. inefficient consultant |
| 7. economic activity level | 17. material delivery schedule |
| 8. labour unrest | 18. transportation schedule |
| 9. crew interfacing | 19. union problems |
| 10. project complexity | 20. legal problems |

Carr [19] included weather conditions and Ashley [7] included learning curve effects in their models. Ahuja and Nandakumar [2] included seven elements (weather, space congestion, crew absenteeism, regulatory requirements,

design changes and rework, economic activity levels and labour unrest), which they considered to be the most significant influences on activity duration estimates in their model PRODUF (PROject DURATION Forecast).

4.2.2 QUEUING MODELS

The word "queue" in French means "line", and queuing theory provides techniques for analyzing the effect that waiting in line has on various situations. Erlang is considered to have laid the groundwork for many of the earliest techniques of queuing analysis from 1909 through 1920. Queuing theory remains an area of active research. It has been applied to various situations across a wide spectrum of different disciplines: telecommunications, vehicular traffic, machine repair/maintenance, inventory control and storage, material handling, computer networking, hospitals, and counter services for many disciplines.

The simplest queuing model can be represented by a system of demand and services. The individual items that demand services are called the customers; the facilities that provide the services demanded are called servers. Customers may enter the network at any particular server, proceed through according to their needs and leave the system after the required services are received. An example is a fleet of hauling trucks (customers) which require loading by a loader (server) - see Griffis [41].

Queuing theory provides mathematical solutions for simple systems and provides measures of effectiveness of the system being modeled. Examples of these measures for a simple concrete delivery system in a construction type project are:

- (1) Average number of units in the queue, e.g. average number of concrete trucks waiting to be emptied.
- (2) The average waiting time or delay before service begins, e.g. the average waiting time for each concrete truck before it is emptied.
- (3) The probability that the total delay can be greater than some value, e.g. the probability that a concrete truck has to wait more than a certain period of time before it can be emptied.
- (4) Expected idle time of total service facility, e.g. the utilization of valuable resources such as labour and tower crane.

Through study of these system efficiency measures, decisions can be made regarding:

- (1) Securing additional service facilities, e.g. installing additional lifting equipment (additional tower crane, hoist, or using a concrete pump with higher capacity).
- (2) Rearranging existing service facilities, e.g. changing layout of delivery routing system to reduce total concrete truck waiting time.

- (3) Establishing a schedule to reduce idle time of the service facilities, e.g. sharing the crane and other lifting equipment with other crews and trades to increase its utilization.

Solutions to simple queuing models can be obtained from tables. However, mathematical solutions for the more complex queuing situations in large construction projects are not readily obtainable.

4.2.3 DISCRETE EVENT SIMULATION

Simulation is a procedure in which experiments are performed on the model of a system in order to determine how the system would respond to changes either in its structure or in its environment. It is a procedure by which system outputs are defined and analyzed as logical and mathematical functions of system input variables and parameters.

There are many general purpose simulation languages, such as GPSS, SIMSCRIPT, SLAM, GASP. High level languages such as the CYCLONE (Halpin [44]) were developed especially for construction projects. Simulation has been applied to numerous problems such as facility design and production planning and scheduling (Mellichamp [84]), material handling and distribution (Phillips [102]), and high-rise construction (Halpin [44]). In general, simulation has the following advantages:

1. It allows managers to experiment with the system in order to determine which external factors are important and how they interact.
2. Decision makers are forced to examine all foreseeable elements of the model in detail during the process of designing a simulation model.
3. Simulation allows decision makers to experiment with different strategies without the risk of disturbing the real system.

Many authors in the construction management literature recommend that simulation should be used to model construction operations because other models cannot treat the learning curve effects, come-back delays, weather, and other stochastic project variables and parameters which arise in the complex and exposed environment of construction projects.

Simulation is a powerful tool that can be used reliably to simulate most of the complex situations that cannot be studied by other modeling techniques. However, models developed using the techniques are generally "custom-made" and can be applied only to the specific project situations which they represent. Use of the simulation technique also requires knowledge of a simulation language. Mathewson [79] has suggested the use of a "(simulation) program generator" to reduce the programming effort required; however, further research and development in this area are required.

4.2.4 MONTE CARLO SIMULATION

Monte Carlo method is a simulation technique whereby values for random variables are sampled from distributions and combined to determine properties of the system under study. It can be utilized to generate durations for each activity in a probabilistic network by randomly calculating a feasible value from the distribution that represents possible outcomes for the activity. Once generated, the durations are treated as deterministic and the normal critical path calculations are performed. The procedure is repeated many times, keeping statistics on each projected project duration and the number of times individual activities were critical. The results of the simulation provide an unbiased projection of the project completion-time distribution and an indication of the "criticalities" of each activity. No assumption is made a priori on the shape of the final distribution. It provides a reliable profile even if the final distribution is dominated by a few activities, provided activities are not correlated. However, it often requires a large number of simulations to produce an accurate projection of the profile of the final distribution and thus requires large amounts of computing time. In addition, there is no measure by which one can estimate the number of simulations required.

4.2.5 PROGRAM EVALUATION AND REVIEW TECHNIQUE (PERT)

The major difference between PERT and CPM is the assumption of distributions for activity durations for PERT. The original developers of PERT chose a beta distribution to estimate the shape of the activity duration distribution. Given the most likely(m), optimistic(a), and pessimistic(b) estimates of an activity duration the mean and standard deviation of the activity duration are approximated by:

$$\begin{aligned}\text{mean} &= (b - a) / 6 \\ \text{standard dev.} &= (a + 4m + b) / 6\end{aligned}$$

The developers of PERT claimed that the beta distribution was chosen for its flexibility. However, Elmaghraby [33] proved that the above approximations actually restrict the shape of the distribution function.

After the expected activity durations are estimated, the mean-time-to-completion of the project is computed by treating the estimated activity durations as deterministic. The assumption that the resulting distribution of the project duration will tends normal, because of the "central limit theorem", is then made. In making the above approximation and ignoring the correlations of network paths, the resulting estimates on expected project durations become optimistic, i.e. underestimated.

4.2.6 DECISION CPM

Decision CPM networks (Naaman [90]) are characterized by having both deterministic activity nodes and decision nodes. The decisions taken at the decision nodes depend on the outcomes of events which are not known with certainty in advance. Completion of the network can be achieved through a number of possible optimal paths. The optimal path can be determined by a lengthy integer programming procedure or an acceptable path can be determined by more economical interactive heuristic procedures. This model forms the basis of more complex ones, such as GERT discussed below.

4.2.7 GRAPHICAL EVALUATION AND REVIEW TECHNIQUE (GERT)

GERT, Graphical Evaluation and Review Technique, developed by Pritsker and Happ (Pritsker and Happ [104], [105]), represents a considerable extension to the PERT/CPM network modeling technique. It makes possible the representation and simulation of less restrictive network types. The special features of GERT include user definable activity time distributions, probabilistic branching, multiple outcomes, feedback, self-looping, and other complex node realization logics; therefore complex models of systems with random variable components can be replicated. Execution of the model is performed by Monte Carlo type simulation

procedures. Model outputs are descriptive rather than optimizing and system improvements are performed by trial and error. Because of the complexity of the modeling logic with GERT, the model of a given system is difficult to develop and understand.

4.2.8 PROJECT LENGTH ANALYSIS AND EVALUATION TECHNIQUE (PLANET)

The idea for PLANET (Kennedy and Thrall [62]) arose from consideration of the problems faced by NASA in administration of the Space Shuttle Program to meet promised deadlines. In order to meet them under limited funds, it is essential to determine activities which are critical or slack such that resources can be "stolen" from the slack activities to expedite the critical ones.

PERT was not considered to be a viable technique as the summing of mean and variances over the critical path tends to produce an optimistic mean completion time. The assumption of a beta distribution for activity duration in PERT also may not be general enough.

GERT developed by Pritsker and Happ allows the user to choose from nine probability distributions. However, the original version of GERT did not include analysis of the critical path. Kennedy and Thrall [62] therefore developed PLANET which uses the Monte Carlo simulation approach to a modified GERT modeling technique with critical path analysis

at each simulation and thus allows feedback, looping, and the inclusion of large variances in the development/testing type activities.

4.2.9 PROBABILISTIC NETWORKING EVALUATION TECHNIQUE (PNET)

PERT considers activity durations as random variables. However, the required project duration is determined solely on the basis of the mean critical path and subsequently the expected completion time for a given network is underestimated. Monte Carlo simulation can be used to solve the problem but it requires considerable computing time. These are the observations that motivated Ang and Abdelnour [4] to develop PNET.

The technique employed considers the correlations between different paths which arise from the sharing of activities which PERT has previously ignored. Ang and Abdelnour [4] stated that joint probabilities correlating the paths are difficult to calculate except for the cases of 0% or 100% correlation. They then proposed a scheme for selecting representative paths. The project completion-time probability can then be calculated as the product of the probabilities of these paths. As the technique is analytical, it is be more economical and efficient than the Monte Carlo simulation technique.

4.3 MATHEMATICAL PROGRAMMING TECHNIQUES

In addition to the modeling techniques described above, other mathematical models have been described in the operations research literature. Of these, linear programming and dynamic programming have been applied to construction problems.

Most applications of mathematical programming techniques described in the construction and industrial engineering literature have been applied to problem of optimal resource allocations (Coskunoglu [24]) and network duration compression (Perera [100]). Extensive research and development work has also been done in the area of industrial engineering. The "Economic Scheduling Path" described by Riggs [110] and the "Multiple Objective Shortest Path Problem" described by White [130] are based on these mathematical programming techniques.

Even though mathematical programming techniques allow an optimal solution to be identified from a large number of alternatives, they have the following disadvantages for construction related problems:

- (1) In most situations, the project objectives, variables, and constraints cannot be easily reduced to mathematical form.
- (2) The effort, cost, and time to reduce a problem situation into mathematical equations are often

excessive for use in construction planning on a day-to-day basis.

- (3) The time required to modify a developed model is often too long. The mode is therefore not responsive to the dynamic project conditions at the production levels.
- (4) The models developed with this techniques are not comprehensible to management at the production level.

4.4 CURRENT PRACTICE IN CONSTRUCTION MODELING

Deterministic modeling techniques have gained acceptance in construction because of their relative simplicity. Among the deterministic models described, the critical path method is the only analytical model that can be used for systematic time analysis of construction projects and activities. The application of the critical path method in construction planning is shown in figure 4.6 and has been briefly described in section 4.1.2. Although the critical path method places no restriction on the level of detail at which planning is to be carried out, traditionally, it has been applied at the activity level, i.e. the smallest element treated is an activity.

The construction process is first broken down into the major activities, activity duration and resource requirement estimates are then assigned to each activity. For example, an activity can be defined as: form and pour a complete

floor slab in five days employing 5 carpenters, 4 masons, 2 general labourers and the tower crane. In the process, implicit management decisions have been made regarding the choice of construction technologies and crew assignments to carry out the operations involved in each activity. The input data are then analyzed using CPM and constrained resource analysis and leveling algorithms.

Willis [131] reviewed the developments in resource constrained scheduling algorithms and stated that:

".... resource constrained scheduling algorithms have focused on algorithm quality using project duration as the only criterion. They have assumed fixed activity duration, fixed resource requirements over the activity durations and fixed resource limits over time." There is "the practical need for flexibility in the definition of resource constraints and requirements"
[131]

Willis further described the "practical requirements" of a system for analysis of resource constrained projects. They include:

- (1) stability in re-scheduling of a resource constrained project such that there will be no drastic changes to the original schedule;
- (2) variable resource requirements over time and variable resource constraints over time;
- (3) facility to allow an activity to be fixed in time;

- (4) facility to allow stretching and squashing of activities;
- (5) facility to allow consideration of variable resource requirements over the duration of an activity; and
- (6) facility to allow assignment of alternative resources.

The requirements simply indicate that the current approach to construction process modeling using CPM has failed to model all of the practical or realistic aspects of the construction planning process. The current approach assumes constant resource requirement over an activity duration such that in the example used earlier, the assigned labour resources and the tower crane have to be assigned "exclusively" to the activity of form and pour floor slab. This is un-realistic because some of the assigned resources are required for only part of the activity duration. For example, the general labourers might be required only to clean and oil the formwork at the start and end of the activity and the tower crane might be needed only for about three hours each day. Current constrained resource scheduling methods neglect the possibility of using over time and a second shift to eliminate resource conflicts. They do not allow activity durations and assigned resources to be modified interactively. In other words, the need exists for a more "flexible" framework to treat the elements that the current approach to construction modeling fails to capture.

In addition, decision making processes, such as the choice of construction technologies and crew assignments, which are only implicit in the current approach to construction planning, must be treated.

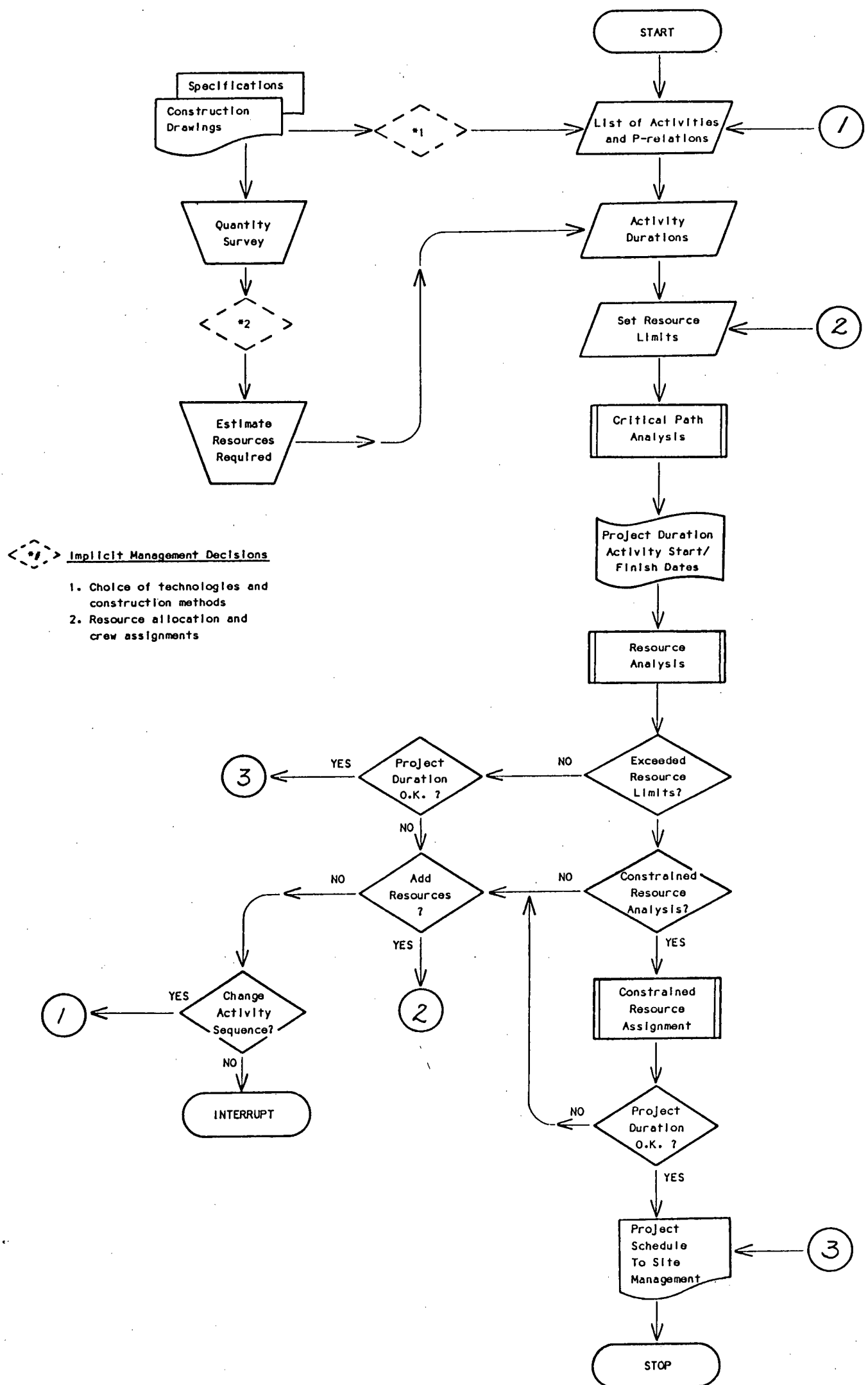


Figure 4.6: Current application of CPM in construction planning

5. PRODUCTION PLANNING AND ASSEMBLY LINE BALANCING

Russell [114] has stated: ".... building construction is characterized by a large number of repetitive and non-repetitive activities, each of short duration despite the best efforts by owners and architects to distinguish one project from another, there is substantial similarity among projects in terms of systems and activity break down." Ashley [7] stated that: "Multiple-unit, multiple-floor, or linearly progressive projects resemble assembly line processes in their structure of a small set of tasks in repeating sequence." Davis [31] stated: "The assembly-line balancing problem is concerned with repetitive operations and large numbers of identical products." The above and other authors have noted the similarities between the repetitive activity design problem and the assembly line design problem. However, few have studied and suggested whether the approach used by industrial engineers for assembly line design problems can be applied to the design of repetitive activities.

In this chapter, the assembly line production process and the line balancing problem are studied in some detail. The similarities and differences between repetitive construction and assembly production will be analyzed to determine whether assembly line balancing techniques can be applied to construction cycle planning.

5.1 PRODUCTION PLANNING

Many of the planning models used in construction, such as bar chart and line-of-balance, have their origin in the field of production planning for the manufacturing industry. Production is a word that describes materials changed by tools, which could be described as controlled forces used to operate on the environment to bring about goal-oriented change. Production managers are faced with the problems of planning, execution, and control of operations in the production process to ensure that the results of the operations are of agreed quantity, on schedule and of specific quality and cost.

Schmenner [117] classified the production processes as follows:

- (1) **Job Shop** - generally custom products; e.g. a machine shop that produces metal or plastic parts which are assembled into other machines.
- (2) **Batch Flow** - lots of products generally designed in-house; e.g. a clothes factory that manufactures products which have to meet orders of a wide variety of materials, models, and sizes.
- (3) **Worker-Paced Assembly Line** - mostly standard products but with opportunities for selected options; e.g. a fast food restaurant where a standard list of food is served but certain options, such as hamburger with no onion or pickles, are possible.

- (4) **Machine-Paced Assembly Line** - same product mix as in (3) but the productivity is more dependent on the equipment as compared to (3) which is more labour intensive; e.g. a automobile production line, or a conveyor assembly line of electronic products. Machine-paced assembly lines are often simply referred to as "assembly lines".
- (5) **Continuous Flow** - standard products with little or no customization possible; usually not produced in discrete units and so have to be measured in tons, barrels, etc; e.g. a paper mill or a petroleum processing plant where productivity is only dependent on the type of raw materials and the capacities of processing equipment.

5.2 ASSEMBLY LINE PRODUCTION

Henry Ford (1863-1947) is usually credited with the creation of the "assembly line era" when the first automobile was introduced. The basic idea of the assembly line is decomposition of the end product into subassemblies, and sub-subassemblies, and so on down the line until the smallest indivisible component is reached. If this subdivision is reversed, we can define the operations or work tasks (the basic indivisible unit of work that cannot rationally be further subdivided) which are necessary to group the components into subassemblies, and so on, until

the end product is reached. Because of the linear aspect of this process it is known as the assembly line production process.

5.2.1 LINE BALANCING PROCEDURE

Balancing an assembly line normally involves the following number of steps:

- (1) The industrial engineer must describe what has to be done in detail, including the descriptions of job elements.
- (2) Each of the job elements is assigned a time which is often determined by reference to established standard or by special stopwatch studies.
- (3) Once times are assigned to specific job elements, the engineer reviews them with the relevant supervisors on the production line to determine whether or not they are reasonable. Changes are made as required.
- (4) Once agreement is reached, the relevant information is used to balance work loads among the workers. One way this is done is by taking work elements from one worker and placing them with another.

- (5) The initial balance is studied for reasonableness and adjustments are made until the line is satisfactorily balanced.
- (6) The "paper" balance is then ready for trial on the factory floor. The engineer, supervisors, and workers all become involved in this activity. If actual element times are larger than predicted, help will be given to the worker to improve time - by changing the layout of the work station, adding fixtures or other equipment, changing production methods, or reducing the total work assignment by re-balancing the assembly line.

5.2.2 EXAMPLE OF LINE BALANCE

The keys to line balance are (1) breaking down a complex product and production process into its component pieces and tasks and (2) juggling the coordination of these pieces and tasks so that the process is smooth and no bottlenecks are built into it. An example of a 20-element assembly production process is shown in figure 5.1.

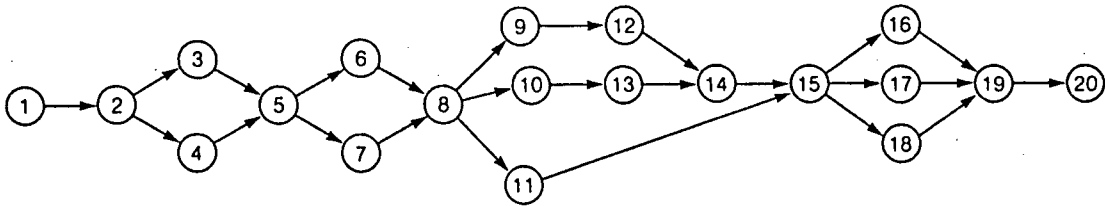


Figure 5.1(a): Precedence network of work elements

JOB ELEMENT	ESTIMATED TIME (minutes)	JOB ELEMENT	ESTIMATED TIME (minutes)
1	0.65	11	1.10
2	0.11	12	1.75
3	0.37	13	0.94
4	0.75	14	0.62
5	0.10	15	0.45
6	0.58	16	0.81
7	0.25	17	0.87
8	1.01	18	1.60
9	1.17	19	0.60
10	0.43	20	0.83

Figure 5.1(b): Job elements and estimated element times

Figure 5.1: Example of a 20-element assembly production process

Source: Schmenner [117], p. 97

The objective is to use the information given to develop a flow line process capable of turning out 300 units of the product in an eight hour day. The suggested possible means of developing the process can be summarized as follow:

Total job element time

= Sum (element time all elements 1 to 20)

= 14.99 minutes

Total production minutes req'd / working day

= 14.99 min/unit x 300 units

= 4497 minutes

Assume a 7.5 hour work day (450 min)

Number of workers req'd/ working day

= 4497 min. / (450 min./worker)

= 10 workers

For perfect balance:

"Control cycle time"

= (14.99 minutes/unit) / 10 worker

= 1.5 minutes

The following is a suggested solution to the assembly balancing problem:

WORK STATION	JOB ELEMENTS	TOTAL TIME/UNIT (minutes)	BALANCE DELAY (minutes)
1	1,2,4	1.51	-0.01
2	3,5,6,7	1.30	0.20
3	8,10	1.44	0.06
4	9,12	1.46	0.04
5	9,12	1.46	0.04
6	13,14	1.56	-0.06
7	11	1.10	0.40
8	15,17	1.32	0.18
9	16,18	1.21	0.29
10	16,18	1.21	0.29
11	19,20	1.43	0.07

**Fig. 5-2: Suggested balance to the assembly line
production process**

Source: Schmenner [117], p. 98

Observations pertaining to this solution are:

1. Eleven work stations are required instead of ten because of the inability to meet the ideal "perfect balance."
2. Some stations have been overloaded while some stations are under-utilized resulting in unproductive idle time.
3. Stations 4, 5, 9 and 10 have workers working on every other unit in order to solve the problem of "over-cycle" (note that the times of job elements 12 and 18 are 1.75 and 1.60 respectively which are over the control cycle time. If only one worker was assigned to work on element 12 or 18, bottlenecks would occur.

5.3 ASSEMBLY LINE BALANCING ALGORITHMS

In general, the objectives in designing an assembly line process are to minimize the number of groupings or work stations with a given cycle time, or to minimize the cycle time for a given number of stations subject to certain restrictive constraints.

Two approaches to the assembly line balancing problem have been adopted by manufacturing production management - the analytical approach (Akagi [3], Wilson [132]) which give an "optimal" solution and the heuristic approach (Arcus [5], Raouf et al [109], Tonge [26]) which gives an "acceptable" solution. The analytical approach employs integer programming technique which most authors agree to be demanding in terms of mathematical modeling effort.

The heuristic approach is the application of selective routines that reduce the size of a problem until it is manageable by manual or computer operations. Sensible rules are used to simulate the decision-making pattern of human beings when they operate unaided in the system. Another reason for the use of heuristics for the ALB problem is that the number of possible groupings of work elements is so large that an exhaustive enumeration scheme is un-realistic.

5.3.1 SYSTEM CONSTRAINTS

Similar to a construction process, an assembly production line is also subjected to certain precedence or technological constraints, i.e. the work tasks have to be performed in a specific order. In addition, zone constraints may arise because of the physical location of specialized equipment or the operator, or because of health or safety regulations.

5.3.2 PRIORITIES OF WORK ELEMENT ASSIGNMENT

Tonge [126] gives a list of the rules that can be used to assist in the assignment of work elements to work stations:

- (1) Choose the task with the largest time.
- (2) Choose the task with the most "immediate" followers.
This increases the number of tasks available for assignment to the next station.
- (3) Choose a task randomly.
- (4) Choose the task which became available first for assignment.
- (5) Choose the task which became available last for assignment.
- (6) Choose the task with the most followers (including followers to its immediate followers). This rule also

increases the number of tasks available for assignment to the next station.

- (7) Choose the task for which the sum of its times plus the times of its followers is the largest (Helgeson and Birnie [48] called this the ranked positional weight).
- (8) Number the tasks such that all followers of a task have a higher number, assigning a number arbitrarily when necessary. Choose the task with the lowest number (following a suggestion of Jackson [53]).
- (9) Number all tasks with no predecessors as 1. If the highest number assigned to any immediate predecessor of a task is n , number that task $n + 1$. Then choose the task with the lowest number (based on the approach of Kilbridge and Wester [63]).

Numerous assignment rules were also recommended by other authors; Raouf et al [109] suggested giving priorities to work elements which are on the critical path.

5.3.3 BALANCED ASSIGNMENT AND SMOOTHING

Another problem often discussed is that of a "balanced" work assignment such that no station is overworked while another station may have an excessive amount of "idle delay". This is measured by the **smoothness index** (proportional to the sum of the squares of idle delays at each work station) as discussed in Moodie and Young [88].

The smoothness of a balance can be improved by "trading and transfer" of work elements between stations.

5.3.4 VARIABLE ELEMENT TIMES

The problem of variable work element times were recognized by some authors. Moodie and Young [88] described an algorithm to consider variable work element times by including the averages and variances of work element times and the problem balanced against a user selected "confidence level". Mansoor [77] discussed the use of a wage incentive scheme to ensure worker productivity. Later, Mansoor [74] also discussed the problem in terms of the selection of N operators out of a pool of M available operators according to their performance ratings to just meet the desired production level.

5.3.5 ELEMENT SHARING, MULTIPLE MANNING AND MULTIPLE STATIONS

Some authors (Arcus [5], Akagi et al [3]) discussed the use of multiple manning of a work station or "parallel" balancing to solve the problem when a work element cannot realistically be broken down further such that the element time is less than the cycle time. Akagi et al formulated the problem in the manner that a worker can move between

stations in order to assist another worker with an element when the work at his station is complete (element sharing). Sarker et al [116] formulated the problem to allow parallel work stations to increase efficiency and productivity and to reduce cycle time below the greatest element time.

5.3.6 RELATED ACTIVITIES

Arcus [5], in his description of COMSOAL, treated the problem by proposing to assign the work elements according to five programs:

1. use no criterion,
2. group tasks by workers position,
3. group task by tools,
4. group tasks by unit's position, or
5. any combination of the above criteria.

This problem, in fact, was studied by Tonge [126] as early as 1960 and later discussed by Agrawal [1]. Agrawal stated that:

"An assembly operation may be considered to be related to some operations and unrelated to others. The relationship can be by ways of their belonging to the same subassembly, interdependent on one another The algorithm employed will be allotting a set of related operations to a worker (or workers) as against the usual operation-by-operation allotment " [1]

The "relatedness" of a set of work elements is determined by the precedence links. Agrawal proposed an algorithm which forms feasible sets (total operation time less than the given cycle time) of related operations starting from the end of the precedence network; the sets are then assigned with priority given to the sets with the largest total times.

Tonge [126] exploited the structure of a network and related the work elements into "sets" and "chains" and employed an hierarchical approach to the task assignment problem. In phase one of his approach, men are assigned to a group of work elements instead of the typical assignment of work element to work station or men; thus the total work element time in any grouping is limited by the total men available instead of the "available station time". In phase two of his approach, the assignment procedure then follows the typical procedure of assigning work elements to each individual station or man.

5.3.7 OTHER CONSIDERATIONS

The following concepts were also discussed by Mariotte [78]:

- **Batching and banking** using an extra-shift or over-time for a short period of time.

- **Multiple Lines** or **multiple shifts** to increase production rate.
- **Off-line stations** and **subassembly lines** where certain work elements are performed before they are joined with the major assembly.

5.4 ASSEMBLY LINE BALANCING AND CONSTRUCTION CYCLE DESIGN

5.4.1 SIMILARITIES BETWEEN ALB AND CONSTRUCTION CYCLE DESIGN

The two planning functions resemble each in that both processes consist of sets of repetitive tasks to produce a large number of similar or identical finished products. They also resemble each other in that the managers are concerned with:

- (1) formulation of operations and works tasks to be carried out to produce the finished products within project constraints;
- (2) choice of technologies, choice of equipment, and layout of work site to carry out the operations in the most efficient and effective manner;
- (3) balanced assignment of the identified operations and work tasks to work stations or workers;

- (4) implementation of a production plan and monitoring of operations at the work site; and
- (5) devising production method improvements to increase productivity, lower production cost, and reduce cycle time for each unit.

5.4.2 DIFFERENCES BETWEEN ALB AND CONSTRUCTION CYCLE DESIGN

Boling [12] described repetitive construction projects as sequential crew systems and stated that a sequential crew system:

"consists of two or more crews following one another in a fixed sequence to complete a particular task on a unit being constructed. Units in these systems are often large and relatively immobile as compared to those processed by typical production systems

In the sequential system, the first crew brings new units into the system and the remaining crews process these units as they become available. Crews perform their assigned work in a fixed sequence with respect to one another, and units are processed by each crew in the same order as they enter the system." [12]

Boling has given a good summary of the differences between a repetitive construction project and a typical assembly production line but stopped short of suggesting an

algorithm for the construction context. The differences between the two systems can be summarized as follows:

- (1) Units in construction projects are large and immobile; worker have to travel along the workface as construction progresses.
- (2) Unit in repetitive construction units can be considered to be introduced into the system when work by the first crew is initiated. In-process inventory is limited to a small number of units; buffer stock of the main assembly is non-existent in most projects. This make the proper balance of crew assignments more critical to avoid unnecessary interruption and idle time.
- (3) Factory type assembly line production produces large numbers of smaller items for an extended period of time; feedback on the effectiveness of the production process can be collected more quickly and modifications for improvement can also be implemented more quickly and easily. Any effort expended on improvement of balance will pay back in future improvements in productivity. In construction projects, there might not be sufficient time to study and implement improvements to the production design once the initial design is implemented. This requires optimization of the initial design and, where possible, certain flexibility in the construction process should be maintained to accommodate changes or improvements.

- (4) Because of the size of the unit, unnecessary relocation of workers lowers productivity significantly. Assignment of work elements therefore has to take into consideration the relatedness so as to reduce relocation of workers from one area to another. Relatedness is, however, difficult to be clearly defined.
- (5) The work elements of construction projects are often restricted by requirements for special trades or equipment, and limited space at the work face. These imposes additional constraints on the work assignment process.
- (6) In construction projects, because of the size of the unit being produced, multiple manning is the norm rather than the exception unless the operations are broken down into the finer details of work tasks.
- (7) Because of the large size of an unit and thus the longer processing time of operations, element sharing can be achieved more easily in construction projects.
- (8) The way the unit can be produced is more flexible (or rather less well defined) in construction projects and the input of experience is therefore desirable in the construction cycle design process. This may necessitate an interactive program which prompts the user for decisions.
- (9) Because of the complexity and skill dependence of construction operations as compared to the more routine

motions for an assembly line, construction operations are more susceptible to interruptions due to variable element times and thus continuity is difficult to maintain. The cycle design system for construction projects must therefore be easy to manipulate and responsive to changes at the work site.

5.5 APPLICATION OF ALB TO CONSTRUCTION CYCLE DESIGN

Because of the more stable environment of the manufacturing industry and the availability of larger product line runs, more effort has been put into developing better methods and computer programs for production planning and control. Relatively well defined manufacturing procedures facilitate more systematic approaches to analysis of production operations. The similarities between assembly line production and repetitive construction projects indicate that assembly line balancing techniques might find application to the construction cycle design problem. Design of construction cycles at the production level however have more stringent work assignment constraints than the design of an assembly production line because of the physical size of and immobility of assembly units in construction projects, the requirements of skilled operators of specific trades and heavy equipment to perform the respective operations, the more flexible construction methods and the more dynamic project environment.

5.5.1 LIMITATIONS OF ALB ALGORITHMS

Even though extensive research and development have been done in designing good assembly line balancing algorithms, the large number of production constraints and the great number of possible assignment rules make it difficult to devise an algorithm to suit all situations and account for all possible alternatives in order to optimize the assembly line design. Moodie [86], quoting statistics from a paper published in 1969, stated that:

".... 81% of the balancing is done either manually or by trial and error methods. Apparently, industrial applications do not always fit into the mold of specific computerized assembly line balancing packages. A computer oriented methodology, which offers the industrial engineer the ability to combine the manual methods with the power of the computer, is interactive programming. where an engineer, who is familiar with the assembly of the product can use his insights, ingenuity, and perceptions in conjunction with the power of the computer, to achieve a good, workable, assembly line balance." and
".... the prudent analyst who knows something about the relationships between the elements which is not given in the precedence matrix" [86]

Moodie then described an interactive program which does not use any specific line balancing algorithms but simply uses the computer to guide the the decision maker through

the manual line balancing process and provides feedback to the analyst to show the implications of different decisions.

The above statements made by Moodie and his choice of a more simplistic approach to the problem indicate that assembly balancing algorithms and heuristics fail to capture all the factors which influence the line design in the manufacturing environment.

In order to capture some of the factors and restrictions that are "far more extensive than just those described by the precedence diagram", Schofield [118] in the Line Sequencing Program developed at Nottingham University (NULISP) uses a set of high level "instructions" to control the line balancing procedures after the lists of work tasks and precedence relationships have been defined. Examples of the commands are:

JOIN* <list of work tasks> - define the set of work tasks to be performed by the same operator or at the same work station.

FIX* <task number> **AT*** <station number> - assign the specified task to be performed by a particular operator with special skilled or at a particular work station equipped with specialized machinery.

MULTI* <no. of operators> **AT*** <station number> - specify the particular work station to be manned by a certain number of operators.

CYCLE* <desired production rate> - define the desired cycle time for production of one unit of the assembled product.

5.5.2 APPLICATION OF ALB PRINCIPLES TO CONSTRUCTION CYCLE DESIGN

Despite the more stringent work assignment constraints in designing construction operations and the limitations of currently available ALB algorithms, the following principles employed in the design of assembly production lines can be applied to construction cycle planning:

(1) Estimation of Resource Requirements for Perfect Balance

The example of line balance for a 20 elements assembly production described in section 2.2 of this chapter illustrates a single iteration of the manual line balancing procedure. The first step after the work tasks and precedence relationships have been defined is estimation of the number of stations or operators required to meet the desired production rate of 300 units each eight hour day. The estimation then becomes a design objective for the decision maker. The number of operators can be increased when perfect balance cannot be achieved. This process is called backward planning.

In the traditional approach to construction planning, backward planning is seldom mentioned in the construction literature and it is only performed by field personnel in an informal manner. This is because the productivities in construction operations are highly influenced by specific project conditions and because of the difficulty of achieving perfectly balanced designs. Estimation of resource requirements is therefore dependent on past experience of the project managers and superintendents involved and there is no guideline for possible improvement to overall project productivity; estimations on resource requirements under perfectly balanced conditions can provide this guideline.

(2) Special Instructions for Interactive Construction Cycle Design

As described by Schofield [118], the elements involved in the design of assembly production line are far more extensive than any single program can realistically include. The elements involved in the design of construction operations are even more extensive as discussed in the previous section. The use of instructions to control the line balancing procedures as described by Schofield can also find applications in the construction cycle design problem.

Applications of the above principles in a decision support system for construction cycle design are described in chapter six.

6. DECISION SUPPORT SYSTEM (DSS) FOR ACTIVITY DESIGN

6.0 OBJECTIVES

Traditional approaches to problem solving have emphasized the use of deterministic quantitative modeling techniques whereby solutions can be generated by solving closed form functions that link all the design variables with the design objective. In chapter three, we have stated that the activity design problem cannot be defined by a closed form function; design solutions therefore depend on the experience, personal judgment and intuition of the management personnel involved in the activity design process.

In this chapter, decision making processes and decision support systems described in the industrial engineering and management science literature are first studied to assist in the development of an understanding of the processes involved in designing a construction activity. A conceptual design of a decision support system which would provide the needed activity design environment is then discussed in terms of five modules - problem recognition, problem definition, solution formulation, design analysis, and design improvement and enrichment.

In dealing with the problem recognition module, only brief statements are made regarding the problem of information representation. The facility that assists in the process of detailed problem definition by defining the physical dimensions of the subassemblies and work category components is described. A systematic format for describing construction technologies that can assist management personnel in comparing and selecting the appropriate construction technology is presented. Input data structures that permit realistic formulation of design solutions are described. The principles of assembly line balancing are adopted for estimating resource requirements to guide management personnel in the resource assignment process. Labour resources are assigned as crews rather than as individual workers. Resources can be assigned to an operation for part of the operation duration. The critical path method and multiple activity charts are adopted to assist in the solution analysis and the design improvement and enrichment processes. Examples of high level instructions are also described to allow management personnel to modify the operation schedule manually and to improve the preliminary design and to produce tactical plans, called the multiple operation time (M.O.T.) charts, for use in the field.

6.1 THE CREATIVE HUMAN DECISION MAKING PROCESS.

A systematic approach to the decision making process as described by Salvendy [115] is represented by figure 6.1 and involves the following steps:

(1) Problem Definition (and Recognition)

Understanding the situation and recognizing the need for a decision. This step involves searching, obtaining, processing and examination of raw data to identify and define the problem.

(2) Problem Solving (Solution Formulation)

Developing, inventing, and analyzing possible courses of action to solve the problem defined. This step involves the process of conceptualizing the problem, drawing on past experience, adapting experience to the new situation, and developing and creating new solutions for the defined problem.

(3) Idea Screening (Solution Analysis)

Choosing the best solution from the set of possible courses of action generated in the problem solving process. This step involves testing the set of

possible solutions for feasibility and choosing the most effective solution.

(4) Idea Enrichment (Design Improvement)

Preparing the solution for action. This step involves examining the course of action chosen in the idea screening process for further improvement. A broad focus is maintained and common-sense is employed to develop a tactical plan to be followed in carrying out the solution.

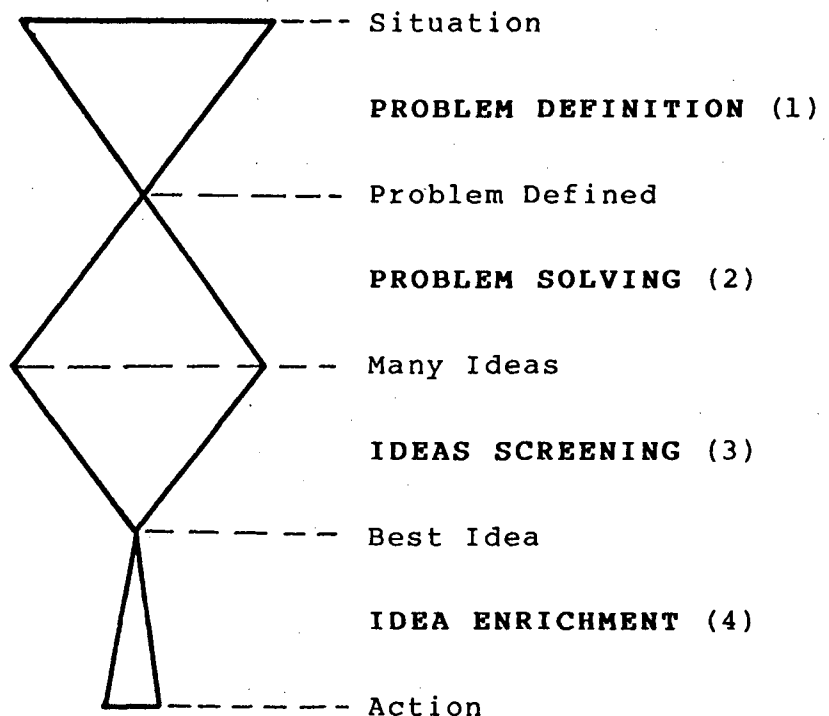


Fig. 6.1: Creative human decision making process

6.2 DECISION SUPPORT SYSTEMS AND DECISION MAKING

In the last decade, extensive research and development have taken place in the fields of management science and knowledge engineering. The objective is to develop expert systems that can simulate the decision making process of human "experts" in problem solving. However, many researchers, such as Godin [40], realize that computers cannot completely replace human experts in the decision making process and advocate a "symbiotic" human-machine relationship whereby:

"The computer churns through vast numbers of computations in employing the embedded scheduling heuristics, but when it needed help (i.e. when the heuristics proved too simple), the human was close at hand to provide very flexible, insightful assistance." [40]

The above system is also described as the "Interactive Decision Support System" (IDSS for short). The IDSS allows decision makers to more closely follow their behavioral process, draw on experience and apply personal judgment and intuition in the decision making process; the computer performs the functions of data and information processing and quantitative analysis. The IDSS, however, cannot assist decision makers in making qualitative decisions such as those involved in conceptual designs and innovations.

To meet the specific needs of qualitative decision making, Young [135] proposed the "Right-Brained or Total

DSS" (TDSS for short) for creative decision making. While Young has described in detail the conceptual design of a total decision support system, with special emphasis on the qualitative aspects of the decision making process, it is too extensive for application to the construction activity design problem at the present stage of research and development in the construction industry.

Based on current understandings of the human decision making process and the concept of interactive decision support systems, a conceptual design for an activity design environment is developed in the following sections.

6.3 DECISION SUPPORT SYSTEM FOR ACTIVITY DESIGN

The approach taken in the conceptual design of the decision support system for activity design is represented by the flowcharts in figure 6.2 and figure 6.3. These charts reflect realistically the process carried out by construction management personnel in designing construction activities. The data base management system (DBMS) shown requires extensive and precise definition of data structures and will not be discussed in this thesis.

Building on the discussions in sections 6.1 and 6.2, the activity design process will be roughly divided into five modules:

Module 1 - Problem Recognition

This module represents the process in which field management personnel draw on a body of information to familiarize themselves with the type of problems represented by the current situation. It also allows them to study the difficulties associated with the particular type of problems and how similar problems have been solved in the past. Solutions that worked in the past can then be adapted for the current situation.

Module 2 - Problem Definition

The first step in problem solving is defining the problem. For construction activity design, the dimensions of the assembly and subassemblies of the physical facility to be constructed must be defined. Using these dimensions, the scope of work to be executed can be determined. Detailed definition of problem dimensions also allows resource requirements to be estimated accurately and facilitates the study of design alternatives.

Module 3 - Solution Formulation

After the problem has been defined, field management personnel have to formulate a preliminary activity design. This process involves selecting the appropriate construction technologies, defining and sequencing construction

operations to produce the physical assembly unit, and estimating and committing the resources - labour, hardware, equipment and work space, to perform the defined operations.

Module 4 - Solution Analysis

The preliminary design solution must then be analyzed by computer routines for feasibility and effectiveness. The defined values of design parameters and variables are processed and analyzed to produce an operations schedule. Idle time and conflicts of resources must be identified and communicated to management personnel for appropriate modifications to the preliminary design.

Module 5 - Design Improvement and Enrichment

This module represents the process through which field management personnel seek to improve the preliminary design by solving problems identified in the solution analysis process. Whether the identified problems can be solved effectively depends on the experience, judgment and intuition of the management personnel. The final design that results from the design improvement process can be analyzed for cost effectiveness. Iterations through module 3 and module 4 to study other design alternatives might be required to produce a design solution that is acceptable in terms of both time and cost. Finally, elements that are not

normally considered in the activity design process can also be included in the final design to produce tactical plans - short cycle schedule, crew assignments, equipment schedules and sub-trades schedules, that can be followed in the field to achieve the goals set for a construction project.

The issues involved in each module are discussed and addressed in the following sections. Through this process, a conceptual design of a decision support system for activity design will be described. Examples of data structures and computer input/output formats that can be used in the activity design environment are also presented.

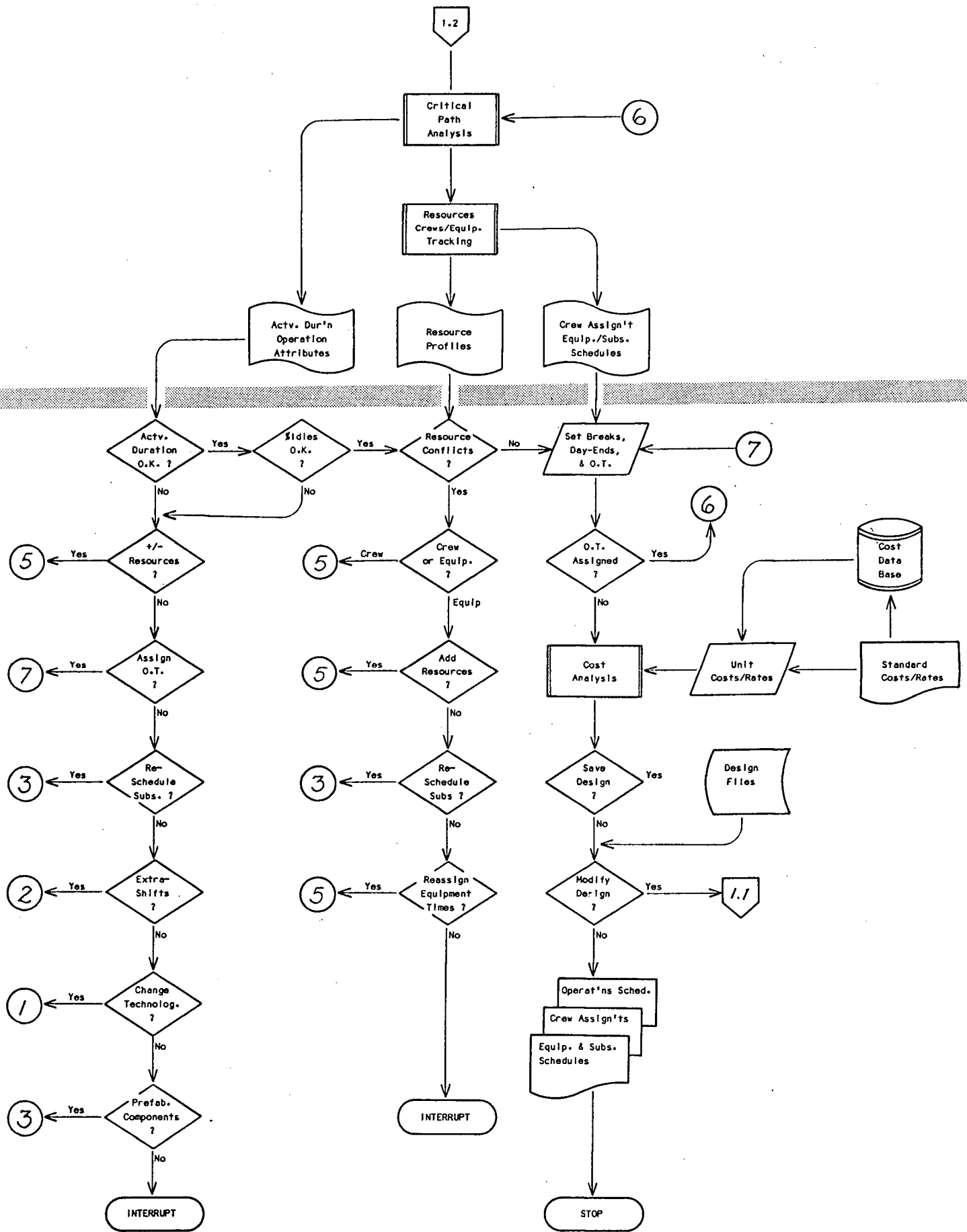


Figure 6.3

6.3.1 MODULE 1 - PROBLEM RECOGNITION

6.3.1.1 REPRESENTATION OF PROJECT INFORMATION

In the design of construction activities, field management personnel have to draw on their experience with similar projects and apply their knowledge of construction methods and technologies. The success of a project is therefore highly dependent on the experience and knowledge of the key management personnel. The ability to represent experience and knowledge help ensure that the a contracting firm's ability to compete is not affected by turn-over in its key management personnel. Experience and knowledge represented in proper formats can also be used to provide an environment for training less experienced construction management personnel.

Experience and knowledge can be represented by two classifications of project information: (1) broad qualitative descriptive statements, and (2) detailed quantitative data. The former represents information which can help management personnel quickly identify the past project that most closely represent the present situation. It includes descriptions of innovations and creative designs which would otherwise be lost amidst the quantitative project data. It could be in the form of brief statements

describing the overall project performance, production systems and technologies employed, operations carried out, and the difficulties, solutions and innovations involved in a project. The latter type of detailed quantitative information are demanding in terms of computer storage and database maintenance. Examples of this type of information are the detailed dimensions of project assembly and subassembly components, operation definitions and crew assignments.

At present, few construction firms have organized records of past projects; the body of information only resides in the minds of key management personnel. For this reason and the limited scope of this thesis, no details of this module will be described in the activity design environment being developed. It is hoped that the activity design environment will also act as a tool by which project information can be collected and processed for future reference.

6.3.2 MODULE 2 - PROBLEM DEFINITION

The level of detail in which a problem is defined will affect how realistic and effective the subsequent design solution is. A construction project can be defined by the dimensions of its subassembly components, e.g. area and thickness of each bay of a floor slab, and the dimensions of each work category component, e.g. the rebar contents of the floor slab subassemblies. This definition process assists in identifying the work tasks required to construct the physical product. These work tasks can then be grouped and assigned to construction operations.

6.3.2.1 CURRENT PRACTICE AND PROBLEM DEFINITION

Modeling tools and systems currently available for construction planning do not provide the facility by which management personnel can define the problem in the detail described above. In the activity planning process, the field management personnel first divide the typical physical assembly into subassemblies along logical breaks, such as the column lines; the subassemblies are then assigned in groups to the corresponding construction operations. The quantities of work in each operation must be calculated manually or derived from values produced by the estimator. In order to identify the most effective construction method for a construction activity, one has to experiment with

different groupings of the subassembly units, thus changing the work content of the operations. Every time the groupings of subassemblies are changed, the work tasks assigned to the corresponding operations will change and thus the work quantities and the resource requirements of operations will have to be recalculated.

6.3.2.2 PROBLEM DEFINITION AND THE DSS

One of the objectives of the decision support system for the Problem Definition module is to provide an environment in which the problem can be defined in detail by specifying the dimensions of each subassembly component and each work category component. The following benefits can be achieved by defining the problem in this detailed manner:

- (1) Using the dimensions specified, simple routines can be used by the computer to calculate accurately the work contents of and thus the resources required to perform the construction operations; the resource requirements calculated can be used to assist in the resource assignment process.
- (2) Because the work content of the operations can be calculated by computer, different ways of grouping the subassemblies for construction in the solution formulation process can be studied readily.

- (3) By defining the dimensions and work content of each assembly unit, the impact of differences in the dimensions of non-typical assembly units can be assessed.

6.3.2.3 PROBLEM DEFINITION AND COMPUTER INPUT FORMAT

Figures 6.4(a) and 6.4(b) show the process of defining the dimensions of a typical assembly component.

The name to be used in describing the assembly divisions (or units) and the total number of similar units in the project assembly group are entered. This is followed by detailed definition of the dimensions of the subassembly components and the work category components. The dimensions of the typical assembly are first entered. Any assembly division with dimensions that deviates from that of the typical division can then be identified and modified.

In the example shown, the areas entered are used to calculate the resources required for formwork and concrete finishing operations, the rebar content is used to calculate the resources required for the rebar installation operation, and the productivity factor (Prodv' F.) is used to reflect possible difficulties involved in constructing the subassembly, e.g. forming of a irregularly shaped area, which will reduce the rate of construction.

Figure 6.4(a): Select assembly component to define

ASSEMBLY DEFINITIONS : SUPERSTRUCTURE

Enter Name of Assembly Division : [Elev.]

Enter Total Number of Assembly Divisions : [25]

Select Assembly Component to Define : SLAB

SLAB

COLUMNS

ELEV. CORE

WALLS

Figure 6.4(b) : Specify dimensions of subassembly and work category components

TYPICAL ASSEMBLY COMPONENT DIMENSIONS :

Assembly Component : SLAB

[Bay]	[Area] < M ² >	[Slab Thkn.] < mm >	[Rebar Content] < tons/M ² >	[Prod' F.]
A-1	90	150	1.0	0.90
A-2	100	200	1.1	1.00
...
B-1	100	200	1.1	1.00
B-2	100	200	1.1	1.00
B-3	65	150	0.9	0.60
B-4	100	200	1.1	1.00
B-5	100	200	1.1	1.00
...
C-4	100	200	1.1	1.00
C-5	85	150	1.0	0.85

Copy Dimensions to Other Assembly Divisions : Yes / No

Modify Dimensions In Assembly Division : Yes / No

Enter Assembly Division No. to Modify : [24]

Figure 6.4: Problem definition

6.3.3 MODULE 3 - SOLUTION FORMULATION

As stated in section 4.5, current practice in construction planning fails to model construction activities in a realistic manner. For example, it assumes that resource consumption has to be constant over the entire duration of a construction operation. It also fails to correctly model the actual construction activity design process. For example, labour resources have to be assigned as individual workers rather than as crews.

The objective of this module is to provide a problem solving environment that reflects the realities of construction activities as practiced in the field. The solution formulation process has been divided into the following processes:

- (1) Review and select construction technologies;
- (2) Define operations;
- (3) Sequence defined operations; and
- (4) Estimate and assign resources.

Some of the features incorporated into the foregoing processes are as follows:

- (1) A data structure for representing construction technologies is described. The computerized record of construction technologies can be used to assist

management in comparing different construction technologies in the solution selection process.

- (2) By using the detailed definition of physical dimensions of subassemblies and work category components developed in the Problem Definition module, operations are defined by selecting the subassemblies to be included into the work content of the operations.
- (3) The sequencing of operations describing an activity is defined in matrix format for clarity. The lags in the precedence relations between operations can be defined as a percentage of the corresponding operation duration.
- (4) Using the principles of assembly line balancing, the resources required to perform construction operations are estimated by computer to assist in the resource assignment process.
- (5) Labour resources are assigned to operations as crews rather than as individual workers. Resources can also be assigned to an operation for a percentage of its duration.

6.3.3.1 REVIEW AND SELECT CONSTRUCTION TECHNOLOGIES

In a construction project, the choice of production technology is of prime importance. It affects the production rate of the construction operations and thus the cycle time. It also imposes certain constraints on labour resource assignments because of possible minimum crew size requirements. Each technology also has associated costs. The choice of construction technology therefore often evolves into a trade-off problem between activity production rate (time) and cost. A production technology that has a higher unit production rate, however, might not be appropriate for a certain situation and will not increase the overall production rate of an activity even at the expense of the extra cost. Whether a technology with a high unit production rate is appropriate depends on whether the operations can be properly balanced. For example, the overall production rate of an activity, say consisting of two operations in parallel, will not be increase by increasing the production rate of one operation alone, rather, the production rates of both operations must also be increased proportionately, i.e. the activity design must be balanced, in order to benefit from using technologies with higher unit production rates.

6.3.3.1.1 CURRENT PRACTICE AND SELECTION OF TECHNOLOGIES

Currently available construction planning techniques and systems do not provide management the facility to study alternative construction technologies and select the most suitable one. Instead, construction personnel draw on their own knowledge of available construction technologies and do limited formal study of one or two alternatives at best. This latter process involves rough estimates of technology costs and resource requirements. This approach does little to encourage innovations and considerations of new developments in construction technologies.

6.3.3.1.2 SELECTION OF TECHNOLOGY AND THE DSS

To facilitate the study of alternative construction technologies, available technologies must be classified by the work categories they are intended for and coded in a systematic format to allow comparison and accurate estimation of cost and resource requirements.

In the following discussion, a data structure is suggested for coding and storing construction technologies in a computer database. The attributes used for classifying and describing construction technologies are also described.

Figure 6.5(a): Select technology by work category

Select Work Category-Group to Review Technologies : **CONCRETE**

CIVIL/SITE **CONCRETE** SUB-TRADES OTHERS

Select Work Category : **FORMWORK**

FORMWORK REBAR POURING CURING FINISHING

Select Assembly Component : **SLAB**

SLAB COLUMNS ELEV. CORE WALLS

Figure 6.5(b): Compare and select technology

Select Slab Formwork System: **EFCO Floating Slab**

[System]	[Unit Production] [Rate]	[Hardware] [Unit Cost]	[Crew Make-Up] [Ratios]
	< M ² /Mn-hr >	< cnd\$/M ² >	< Carpenter > < Gen. Labr >
EFCO Floating	4.8	37.50	0.9 0.1
FORM-Ezy	6.4	47.75	0.8 0.2
.....	
.....	

Review detailed descriptions of selected technology : **Yes** / No

Figure 6.5: Review and select construction technologies

6.3.3.1.3 ATTRIBUTES OF CONSTRUCTION TECHNOLOGIES

Figures 6.5(a) and 6.5(b) show the computer input formats used to assist in selecting alternative construction technologies.

The following attributes used in selecting construction technology are noted:

(1) Work Category Group, Category and Assembly Component

These attributes, as shown in figure 6.5(a), identify the work category for which the construction technology is intended. They are used for classifying construction technologies. Construction technologies can then be retrieved by the system user for comparisons by specifying their classifications. The work breakdown structure by work/component categories described in chapter two can be used as a classification scheme for construction technologies; a comprehensive scheme has not been developed in this thesis.

(2) Unit Production Rate, Hardware Unit Cost and Crew Make-Up Ratios

Unit Production Rate describes the time required to place a single unit (M^2 , M^3 , etc) of a construction operation using the selected technology. It determines the

production rate of the operation. In the decision support system for activity design, it is used to calculate the resource requirements to achieve a specified operation duration. Higher productivity can be achieved usually only at the expense of higher cost; in other words, the construction technology selection process is a trade-off between time and cost. For the example shown in figure 6.5(b), the higher productivity of FORM-Ezy is achieved at the expense of a higher hardware cost.

The cost associated with a construction technology is two-fold: hardware cost and labour cost. Hardware Unit Cost represents the cost for either renting or fabricating the system hardware. Labour cost would be best specified separately, because hourly labour rates would depend on the geographic location of the project and other project conditions.

Crew Make-Up Ratios identify the ratios of the numbers of men required for each labour type in employing the construction technology. For example, to dismantle and install a 240 M^2 floor slab using the EFCO Floating form will require 50 man-hours ($240 \text{ M}^2 / 4.8 \text{ M}^2/\text{Mn-hr}$) - 45 carpenter-hours ($50 \text{ Mn-hr} \times 0.9$) and 5 general labourer-hours ($50 \text{ Mn-hr} \times 0.1$). The rental cost of formwork will be \$9,000.00 ($240 \text{ M}^2 \times \37.50).

Displaying the three attributes of construction technologies side-by-side can assist management in selecting

an appropriate technology for the preliminary design solution.

Other attributes useful in the activity design process, such as minimum crew size requirements and the work tasks involved, can also be included in the attribute list. For example, the system user may wish to review the work tasks involved in a construction method, as shown in Figures 6.6. In general, breakdowns of construction technologies to this level of detail are not readily available; therefore, their treatment is not pursued further in this thesis.

Figure 6.6(a): Review work tasks of selected technology - page 1

EFCO Floating Slab Formwork System Work Tasks :				Page 1 of 3
Literature File No. : SibFm-012				
Slab Formwork Dimension : 20 M by 10 M Bay				
** INSTALL AND DISMANTLE FORM **				
< all time in minutes >	No. of Units	Unit Time	Total Time	Comments
01 Set roller support bracket ahead	8	40	320	
02 Lower support brackets & form	8	15	120	
03 Strip slab edge hand rail (1 end)	1	30	30	
04 Attach tugger winch	1	30	30	
05 Position rolling scaffold	1	15	15	
06 Roll slab form out to pick-points	1	30	30	
07 Crane hookup 4 points	4	5	20	
08 Slab swing-out and reset	1	20	80	4 Men & Crane
09 Clean and oil form	784sf	6/100sf	46	
10 Install filler panel	1	90	180	2 men

Figure 6.6(b): Review work tasks of selected technology - page 2

EFCO Floating Slab Formwork System Work Tasks :				Page 2 of 3
** SPLITTING OF FORM **				
< all time in minutes >	No. of Units	Unit Time	Total Time	Comments
11 Remove 1 bolt at bearing blocks	4	5	20	
12 Attach tugger winch	1	30	30	
13 Position rolling scaffold	1	15	15	
14 Roll slab form out	1	30	30	
15 Crane hook up 4 points	4	5	20	
16 Slab swing out and re-set	1	20	80	4 Men & Crane
17 Install 1" bolt at bearing blocks	4	5	20	

Figure 6.6: Review work tasks of construction technology

Source: Economy Forms Corporation, Des Moines, Iowa, USA.

6.3.3.2 DEFINE CONSTRUCTION OPERATIONS

Construction of a floor assembly unit is accomplished by completion of all the subassembly components defined in the problem definition process. The simplest construction method is to construct the whole floor assembly as a single section; for example, the formwork and rebar installation for the complete floor slab are completed before concrete is poured and finished. Although simple, this method could have an undesirably large cycle time and could be accompanied by considerable idle time for key trades.

To shorten cycle time and because of other economic considerations, the floor assembly is often constructed in several major sections. For example, a floor assembly can be divided into fifteen sub-assemblies, say, Bay-A1 to Bay-C5. Construction operations can be performed in three sections of five bays. The formwork and rebar can be installed in the first section, concrete can then be poured and finished in the first section while formwork and rebar are being installed in the second section and so on until construction of the floor assembly is completed. By constructing the floor assembly in three sections, fewer formwork units could be required and cycle time could be reduced.

Changes in construction method will require the definitions of construction operations to be changed. For example, if the floor assembly is constructed in three sections instead of a single section, the operation, say

Install Slab Formwork, has to be redefined as three operations, say, Install Slab Formwork Section #1, Install Slab Formwork Section #2 and Install Slab Formwork Section #3.

6.3.3.2.1 DEFINING AN OPERATION

The process of defining an operation is shown in figures 6.7(a) and 6.7(b). An operation is first identified by its work categories as shown in figure 6.7(a). The process of identifying the operation by its work categories can facilitate collecting project information for cost accounting of the current project and for estimating the costs of similar projects in the future. After the operation is identified by its work categories, the defined dimensions of the subassembly components and work category components, e.g. the dimensions of the floor slab subassemblies and rebar contents in each subassembly, can be retrieved. The user can then define the work assignment of an operation by selecting the respective subassemblies to be included in the operation.

6.3.3.2.2 DEFINING RELATED OPERATIONS

Construction operations that belong to different work categories can be related to each others by their work assignments, i.e. the same or similar groups of

subassemblies are assigned to the operations. In the example shown in figures 6.8(a) and 6.8(b), the rebar operation RbrSlb-1, Rebar Floor Slab Section #1, is related to the formwork operation InsSlbFm-1, Install Slab Formwork Section #1.

Normally, both operations have to be defined by assigning selected subassemblies to the operations. Thus, a set of floor slab subassemblies, say A-1, A-2, B-1, B-2, and C-1, have to be assigned to the formwork operation, InsSlbFm-1. The assignment process must then be repeated by assigning, once again, the floor slab assemblies A-1, A-2, B-1, B-2, and C-1 to the rebar operation, RbrSlb-1.

In the activity design environment developed, operations related in the above manner can be defined conveniently as illustrated in figure 6.8. The operation to be defined is first related to an already defined operation. The work assignment of the related operation is then retrieved, the user can accept the already defined work assignment or add or delete sub-assemblies as required. The quantity of work of the defined operation is then calculated using the work category component dimensions specified in the Problem Definition module. In the example shown, the work assignment of the rebar operation, RbrSlb-1 has been related to the formwork operation, InsSlbFm-1, the quantity of rebar to be installed can be calculated from the rebar content of the subassemblies specified in the problem definition process.

6.3.3.2.3 REDEFINING OPERATIONS

An operation can be redefined using a computer input/output format similar to figure 6.7(b), by adding or deleting subassemblies from the assignment of an operation. Using this new definition, the computer can recalculate the total quantity of work and resource requirements. How these calculated resource requirements are used in guiding the resource assignment process is described in section 6.3.3.4.

Figure 6.7(a): Select operation to define

Select Work Category-Group : **CONCRETE**

CIVIL/SITE **CONCRETE** SUB-TRADES OTHERS

Select Work Category : **SLAB**

SLAB COLUMNS ELEV. CORE WALLS

Select Work Category Component : **FORMWORK**

FORMWORK REBAR DELIVERY CURING FINISHING

Select Work Category Sub-Component : **INSTALL**

INSTALL DISMANTLE

Enter Name of Operation : [InsSlbFm-1]

Enter Description : [Install slab formwork BAY<A1,A2,B1,B2,C1>]

Selected Slab Formwork System : **EFCO Floating Slab**

Change selected system : **No / Yes**

Figure 6.7(b): Assign subassemblies to an operation

Operation : **InsSlbFm-1**

Install slab formwork BAY<A1,A2,B1,B2,C1>

Selected Slab Formwork System : **EFCO Floating Slab**

Move cursor and press <Enter>/ to include/remove assembly.

[Bay]	[Area] < M ² >	[Prod' F]
A-1	90	0.90
A-2	100	1.00
...
B-1	100	1.00
B-2	100	1.00
B-3	65	0.60
B-4	100	1.00
B-5	100	1.00
C-1	90	0.90
...

Figure 6.7: Defining an operation

Figure 6.8(a): Select related operation to define

Select Work Category-Group : **CONCRETE**

CIVIL/SITE **CONCRETE** SUB-TRADES OTHERS

Select Work Category : **SLAB**

SLAB COLUMNS ELEV. CORE WALLS

Select Work Category Component : **REBAR**

FORMWORK **REBAR** DELIVERY CURING FINISHING

Enter Name of Operation : [RbrSlb-1]

Enter Description : [Slab Rebar BAY<A1,A2,B1,B2,C1>]

Enter Related Operation : [InsSlbFm-1]

Selected Slab Rebar System : **Install in place**

Change selected system : No / Yes

Figure 6.8(b): Review and modify assignment of operation

Operation : **RbrSlb-1** Related to : **InsSlbFm-1**

Rebar Slab BAY<A1,A2,B1,B2,C1>

Selected Slab Rebar System : **Install in place**

Move cursor and press <Enter>/ to include/remove assembly.

[Bay]	[Rebar Content] < tons/M ² >	[Prodv' F]
A-1	1.0	0.90
A-2	1.1	1.00
...
B-1	1.1	1.00
B-2	1.1	1.00
B-3	0.9	0.60
B-4	1.1	1.00
B-5	1.1	1.00
C-1	1.0	1.00
...

Figure 6.8: Defining related operations

6.3.3.3 SEQUENCE DEFINED OPERATIONS

6.3.3.3.1 OPERATIONS SEQUENCE AND THE P-MATRIX

Operations defined to construct physical assemblies must be performed in a specified but not necessarily unique sequence which is governed by technological and other project constraints. Determining the best sequence is a design problem in itself, the solution of which requires considerable construction experience.

The sequence of operations is defined by identifying the immediate predecessors or immediate successors of each operation. In industrial engineering, the P-matrix (or precedence matrix) is often used to represent the sequential relations between operations. This matrix format has the advantage of simplicity and clarity. However, when the number of operations and thus the size of the matrix increases, the process of manually searching for the immediate predecessors or successors can become tedious. This problem can be solved by adding a column or a comment line on the screen that shows the immediate successors of the operation under the cursor. The process of sequencing defined operations in matrix format is shown in figure 6.9.

Enter Active Assembly Division : [4]

ENTER IMMEDIATE SUCCESSORS OF OPERATION:

[Type(s) of relation; Lag in (%duration) or (hr:min)]

Type: 1 = FS, 2 = SF, 3 = SS, 4 = FF

	Operation	Assm'								
	I.D.	Div.	2	3	4	5	6	7	8	9
1	DsmSibFm-1	3	1;0	0	0	0	0	1;0	0	0
2	InsSibFm-1	4	*	1;0	0	0	0	0	0	0
3	RbrSib-1	4		*	3;80%	1;0	0	0	0	0
4	SlvSib-1	4			*	1;0	0	0	0	0
5	CncrSib-1	4				*	1;0	0	0	0
6	CureSib-1	4					*	0	0	0
7	InsSibFm-2	4						*	1;0	0
8	RbrSib-2	4							*	9;80%
9	SlvSib-2	4								*
							

Operation: **RbrSib-1** Successors: 3, SlvSib-1; 4, CncrSib-1;

Figure 6.9: Sequencing operations - the P-Matrix

6.3.3.3.2 OPERATIONS SEQUENCE AND LAG CALCULATIONS

There are four typical sequential relationships, namely finish-to-start, start-to-finish, start-to-start, and finish-to-finish. Each relationship is further described by a lag value. Traditionally, these lag values are entered in time units, e.g. 1 day. When operation durations are constant parameters, this is a useful way of describing lags. In reality, however, operation durations are decision variables. Thus, when the lag is defined in time units, every time a change is made to the operation duration, the lag must be recalculated manually.

To facilitate the process of changing the durations of operations, it is suggested that lags be entered as percentages of operation durations. When the operation durations are changed, the computer can automatically recalculate the lag values to be used in the network analysis.

6.3.3.3.3 REPETITIVE CONSTRUCTION AND THE P-MATRIX

A repetitive construction project is characterized by a number of identical or very similar assembly units. Construction of an assembly unit is initiated by one crew that performs an operation at the location which will be occupied by the physical facility. Other crews then follow to carry out the operations required to complete the construction of the assembly. This is the sequential crew

system described by Boling [12]. The complete sequence of operations required to construct a typical assembly is called the "typical cycle".

Even though the typical cycle can be identified as a distinct sequence of operations, construction of the assembly units are not independent of each other. In the construction of a high-rise building, for example, while some crews are still performing their assigned operations in a construction cycle, the crew that has initiated and completed its operation(s) in the particular cycle could have initiated another construction cycle. Thus, two or more construction cycles can be in progress at any one time and overlap each other. For example, while the formwork dismantling crews are working on the 3rd construction cycle (or 3rd floor assembly), the formwork installing crew could be working on the 4th construction cycle (or 4th floor assembly). The smooth transition or reassignment of labour crews from one cycle to the next is critical to avoiding idle time and resource conflicts.

To identify clearly the interface between cycles and the transition from one cycle to the next, the specific assembly division (unit) on which an operation is being performed must be identified. The extent to which the operations in each division must be defined in the P-matrix depends on the degree to which the cycles overlap. The operations defined in the P-matrix must describe the complete construction cycle of an assembly unit.

In addition, a small number of non-typical assembly units exists for most repetitive projects. Sometimes, the deviations of these non-typical units might be significant enough to require modification to the typical construction cycle design. Transitions between non-typical and typical construction cycles must also be considered in the cycle planning process.

6.3.3.3.4 SEQUENCING OPERATIONS WITH THE P-MATRIX

Figure 6.9 shows an example of sequencing the defined operations in matrix format. The construction cycle design of the 4th floor assembly is being formulated. The total work quantities for each operation can be calculated automatically from the subassembly and category-component dimensions of floor assembly divisions 3 and 4 defined in the problem definition process.

The operation DsmSlbFm-1, Dismantle Slab Formwork Section #1, of the 3rd floor assembly (Assm' Div. 3) is identified as the immediate predecessor to the operation InsSlbFm-1, Install Slab Formwork Section #1, of the 4th floor assembly (Assm' Div. 4).

The operation RbrSlb-1, Rebar Slab Section #1 has a Start-to-Start relation with the operation SlvSlb-1, Install Sleeveings in Slab #1, with a lag of 80% the duration of RbrSlb-1.

6.3.3.4 ESTIMATE AND ASSIGN RESOURCES

The purpose for evaluating different construction technologies and methods is to design the most effective solution, in terms of labour, hardware and special equipment costs, within time and other project constraints. The cost of labour accounts for a major portion of the total cost of any construction project. Therefore, careful planning is required to eliminate labour idle time. Use of hardware and special equipment must be maximized to minimize the cost.

Work space constitute another resource that has to be managed carefully. Proper site planning helps ensure that all construction operations can progress in a smooth manner. Detailed site planning requires the use of schematic models and a graphics interface between the computer and the system user. Treatment of this resource is beyond the scope of this thesis. In the activity design environment developed, work space, however, can be treated as a special resource to be shared by construction operations.

The objective of this subsection is to describe a facility that assists in the resource assignment process. An environment is provided where resources can be assigned in a manner that reflects the actual construction process.

The processes of estimating resource requirements and assigning labour crews and special resources to perform the construction operations will be described. The principles of assembly line balancing have been adopted for estimation of

resource requirements. Labour resources are assigned as crews rather than as individual workers. Hardware and work space are considered as special resources and can be assigned to a construction operation. Resources can be assigned to an operation for part of its duration.

6.3.3.4.1 CURRENT PRACTICE AND RESOURCE ASSIGNMENT

Currently available construction modeling techniques and systems fail to assist decision makers in resource allocation because of their inability to reflect the actual process of labour assignment. The following additional problems with the current practice of resource assignment can be identified:

- (1) In the traditional approach to construction planning, durations are first assigned to construction activities for a CPM analysis, and then resources are assigned consistent with these durations to permit a resource analysis. These resource requirements are calculated manually from quantity take-off data and standard productivity data. Their estimation to meet a "target cycle time" is part of the process often identified as backward planning, i.e. set the duration, then allocate the resources to achieve it. Currently available construction modeling techniques and systems fail to assist in the backward planning process.

- (2) In adopting currently available modeling techniques and systems, labour resources have to be assigned as individual workers; for example, 4 carpenters and 1 general labourer could be assigned to install slab formwork. No proper identification is given to labour groups to allow them to be tracked as a unit from operation to operation. In reality, labour crews are formed and assigned to carry out certain sets of operations. Once the crews are formed, their members work together for extended periods of time except when conditions require some crews to be split temporarily.
- (3) Currently available construction modeling techniques and systems also fail to reflect the actual resource assignment process because they require resources to be assigned to an operation for its complete duration. In practice, certain resources are employed by a construction operation only for part of its duration; for example, the tower crane may be required for only two hours during the eight hour duration of the formwork dismantling operation. One way to treat this problem is by decomposing an operation into sub-operations such that resources can be assigned to one of the sub-operations instead of the complete operation. The process, however, increases the number of operations defined and make the network logic more difficult to comprehend.

In the following subsections, the problems identified will be treated.

6.3.3.4.2 ALB AND ESTIMATION OF RESOURCE REQUIREMENTS

In the assembly line balancing procedure described in chapter 5, "perfect-balance" is used as the objective to estimate the total resource pool required. Although perfect balance cannot usually be achieved in the dynamic construction environment, and even in the more static manufacturing environment, it serves as a goal and a benchmark in formulating an effective design solution. When more resources are required than the estimated values under perfect balance, it indicates that further improvement to the design might still be feasible. This principle will be used to assist in the backward planning process of resource assignment.

Figure 6.10(a) shows a computer input format that can be used in the activity design decision support system. The work category group of the activity is first identified. Using the dimensions of subassemblies and work category components from the problem definition process, and using the unit production rates of the selected production technologies, the computer can calculate the total man-hour requirements for each trade to construct the assembly unit. By dividing the total man-hour requirements by the target cycle time, the numbers of men required for each trade can

be calculated. These number can then be fine tuned by the user to reflect considerations which cannot be quantified. In the example shown, the total resource requirements for the Concrete work category group, which include all operations in a typical high-rise structure cycle that are normally performed by the general contractor, are calculated. The numbers of men required for each labour type are rounded and are used as the maximum resource levels for the structure cycle. The goal for the management is then to balance the construction operations such. that the total labour resources used by the operations will be below these levels.

Special resources such as a tower crane and prefabrication areas are not necessarily active for the complete construction cycle duration. Consequently, the assumption of perfect balance cannot be used to estimate the total resource requirements. The decision maker must use his personal judgment or draw on his experience to assign the maximum levels of major equipment and hardware. An example of a computer input format for assigning maximum levels of special resources is shown in figure 6.10(b). In this figure, [Cost/Unit] indicates the cost for employing the resource per time unit and is used in cost analysis of the design solution; [Max. Unit] indicates the maximum number of units available.

Figure 6.10(a): Estimate and assign labour pool

Estimate by Work Category-Group : **Yes** / No

Select Work Category-Group : **CONCRETE**

	CIVIL/SITE	CONCRETE			
			[Carpenter]	[Masonry]	[Steel Wkr] [Gen. Labr]
Formwork		240			20
Rebar				160	10
Pouring	20	80			80
Finishing		112			8
Total :	260	192	160	118	<Mn-Hr>

Enter Desired Cycle Time : [35] HOURS / DAYS

Estimated Resource Requirements (If perfectly balanced) :

7.4	5.5	4.6	3.4	<Man>
-----	-----	-----	-----	--------------------

Enter Resource Pool :

[8]	[6]	[5]	[4]	<Man>
-------	-------	-------	-------	--------------------

Enter Special Resource Pool : **Yes** / No

Figure 6.10(b): Assign special resource pool

SPECIAL RESOURCE POOL :

[I.D.]	[Type]	[Description]	[Cost/Unit]	[Max. Units]
Tcrane	Equipment	Tower Crane	\$1000.00 / Day	1
CncrPmp	Equipment	Concrete Pump	\$125.25 / Hour	1
SlbFm	Hardware	EFCO Floating Slab Form	\$750.00 / Week	10
ClnmFm	Hardware	EFCO Modular Column Form	\$375.00 / Week	9
ZonS1	WorkZone	Storage Yard Zone 1		1
ZonW2	WorkZone	Active Work Zone 2		1
.....		

Figure 6.10: Estimate and assign resource pools

6.3.3.4.3 ASSIGNING LABOUR CREWS

Figures 6.11(a) and 6.11(b) show how labour resources can be assigned in a realistic manner. In figure 6.11(a), the list of defined operations are retrieved and displayed to the user. After an operation has been selected for resource assignment, the user is prompted to enter the operation duration. Using the ALB principle the labour resources required to perform the operation within the specified duration can be calculated by the computer based on the work assignment of the operation and the selected construction technology. Crews are then formed, using the calculated resource requirements as the guideline, and assigned to perform the operation. By identifying the committed resource as crews, the sequence of operations performed by each crew can be identified for productivity control and study. The followings cases in resource assignment are worthy of note:

(1) Crews assigned to more than one operation

Operations that do not overlap in time can be performed by the same crew; for example, within a five day construction cycle, a formwork crew can perform the operation of installing slab formwork on one day and perform the operation of installing building core formwork on next. For this case, the management can assign the same crew to two or more operations. As operations that share the same

crew cannot overlap in time, they are treated as having finish-to-start relationships in the network analysis.

(2) Mixed Crew and Multiple Crews

The term mixed crew is used to describe a crew made up of more than one labour types. In the example shown in figure 6.11, a mixed crew of 3 carpenter and 1 general labourer can be formed to install the slab formwork section. However, this would mean that the general labour will be idle more than 50% of the time. To solve this problem, one can assign a crew of 3 carpenters for the complete operation duration and a crew of 1 general labourer for 50% of the time. This case can then be identified as a multiple-crew assignment one. The use of the assignment procedure then allows the general labour to be assigned to another operation when no longer needed.

To solve the second problem in the traditional approach to construction planning and to allow labour resources to be employed more effectively, the additional attributes of [Duration, Lag] are defined for each crew assignment. Duration indicates that the assigned crew is to be employed only for this specified period of time or percentage of the operation duration; lag indicates the time when the crew will be employed in terms of time from the start of the operation; examples are described in the next section.

6.3.3.4.4 ASSIGNING SPECIAL RESOURCES

Figures 6.12(a) and 6.12(b) show the computer input formats for assigning special resources to construction operations. A list of the special resource type identified can be retrieved and the corresponding resources assigned to the specified operation. For the example shown in figure 6.12(a), the tower crane is to be employed in the operation InsSlbFm-1 after 20% of the operation is completed and for 40% of the total operation duration. In the example shown in figure 6.12(b), ten units of the hardware SlbFm (EFCO slab formwork) are available, five units are assigned to the operation InsSlbFm-1. The resource is employed for 100% of the operation duration.

Figure 6.11(a): Select operation to assign resources

CREW and SPECIAL RESOURCE ASSIGNMENT

Select from operation list: **InsSlbFm-1**

[No]	[I.D.]	[Description]
1	InsFmSlb-1	Install Slab Formwork BAY<A1,A2,B1,B2,C1>
2	RbSlb-1	Rebar Slab BAY<A1,A2,B1,B2,C1>
3	SlvSlb-1	Mechanical Sleeveings BAY<A1,A2,B1,B2,C1>
4	CnrcSlb-1	Pour Concrete Slab BAY<A1,A2,B1,B2,C1>
5	CureSlb-1	Cure Concrete Slab BAY<A1,A2,B1,B2,C1>
6	DsmFmSlb-1	Dismantle Slab Formwork BAY<A1,A2,B1,B2,C1>
7

Figure 6.11(b): Assign labour crew to meet target operation duration

Operation : **InsSlbFm-1** Min. Crew Size : **3** Neglect : **No / Yes**
Install Slab Formwork BAY<A1,A2,B1,B2,C1,C2> Content : **480 M²**

RESOURCE POOL : **[Carpenter]** **[Masonry]** **[Steel Wkr]** **[Gen. Labr]**

Total :	8	6	5	4	<Man>
Balance :	5	6	2	2	

CREW FORMED :

SlbFmCrw-1	3			0	
SlbRbCrw-1			3	2	

Enter Desired Operation Duration : **[7]** HOURS / DAYS

Estimated Resource Requirements :

	2.5		0.5	<Man>
--	------------	--	------------	--------------------

ASSIGN CREW :

[SlbFmCrw-1]	3		1	
-----------------------	----------	--	----------	--

Enter [Duration;Lag] <%duration or hr:min> : **[100%;0]**

ADD ANOTHER CREW : **No / Yes**

ASSIGN SPECIAL RESOURCES : **No / Yes**

Figure 6.11: Assigning labour crews to operations

Figure 6.12(a): Select special resource type to assign

Operation : InsSlbFm-1
 Install Slab Formwork BAY<A1,A2,B1,B2,C1,C2>

ASSIGN SPECIAL RESOURCES :

EQUIPMENT	HARDWARE	WORK-ZONE
Select EQUIPMENT from list : TCrane		
[I.D.]	[Description]	[Cost/Unit] [Max. Units]
TCrane	Tower Crane	\$1000.00 / Day 1
.....

Enter No. of Units to be Assigned : [1]

Enter [Duration;Lag] <%duration or hr:min> : [20%;40%]

ASSIGN ANOTHER SPECIAL RESOURCE : No / ☒ Yes

Figure 6.12(b): Assign special resources to operation

Operation : InsSlbFm-1
 Install Slab Formwork BAY<A1,A2,B1,B2,C1,C2>

ASSIGN SPECIAL RESOURCES :

EQUIPMENT	HARDWARE	WORK-ZONE
Select HARDWARE from list : SlbFm		
[I.D.]	[Description]	[Cost/Unit] [Max. Units]
SlbFm	EFCO Floating Slab Form	\$750.00 / Week 10
CmnFm	EFCO Modular Column Form	\$375.00 / Week 9
.....

Enter No. of Units to be Assigned : [5]

Enter [Duration;Lag] <%duration or hr:min> : [100%;0]

ASSIGN ANOTHER SPECIAL RESOURCE : ☒ No / Yes

Figure 6.12: Assigning special resources to operations

6.3.4 MODULE 4 - SOLUTION ANALYSIS

As mentioned in section 6.2, the relationship between the computer and the decision maker in a decision support system can be described as symbiotic. In other words, the computer and the decision maker depend on each other to solve a problem.

In the description of the decision support system for activity design, the computer functions mainly to provide an environment in which management personnel can formulate a design solution in a realistic manner. Another major function of the computer is to analyze the design solution formulated by the user in order to produce an overall schedule. Conflicts between operations in using shared resources must be identified and the effectiveness in using resources must be determined. Findings from the analysis must be communicated to the user for possible modification and improvement.

6.3.4.1 CURRENT PRACTICE IN RESOURCE ANALYSIS AND CYCLE DESIGN

Traditionally, resources are assigned to activities and resource profiles are produced to study the labour resource usage. If a resource profile indicates that the resource usage fluctuates too much or that the maximum level of a resource exceeds the maximum level available, then

management must make the appropriate decisions to solve the problem.

Some problems can be resolved through the use of levelling and allocation algorithms which rely on the use of activity floats to achieve specified objectives - continuity of resource usage, however, is generally not considered a design objective by most algorithms.

The goal in construction cycle design is to achieve a balanced cycle. In other words, the goal is to eliminate all floats between operations so that they can progress smoothly without interruption. An uninterrupted cycle design also indicates that the resources level will remain constant. The usefulness of resource levelling for designing construction cycles is therefore questionable. While a resource constrained scheduling algorithm might be able to resolve conflicts in using shared resources, it is only achieved by interrupting and delaying construction operations; in doing so, it defeats the goal of a balanced cycle.

At present, there is no algorithm that can guarantee that a balanced cycle design can be obtained. The system user must depend on his experience, personal judgment and intuition, assisted by the computer, to formulate a satisfactory cycle design. The results of the solution analysis and the formats in which they could be presented are described in sections 6.3.4.2 and 6.3.4.3 below. How

these results can be used to improve the balance of the cycle design is discussed in section 6.3.5.

6.3.4.2 CRITICAL PATH METHOD FOR SOLUTION ANALYSIS

Of the analytical models reviewed in chapters four and five, the critical path method is the simplest method that can perform the required analysis and requires the least programming effort. Discrete event simulation and deterministic mathematical programming techniques could also be used to perform the required analysis and provide the required information. However, both require excessive programming effort for day-to-day use in the field and both require sophisticated simulation and mathematical programming software to reside in the decision support system.

In addition to its simplicity, the critical path method has the advantage of having been used in the construction industry for an extended period of time and the underlying concepts are comprehensible to project management personnel. The critical path method is therefore adopted as an appropriate analytical tool for the decision support system. However, because of the need to consider the overlapping of construction cycles, as stated in section 6.3.3.3, additional computer routines might be needed. These routines will not be treated in this thesis.

6.3.4.3 PRESENTATION OF ANALYSIS RESULTS

After the tentative solution has been analyzed, the results have to be communicated to the user so that solution refinement can take place. Three types of output can be identified: (1) critical path analysis results, (2) status of committed resources, and (3) work schedules for labour crews and special resources.

6.3.4.3.1 CRITICAL PATH ANALYSIS RESULTS

Critical path analysis results can be presented in several formats. Current practice uses tabular outputs and bar charts. The activity information includes: early start time (EST), late start time (LST), early finish time (EFT), late finish time (LFT), free float (FF) and total float (TF).

Figure 6.13 represent one of the formats in which critical path analysis results can be presented. Activity planning at the production level requires time units to be in hours and minutes. Two attributes that can be used to assist the user in the design improvement process have been identified in the table:

(1) [FF/Duratn] - the ratio of free float to the operation duration. It indicates the percentage of time that the crew assigned to the operation will be idle, presuming all operations start at their earliest time. However, unavailability of resources may preclude the

early start of an operation. Crew assignments therefore impose additional constraints on the critical path network logic - having the same crew assigned to two operations imposes a finish-to-start relation between them.

- (2) [Lbr Cost/Duratn] - the ratio of total labour cost of the operation to the operation duration. It provides a rough estimate of how much labour cost could be saved by eliminating the idle time of an operation. When the cycle duration has to be shortened, this ratio may help indicate which critical operation will cost less to shorten. The exact amount of saving or cost, however, depends on the method chosen to achieve the objective.

6.3.4.3.2 STATUS OF COMMITTED RESOURCES

In order to identify all conflicts in resource usage, one normally has to study the profiles of each resource type. When the number of resource types assigned is large, this process can become tedious. Figure 6.14, the resource status table, shows how summary information regarding the usage of special resources - equipment, hardware and work areas, can be represented in tabular form which can help identify problem areas.

The [Active Time] and [%Idle] indicate how effectively the resources are being used. For example, the prefabrication area, labelled PfZone-A1, is occupied for 27

hours and is unoccupied for 8 hours (or 24%) of the 35 hours cycle. Conflicts in using the resource can also be identified and the operations that are competing for it are listed to guide the user in resolving conflicts. In the example shown, conflicts in using the tower crane are indicated; between 15:00 - 16:00 (working hours are measured from start of the construction cycle), the operations RbrClm-S1 and InsSlbFm-3 both require the use of the tower crane; between 17:00 - 18:00, the operation InsSlbFm-3 is again competing with RbrClm-S2 for the tower crane. This information, together with use of the multiple activity chart described in the next section, can help management identify quickly the problems and alternative solutions.

6.3.4.3.3 WORK SCHEDULES FOR LABOUR CREWS AND SPECIAL RESOURCES

Field management personnel need detailed tactical plans to direct labour crews and to schedule special resources in order to perform the construction operations for a given cycle. In the DSS for construction cycle design being developed, labour resources are assigned as crews rather than as individual workers. The multiple operation time (M.O.T.) chart shown in figure 6.16 illustrates how the multiple activity chart described in section 4.1 can be adapted to provide detailed work schedules for crews and special resources.

The multiple activity chart is a modeling technique introduced in industrial engineering for work method studies and for studying the balance of work assignments in assembly production lines. Although it has been mentioned in the construction management literature (Halpin and Woodhead [43], Nicholis [91]), no computerized application in construction planning has been described. It can show the sequences of operations performed by each crew along side each other and is therefore useful for studying and improving the balance of work assignments and in resolving conflicts in the usage of shared resources.

The M.O.T. chart can be derived from the critical path analysis results. An operation is plotted by its start and finish time under the crew (or crews) that is assigned to perform it. Thus, a column in the M.O.T. chart represents a work schedule for the corresponding labour crew or special resource. Floats, or imperfect balance of construction operations are shown as idle time (IDLE for labour crews and AVAILABLE for special resources). Breaks can also be shown to indicate coffee and lunch times. Although not shown in the given example, it is also possible to indicate conflicts in using shared resources, such as the tower crane and work areas. How the M.O.T. chart can be used for design improvement will be discussed in section 6.3.5.

To facilitate the study of interactions between labour crews and special resources, the user can enter the order in which the selected crews and special resources are to be

reported, as shown in figure 6.15. For example, the work schedules for two work areas can be selected for display side by side to determine whether overcrowding in one area can be eliminated by assigning certain operations to the other work area, or by changing the sequence of construction operations.

* * C R I T I C A L P A T H A N A L Y S I S R E S U L T S * *

Activity Duration: 36:30

Operation I.D.	EST	LST	EFT	LST	FF	Duratn	<u>FF</u> <u>Duratn</u>	<u>Lbr Cost</u> <u>Duratn</u>
InsSlbFm-1 (Elev. 4)	0:00	0:00	7:00	7:00	00:00	7:00	0.00	\$112.50
InsSlbFm-2 (Elev. 4)	7:00	7:00	14:00	14:00	00:00	7:00	0.00	\$112.50
InsSlbFm-3 (Elev. 4)	14:00	14:00	21:00	21:00	0:00	7:00	0.00	\$112.50
.....
RbrCw-1 (Elev. 5)	24:00	24:00	28:00	28:00	00:00	4:00	0.00	\$ 87.50
RbrCw-2 (Elev. 5)	28:00	25:00	33:00	35:00	2:00	5:00	0.40	\$ 87.50
.....

Figure 6.13: Critical path analysis results

SPECIAL RESOURCE STATUS :

Cycle Time : 35:00

Resource I.D.	Active Time	%Idle	Max. Avail.	Max. Used
TCrane	xx:xx	x.xx	1	2
PfZone-A1	27:00	0.24	1	1
PfZone-A2	30:00	0.15	1	1
.....
WrkZon-E3	35:00	0.00	1	1
.....

TCrane Conflicts:

15:00 - 16:00 RbrCIm-S1; InsS1bFm-3
 17:00 - 18:00 InsS1bFm-3; RbrCIm-S2

Figure 6.14: Resource Status Table

MULTIPLE OPERATION TIME CHART :

Report to : Screen / Printer

Report ALL Crews/Resources : Yes / No

Select Crews/Resources to Report :

Crew#1	Crew#2	Crew#3	Crew#4	Crew#5	Crew#6	Crew#7	Crew#8
FmCrw#1	FmCrw#2	RbrCrw#1	RbrCrw#2	CnCrCrw#1	TCrane	GenLbr#1	PfZon#1

Crew/Resource I.D.	Description
FmCrw#1	Formwork crew #1, 6 carpenters, 1 general labour
FmCrw#2	Formwork crew #2, 5 carpenters
.....
.....
CnCrCrw#2	Concrete finishing and clean-up crew, 3 masons, 1 general labour

Figure 6.15: Select crews and special resources to report in M.O.T. chart

*** MULTIPLE OPERATION TIME CHART ***

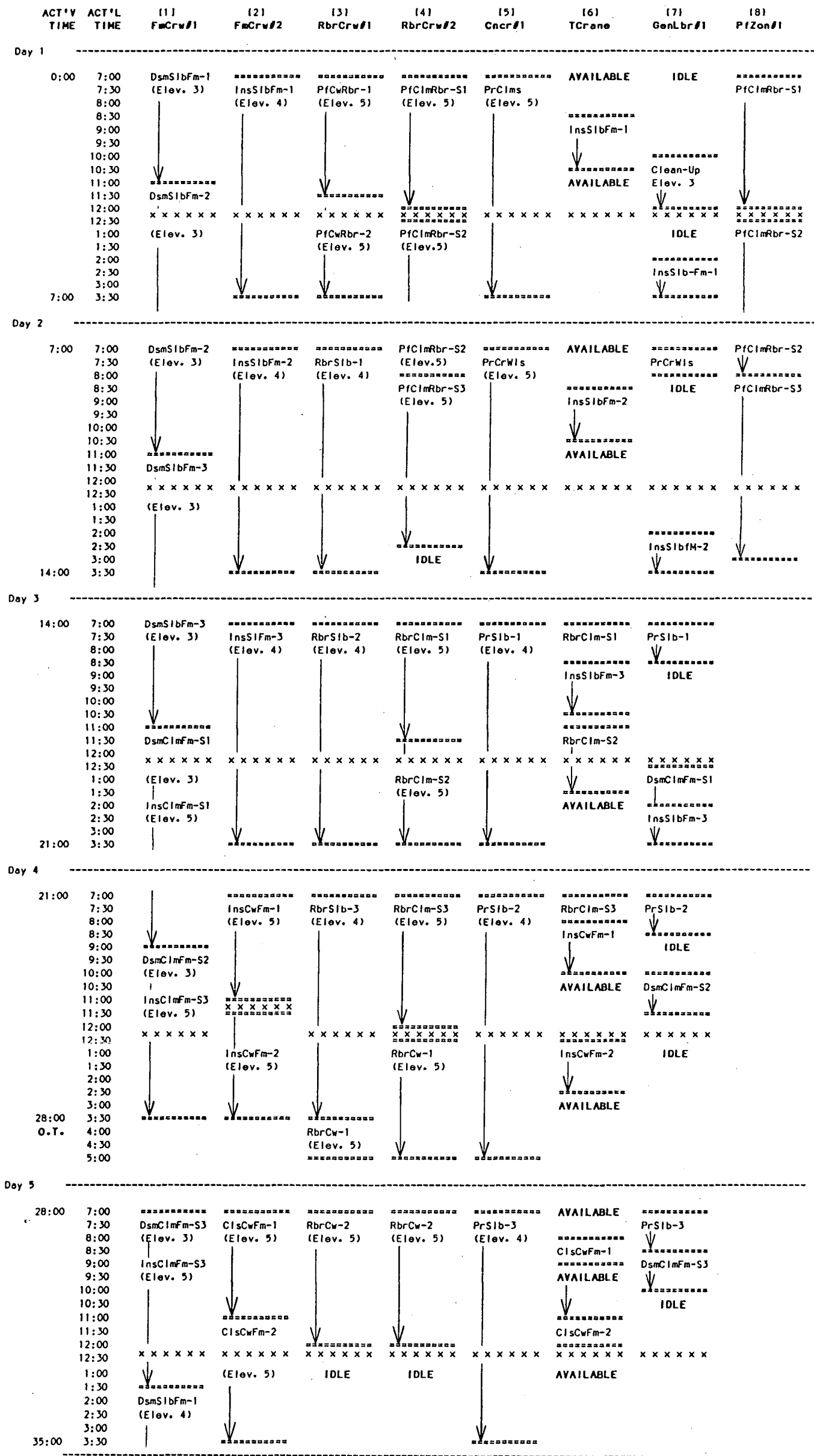


Figure 6.16: Multiple Operation Time (M.O.T.) Chart

6.3.5 MODULE 5 - DESIGN IMPROVEMENT AND ENRICHMENT

6.3.5.1 DIFFICULTIES IN IMPROVING AN ACTIVITY DESIGN

A balanced cycle is not usually achieved in the initial design solution. The initial solution must be modified to resolve resource conflicts and to improve effectiveness of resource usage. The design improvement process is the most important and yet most complex process in designing a balanced construction cycle. As stated in chapter three, the design parameters and variables are linked to each other but the linkages cannot be defined precisely. Because of the complex linkages, changing the value of a design variable could have a significant effect on the overall cycle design. For example, in assigning over-time to an operation to eliminate conflicts in using a shared resource, the start times and finish times of the successors to the operation might be affected and could cause conflicts between other operations for shared resources.

Adding to the complexity is the number of design variables that can be modified to solve a given problem (see figure 6.3). For example, conflicts in using shared resources can be eliminated by:

- (1) assigning over-time or extra shifts to one or more of the operations competing for the shared resource;

- (2) speeding up an operation by increasing the crew size so that the operation can use the shared resource at an earlier time;
- (3) changing the construction technology of one or more operations. For example, a concrete pump could be used for pouring concrete in order to free the tower crane for other operations;
- (4) a combination of the above courses of action.

Each feasible course of action must be carefully considered in order to select the course of action which is most cost effective and does not seriously upset the original operations schedule. The latter concern has been identified by Willis [131] as the requirement of "stability in re-scheduling" and has been discussed in section 4.5.

6.3.5.2 AN APPROACH TO SOLUTION IMPROVEMENT

The nature of the activity design problem precludes a realistic, solvable mathematical programming formulation. Consequently, a trial-and-error approach to problem solving is required. A manual process tends to be tedious and the solution obtained is in general less accurate than that obtained by computer routines. So the goal becomes to create an environment which uses the power of the computer to identify problems, suggest solutions, analyze them, and

incorporate the experience, judgment and intuition of the user and analyze potential improvements.

The critical path analysis results as shown in figure 6.13 and the resource status table can be used to identify conflicts in using shared resources and the competing operations. By studying the M.O.T. chart together with the P-Matrix, the user can gain insights into the possible impact of a course of action on the overall cycle design.

After an operation has been chosen for modification, the computer can suggest a list of possible courses of action (see Figure 6.17). The computer can then guide the user to particular steps of the solution formulation process according to the action selected. This is then followed by analysis and this process is repeated until a satisfactory design is achieved.

Modify Operation : RbRCw-2 (Elev. 5)

1. **Re-Define Labour Crew**
2. Re-Schedule Operations
3. Re-Assign Resources
4. Assign Over-Time
5. Add Extra Shift
6. Change Production Technology
7. Prefabricate Components

Select Action to Take : [1]

Figure 6.17: General rules for design improvement

6.3.5.3 SOLUTION ENRICHMENT AND THE M.O.T. CHART

Any model of a problem situation is necessarily a simplification of reality. For the activity design environment being developed, although emphasis has been put on modeling the problem and the decision process in the most realistic manner, not all of the project elements have been treated. Examples of these elements are:

(1) Inclusion of Infrequent Work Tasks and Operations

Many work tasks and infrequent operations in a construction project are not normally scheduled. Examples of these include delivery of stock materials such as rebar and timbers, general clean-up and maintenance of equipment. Inclusion of these smaller and non-regular operations in the cycle planning tends to complicate its design. However, these work tasks and operations must be performed and cannot be neglected. For example, if the inventory of rebar and timbers are not well maintained and organized, the productivities of the reinforcing and formwork crew can be adversely affected.

(2) Assigning Different Breaks to Different Crews

An additional tool for field management to remove conflicts in the usage of shared resources is by

assigning breaks to different crews at different times. If managed carefully the process can help to eliminate idle time and improve transitions between operations.

(3) Assignment of Temporary Help to Operations

Currently available methodologies and systems for construction planning require resources to be assigned to an operation for its entire duration. In the activity design environment proposed herein, resources can be assigned to an operation for part of its duration. For example, from study of the M.O.T. chart, management might decide to assign an idle general labourer to an operation to reduce the duration or simply to ensure that a critical operation can be completed in time.

6.3.5.4 INSTRUCTIONS TO MANIPULATE THE M.O.T. CHART

To improve the initial solution and to include elements not considered at the outset in the problem definition and solution formulation processes, the system user should be allowed to manipulate the M.O.T. chart to obtain a more realistic work schedule that can be followed at the construction site.

Schofield [118] has described the use of high level instructions to capture some of the factors and restrictions

that are "far more extensive than just those described by the precedence diagram" in the Line Sequencing Program developed at Nottingham University (NULISP). A similar set of instructions could be used in the construction cycle design decision support system to treat the elements described earlier. Here are some examples of possible commands:

- Commands for assigning and removing labour crews breaks so as to eliminate conflicts in using shared resources or to ensure a smooth transition between operations.

```
[ASSIGN] [BREAK] <name> TO <crew I.D./ALL> FROM <hr:mn>
      TO <hr:mn>
```

```
[REMOVE] [BREAK] <crew I.D.> <name>
```

```
[MOVE] [BREAK] <crew I.D.> <name> TO <hr:min>
```

- Command for assigning over-time to operations in order to eliminate conflicts in using shared resources or to crash the durations of critical operations.

```
[ASSIGN] [O.T.] TO <crew I.D./ALL> FROM <hr:min> TO
      <hr:min>
```

- Commands for assigning and re-assigning defined operations or infrequent work tasks and operations, such as general clean-up and other site maintenance work, to idle resources.

[ASSIGN] [JOB] <name / operation I.D.> TO <resource I.D.> FOR <hr:min>

[REMOVE] [JOB] <crew I.D.> <name / operation I.D.>

- Command for manually crashing an operation without redefining it. In reviewing the M.O.T. chart, the user might decide that the production rate of a particular operation can be increased slightly without assigning additional resources. This command allow the bypass of more tedious processes.

[CRASH] <operation I.D.> BY <hr:min.>

- Command similar to [CRASH] but it is used for manually stretching the duration of an operation.

[STRETCH] <operation I.D.> BY <hr:min>

- Command which allows the system user to return from the manual mode to the system guided mode (Figure 6.17).

[RETURN]

The instructions described above provide flexibility to the user and permit the application of judgment and intuition to "enrich" an activity design by including elements not considered in the solution formulation process. The modified design can be reanalyzed, if required, and the M.O.T. chart plotted for use in the field.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The conceptual design of a decision support system for activity design developed in chapter six meets the objective set for this thesis by providing an environment in which management personnel at the production level can design repetitive construction cycles. This system specification provides a planning environment that realistically reflects and captures the decision making process that construction management personnel mentally go through, albeit imperfectly, in designing construction activities. The information captured in the formulation of a design solution for a given situation can be used for future reference and for educating less experienced management personnel.

The decision support system can function as a medium whereby management personnel can systematically define a problem and document and analyze the impact of certain decisions on the activity design; no sophisticated algorithm is employed to seek "optimal" design solutions.

It provides an environment in which management can define a problem and formulate design alternatives in a realistic manner.

By recording construction technologies in a systematic format, the system user can compare and experiment with different technologies and select the most appropriate ones for construction.

The decision support system provides accurate estimates of resource requirements for use in the resource assignment process. Labour resources can be assigned as crews; work areas are treated as a special resource to permit consideration of site planning in the activity design process. Resources can also be assigned for only part of an operation's duration.

Results from analysis of the initial design solution are presented in formats, the resource status table and the multiple operation time chart, that can help management personnel identify problems with the design and formulate improvements to it.

Instructions can be used to provide the flexibility for construction management personnel to consider elements not usually included in the solution formulation process and to produce tactical plans that can be followed at the field level.

7.2 RECOMMENDATIONS FOR FUTURE RESEARCH

7.2.1 COMPUTER PROGRAMMING AND FIELD APPLICATION

This thesis has been limited to the conceptual design of a decision support system for activity design. The proposed system has not been programmed for computer application. In order to test whether this decision support system captures fully the realities of construction processes and is acceptable to construction management personnel at the production level, a prototype system must be developed and tested.

On-site documentation of the detailed decision process involved in designing a construction cycle is also required. Historical project information and available construction technologies should be categorized in formats suitable for computer application.

7.2.2 GRAPHICS INTERFACE FOR CYCLE DESIGN

In certain types of project, such as high-rise construction and mass housing development projects, the typical assembly can be defined by relatively simple geometry and a standardized set of building components. For these types of projects, it is possible to design a graphics interface for problem definition and solution formulation. For example, in a high-rise construction project, the plan

of a typical floor can be defined graphically and the building components, such as columns and beams, can be selected from a list and located in the plan. The dimensions of each subassembly and components can then be entered directly on the floor plan. The floor plan thus defined can also be used for site planning and for studying flyform layouts.

7.2.3 INTEGRATION WITH OTHER MANAGEMENT FUNCTIONS

The process of designing a construction cycle at the production level is part of the total project management process. The activity design function must be integrated with other project management functions so that relevant information, such as construction expenditures can be collected and use in project cost accounting and other functions. Integration of the decision support system with the estimating function can reduce the total effort required for problem definition. Russell [114] has illustrated how the activity design function relates to other functions in the total project management system for repetitive construction projects.

One of the requirements for integration of project management functions is the standardization of work breakdown structures for all levels of the project management hierarchy. The work breakdown structures described by Ponce-Campos and Ricci [103] can be used as a

framework by which the required standardization can be achieved.

7.2.4 INTEGRATION WITH OTHER MODELING TECHNIQUES

Taken individually, existing models cannot be used to solve the construction cycle design problem. However, it is possible to make use of them in the decision support system for analyzing design alternatives. For example, simulation and animation can be used to communicate the impacts of certain decisions to the system user in a more dynamic and effective manner and deterministic mathematical programming techniques, such as linear programming, could be used to solve sub-problems of the activity design problem.

Simulation and mathematical programming techniques, however, requires excessive programming effort that prohibits it from day-to-day use in the field. The programming effort required will be greatly reduced if "program generators" which can interpret the network logic and then generate the programs required for simulation and mathematical analysis could be developed.

7.2.5 DETAILED PLANNING OF CONSTRUCTION CYCLE OPERATIONS

One topic that has not been discussed in detail in this thesis is the assignment of work tasks within defined crews, in other words, the detailed design of the operations in a construction cycle. This process is assigned to the user. For example, in assigning a tower crane to the formwork installation operation say thirty minutes after the operation has started and for a period of one and a half hours, the user has mentally decided that certain set of work tasks has to be performed prior to use of the crane and that another set of work tasks requires use of the crane for 90 minutes. The operation design process involves assigning the set of work tasks associated with the construction technology selected (see figures 6.6(a) and 6.6(b)) to individual crew members.

At present, few production operations, except those documented by specialized hardware suppliers, such as the Economy Forms Corporation, have been documented to this level of detail. To collect and document the required information, production method study techniques described in the industrial engineering literature, such as time-lapse photography, could be used.

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