Analyzing Linear Construction Operations Using Simulation and Line of Balance

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The results of an investigation involving the use of simulation and the line of balance concept to analyze linear construction operations are presented. The line of balance concept is presented, its benefits and limitations are discussed, and the barriers to its implementation are addressed. The statistics collection capabilities of MicroCYCLONE, a Monte Carlo discrete event process interaction simulation program that lends itself to the modeling of construction process applications, were enhanced to foster the monitoring of partially completed production units and stage buffer quantities for repetitive processes during the simulation of a linear construction operation. The enhancements provide the information necessary to perform line of balance analyses of linear construction models. Statistics collected with the enhancements can be used to generate realistic production flow line curves and stage buffer charts at multiple locations in a single model as time evolves. These graphical plots can be easily used to identify potential bottlenecks, to determine what is wrong with an operation, and to design corrective measures for improving system performance. The significance, capabilities, and implementation of the statistics collection enhancements are discussed. An illustrative case study is provided.

Linear construction operations are operations that involve repetitive units of construction elements. Some classic examples of linear construction projects include highways, high-rise buildings, tunnels, and pipelines. The repetitive construction units of these four examples can be expressed in terms of number of road sections, floors, tunnel rings, and lengths of pipe, respectively. Each of these repetitive units can be further subdivided into a sequence of processes that is repeated for each unit of the operation. For example, the sequence of processes for a road construction operation may include earth hauling, base delivery, base spreading, and asphalt rolling. Linear construction operations often consist of repetitive processes with different production rates. This phenomenon of production rate imbalance, which is shown in Figure 1, has the potential for negatively affecting project performance by causing work stoppages, inefficient use of allocated resources, and excessive costs. Production rate imbalance occurs when the production curves of "leading" processes intersect the line of balance (LOB) curves of "following" processes because of different production rates (i.e., production curve slopes) and insufficient lag between start times of processes.

The results of an investigation involving the simulation analysis of linear construction operations using the LOB concept are presented.

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LOB CONCEPT

The LOB method consists of a family of graphical or analytical linear scheduling techniques including the time space scheduling method (TSSM) (*1*), vertical production method (VPM) (*2*), velocity diagrams (*3*), linear scheduling method (LSM) (*4,5*), repetitive project model (RPM) (*6*), and LOB scheduling (*7–9*).

The LOB method was originated by the Goodyear Company in the early 1940s and was developed by the U.S. Navy during World War II for the programming and control of both repetitive and nonrepetitive projects (*10*). Because of the immense popularity of network scheduling techniques including the critical path method (CPM) in this country, the LOB technique has never been fully developed and implemented by the U.S. construction industry. However, there has been a higher level of use of this method by European contractors (*11*). The method has been applied to repetitive construction projects (*12*), planning of residential construction (*13*), resource scheduling and coordination among subcontractors (*14*), the scheduling of road pavement projects (*12*), and modeling production activities for multifacility projects (*15*).

Typical process production (or flow line) curves are shown in Figure 2. 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.

From a set of process production curves for a linear operation as shown in Figure 1, an aggregate production curve for the overall operation can be determined using a variety of graphical or analytical techniques. The overall production curve is referred to as the LOB for the operation. The LOB concept can be applied to the manufacture or construction of any linear operation, such as sections of road completed, the number of washing machines produced, and so forth (*13*). LOB methodology can be used to determine at any given time (*a*) shortages of delivered materials that may affect production; (*b*) materials that are being delivered in excess, which may cause additional material handling or require additional storage space; (*c*) the jobs or processes that are falling behind

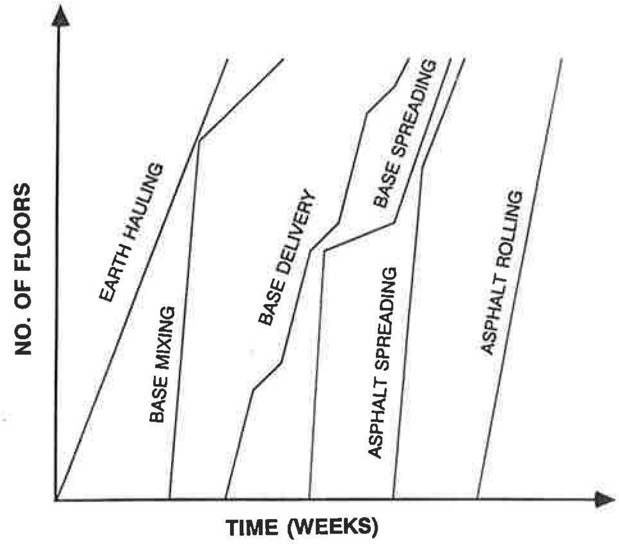

FIGURE 1 Production (or flow line) curves for repetitive processes.

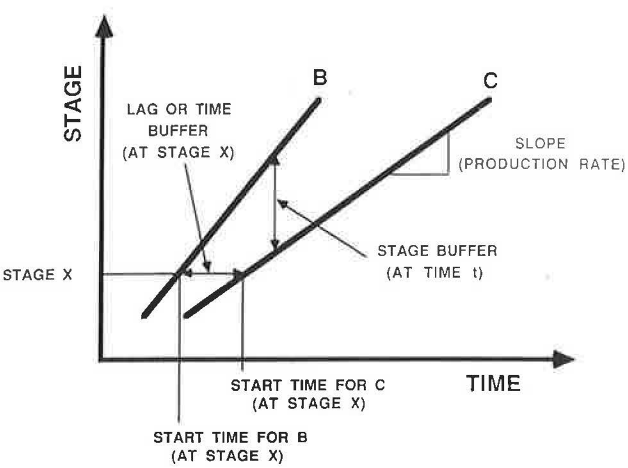

FIGURE 2 Process production curves (*6*).

and the required rate of production to satisfy the required LOB quantities; (*d*) the jobs or processes that are ahead of schedule, which may be placing heavier demands on operating capital than necessary; and (*e*) a forecast of partially completed production units by job, workstation, or process to support the delivery schedule of finished units (*13*).

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. The format involves the generation of production curves for the repetitive processes, as shown in Figure 1. The LOB plot for a linear construction operation can easily be constructed, show at a glance what is wrong with the progress of a operation, and detect potential bottlenecks.

Although LOB methodology can be used to aid in the planning and control of any type of operation, it is better suited for application to linear than to nonlinear operations. A major limitation of the LOB methodology is that it assumes that production rates are linear (i.e., constant rate of production over time). Because of the stochastic nature of construction processes (*7*), the assumption that production rates of construction projects and processes are linear may be erroneous. Another limitation of the LOB methodology is that it does not lend itself well to computer computations. In addition, the objective of many planning techniques based on the LOB concept is to reduce project duration with little or no regard for project cost (*6*).

Barriers to Implementation

Despite the broad use of LOB by the European construction industry (*11*), the U.S. Navy (*10*), and the manufacturing industry, the application of LOB by the U.S. construction industry has 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 U.S. construction industry that the LOB methodology exists (*10*).
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 that are not being used by their counterparts or competitors (*13*).
3. Network techniques can be easily computerized, whereas the LOB methodology does not lend itself well to computerization. Because of the popularity of the relatively inexpensive microcomputer in the U.S. construction industry, there is a resistance to changing to a planning method that is not currently supported by computer.

OPERATION MODELING

Construction Simulation Systems

In the construction domain, the use of simulation has involved either a commercial simulation package (e.g., GPSS, SIMAN, SIMSCRIPT, SIMULA, SLAM, etc.) or a custom-developed simulation package 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 are all based on the CYCLONE (CYCLic Operation NEtwork system) modeling format developed by Halpin (*16*). The MicroCYCLONE modeling elements are shown in Figure 3.

MicroCYCLONE is a microcomputer-based version of CYCLONE developed by Halpin (*16,17*). INSIGHT (INTeractive SImulation of construction operations using GrapHical Techniques) was developed by Kalk (*18*) as a separate implementation of the CYCLONE modeling system. Working with Carr, Chang (*19*) developed RESQUE (RESource based QUEueing network simulation) based on the CYCLONE

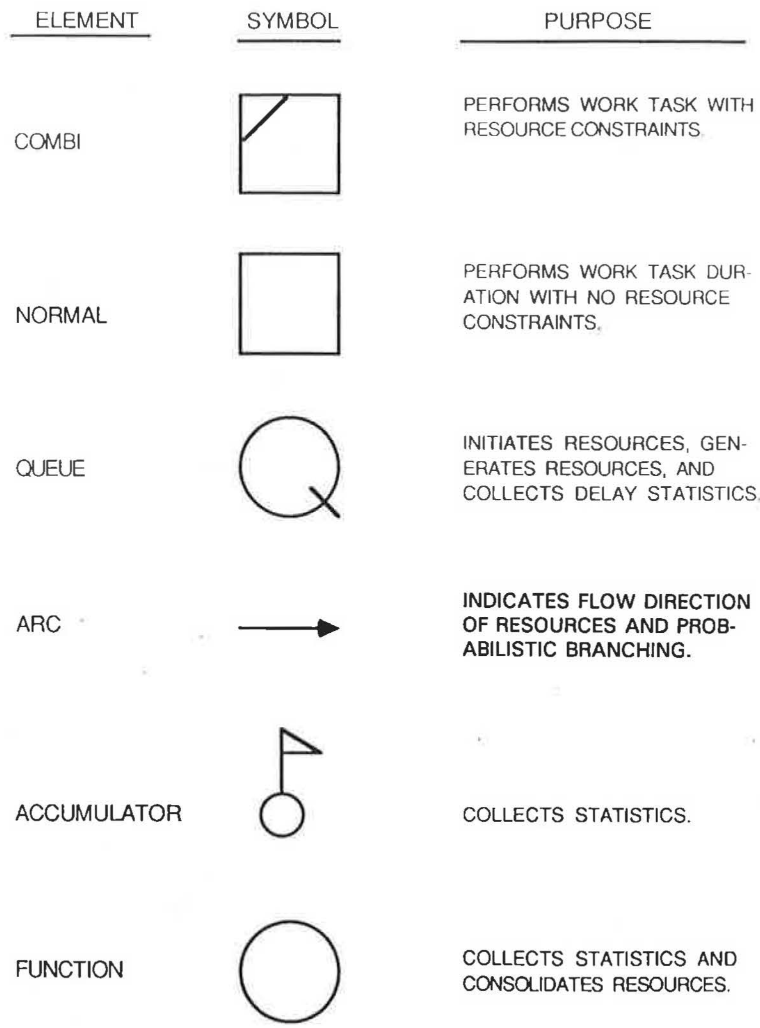

FIGURE 3 MicroCYCLONE modeling elements (*7*).

modeling format, which allows the modeling of nonidentical 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 U.S. Naval Civil Engineering Laboratory (*20*).

MicroCYCLONE is a Monte Carlo system that 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 (*21*). 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.

Breakdown of Construction Operations

The sequential logic of necessary processes for an operation can be conceptually modeled using a link-node diagram. A link-node diagram of a simple road construction operation including earth hauling, base delivery, base spreading, and asphalt rolling is shown in Figure 4.

A link-node diagram consists of links representing the cycling of equipment units between two locations and nodes representing points of transfer between two links. In a study performed by Teicholz (*22*), a two-link diagram was used to depict simulation models for simple construction systems involving a server (loader, pusher, etc.) and a processed unit (truck, tractor scraper, etc.). An example of a three-link diagram is a paving material distribution system (*23*) in which the first link represents the generation of asphalt batches, the second link represents the cycling of the trucks between the batch plant and the pavers, and the third link represents the cycling of the pavers. The road construction operation discussed here is a four-link simulation system.

The link-node diagram can be extended to model a linear construction project in a LOB context where links and nodes denote individual repetitive processes and stage buffers, respectively. For the purpose of this investigation, a process was defined as a group of related work tasks that transform or transport resources to produce partially completed work

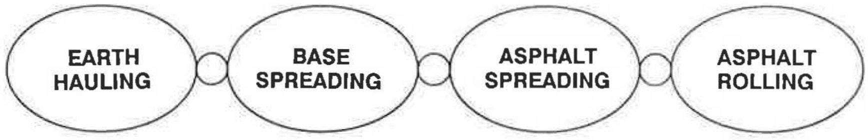

FIGURE 4 Link-node diagram of the road construction model.

units. Once a process yields a partially completed work unit (i.e., section for the road construction example) it enters a stage buffer or storage queue to await entry into the next process. If the next process is ready for the partially completed work unit, it moves directly into the next process with no waiting in the stage buffer. If the next process is busy, partially completed work units may build up in the stage buffer. When a stage buffer is empty and the next process is idle, a work stoppage can occur.

By collecting intermediate statistics for partially completed work units as they move through stage buffers from one repetitive process to the next, process cycle monitoring and stage buffer monitoring can be fostered during a simulation. Process cycle monitoring can be used to generate theoretical process production curves, system constrained production curves, and the LOB. Stage buffer monitoring can be used to generate stage buffer charts depicting the number in queue as time evolves during the simulation.

STATISTICS COLLECTION

The existing MicroCYCLONE Version 2.5 provides a report for process cycle monitoring reflecting the task repetition number and corresponding simulation time for COMBI (i.e., a work task constrained by resources) and NORMAL (i.e., a work task not constrained by resources) elements. The term "process cycle monitoring" as used in this paper denotes the collection and recording of process repetitions (i.e., completion of production units or production cycles) and corresponding simulation times for distinct processes during the simulation of a multiple-process operation.

The stage buffer monitoring enhancement presented here allows the user to track quantities of partially completed production units at any point in a model during a simulation. Stage buffers are work reservoirs that occur at queues between individual processes (*13*). When a stage buffer becomes empty, the following process must remain idle until a production unit enters the preceding stage buffer. When a stage buffer has one or more units, the following process continues to operate without interruption.

Enhancement Methodology

Although intermediate statistics required to measure process production rates and stage buffer quantities are calculated by the existing MicroCYCLONE program, only final statistics are retained for the user. Under the direction of Halpin, Lutz (*24*) developed process cycle and stage buffer monitoring enhancements for use with MicroCYCLONE. The enhancements consisted of the coding of several subroutines to foster the collection and recording of initial, intermediate, and final process and stage buffer statistics.

The simulation flow diagram for MicroCYCLONE is shown in Figure 5. As shown in Figure 5, the code enhancement facilitates the collection of intermediate statistics after the termination of work tasks associated with end event time (EET) and before units are released from the terminated elements. The enhancement works in conjunction with existing CYCLONE methodology and modeling elements to perform process and stage buffer monitoring.

Process cycle monitoring statistics required for analyzing linear construction operations include the process production cycle number as time evolves during the simulation for certain FUNCTION elements (e.g., non-COUnter and non-CONsolidate FUNCTION elements) for multiple-process models. The current version of MicroCYCLONE allows the use of one ACCUMULATOR and multiple FUNCTION elements for a single model. These elements provide for the collection of production cycle statistics and final statistics, respectively. The existing SIMULA module of MicroCYCLONE generates these intermediate statistics but does not capture them in report form for the user. The process cycle monitoring enhancement consists of several small subroutines in SIMULA that essentially allow the user to place counters at multiple locations in the same model.

Stage buffer monitoring statistics required for analyzing linear construction operations included the number in queue as time evolves during the simulation for stage buffer QUEUE elements placed between individual processes in a multiple-process model. As in the case of the process cycle monitoring enhancement, the existing SIMULA module of MicroCYCLONE generated these intermediate statistics but did not capture them in report form for the user. The stage buffer monitoring enhancement consists of several small subroutines in SIMULA that allow the user to place SINK elements between processes of multiple-process models.

Statistics Collection Mechanism

As shown in Figure 6, the statistics collection mechanism consists of a FUNCTION element followed by a SINK element. The developed statistics collection mechanism provides two new features to the existing MicroCYCLONE program; it allows the use of multiple counters in a single model and tracks the number of partially completed production units in queue as time evolves during the simulation for SINK elements. The existing program only allowed the use of one counter in a single model. The SINK element performs the same function as a QUEUE element and has typically been used at the end of the model to collect completed production units. However, multiple SINK elements can now be used in

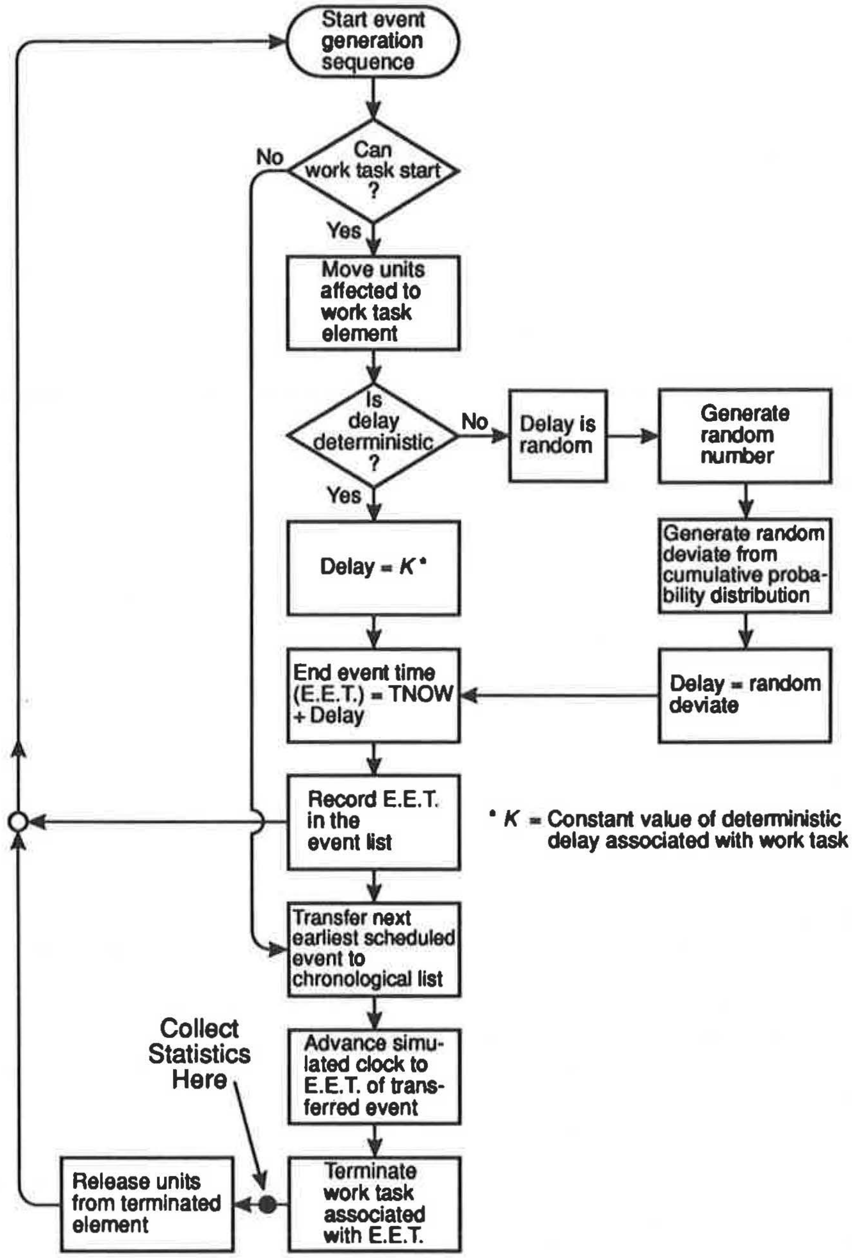

FIGURE 5 MicroCYCLONE simulation flow diagram (*7*).

the place of QUEUE elements in a single model to collect additional statistics.

Collection of Statistics

One application of the statistics collection mechanism is to foster the collection of statistics for individual processes during the simulation of a multiple-process linear construction model as shown in Figure 6. This can be accomplished by inserting a statistics collection mechanism after each distinct process in the model. Additional statistics (i.e., element label, cycle number, and simulation time) are collected in a file on the specified data disk entitled "*filename*.FUN" for non-CON and non-COU FUNCTION elements. Additional statistics (i.e., element label, quantity in buffer, and simulation time) are collected in a file on the specified data disk entitled "*filename*.QUE" for SINK elements. These elements are specified in the Network Input statements as discussed in the MicroCYCLONE User's Manual (*17*).

After a simulation has been completed, the statistics collection files (i.e., "*filename*.FUN" and "*filename*.QUE") are imported into a spreadsheet program for data manipulation as required. As shown in Figure 6, these data are used to generate system constrained process production or flow line curves (i.e., curves representing the realistic production be-

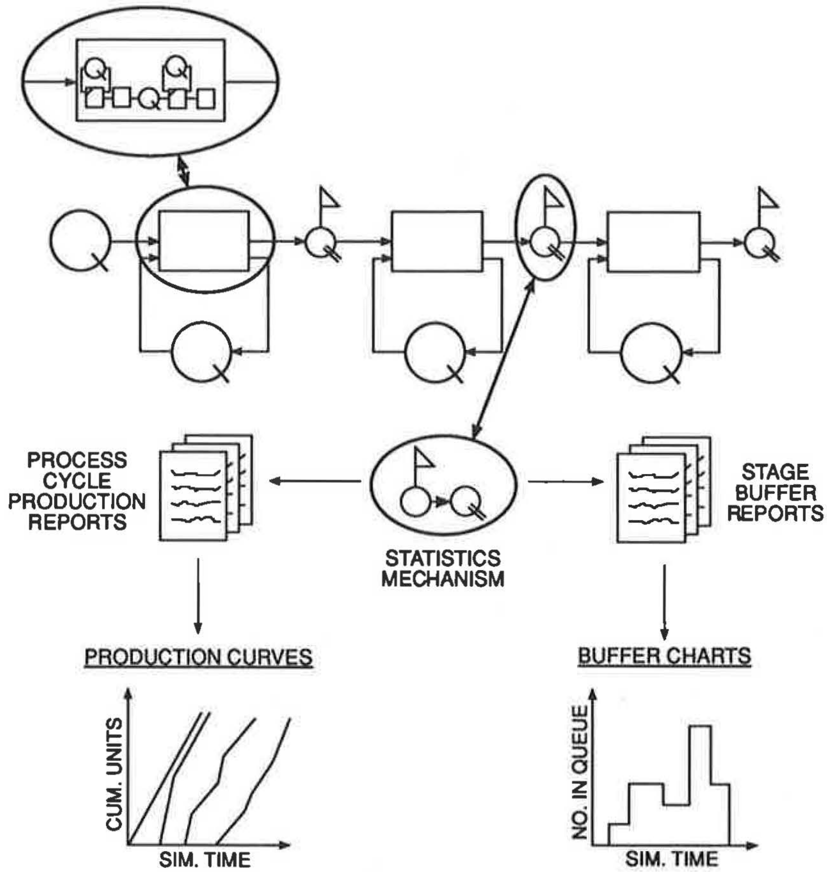

FIGURE 6 Process cycle and stage buffer monitoring enhancements.

havior of individual processes in a multiple-process model as constrained by the system during simulation) and to generate stage buffer charts. A statistics collection mechanism consisting of a generic FUNCTION element followed by a SINK element was developed to collect initial, intermediate, and final statistics between processes. The statistics collection enhancements of MicroCYCLONE are significant because they allow the user to collect statistics anywhere in a simulation model instead of at just one location, as previously provided by the program. By placing statistics mechanisms between processes of a multiple-process model, process production flow line curves and stage buffer charts can be generated. These graphical plots can be easily used to identify potential bottlenecks, to determine what is wrong with an operation, and to design corrective measures to improve system performance.

SIMULATION ANALYSIS

Seven operations were selected for simulation experimentation using the LOB concept: a precast concrete plant, stone cutting plant, match casting plant, steel erection, sewer line installation, road construction, and high-rise building construction. The experimental methodology used and the results from an illustrative case study involving a road construction model are provided.

Experimental Methodology

Each of the seven operation models was broken down into a set of individual processes and stage buffers using the previously described systematic approach. For each operation, stochastic simulations were performed for each individual process and for the overall operation using controlled random number streams. The mean simulation cycle times from these runs were used to plot the theoretical set of flow line curves and the LOB for the operation. The theoretical plot is based on entering work units being abundant (i.e., the ideal production curves disregarding the other processes in the operation), and the LOB plot is based on the simulation of the overall operation. Since interdependencies between processes are ignored for the theoretical curves, the curves all begin at the origin and may intersect.

Models were then developed for the seven operations using the previously discussed statistics collection enhancements. Statistics collection mechanisms were positioned between individual processes to monitor the production rate and buildup of partially completed production units for each process. Stochastic simulations were performed using controlled random number streams. Mean simulation cycle times and buffer quantities were used to produce sets of system-constrained flow line curves, the overall LOB, and buffer charts. System-constrained production curves begin when the processes are actually initiated during the simulation and cannot intersect, since processes are affected by the characteristics and production rates of preceding processes. The buffer charts provide plots of the quantity of partially completed production units in queue between processes during the simulation.

Case Study: Road Construction Operation

The road construction case study involves the installation of the base and asphalt layers onto a prepared subgrade. The project involves eight separate processes. Since some of the processes are rather involved, detail to the subprocess level has been provided. Process models were obtained from Halpin's (*17*) standard model library, and time durations were based on job history data and estimates based on *Caterpillar Performance Handbook* (*25*) and other references. Major resources include a base mixing plant and an asphalt mixing plant. Material stockpiles include stockpiles for earth, base mix materials, and asphalt materials. The processes include earth hauling, base mixing, base delivery, base spreading, asphalt loading, asphalt delivery, asphalt spreading, and asphalt rolling.

The MicroCYCLONE model for the road surface construction is presented in Figure 7 with no shared resources. The resource requirements for each process have been itemized. Equipment breakdown and a constant incremental increase in travel time have been modeled for the three transportation processes. The processes are stochastic.

Theoretical Production Curves

The theoretical production curves and LOB for the road construction operation are shown in Figure 8. Several observations can be made about the project by analyzing the curves. First, the phenomenon of production rate imbalance exists because the production rates or slopes of the eight processes are not consistent. Second, some of the production curves for the individual processes are approximately linear, whereas others are nonlinear. Some of the curves exhibit the effect of constant change in travel time. Third, the constraining process for the road construction case study is the base delivery process since it dictates the slope of the overall production curve. Fourth, a potential exists for the buildup of partially completed units between the earth hauling and base mixing processes and between the base mixing and base delivery processes. Fifth, the production curves for three of the processes—base spreading, asphalt spreading, and asphalt rolling—are clustered together

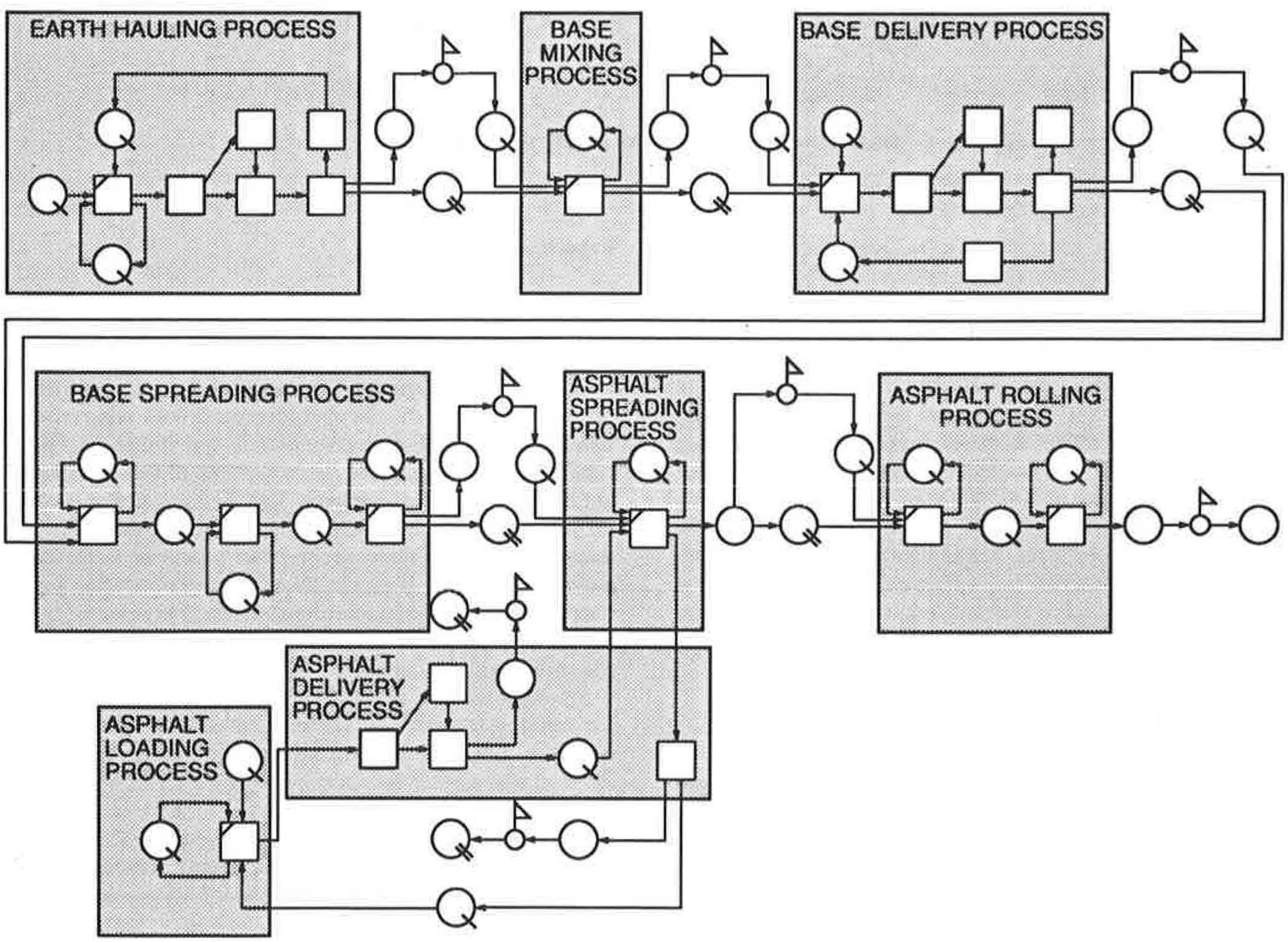

FIGURE 7 MicroCYCLONE model for the road construction case study.

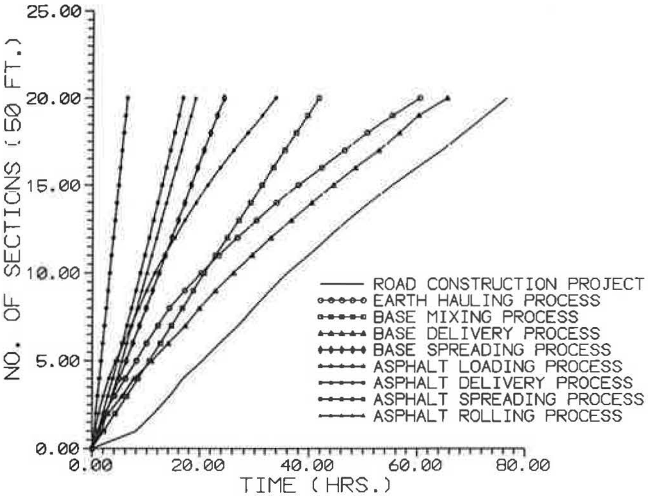

FIGURE 8 Theoretical process production curves for the road construction case study.

with a similar slope; these three processes are approximately balanced.

System-Constrained Production Curves

The system-constrained process production curves yielded from the data provided in the process monitoring report for the road construction processes are presented in Figure 9. Each of the eight production curves is either approximately linear or approximately curvilinear. The curves fall under two general slope categories; the earth hauling and base mixing processes have approximately the same slope, and the six remaining curves have approximately the same slope. The earth hauling process include a transportation cycle with constant increase in travel time. This nonstationarity effect is evident in the shape of the earth hauling and base mixing processes.

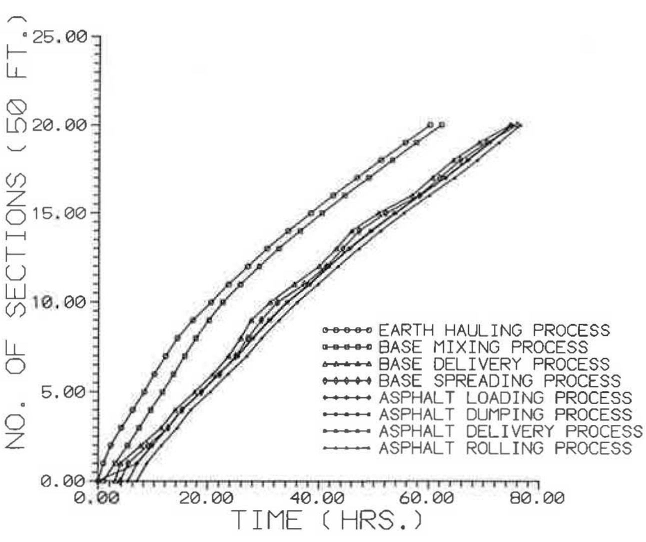

FIGURE 9 System-constrained process production curves for the road construction case study.

An analysis of the production results (*24*) indicated that the constraining process for the group of five processes is the base delivery process (i.e., the base delivery process is the slow runner of the relay team). The earth hauling process does not appear to initially constrain the base mixing process. However, approximately 20 hr into the simulation the diminishing slope of the earth hauling curve because of nonstationarity appears to begin constraining the base mixing curve. As with the theoretical curves, it appears that stage buffers located between the earth hauling and base mixing processes and between the base mixing and base delivery processes may have the potential for buildup of partially completed production units.

It is apparent from the theoretical and system-constrained production curves that the overall production of the road construction project could be improved if the production rates for the earth hauling, base mixing, and base delivery processes were enhanced. A base mixing plant with a larger capacity and additional trucks for the earth hauling and base delivery processes should increase performance of the overall operation.

Buffer Charts

On the basis of the data from the stage buffer monitoring report, it was determined that only two stage buffers accumulated partially completed road sections during the simulation. As surmised from the theoretical and system-constrained production curves, the stage buffers immediately following the earth hauling and base mixing processes accumulated partially completed units. The stage buffer charts for the buffers following the earth hauling and the base mixing processes are shown in Figure 10. One road section is built up in the stage buffer (Statistics Collection Mechanism 1) preceding the base mixing process until the nonstationarity effect of constant change in travel time of the earth hauling process begins to constrain the base mixing process approximately 20 hr into the simulation. The stage buffer (Statistics Collection Mechanism 2) following the base mixing process accumulates between one and three road sections from approximately 8 to 76 hr into the simulation.

CONCLUSIONS

Previously developed planning techniques for linear construction operations based on the line of balance concept assume that process production curves are linear with respect to time. On the basis of the research performed, mean production curves for individual processes can be either linear or nonlinear. The use of simulation to generate the theoretical production curves and LOB for an operation is significant because simulation can provide realistic plots. These graphical plots can be used to easily determine what is wrong with an operation, to locate bottlenecks in the system, and to develop alternatives for improving the performance of the system.

In the cases analyzed, the phenomenon of production rate imbalance existed because the slopes of the individual processes had different characteristics. This production rate imbalance hindered production levels for individual processes and caused the buildup of partially completed production units

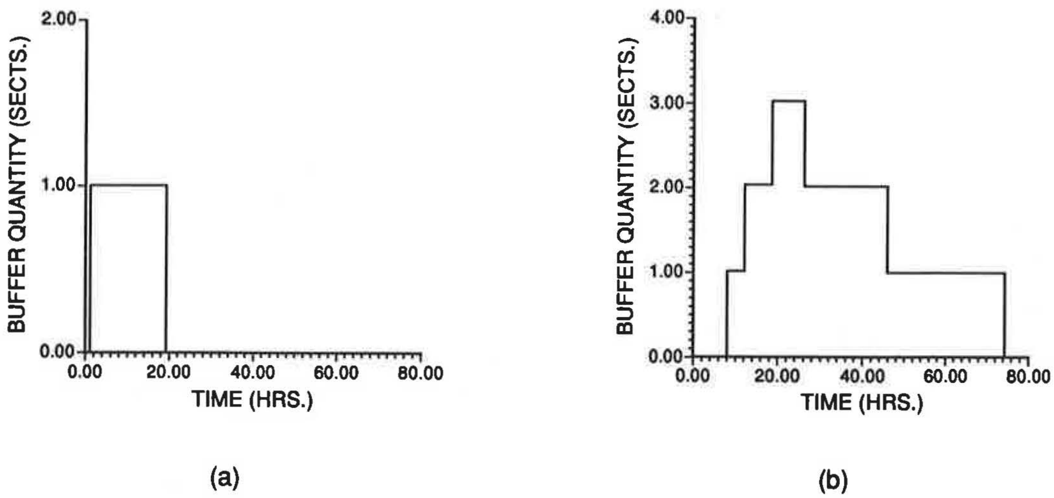

FIGURE 10 Buffer charts for the road construction case study: *a*, Statistics Collection Mechanism 1; *b*, Statistics Collection Mechanism 2.

in stage buffers between processes. An efficient method for improving the production characteristics of individual processes is needed to improve overall system performance.

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Publication of this paper sponsored by Committee on Construction Management.