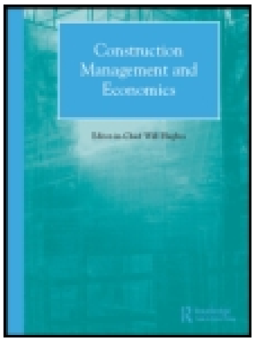

Construction Management and Economics

ISSN: 0144-6193 (Print) 1466-433X (Online) Journal homepage: https://www.tandfonline.com/loi/rcme20

Planning repetitive construction: Current practice

James D. Lutz & Adib Hijazi

To cite this article: James D. Lutz & Adib Hijazi (1993) Planning repetitive construction: Current practice, Construction Management and Economics, 11:2, 99-110, DOI: 10.1080/01446199300000003

To link to this article: https://doi.org/10.1080/01446199300000003

Published online: 24 May 2006.

Construction Management and Economics (1993) **11**, 99–110

Planning repetitive construction: Current practice

JAMES D. LUTZ[1] and ADIB HIJAZI[2]

[1]*Department of Civil Engineering, Auburn University, Auburn, AL 36849, USA* and
[2]*Construction Division, Al-Rasheed House Establishment, PO Box 6335, Riyadh 11442, Saudi Arabia*

Received 1 June 1991; revised 9 March 1992

This paper presents a review of existing techniques for planning and analysing linear construction operations. The family of techniques which are based on the line of balance (LOB) concept (e.g. linear scheduling method, vertical production method, line of balance scheduling, repetitive project model, velocity diagrams, and time space scheduling method) are introduced, the line of balance concept is discussed, and the barriers to implementation for LOB are addressed. Field monitoring techniques (e.g. work sampling, activity sampling, Timelapse, MPDM, questionnaires, crew balance chart, and video) and analytical planning techniques (e.g. network scheduling, linear programming, dynamic programming, queueing, and simulation) are described. Repetitive construction modelling requirements are introduced, and simulation applications are discussed. The evolution and capabilities of simulation programmes which lend themselves to use by the construction industry are presented. Benefits and limitations of the techniques presented are also addressed.

Keywords: Linear construction, repetitive construction, simulation, line of balance, construction operations.

Introduction

The numerous techniques available for planning construction processes can be categorized as either line of balance (LOB) techniques, field monitoring techniques, or analytical techniques. Planning techniques based on the line of balance concept involve a graphical plot depicting cumulative production versus time. Field monitoring techniques are simple methods involving observations and recorded images to determine a level of efficiency or rate of production. Analytical techniques involve the use of mathematical conceptions or models to determine production rates and resource utilization.

The purpose of this paper is to present a review by the authors (Lutz, 1990; Hijazi, 1989) of existing techniques for planning and analysing linear construction operations. This paper will begin with some background information on linear construction operations. The background will be followed by a discussion of the line of balance concept and the family of techniques (e.g. linear scheduling method, vertical production method, line of balance scheduling, repetitive project model, velocity diagrams, and time space scheduling method) based on the LOB concept. Field monitoring or observational techniques (e.g. work sampling, activity sampling, timelapse, MPDM, questionnaires, crew balance chart, and video) and analytical techniques (e.g. network scheduling, linear programming, dynamic programming, queueing and simulation) are then presented. Modelling requirements for repetitive construction are addressed. The evolution and capabilities of simulation programmes which lend themselves to use by the construction industry are presented, and their applications are discussed. Finally, benefits and limitations of the techniques presented are also addressed.

Linear construction

Linear construction projects are projects which involve repetitive units of construction elements. Some classic examples of linear construction projects include high rise buildings, tunnels, highways, and pipelines. The repetitive construction units of these four examples can be expressed in terms of number of floors, tunnel rings, road sections, and joints of pipe, respectively. Each one of these repetitive units can be further broken down into a sequence of processes which are repeated for each unit of the project. For example, the sequence of processes for a high rise building construction project may include form erection, steel installation, concrete placement, form removal, curtain wall installation, and glazing. This generic classification hierarchy for the breakdown of a linear construction project presented in a building construction context is shown in Fig. 1.

The repetitive nature of linear construction projects along with the construction industry's emphasis on standardization and modularization over the last several

0144–6193

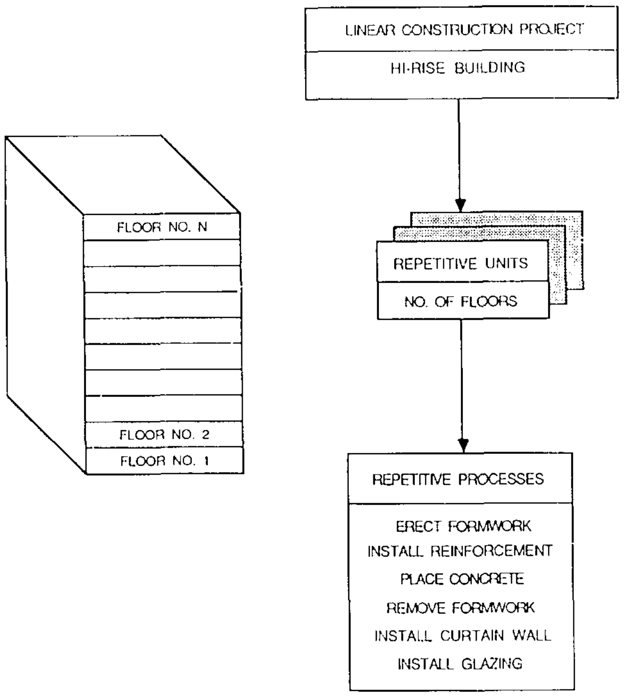

Figure 1 Hierarchical classifications for a linear construction project (adapted after Hijazi, 1989)

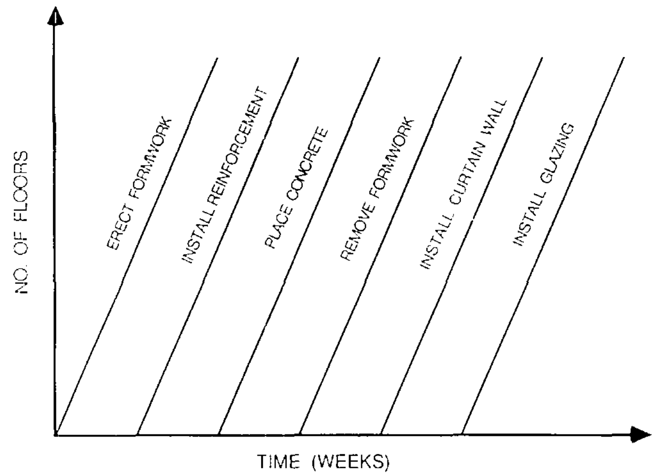

Figure 2 Typical production curves for repetitive processes

decades have triggered the development of various planning techniques and strategies for linear construction projects at both the macro-level (i.e. project management level) and the micro-level (i.e. field management level). At the macro-level, project managers and engineers are primarily concerned with project organization, sequence of activities, and control functions. At the micro-level, superintendents and foremen are primarily concerned with the steps required to complete the activities which they have been assigned.

Production or flow line curves for the repetitive processes involved in the installation of the superstructure and exterior closure of a high rise building is present in Fig. 2. The slope of each production curve yields the production rate for one of the repetitive processes in terms of floors per week. The production curves also provide the duration of each repetitive process as well as the total length of the project.

Linear construction projects often consist of repetitive processes which have different production rates. This phenomenon of production rate imbalance has the potential for negatively impacting project performance by causing work stoppages, inefficient utilization of allocated resources, and excessive costs. Production rate imbalance occurs when the production curves of 'leading' processes intersect the LOB curves of 'following' processes because of different production rates (i.e. production curve slopes) and insufficient lag between start times of processes.

Halpin and Woodhead (1976) compared this phenomenon of production rate imbalance to the flow of water through a series of cascaded reservoirs as presented in Fig. 3. Each reservoir represents a repetitive process or work station. Repetitive construction units must flow from leading processes to following processes or from higher reservoirs to lower reservoirs. In the event that a leading reservoir (e.g. erect formwork) is producing more work units than that of the next following reservoir (e.g. install reinforcement), the rate of the following reservoir constrains the rate of the system and a build-up of surplus units will occur. In the event that a following reservoir (e.g. place concrete) produces units more quickly than the previous leading reservoir (e.g. install reinforcement), then the following reservoir runs out of work and a work stoppage will occur. An example of production rate imbalance is presented in Fig. 4.

The line of balance concept

As presented in Fig. 5, the line of balance (LOB) method consists of a family of graphical and/or analytical linear scheduling techniques including the time space scheduling method (TSSM) (Stradal and Cacha, 1982), vertical production method (VPM) (O'Brien, 1975), velocity diagrams (Roech, 1972), linear scheduling method (LSM) (Johnston, 1981; Chrzanowski and Johnston, 1986), repetitive project model (RPM) (Reda, 1990), and line of balance scheduling (Halpin and Woodhead, 1976; Carr and Meyer, 1974; Khisty, 1970). The application of LOB, the LOB concept, benefits and limitations, and barriers to implementation are discussed in the following sections.

Application of LOB

The line of balance (LOB) method was originated by the Goodyear Company in the early 1940s and was devel-

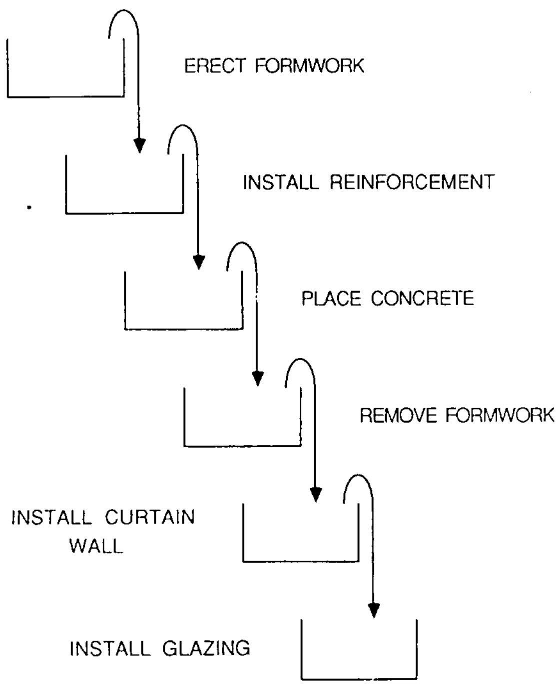

Figure 3 Cascading effect of repetitive work units

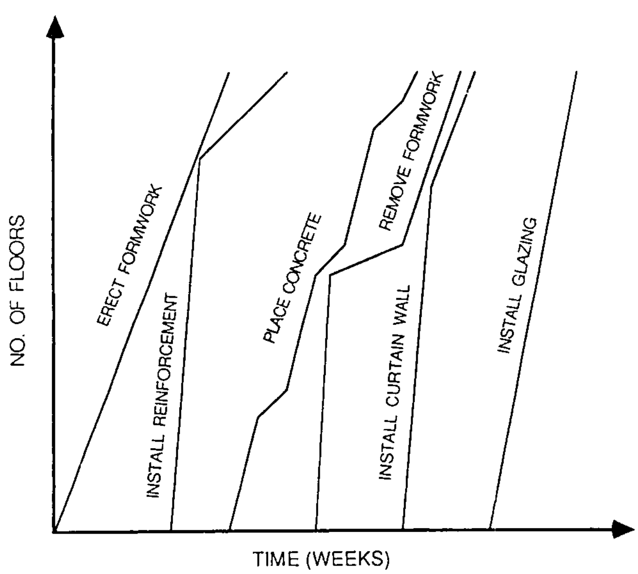

Figure 4 Non-balanced production curves for repetitive processes

oped by the US Navy during the Second World War for the programming and control of both repetitive and non-repetitive projects (Turban, 1968). Because of the immense popularity of network scheduling techniques including CPM (critical path method) in this country, the LOB technique has never been fully developed and implemented by the US construction industry. How-

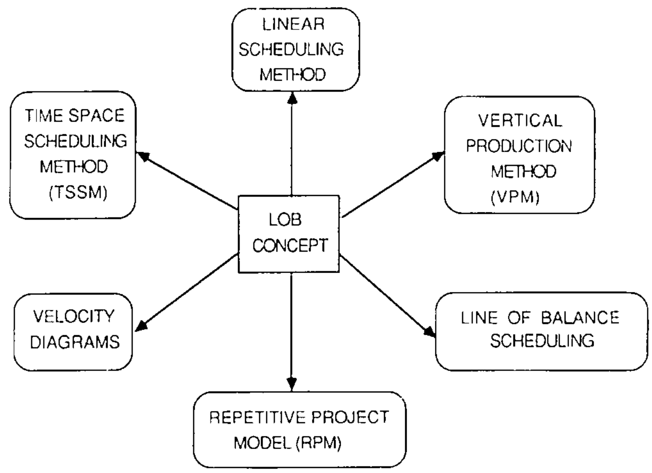

Figure 5 Planning techniques based on the line of balance concept

ever, there has been a higher level of utilization of this method by European contractors (Dressler, 1980). The method has been applied to repetitive construction projects (Arditi and Albulak, 1979), to planning of residential construction (Lumsden, 1968), to resource sheduling and co-ordination among subcontractors (Levine *et al.*, 1976), to the scheduling of road pavement projects (Arditi and Albulak, 1979), and to modelling production activities for multifacility projects (Skibniewski and Molinski, 1989).

The LOB concept

Typical process production (or flow line) curves are depicted in Fig. 6. As shown, the production curves for processes B and C are plotted in terms of stage number as a function of time. Stages represent the cumulative number of production units completed at a certain time (e.g. number of floors, number of road sections, etc.). The production rate for a process can be determined from its slope and expressed in terms of units per time. The horizontal distance between the production curves for two consecutive processes at a particular stage represents the lag or time buffer between those processes at that stage. The vertical distance between production curves for two consecutive processes at any given time represents the stage buffer (i.e. number of units in queue between processes) at that time.

Illustrative examples of balanced and non-balanced process production curves for a linear project were presented in Figs 2 and 4, respectively. From a set of process production curves for a repetitive project, an aggregate production curve for the overall project can be determined using a variety of graphical and/or analytical

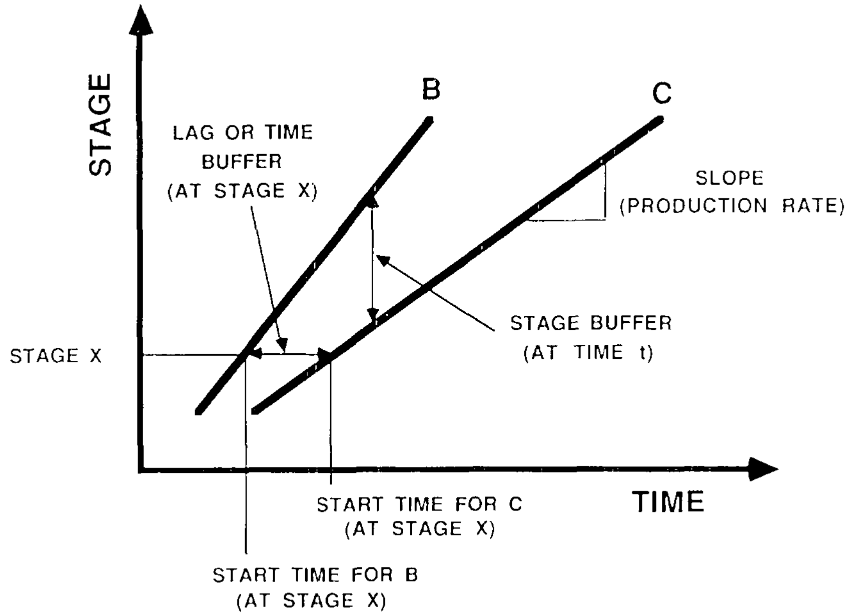

Figure 6 Process production curves (adapted after Reda, 1990)

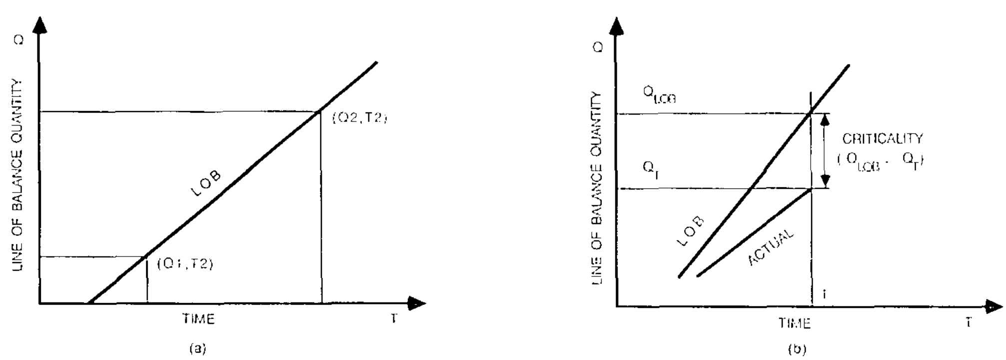

Figure 7 LOB concept (a) quantity-time diagram (b) actual versus forecasted plot (adapted after Lumsden, 1968)

techniques. This overall production curve is referred to as the line of balance (LOB) for the project.

The conceptual LOB for a project is presented in Fig. 7. As shown in the figure, the LOB is nothing more than a quantity-time diagram (i.e. a production curve) for an overall project. The LOB methodology focuses on the required delivery of completed units (e.g. floors, rings, sections, etc.) and is based on a knowledge of how many processes of any type must be completed at certain times to support the programmemed completion of units. The required number of completed production units at any given time is referred to as the line of balance quantity. The LOB is determined from the rate of delivery of materials, components, and completed processes which are required to produce finished units. Since the rates are assumed to be linear, then a linear relationship exists between the line of balance quantity and time (Lumsden, 1968).

The LOB provides a production forecast required to meet delivery requirements. Often, the actual completion of units will vary from the proposed or forecasted schedule as presented in Fig. 7a. The difference between the cumulative number of production units delivered and the LOB quantity at any given time is termed the 'criticality'. The criticality can be either positive or negative. Figure 7b illustrates a condition of negative criticality since the actual progress is less than the production forecast. In cases where the actual progress is the same as the production forecast, then the condition of 'zero criticality' exists.

The LOB concept can be applied to the manufacture or construction of any repetitive project whether it involves the number of floors completed, the number of washing machines produced, etc. (Lumsden, 1968). LOB methodology can be used to determine at any given time:

1. shortages of delivered materials which may impact production,
2. materials which are being delivered in excess which may cause additional material handling or require additional storage space,
3. the jobs or processes which are falling behind and the required rate of acceleration to satisfy the required LOB quantities,
4. the jobs or processes which are ahead of schedule which may be placing heavier demands on operating capital than necessary, and
5. a forecast of partially completed production units by job, work station, or process to support the delivery schedule of finished units (Lumsden, 1968).

Benefits and limitations

As stated earlier, the major benefit of the LOB methodology is that it provides production rate and duration information in the form of an easily interpreted graphics format. This format involves the generation of production curves for the repetitive processes as was presented in Figs 2 and 4. The LOB plot for a linear construction project can be easily constructed, can show at a glance what is wrong with the progress of project, and can detect potential future bottlenecks.

Although LOB methodology can be used to aid in the planning and control of any type of project, it is better suited for application to repetitive projects as opposed to non-repetitive projects. A limitation of the LOB methodology is that it assumes that production rates are linear (i.e. constant rate of production over time). Due to the stochastic nature of construction processes (Halpin and Woodhead, 1976), the assumption that production rates of construction projects and processes are linear may be erroneous. Additionally, the objective of many planning techniques based on the LOB concept is to reduce project duration with little regard for project cost (Reda, 1990).

Barriers to implementation

Despite the broad use of LOB by the European construction industry (Dressler, 1980), the US Navy (Turban, 1968), and the manufacturing industry, the application of the LOB methodology by the US construction industry had been very limited. Some barriers to implementation of the LOB methodology include the following.

1. There is a lack of awareness among practitioners in the US construction industry that the LOB methodology exists (Turban, 1968).
2. Owners and contractors began adopting network techniques as planning tools at about the same time that the LOB methodology was originated and developed. These entities are reluctant to adopt new planning tools which are not being used by their counterparts or competitors (Lumsden, 1968).
3. Computerized tools employing network techniques are widely available whereas computerized tools employing the LOB methodology are not currently commercially available. However, researchers at several universities have attempted to computerize the LOB methodology and have working prototypes. For example, Skibniewski and Molinski (1989) have developed a prototype programme which aids the user in modelling production activities for multifacility projects. Due to the popularity of the relatively inexpensive microcomputer in the US construction industry, there is a resistance to change to a planning method which is currently not supported by computer.

Field monitoring techniques

Field monitoring techniques investigated include work sampling, activity sampling, crew balance, questionnaires, method productivity delay model (MPDM), Timelapse, and video methods. These techniques are presented in Fig. 8. The major benefit of these methods is that they are simple and can be quickly administered. They provide information feedback on ongoing projects which can be used to determine actual production, delay types and impact, resource utilization, and comments from field personnel. A major drawback of these techniques is that they cannot be used in the initial planning phases (i.e. before the project begins). Additionally, these methods do not have flexibility to forecast output variation as input variables are changed. In other words, these methods cannot be used to determine the impact of external factors, varying resource mixes, change in scope or work, learning curve development, and change in travel time (e.g. cannot be used to conduct a sensitivity analysis).

Analytical techniques

Analytical techniques investigated include network scheduling, linear programming, dynamic programmeming, queueing theory, and simulation. These techniques are presented in Fig. 9. The major benefit of these mathematically based techniques is that they can be used for modelling both before and during the project to forecast project duration, production rates, and project costs. These models also have the capability to investigate output variation as input elements change. This flexibility allows the modelling of external factors, non-stationarity factors, equipment breakdown, etc. The benefits and limitations of the various analytical techniques are presented below.

Network scheduling

Some of the major network scheduling methods which have been used in the construction industry are CPM (critical path method), programme evaluation and review technique (PERT), decision critical path method (DCPM), and graphical evaluation and review technique (GERT). The mechanics of these methods involve the use of a geometric representation (i.e. network) or a flow chart which depicts the precedence between activities. Computer programmes eliminate the need to prepare a network, but the network notation provides an easily understood output format for management personnel.

The CPM method is a deterministic approach which has resource levelling applications. PERT is a stochastic approach which allocates a probabilistic (i.e. unimodal beta function) distribution for all activity durations. DCPM is a deterministic method similar to CPM which introduces decision nodes into the network to provide decision alternatives based on resource constraints, etc. The GERT method combines concepts of PERT and DCPM type networks with flow graph techniques (Naaman, 1974). It is a stochastic technique which allows the use of various types of distributions to model the duration input.

A drawback in the use of the CPM and PERT network methods in the construction industry involves the emphasis on finding an optimal solution based on the shortest project duration. The optimum solution in construction usually involves a minimization of resource utilization or cost and not necessarily the shortest duration (Birrell, 1980). Another drawback involves the limitations placed on input modelling. Further discussion on network scheduling can be found in numerous sources including O'Brien *et al.* (1985), Naaman (1974), and Birrell (1980).

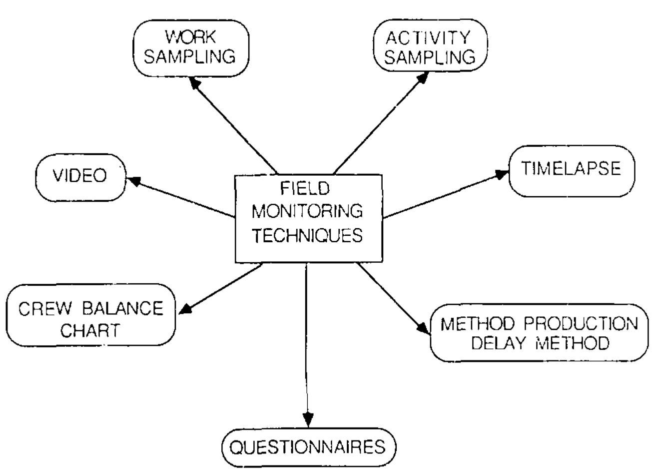

Figure 8 Field monitoring techniques

Linear programming

Linear programming is an optimization technique which provides a means of mathematically representing general information concerning a process. An objective function, a linear mathematical minimization or maximization function, is developed to represent the desired goal. Relevant constraint equations are then defined to express the mathematical relationship among the various decision variables. In the case of a concrete placement project where production is to be maximized given a reasonable number of transit-mix trucks, a distribution pump, placement crews, and resource cost and capacity information, an objective function is developed as a function of the involved parameters (e.g. costs associated with the various resources). Constraint equations defining boundaries for the amount of available resources are then prepared. Further information on the application of linear programming to solve construction problems can be found in several sources including Stark and Mayer (1983) and Perera (1983). A limitation of linear programming is that it assumes that a linear relationship exists between variables. Additionally, solutions to stochastic applications can become quite complex and cumbersome (Dressler, 1974; Crandall and Woolery, 1982).

Dynamic programming

Dynamic programming (DP) or multistage programming is an analytical technique similar to linear programming which was developed to improve the computational efficiency of mathematical programmeming problems by breaking them down into smaller problems or stages (Taha, 1982). These stages are linked through recursive computations in a manner which will provide an optimum solution once the last stage is reached. The major benefits of dynamic programming are that it is not constrained by linear assumptions and that it can be readily computerized. The major disadvantages are that it generally requires stylized input needed for each new situation and that its output must be converted into a graphical format to be easily interpreted by field management personnel. Further discussion on this topic can be found in Taha (1982), Selinger (1980), Russell and Caselton (1988), and Dressler (1974).

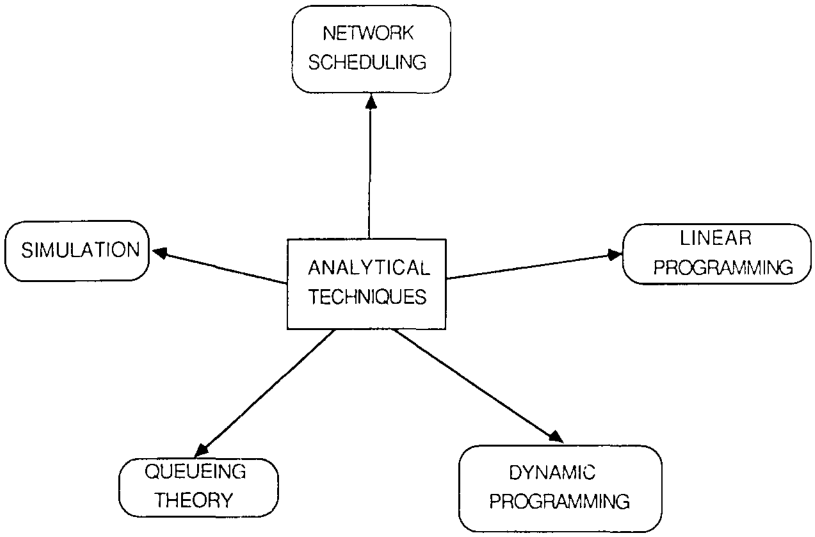

Figure 9 Analytical planning techniques

Queueing theory

Queueing theory is an analytical technique which has the advantage of addressing stochastic input (i.e. random arrival times of transit units). Processes are broken down into various production stages, and each stage has a server with arriving entities (i.e. an earthmoving operation may consist of a loader as a server and trucks as arriving entities). Arriving entities can arrive from either a finite or an infinite population. Both arrival and service times can be fit to a stochastic distribution. Statistics including waiting time at the queue for arriving entities to be serviced can be estimated. Some limitations of queueing theory include its simplifying assumptions (e.g. homogeneous resources, exponential distributions, etc.) and the difficulty which can be encountered when formulating models for large processes with complex resource flows. Additional information concerning the potential application of this method to construction can be found in Halpin and Woodhead (1976).

Simulation

Simulation is the process of designing a mathematical-logical model of a real system and then experimenting with this model on a computer to permit inferences to be drawn about the system (Pritsker, 1986). Simulation is not an ordinary optimization technique, but it can be used to estimate the output of a process by varying the input conditions. Experimentation in the form of a sensitivity analysis can be used to aid the search for a preferred solution. Benefits of simulation include that it can model stochastic models (i.e. random duration, probabilistic branching, etc.). Unlike linear programming, simulation is not constrained by linear assumptions. The steps involved in a simulation study are presented in Fig. 10. Further information on simulation applied to construction processes can be found in Halpin and Woodhead (1976).

Modelling requirements

Although all of the previously discussed line of balance, field monitoring and analytical techniques are effective planning techniques, a planning technique satisfying the specific modelling needs of repetitive construction should be used for planning linear construction operations. These modelling needs and the benefits of simulation are presented in the following sections.

Modelling needs

Several major requirements for a modelling technique for repetitive construction were that it possess the flexibility to perform planning functions before and after the start of the project and that it have the capability to determine the change in output from varying input parameters or conditions. Additionally, a mathematical based technique which can be computer based and executed is desired to add additional flexibility and efficiency. Although field monitoring techniques play a very important planning role in construction planning, they can only be performed after the project has commenced, are typically project specific, are not mathematically based, and are not computer executed. Therefore an analytical technique is desired for modelling linear construction operations.

An appropriate analytical planning technique necessary to investigate the LOB phenomenon must be well suited for modelling the characteristics of repetitive construction. An important characteristic of construction activities is that they are stochastic and not deterministic. For example, construction operations often involve transit units which have non-constant or random arrival times, equipment with random breakdown, etc. The linear and dynamic programming techniques cannot properly represent stochastic elements. The complexity of attempting to model stochastic construction activities with either linear or dynamic programming makes them infeasible for most construction projects.

Unlike the manufacturing industry, activities in the construction industry very seldom reach the steady state level because construction processes typically have short durations. Consequently, construction processes usually operate in the transient or 'warm-up' phase. Network scheduling and queueing theory as well as

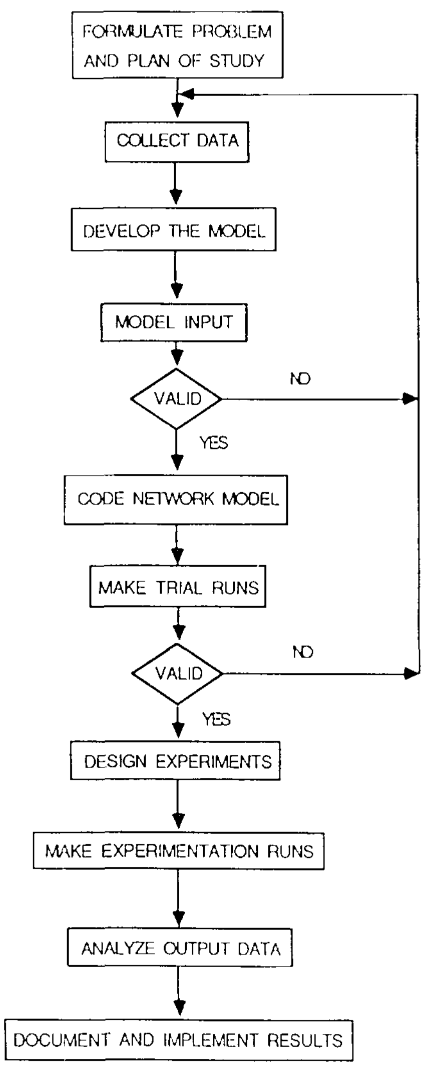

Figure 10 Steps involved in a simulation study (adapted after Law and Kelton, 1982)

linear and dynamic programming ignore the transient phase and assume that the activity is operating at steady state.

Benefits of simulation

Unlike the other analytical techniques, simulation is a dynamic comprehensive technique which provides a true representation of the output behaviour as it evolves over time (i.e. it accurately models processes through the transient phase). Simulation can determine output based on variation in input and can support both deterministic and stochastic input elements. Resource utilization and average waiting time of routeing entities can be estimated. Unlike the other previously discussed techniques, simulation easily handles input modelling (i.e. assignment of appropriate durations to the stochastic input elements based on a desired distribution type) as well as output modelling (i.e. determining the statistical characteristics of the output parameters based on performing numerous simulation replications on the same model). Furthermore, simulation can efficiently locate bottlenecks in the system.

Although simulation has existed as a technique for several decades, its full potential for use in construction planning is just now being realized. The advent of the inexpensive and powerful microcomputer has increased the acceptance of computer technology by the industry and has triggered the use of simulation as a planning and decision-making tool. Furthermore, several simulation systems have recently been developed which specifically address construction process modelling needs including CYCLONE (Halpin, 1973), INSIGHT (Kalk, 1980), RESQUE (Chang, 1986), UM-CYCLONE (Ioannou, 1989), and STEPS (Mohieldin, 1989).

Simulation applications

Discussions pertaining to the use of simulation as a planning tool can be found in work by Crandall (1977; 1982), Pritsker (1986), and Halpin (1977) among others. Some of the major applications of simulation are presented in the following sections.

Use as an optimization tool

Although not a mathematically based optimization technqiue, simulation is often used as an optimization tool to seek an improved or preferred solution. This typically involves making numerous replications of simulation runs in the form of a sensitivity analysis to forecast duration, productivity, and cost for various resource mixes and/or technology types. This is further described by Benjamin and Greenwald (1973), Riggs (1980), and Tavakoli (1983) among others.

Supporting tool for network scheduling

Simulation was originally developed as a supporting system to improve the capabilities and efficiency of networking techniques. Carr (1979) developed a system entitled Model for Uncertainty Determination (MUD) which uses a coupled simulation-network scheduling methodology to provide sampling of an unbalanced estimate of activity duration, a criticality index, and an expected duration. Working with Halpin, Dabbas (1981) integrated a CPM network software system, Project I, with the CYCLONE simulation methodology to model repetitive activities. This hybrid technique was an effective planning tool for upper management which provided improved estimates for activity durations.

Miscellaneous applications

Benjamin and Greenwald (1973), Davis (1964), and Shahbodaghlou (1987) investigated the impact of weather on project planning using both simulation and network scheduling methodolgies. The research was focused on the impact of weather conditions on the sampled durations of involved activities and on the determination of the best starting time.

Simulation has also been used in conjunction with the LOB concept to address the planning of linear construction projects. Kavanagh (1985) developed a system which combined these two techniques called SIREN (simulation of repetitive networks). For further discussion on the application of simulation to model repetitive-unit construction, refer to Ashley (1980). The simulation technique has also been used in conjunction with Timelapse and with a process planning module (Mohieldin, 1989). The use of simulation in conjunction with heuristics (Mohieldin, 1989) and gaming theory (Halpin and Skibniewski, 1989) have been proposed by Bernold and Halpin, respectively.

A recent research thrust has involved using simulation to model non-stationarity effects (e.g. change in travel time, learning curve development, etc.). Further discussion pertaining to this topic is provided by Hijazi (1989) and Mohieldin (1989).

Construction simulation systems

In the construction domain, the use of simulation had involved either a commercial simulation package (e.g. GPSS, SIMAN, SIMSCRIPT, SIMULA, SLAM, etc.) or a custom developed simulation package specifically designed to model the unique characteristics of construction projects. Simulation packages developed specifically for application to construction operations include MicroCYCLONE, INSIGHT, RESQUE, and STEPS. These packages were based on the CYCLONE (cyclic operation network system) modelling format developed by Halpin (1973).

MicroCYCLONE is a microcomputer based version of CYCLONE developed by Halpin (1990). INSIGHT (interactive simulation of construction operations using graphical techniques) was developed by Kalk (1980) as a separate implementation of the CYCLONE modelling system. Working with Carr, Chang (1986) developed RESQUE (resource based queueing network simulation) based on the CYCLONE modelling format which allows the modelling of non-identical resources. A new construction simulation package for planning horizontal earthwork operations called STEPS (structured environment for process simulations) was recently developed as part of a joint research project between the University of Maryland and the US Naval Civil Engineering Laboratory (Bernold and McCahill, 1986).

The MicroCYCLONE system

MicroCYCLONE is a Monte Carlo system which uses discrete event process interaction simulation to model and simulate the interaction between resources as resource units flow through a model. CYCLONE was developed to overcome the limitations of existing methods including CPM, PERT, queueing theory, and GERT (Lluch, 1981). Time and production parameters are calculated and stored in data files as resource units cycle in the model until the end of the simulation period has been realized.

Basic modelling elements

As presented in Fig. 11, the basic modelling elements of MicroCYCLONE consists of two active elements (e.g. COMBI and NORMAL) and four idle elements (e.g. QUEUE, FUNCTION, ARC, and ACCUMULATOR). The COMBI element represents a resource constrained operation which is activated when resource units are available at the two or more preceding QUEUE elements. The NORMAL element represents a task that will be activated whenever an element preceding it is completed. The task duration of both COMBI and NORMAL elements can be a constant or a random variable specified by the user. A QUEUE element stores resource units of a particular type until resource units of other types are available in other QUEUES preceding a COMBI. A QUEUE can be assigned a GENERATE function which splits an incoming unit into a specified number of units. The FUNCTION element provides statistics and can be used to consolidate multiple resource units into one resource unit. An ARC represents the flow direction of resource units. One ACCUMULATOR is permitted for each model and is primarily used to count the number of completed units at the end of the model.

System development

Working with Halpin, a number of researchers have participated in enhancing the original CYCLONE system for modelling repetitive construction processes. Riggs (1979) added built-in cost optimization routines, and Lluch (1981) down-loaded the main version of CYCLONE to the microcomputer environment. Niederhauser (1984) developed standard models for various types of construction operations. AbouRizk (1985) added the sensitivity analysis and BETA modules. Bernold (1985) improved the graphical presentation of MicroCYCLONE to study production transient curves. Hijazi (1989) added an input routine which allows the user to specify non-stationarity parameters to model change in travel time. AbouRizk (1990) was involved in some recent enhancements including the installation of a random number generator, allowing the use of common random numbers, sampling from statistical distributions, and improving the graphical representation of the system. Lutz (1990) was involved in the most recent enhancements including the addition of a statistics collection mechanism to foster production and stage buffer monitoring and the addition of learning duration input parameters for modelling the effect of learning development.

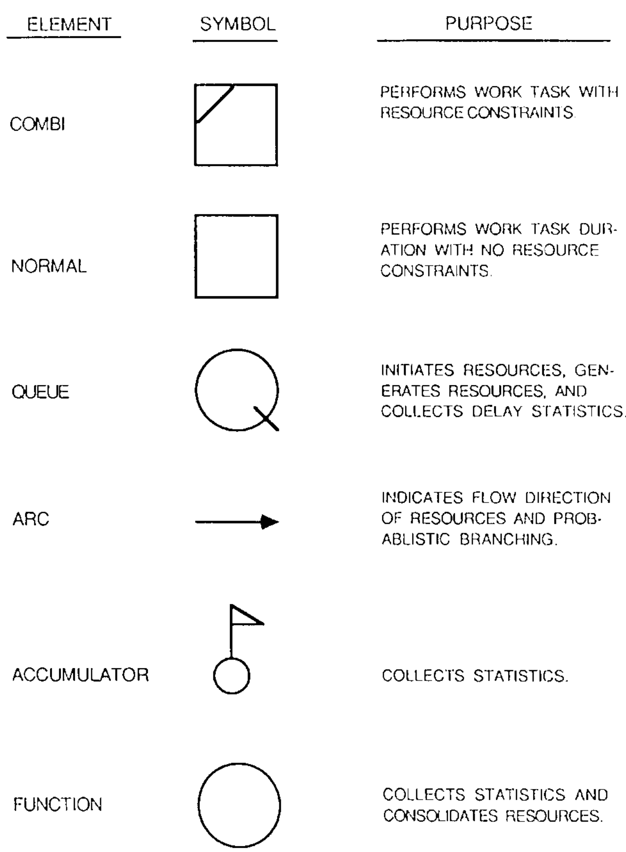

Figure 11 MicroCYLONE modelling elements (Halpin and Woodhead, 1976)

Conclusions

A whole family of linear scheduling methods including time space scheduling (TSSM), vertical production method (VPM), velocity diagrams, linear scheduling method (LSM), repetitive project model (RPM), and line of balance scheduling have been developed to aid in planning linear construction projects. In simple terms, the line of balance is actually the forecasted production curve for a project plotted on a quantity-time diagram. The major benefits of the LOB methodology are that it is a simple method, has an easily interpreted graphics format, can be used quickly to determine what is wrong with a project, and can identify potential future bottlenecks. The major limitations of the LOB methodology are that it assumes that production is linear and that computerized tools for automating this approach are not currently commercially available. For a number of reasons including lack of awareness and resistance to change, the LOB approach has not been widely accepted or used by the US construction industry.

Although the field monitoring techniques were found to be effective in data collection and methods improvement, the value of using these observational techniques to plan repetitive construction is limited because these techniques cannot be used to model the initial phase of an operation and cannot be used to forcast output variation as input variables are changed.

The analytical techniques investigated were found to be effective in modelling and planning linear construction operations, and simulation was found to be a quite versatile technique. Simulation is a dynamic comprehensive planning technique which provides a true representation of output behaviour as it evolves over time, which determines output based on variation in input, and which supports stochastic input elements. Simulation programmes based on the CYCLONE methodology lend themselves well to the application of repetitive construction and have been used in conjuction with other techniques including network scheduling, Timelapse, and heuristics. The development of a hybrid planning methodology combining the simplicity of the line of balance concept with modelling capabilities of simulation should be investigated.

References

AbouRizk, S.M. (1985) Sensitivity analysis of construction operations, MS Thesis, Georgia Institute of Technology, Atlanta.

AbouRizk, S.M. (1990) Input modeling for simulation of construction operations, PhD Dissertation, Purdue University, West Lafayette.

Arditi, D. and Albulak, M. (1979) Comparison of network analysis with line of balance in a linear repetitive construction project, *Proceedings of the Sixth INTERNET Congress*, Vol. 2, September, Garmisch-Partenkirchen, West Germany, 13–25.

Arditi, D. and Zeki, A. (1986) Line of balance scheduling in pavement construction, *Journal of Construction Engineering and Management*, **112**, 411–24.

Ashley, D.B. (1980) Simulation of repetitive unit construction, *Journal of the Construction Division*, **106**, 185–93.

Benjamin, N. and Greenwald, T. (1973) Simulation effects of weather on construction, *Journal of the Construction Division, ASCE*, **99**, 175–90.

Bernold, L.E. (1985) Productivity transients in construction processes, PhD Dissertation, Georgia Institute of Technology, Atlanta.

Bernold, L. and McCahill, D. (1986) Improvement to expeditionary construction through computer modeling and simulation, Use of Artificial Intelligence and Automation, Proposal Submitted to the Office of Naval Research, Arlington, VA.

Birrell, G.S. (1980) Construction planning—beyond the critical path, *Journal of Construction Engineering and Management*, **106**, 389–407.

Carr, R.I. (1979) Simulation of construction project duration, *Journal of the Construction Division*, **105**, 117–28.

Carr, R.I. and Meyer, W.L. (1974) Planning construction of repetitive building units, *Journal of the Construction Division*, **100**, 403–12.

Chang, D.Y. (1986) RESQUE: A resource based simulation system for construction process planning, PhD Dissertation, The University of Michigan at Ann Arbor.

Chrzanowski, E.N. and Johnston, D. (1986) Application of linear scheduling, *Journal of Construction Engineering and Management*, **112**, 476–91.

Crandall, K. (1977) Analysis of scheduling simulation, *Journal of the Construction Division*, **103**, 387–94.

Crandall, K. and Woolery, J. (1982) Schedule development under stochastic scheduling, *Journal of the Construction Division*, **108**, 321–9.

Dabbas, M.A.A. (1981) Computerized decision making in construction, PhD Dissertation, Georgia Institute of Technology at Atlanta.

Davis, C. (1964) Construction project simulation effects of weather, PhD Dissertation, Submitted to Stanford University, Stanford.

Dressler, J. (1974) Stochastic scheduling of linear construction sites, *Journal of the Construction Division*, **100**, 571–88.

Dressler, J. (1980) Construction management in West Germany, *Journal of the Construction Division*, **106**, 477–87.

Halpin, D.W. (1973) An investigation of the use of simulation networks for modeling construction operations, PhD Dissertation, The University of Illinois at Urbana-Champaign.

Halpin, D.W (1977) CYCLONE-method for modeling job site processes, *Journal of the Construction Division*, **103**, 489–499.

Halpin, D.W. (1990) MicroCYCLONE user's manual, *Division of Construction Engineering and Management*, Purdue University, West Lafayette.

Halpin, D.W. and Skibniewski, M. (1989) Simulation gaming for knowledge acquision, A proposal submitted the National Science Foundation, Purdue University, West Lafayette, pp. 1–16.

Halpin, D. and Woodhead, R. (1976) *Design of Construction and Process Operations*, John Wiley and Sons, New York.

Hijazi, A. (1989) Simulation analysis of linear construction processes, PhD Dissertation, Purdue University, W. Lafayette.

Ioannou, P.G. (1989) UM-CYCLONE user's guide, Department of Civil Engineering, The University of Michigan at Ann Arbor.

Johnston, D.W. (1981) Linear scheduling method for highway construction, *Journal of Construction Engineering and Management*, **107**, 247–61.

Kalk, A. (1980) INSIGHT interactive simulation of construction operations using graphical techniques, Technical Report No. 238, Department of Civil Engineering, Stanford University.

Kavanagh, D. (1985) SIREN: A repetitive construction simulation model, *Journal of Construction Engineering and Management*, **111**, 308–23.

Khisty, C.J. (1970) The application of the line of balance technique to the construction industry, *Indian Concrete Journal*, **44**, 297–300, 319–20.

Law, A.M. and Kelton, W.D. (1982) *Simulation Modelling and Analysis*, McGraw Hill, New York.

Levine, H.A., Aliberti, E.M. and Ford, B.P. (1976) The application of the line of balance on an international project, *Proceedings of the Fifth INTERNET Congress*, pp. 251–8.

Lluch, J.F. (1981) Analysis of construction operations using microcomputers, PhD Dissertation, Georgia Institute of Technology at Atlanta.

Lumsden, P. (1968) *The Line of Balance Method*, Pergamon Press, London.

Lutz, J.D. (1990) Planning linear construction projects using simulation and line of balance, PhD Dissertation, Purdue University.

Mohieldin, Y.A. (1989) Analysis of construction processes with nonstationarity work task durations, PhD Dissertation, The University of Maryland.

Naaman, A. (1974) Networking, methods for project planning and control, *Journal of the Construction Division*, **100**, 357–72.

Niederhauser, D.E. (1984) The application of standard models in MicroCYCLONE, MS Thesis, Georgia Institute of Technology at Atlanta.

O'Brien, J.J. (1975) VPM scheduling for high rise Buildings, *Journal of the Construction Division*, **101**, 895–905.

O'Brien, J.J., Kreitzberg, F.C. and Mikes, W.F. (1985) Network scheduling variations for repetitive work, *Journal of Construction Engineering and Management*, **III**, 105–16.

Perera, S. (1983) Resource sharing in linear construction, *Journal of the Construction Division*, **114**, 102–11.

Pritsker, A.A.B. (1986) *Introduction to Simulation and SLAM II*, John Wiley, New York.

Reda, R. M. (1990) RPM: Repetitive project modeling, *Journal of Construction Engineering and Management*, **116**, 316–30.

Riggs, L.S. (1979) Sensitivity analysis of construction operations, PhD Dissertation, Georgia Institute of Technology at Atlanta.

Riggs, L.S. (1980) Simulation of construction operations, *Journal of the Construction Division*, **106**, 145–63.

Roech, W. (1972) Network planning and velocity-diagrams in housing construction, *Proceedings of the Third INTERNET Congress*, Book II, Stockholm, Sweden, pp. 415–22.

Russell, A. and Caselton, W. (1988) Extensions to linear scheduling optimization, *Journal of the Construction Engineering and Management*, **114**, 36–52.

Selinger, S. (1980) Construcion planning for linear projects. *Journal of the Construction Division*, 195–205.

Shahbodaghlou, F. (1987) A feasibility model for the use of weather protection in cold region constructions, PhD Dissertation, Purdue University at West Lafayette.

Skibniewski, M. and Molinski, J. (1989) Modelling of building production activities for multifacility projects, *Construction Management and Economics*, **7**, 357–65.

Stark, R. and Mayer, R. (1983) *Quantitative Construction Management*, John Wiley and Sons, New York.

Stradal, O. and Cacha, (1982) Time space scheduling method, *Journal of the Construction Division*, **108**, 445–57.

Taha, H.A. (1982) *Operations Research: An Introduction*, 3rd edn, Macmillan, New York.

Tavakoli, A. (1983). Productivity analysis of heavy construction, PhD Dissertation, Georgia Institute of Technology at Atlanta.

Turban, E. (1968) The line of balance – a management by exception tool, *Journal of Industrial Engineering*, **19**, 440–8.