A GPSS-V MODEL OF A LARGE, HIGH-VOLUME MACHINING LINE

Leo E. Hanifin, D.E.
Chrysler Corporation, Detroit, Michigan

Simulation is a proven tool and has been accepted and fruitfully applied in many fields. To meet the needs of these applications, many simulation languages have been developed and refined to the point that they too are widely accepted and employed. However, in the "hands-on" area of manufacturing systems, the application of this tool lags begind the state of the hardware development. This is unfortunate, in that many manufacturing systems lend themselves extremely well to simulation techniques.

Too often increased productivity is sought by attacking individual trouble areas in the system, rather than improving the configuration or management of the entire system. This is often due to the lack of ability to approach the analysis of an extremely complex system. A sophisticated tool is needed and simulation can fulfill this need.

Using simulation, experiments can be performed which alter the physical production systems and/or the management of such systems; and a high degree of confidence can be had in the results obtained. The analogous experiments on the real system more often than not involve investments of millions of dollars, and, often more importantly, the risk of lost production.

Hence, the field of manufacturing invites the application of simulation techniques to aid in the development of systems which produce more for less cost. In fact, as the world industrial community approaches the limits of one non-renewable resource after another, it becomes absolutely necessary to draw the greatest possible production from both new and existing manufacturing systems. What follows is the description of a simulation model and experiment which investigates various changes in the design and management of a specific system which might increase productivity.

THE REAL SYSTEM

The real system to be investigated is a transfer line. (A schematic diagram of a transfer line is shown in Figure 1.) A transfer line might be defined as a number of machining stations, in series, integrated into one system by a common transfer mechanism and a common control system. A machining station is a single stopping point, where a machining operation(s) is(are) performed on the workpiece. Each workpiece must pass through and stop at each station.

The specific transfer line investigated has 76 stations. The machining operations performed are chamfering, reaming, facing, spot-facing, boring, drilling and tapping. This line has the capability of performing 538 distinct operations. But only approximately 350 operations are performed on any one workpiece. The additional capability allows the machining of three different workpieces. During the machining of any one workpiece, certain stations are inoperative and some tools at active stations are removed.

The operation of the line is directed by the jobsetter. It is his responsibility to set-up, adjust and change all tools, to diagnose line breakdowns and to contact necessary maintenance personnel.

This transfer line is palletized. That is, the workpiece is first mounted accurately on a pallet (a large, rigid constraining system) which is, in turn, transfered from station to station. The rigid pallet is necessary for the required accurate machining of such a substantial workpiece.

The stations of the transfer line are connected by "ways", upon which the pallets ride. Each straight, uninterrupted section of the line is served by a "transfer bar" which effects the movement of pallets from one station to the next. There are four or five transfer bars per line. All pallets on any transfer bar move at the same time.

The line can be divided into two or more *sections* (stages) by providing the space, manpower and facilities required for the storage of semi-finished workpieces between any two stations. This in-process storage facility is called a *bank*. (See Figure 1) A bank essentially decouples the sections of the line on either side of it, allowing either section to run while the other is down for any reason. The largest number of workpieces that such a bank can accommodate is the *bank capacity* (N). The existing system does not have such a bank.

With a palletized system, the workpieces can be banked while still mounted on the pallets, or separately, after being removed from the pallets. It is desirable to bank on the pallets, so that both rough and finish operations on any specific workpiece are performed while it is mounted in the same position on the same pallet. The best way to guarantee this is to never remove a workpiece from its pallet between the start and finish of the line.

Each section can be in any one of three states:

1. *Up*: working to produce finished workpieces.
2. *Repair*: not producing due to machine failure, tool change or adjustment, changeover or personnel related problems in that section.
3. *Forced down*: not producing either because its first station has no workpiece to work on (starvation) or its last station has nowhere to place its present workpiece (*blocking*).

In either state two or three, the section is considered down.

Cycle time (1/H) is the time between successive movements of workpieces *when the line is up*. Hence, H is the *gross production rate* of the transfer line. That is, if the entire line remained up for 'X' minutes, the production during that time would be HX workpieces. The *net production rate* (R) is the number of workpieces produced by the last section per unit of time (over a long period of time). Thus, by definition, $R \leq H$.

The efficiency (E) is the fraction of time the line is up. Hence, it is the net production rate divided by the gross production rate: $E = R/H$

Runtime (*runtime duration*) is the amount of time a section is in an uninterrupted "up" state. *Downtime* (*downtime duration*) is the amount of time between successive runtimes of any one section. During any one downtime, the section can be in state two (repair) or state three (forced down) or a sequence of both. *Repair time* is the amount of time necessary to make a section available after it enters state two. Repair time is caused by a variety of problems, including mechanical and electrical failures, tool wear and breakage, changeover and personnel problems.

In order to attain an accurate qualitative and quantitative description of the runtimes and downtimes of the real line, the operation of the line was observed for seven days (24 hours a day). A manual observation was necessary to ascertain the number, duration, location and cause for all downtime occurrences. The cycle time and production counts were automatically recorded on a strip chart. This manual and automatic observation allowed an accurate quantitative description of the existing system's operation and downtime, which will be called the "downtime history."

WAYS TO INCREASE PRODUCTION

The establishment of a quantitative downtime history facilitates the determination of those changes which may lead to increased production. The four general categories of changes which were identified as ways to increase the production of a transfer line are:

1. INCREASE THE GROSS RATE OF PRODUCTION - (Decrease the cycle time). This decrease in cycle time can be accomplished by either increasing the transfer speed or the machining speed. However, increasing the machining speed will, most probably, increase the amount of wear per cycle on the cutting tools. That is, both the cycle time decrease and the resultant wear rate increase would cause greater wear during any specific period of time. Therefore, there would be a greater number of downtime occurrences during any extended period of time, negating at least part of the positive effect of this increase in gross production rate.

2. DECREASE THE FREQUENCY OF DOWNTIMES - This basically is a tooling or reliability consideration. Improvements here include increasing tool life and increasing machine reliability, thereby reducing the number of tool changes and maintenance downtimes.

3. DECREASE THE DURATION OF DOWNTIMES - (Through faster maintenance and tool change). Increasing the number and quality of maintenance personnel, establishing efficient tool set-up procedures and providing for the availability of tools and machine parts all contribute to reduced downtime duration. On large, complex transfer lines diagnosing the cause of stoppage is often a significant component of the entire downtime. Hence, improved diagnostics offer another way to effect decreases in downtime durations. Of course, hurried repairs may decrease downtime duration at the expense of increased downtime frequency.

4. REDUCE THE IMPACT OF DOWNTIME ON THE LINE - This can be affected through various system configurations and/or management strategies. Obvious possibilities here include redundant sections of lines or dividing the line into two sections by placing a bank between any two stations.

All attempts at drawing greater production from a transfer line must fall within one or more of these four classifications. As was exemplified above, there are interactions between these four mechanisms. An obvious improvement in one of these four areas may be negated by the negative effects in another. While these interactive effects result in a complex problem, a well constructed simulation model can accurately incorporate and assess such relationships. However, before developing such a model, past efforts to simulate transfer lines should be investigated.

PAST SIMULATION MODELS OF TRANSFER LINES

Prior to the advent of pre-programmed processors tailored specifically for simulation programming, even the simplest simulation models required extensive programming in such general purpose languages as Fortran or Algol. This necessarily limited the complexity of the model. A typical investigation of this type was performed by Metzger (1) 1963. Metzger's model simulated a series of production stations, with banking between any or all stations. But even with a Fortran program of 570 statements, systems of only nine or fewer stations were investigated.

Freeman (2), in 1964, developed another general simulation model of an automatic production line. A three-section line was simulated using Algol. However, there was no attempt to quantatively justify the use of exponential distributions for the runtimes and repair times.

These and other early models suffer from the same two drawbacks. First, due to the complexity in programming, only the simplest lines were simulated. Secondly, in each case, the models developed represented no real, specific line.

The development and marketing of pre-programmed simulation software packages, such as GPSS, GASP, SIMSCRIPT and DYNAMO, partially solved the first of these two problems. By employing preset program blocks, which are common to many simulation problems, the modeler can devote his energies more to the problems of general model structure and less to the minute details of programming.

Anderson and Moodie (3), in 1969, effectively employed GPSS-III (General Purpose System Simulator - Version III) to model a general production line. However, there was no simulation of breakdowns; the only bank usage was due to differences in production rates (cycle times) between the sections. Hence, this model is inappropriate for application to automatic transfer line simulation.

The advent of these simulation programs and languages led to several efforts to simulate specific production line systems. One of these, performed at the University of Windsor in 1973, (4), used GPSS/360 to simulate a semi-automatic wheel rim line at the Kelsey-Hayes Corporation. Another, developed by the Buhr Corporation using GPSS/360, simulated the Front Spindle Manufacturing Area at Chevrolet's General Parts Manufacturing Plant in 1971, (5). This area involves a number of automatic production lines. Due to the strict mirroring of a specific, real system, neither of these simulations allow any inferences as to the system behavior of the transfer lines to be investigated here.

However, there is one significant point regarding modeling philosophy to be noted here. In both of these models the following logical, but unnecessary, assumption was made: The "transactions", which flow through a GPSS simulation model, are simulating physical entities; in the case of production lines, they are simulating workpieces. This assumption leads to a duplication of the actual line configuration in the GPSS block diagram. This practice makes the model easier to develop and easier to understand by the non-practitioner of simulation (adding credence to the model's validity). However, rigid adherence to the detailed duplication of the line and the use of transactions to represent workpieces both lead to inordinately large expenditures of computer (CPU) time.

This "mirror" philosophy has recently been applied to transfer lines in the automotive industry. A Cincinnati-Milacron model required approximately 27 minutes of CPU (on an IBM 370 computer) to simulate 80 hours of transfer line operation (6). Comparable amounts of computer time are required for a model at Ford Motor Company, which also employs this "mirror" philosophy of GPSS simulation modeling (7). Neither Cincinnati-Milacron nor Ford have published detailed model descriptions or simulation results. Similarly, several other companies have developed GPSS models of production lines, but have, for various reasons, failed to publish or release any detailed model description or results. For example, Ingersol-Milling Maching Company (8), used GPSS-V for several transfer line applications.

While this review of past simulations of transfer lines brought up little by way of directly applicable models, it did bring to light several pitfalls which must be avoided if a significant, functional model is to be developed:

1. A model must not be so general that its results are not directly applicable to any one, real line.
2. Conversely, a model must not be so specific that, without major modifications, it is only useful for the one line presently being analyzed.

3. The model must be designed such that the expense of the necessary CPU time does not make the simulation economically prohibitive. To this end, past studies would indicate that the model should not

a. simulate the occurrence of each operation, or
b. use the GPSS transaction to simulate each workpiece.

SIMULATION MODEL DEVELOPMENT

The description of the real system and the investigation of past simulation efforts allow the development of a simulation model of this specific transfer line. This development is divided into "Simulation Philosophy", "Changes to be Simulated", "Modeling Assumptions" and "Model Programming".

Simulation Philosophy

Preliminary models were created and run in order to both demonstrate the feasibility and applicability of GPSS simulation of transfer lines and to develop a simulation philosophy to be carried on into the final models (8). As experience was gained in model building, three major concepts emerged. These three principles will be called "non-mirror simulation", "duplication of downtime history" and "general model-specific data". They represent the heart of the philosophy used in creating the model presented here.

"Non-mirror Simulation" - As stated above, past efforts to simulate transfer lines often sought to design a model which is a mirror of the actual real system. In GPSS jargon, this means that facilities or advance blocks represent machines (stations), storages or queues represent banks and transactions represent workpieces. The transactions (workpieces) flow through the model (transfer line), being machined and, at the same time, wearing the tools and parts. This technique allows for an easier, faster creation of models. Also, due to the marked similarity between the GPSS block diagram and the real line's layout, the model is more easily understood by the non-practitioner of simulation. This adds credence to the model's validity and the job of 'selling' the model to management is made easier.

However, the mirror technique has its drawbacks. First, this simplistic, building-block approach can lead to invalid models (9). Secondly, and more likely, the rigid adherence to duplication of the real line often leads to undue modeling detail. Each movement of each workpiece is simulated, followed by a check of the status of all system components. Such a technique is computationally inefficient and leads to inordinately long computational times.

In contrast, the model presented here represents an excursion from this mirror philosophy. There are no workpieces, except in the banks; transactions represent downtime events. Each operation is not simulated. Rather, the cardinal event is the occurrence of a downtime and the determination of the consequences of such. In short, only events which interrupt production are actually simulated. Production is determined by calculating (in the model) how long the section has been running since its last downtime.

"Duplication of Downtime History" - All past analytical and simulation efforts encountered, including the preliminary models of this project, sought to describe downtime occurrence and duration by using a specific probability density function(s), which were 'typical' or 'representative'. Lifetimes were often normal, while repair times were exponential or geometric. In simulating, specific lifetimes and repair times are selected at random from these distributions. Often, assumed distributions were used without proof that there exists a real transfer line which actually fits these distributions.

In the model described here, there is no fitting of data to specific probability distributions or random generation of a stream of downtime events. Rather, the actual downtime history (stream of downtime events) in the plant is used as an environment within which each model runs. This duplication of a downtime history is accomplished using the GPSS "Jobtape" capability. The advantages of this technique are many:

1. The exact plant recorded environment is duplicated. The data is not forced to fit any simple distribution.
2. Patterns in the downtime history are not lost. On a real transfer line there are often several short downtimes in rapid succession (as many as 20 per hour) attributable to one station. Except in an extremely complex model, such patterns are lost in the random generation of a downtime stream.
3. Replication of experimental conditions is guaranteed. Every transfer line simulated using a specific jobtape for the environment experiences the exact same downtime history.
4. This generation of a jobtape from real data allows for an easier re-application of the models, especially by personnel not intimately familiar with GPSS simulation or the determination of representative probabilistic descriptions.

"General Model-Specific Data" - The concept of duplicating a downtime history gives rise to the idea that any tailoring of a model to represent a specific transfer line could be accomplished via the downtime history (jobtape), rather than in the model logic itself. While this is not entirely true, the model logic can be written in as general a manner as possible without compromising the accuracy or validity of the simulation. Such an effort was made in the programming of the simulation model below. For example, actual parameter values associated with a specific line are set equal to variable (savevalue) names in the beginning of the model to allow for easy alteration. Such practice fosters a more universally applicable model, capable of accepting data from another real transfer line after minor software modifications.

Changes to be Simulated

Based upon the "Ways to Increase Production" presented above, specific changes in the design or management of the transfer line must be selected which merit simulation. The changes simulated in this project were those envisioned to cause improvements in the net production rate. Four such changes were decided upon:

1. Implementation of a Bank - An automatic bank was simulated between two stations, dividing the line into two sections. This bank has a limited capacity. No additional personnel is required on the line to start or operate this bank.
2. Reduction in Cycle Time - A faster transfer between stations was simulated. This in effect increases the gross production rate proportionally, while increasing the amount of wear per unit of time.
3. Reduction in Downtime Duration - A linear multiplication factor was used to scale the duration of each downtime event. While it is very difficult to determine the specific action necessary to attain any given reduction in downtime duration, it is important to include this variable to allow the assessment of the complex interactive effects between downtime duration, cycle time and the impact of banks of various capacities and locations.
4. Additional Jobsetter - A second jobsetter was simulated. In this two jobsetter configuration one jobsetter is assigned to each section.

Modeling Assumptions

The development of a simulation philosophy and the selection of those changes to be simulated allows the specification of the modeling assumptions:

1. The transfer line consists of a number of stations in series. The line length is variable.
2. The line is divided into two sections, separated by one bank. The bank can be located between any two stations. The size of the bank is variable between zero and any positive number.
3. Banking systems are fully automatic and activated without delay. That is, if there is a need for a workpiece at the second section or a need by the first section for a place to put a workpiece, and if the bank can fulfill this need, then it will always do so immediately. The decision to use the bank and the order to do so are part of the line's controlling logic.
4. The bank is filled halfway at the beginning of the simulation.
5. The cycle time of the line is constant for any one simulation run, but can be set to any value.
6. All variation in cycle time is a direct result of variation in transfer speed, not machining speed.
7. The wear rate per cycle for all machine parts and tools is independent of the cycle time.
8. While the line is running, the rate of wear per unit time for all machine parts and tools is inversely proportional to the cycle time.
9. Starvation of the first station due to the lack of unmachined workpieces is possible.
10. Blocking of the last station due to lack of storage space is possible.
11. If any one station in a section fails, the entire section stops.
12. Each section always assumes one of three states:
    a. up (running)
    b. down for repair
    c. forced down by the failure of the other section.
13. The two sections are synchronous in their operation. All workpieces in the line transfer from one station to the next at the same time.
14.. Wear dependent downtimes (failures) cannot occur while the section in question is down.
15. Time dependent downtimes wait until the appropriate section(s) is running before impacting the line.
16. The presence of a jobsetter is required for all repairs on the entire line. While the jobsetter does not actually perform all repairs, this assumption is an accurate description of the existing system in that the jobsetter is usually responsible for the diagnosis of the problem and contacting any necessary, additional maintenance personnel.
17. When there are two jobsetters assigned to the line, one jobsetter is assigned to each section. Unless there are simultaneous failures within one section, the failure never has to wait for a jobsetter before repairs can commence.
18. The downtime history recorded in the plant is used as an environment within which the simulation model runs. That is, the wearing of parts, the occurrence of time dependent failures and the duration and location of all downtime events used for the simulation model are the same as that recorded in the plant.

Model Programming

The above assumptions are embodied in two GPSS-V programs. The first, Model I.C.01, employs a "Help" block to translate the downtime history from cards into a GPSS Jobtape. Each transaction on this jobtape represents a downtime event, with its parameters carrying all the relevant properties and values of the respective downtime as it was observed in the plant. The second GPSS-V program, Model I.B, is the actual transfer line model which runs within the environment of the GPSS Jobtape Downtime History by accepting transactions from it. The interaction of these two programs, within the framework of the entire project, is shown schematically in Figure 2.

This transfer line model (I.B) employs 358 GPSS blocks and over 750 statements. Figure 3 summarizes its general logic.*

A few concepts of the model logic merit brief discussion. In general, the transactions in the simulation model represent downtime events arriving into the model from the jobtape. The consequences of any downtime are triggered as the transactions trigger the logic of each block they enter.

There is no generation of random numbers. Therefore, replication of experimental conditions from one design point to another is insured by the set downtime history on the jobtape.

Nowhere in the model is the number of stations in the line set. This number of stations is set only by the downtime history.

For each section, five time measurements are recorded:

1. runtime
2. time required for repairs
3. time spent waiting for a jobsetter
4. time spent forced down by the other section being down
5. total downtime

Each of these measurements is tabulated and the mean, standard deviation, number of occurrences and other statistics are calculated.

During any shift change, all work, including repairs and tool changes, stops.

These models possess the capability to alter the values of the five factors selected in the design of the experiment. The programming and techniques for such flexibility varies from factor to factor.

Banking - Both the bank location and capacity are completely variable and are set to any non-negative integer values at the start of each simulation. Only one statement is required to alter either value. The value of bank location indicates the number of the last station before the bank. The value of the bank capacity, of course, indicates the maximum number of workpieces which the bank can hold.

Cycle Time - Like the banking factor levels, the cycle time is set at the beginning of the simulation run using only one statement. Cycle time can be set to any value to the nearest one-thousandth of a minute (0.06 seconds). As the cycle time is reduced and the line speeds up, the amount of wear during any period of time is determined using the ratio of the cycle time when the data was collected to the simulated cycle time in a linear proportional relationship.

Number of Jobsetters - Changes to the block diagram itself are required to supply an additional jobsetter for the simulation. Approximately forty statements are involved in the alteration of model I.B.02 (one jobsetter) to model I.B.03 (two jobsetters).

Downtime Duration Factor - The downtime duration is altered by a multiplication factor in the variable which calculates the downtime duration. Although only fractional multipliers were used, any positive number, even greater than one, could be used to scale all downtime durations. Again, only one card is changed to employ a new downtime factor.

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*For a more complete logic flow diagram, a GPSS block diagram and a documented program listing, consult reference 10.

DESIGN OF THE SIMULATION EXPERIMENT

In this simulation experiment there are five variable factors to be investigated: bank location, bank capacity, cycle time, number of jobsetters and duration of downtime (downtime factor). The following values of each factor were included in the experiment:

1. Bank location: after stations 29, 38 and 46. These are the locations at which banks are physically feasible on the real transfer line.
2. Bank capacity: 0, 10, 20, 30, 40, 50, 75 and 100 workpieces. Because of the fact that this line is a palletized line, bank capacities above one hundred are not feasible due to both space and economic considerations.
3. Cycle time: 18.66, 17.66, 16.66 and 15.66 seconds. These represent the existing cycle time and reductions of one, two and three seconds respectively.
4. Downtime factor: 1.00, 0.95, 0.90 and 0.80. These represent the amount of downtime logged in the plant and reductions of five, ten and twenty percent respectively.
5. Number of jobsetters: one and two.

Any one combination of specific values for all five factors defines a "design point." If all design points, from the above levels, were simulated, 768 different configurations of the transfer line would be investigated. Such a full factorial experiment design is not only inefficient, but unnecessary. Therefore, 152 system configurations (design points) were selected to be simulated for one week each. Figure 4 maps these design points on the factor space. Both bank capacity and number of jobsetters are varied across the entire experiment. Sub-experiments A, B and C investigate the impact of varying bank location, cycle time and downtime factor respectively. Sub-experiment D varies cycle time and downtime factor simultaneously.

Finally, a "length of simulation" must be determined for the entire experiment. Any production improvement effected by altering a factor causes increased wear and more downtime events to occur in any given time period. Thus, the downtime history is compressed in time. Due to this increased system efficiency, the history, which originally covered seven days, covers less than that. Seven days cannot be simulated, because after a certain (simulated) time, the downtime history is exhausted and the occurrence of downtime ceases. However, in the simulation experiment, the downtime history was never compressed into less time than five full days. Therefore, the results reported here are for responses after five days (fifteen shifts) of operation. This is one standard work week, three shifts per day, without overtime operation.

RESULTS

Over thirty responses (output variables) were tracked throughout the five days of simulated time. Among these are total production, average production per shift, bank usage, jobsetter utilization and downtime and runtime for both sections. Downtime is divided into time required for actual repair work, time spent waiting for a jobsetter and forced downtime (one section is forced down by the breakdown of the other).

Also, two efficiencies are reported: "analytical" and "real". The reason for this revolves around the occurrence of one event which causes the breakdown of both sections, regardless of the presence or state of a bank. These are referred to as "DOWNT" type downtimes (for DOWN Total line). Analytical models do not allow for such an event. Therefore, in order to allow for comparison of these simulation results with the results of analytical models, the "analytical efficiency" is calculated without the "DOWNT" type downtimes. However, in reality the possibility of DOWNT type downtimes is not negligible. So, in order to allow comparison of the simulation results to the real world, the "real efficiency", which includes DOWNT type downtimes, is also calculated and presented in each report.

It is impractical and unnecessary to discuss all of these responses to all factors. In limiting the number of responses presented, the most uniformally acceptable measure of productivity was selected: average production per shift.

Using costs and the value of production, a conversion could be made to a productivity response in units of dollars. But the complexity of such a conversion would cloud the true effect of altering the five factors. Also, such a productivity response would not be universally acceptable. Finally, any changes in external or internal economic conditions would also require a reconversion of results. Therefore, average production per shift will be the primary response discussed.

Describing the effect of making changes in the system is one main objective of this study. Since all changes are relative, a base point (or base design point) must be established, against which to compare the productivity of other systems. For the presentation of these results, the base point will be the "existing system"; that is, the system as it now operates in reality. In terms of factor levels, the existing system has the following conditions:

bank location:	46
bank capacity:	0
number of jobsetters:	1
cycle time:	18.66 seconds
downtime factor:	1.00

Hence, any mention of the 'existing system' will indicate the system with these factor levels.

Main Effects on Average Production per Shift

The "main effect" of a factor is the effect on the response observed when only that one factor is varied. Figures 5 through 9 graphically illustrate the "main effect" of each of the five factors studied.

Figure 5 presents the impact of bank location. The average production per shift is plotted against bank capacity for three different bank locations and one and two jobsetters. There are six curves. The top three are for the three bank locations with two jobsetters; the bottom three are for the same three bank locations with one jobsetter. The dashed line, which represents bank location at station 29, yields the lowest production for all combinations of bank capacity and number of jobsetters except one. Consequently, this bank location was eliminated from further consideration. Comparing the dotted line and the solid line, bank locations 38 and 46 respectively, we see that each is superior in some combinations of bank capacity and number of jobsetters. The difference in all instances is quite small. Therefore, since no definative statement can be made as to which of these two bank locations is better, and since the existing system is most receptive to the introduction of an automatic bank at location 46, the bank location was considered fixed at station 46. This in effect eliminates bank location as a variable factor for the remaining analysis.

Figure 6, a presentation of the impact of bank capacity, indicates that there is a well defined pattern of large initial increases in production as the bank capacity increases from zero, followed by an asymptotic approach to some limiting value of production. Each point on this curve represents the average response of those 18 design points with the same bank capacity, but varying bank location, cycle time, downtime factor and number of jobsetters.

The form of this relationship between production and bank capacity is very similar to that predicted by analogous analytical models which vary only bank capacity.

Figure 7 illustrates the impact of reducing the cycle time and indicates a linear relationship between reduction in cycle time and the resulting percentage increase in production. The average impact of a reduction in cycle time of two seconds is approximately an eight percent increase in production. Each point on this plot is the average of sixteen different design points,with different combinations of bank capacity and number of jobsetters, but the same cycle time. While this linear relationship is not surprising, the inclusion of the cycle time as a variable is necessary to allow the assessment of the impact of other variables under a variety of cycle times.

Figure 8 also illustrates a linear relationship; this relationship is between the reduction in downtime and its impact on production. The percent increase in production due to downtime reduction is plotted against the percent reduction in downtime duration. Each point on the line is the average of 16 design points with the same downtime factor. On an average a ten percent reduction in downtime duration will increase production approximately eight percent.

The last factor to be considered is the addition of a second jobsetter to the line. If a second jobsetter were added to the existing line during the week simulated, production would increase 2.17 percent. However, this existing line has no bank and the second jobsetter is needed more when there is a bank present dividing the line into two sections. This is illustrated in Figure 9, where the lines describing average production per shift for one and two jobsetters are always further apart when a bank of any capacity is present. This is logical in that, with a bank present, one section can run while the other section is down; thus it is more likely that the running section fail while the jobsetter is busy on the down section, so requiring a second jobsetter. This non-additive effect of the bank capacity and the additional jobsetter is the vertical distance between any two points on the two curves. This interactive effect can account for as much as a 2.4 percent increase in production.*

Processing Information

In the entire experiment, 152 weeks of transfer line operation was simulated (1,094,400 minutes). This simulation expended 136 minutes of processor (CPU) time on an IBM System 370/Model 158 computer. Hence, 0.895 minutes of CPU were required to simulate each week's operation of the transfer line. The storage requirement for each run was 188K. Eight nine-page reports were generated for each week, resulting in 11,448 pages of output. The total cost of these runs was $1,743.52, or approximately $11.47 per week (design point) simulated.

The computer costs for development of these models was approximately $2,617. This includes the computer usage costs incurred while installing the GPSS-V processor, developing and testing the preliminary family of transfer line models (I.A.xx), developing the models presented here (I.B.xx and I.C.01) and creating the jobtape.

MODEL VERIFICATION

Literally, verification implies proof of truth. However, the application of such absolute concepts to simulation modeling runs counter to the nature of simulation. The verification of simulation is not a true-false or yes-no type question. Rather, verification is a matter of establishing confidence in the model. It is a process by which a degree of confidence in and confirmation of a model is developed spep-by-step. "If, in a series of empirical tests of a model no negative results are found but the number of positive instances increases then our confidence in the model will grow step by step." (11, p. B-93). Two such empirical tests are the comparison of the simulation model with the real system and with analogous analytical models.

Comparison to the Real System

Van Horn differentiates between verification and validation as follows: "Verification insures that a simulation model behaves as the experimenter intends. . . Validation tests the agreement between the simulation model and the real system" (12, p. 232). Assuming that realism is what is intended of the simulation model, validation is one step in the verification process.

The first step in insuring this match is to check the environment within which the simulation runs. Often, in simulation experiments, this step would entail the inspection of random number streams and the comparison of simulated and real distributions of runtime and downtime durations. However, since no random determination of events was employed in these models, neither of these techniques is applicable. The 785 transactions on the jobtape were listed. Since each transaction represents a downtime event, the parameters of each transaction were compared with the appropriate properties of the corresponding downtime event from the original downtime history. No discrepancies were found. Hence, it can be said with a high degree of confidence, the jobtape was created and is functioning properly; and therefore, the simulation model is running in the proper environment.

During the first five days logged in the plant, the real existing system was up 44.8847 percent of the time. The "real efficiency" of the simulated existing system was 44.8846 percent during the first five simulated days. Thus, within any reasonable accuracy, the simulation model has exactly duplicated the behavior of the real system.

Comparison to an Analytical Model

The simulation model's ability to duplicate the real existing system's behavior has been verified. However, to raise the confidence in the model as a predictive tool, it must be compared to an analytical model which predicts the changes in efficiency as one factor changes. J. A. Buzacott's stochastic (Markov chain) model was used for this comparison (13).

For bank capacities from zero to 100, Figure 10 compares the "analytical efficiency" from the simulation model to the efficiency calculated using the analytical model. The general responses to banks of various capacities, as predicted by the simulation and analytical models, are very similar. However, there are two notable differences between the curves of Figure 10. First, the simulation model predicts a slightly lower efficiency when there is no bank. Secondly, the analytical model yields a much more optimistic prediction of the impact of banking.

The small difference in efficiencies for the system without a bank can be attributed to the analytical model's assumption that the breakdown rate for a section already down (either forced down or broken down) is zero. In the real system, time dependent downtimes can occur while the system is down. This possibility is reflected in the simulation model. While this inclusion accurately reflects reality, it lowers the simulated efficiency below the analytical efficiency.

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*For a discussion of all interactive effects consult reference 10.

The differences in the predicted impact of banking can be attributed to three causes. First, the data collected at the plant does not fit the distributions assumed by the analytical model. The real distribution of downtime durations have much higher standard deviations, indicating more very short and very long downtimes than the assumed geometric distributions of the analytical model. The bank has very little effect on the impact of very long downtimes. Therefore, the simulation model indicates a lower increase in efficiency, due to banking, than does the analytical model.

The second reason for this difference in the predicted effect of banking is that patterns exist in the real data. That is, a series of several successive failures in one section, or even one station, often occurs in the plant. This is simply a characteristic of the behavior of a real system. These patterns, while present in the real data, are lost in the analytical model because of the assumption that the system has "no memory". Again, the occurrence of several successive downtimes on one section is detrimental to the positive impact of the bank; and therefore lowers the simulated increase in efficiency below the analytically predicted efficiency.

The third reason for differences between the predicted efficiences deals with the basic differences between the analytical and simulation techniques. In applying the simulation model a distinct stream of downtime events is employed as an environment for the simulated transfer line. This stream can be either randomly generated from some distribution(s) or a duplication of some observed downtime, as in the simulation model presented here. Since either stream is necessarily a finite sample, the efficiency of the simulated transfer line can be expected to vary somewhat from that of the analytical model. This is true even if the simulated stream of downtimes and runtimes exactly fit the distributions assumed for the analytic model. The difference is dependent upon the amount of time simulated and would be present with a bank of any capacity including zero. As the length of time increases, the differences caused by this effect lessen. Since the simulation presented here ran for 120 hours, the effect of this mechanism should be minimal.

All three of these factors lead to a more conservative prediction by the simulation model; and one which more accurately reflects reality. Because of these differences between the magnitudes of the efficiency increases predicted by these two methods, the choice of the model employed may well dictate the investment decision. Such overly optimistic predictions by the analytical model might well lead to unwarranted capital investments.*

Observation of Simulation Runs

The last test of any real system is usually to turn it on and watch it run. By using GPSS blocks designed for this purpose, the same can be done for a simulation model. By adding "TRACE", "UNTRACE" and "PRINT" blocks at the appropriate locations, the movement of transactions throughout the model and the changing of system variables can be observed continuously. Over fifty such blocks were added to the simulation model and its operation was observed for over eight hours. During that time, the line was always performed as was intended.

All of these steps of verification have yielded positive results. Confidence in the simulation model has been raised to the point that management and investment decisions can be based on its predictions.

CONCLUSIONS

The application of this model to the specific transfer line predicted that significant increases in productivity are attainable through expeditious changes in line design and/or management strategy. Adding a bank with the capacity for 50 workpieces, after station 46, increases productivity 7.35 percent. Adding a second jobsetter and that bank together increases production 11.93 percent over the existing system.

Decreasing the duration of all downtimes ten percent, along with the bank and the second jobsetter, increases productivity 20.28 percent; reducing the cycle time two seconds, along with the bank and second jobsetter, nets a 22.65 percent increase.

Finally, implementing all four of these changes simultaneously produces a 30.78 percent increase in productivity.

In this simulation model, a tool has been developed which can be applied to other transfer lines, as well as to the line investigated. The model developed is extremely flexible. With minor, one-statement, modifications, any of the five factors can be altered: bank location, bank capacity, number of jobsetters, cycle time and downtime duration. Provided the applicable downtime history, the model can be immediately applied to any line, of any length or cycle time.

This model represents an improvement over analytical models in the areas of accuracy, complexity and flexibility. Behavioral interactions clearly visible using the simulation models would be masked by the simplifying assumptions which characterize the applicable analytical models.

The model goes far beyond the predictive accuracy originally envisioned. Even using the exact distribution of downtimes and runtimes from the plant, a simulation model employing random event generation would not duplicate the patterns of the plant, and thus would lose accuracy. The model presented here does not suffer from this shortcoming.

The size, complexity and the probabilistic nature of large manufacturing systems make their analysis a difficult task. However, a well designed simulation model, including all significant factors, can provide needed insight into behavior of the system, and even accurate predictions of the expected impact of various changes in system design and management strategy.

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*For a complete discussion of the comparison of these two models consult reference 14.

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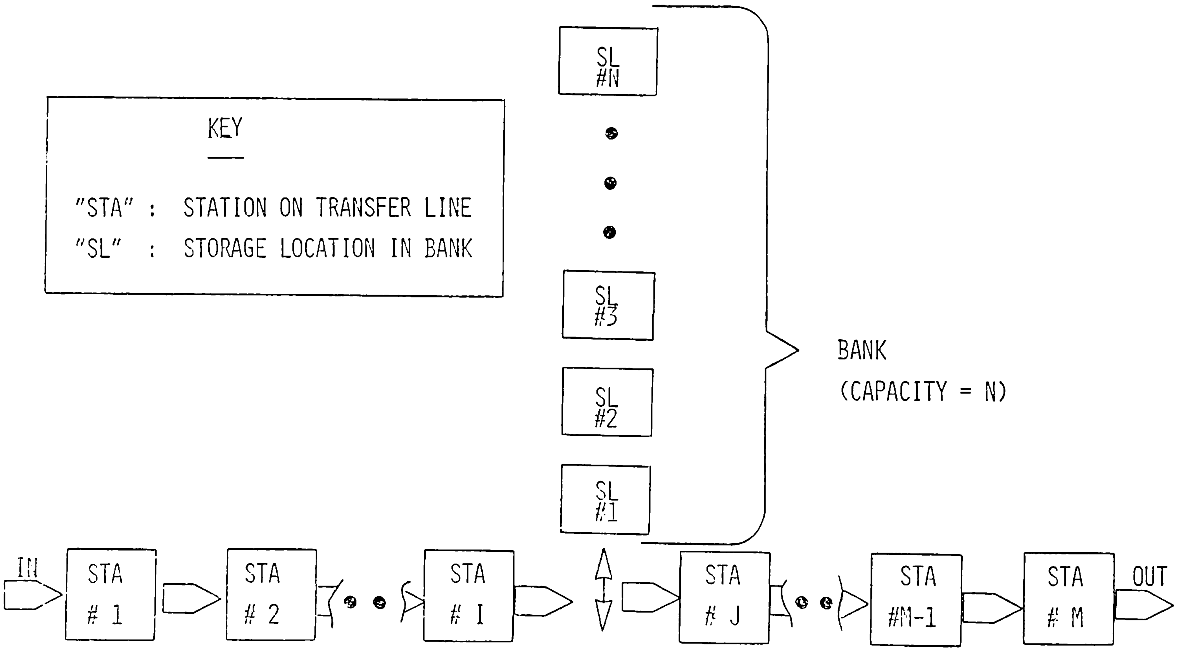


Figure 1 - Transfer line with bank

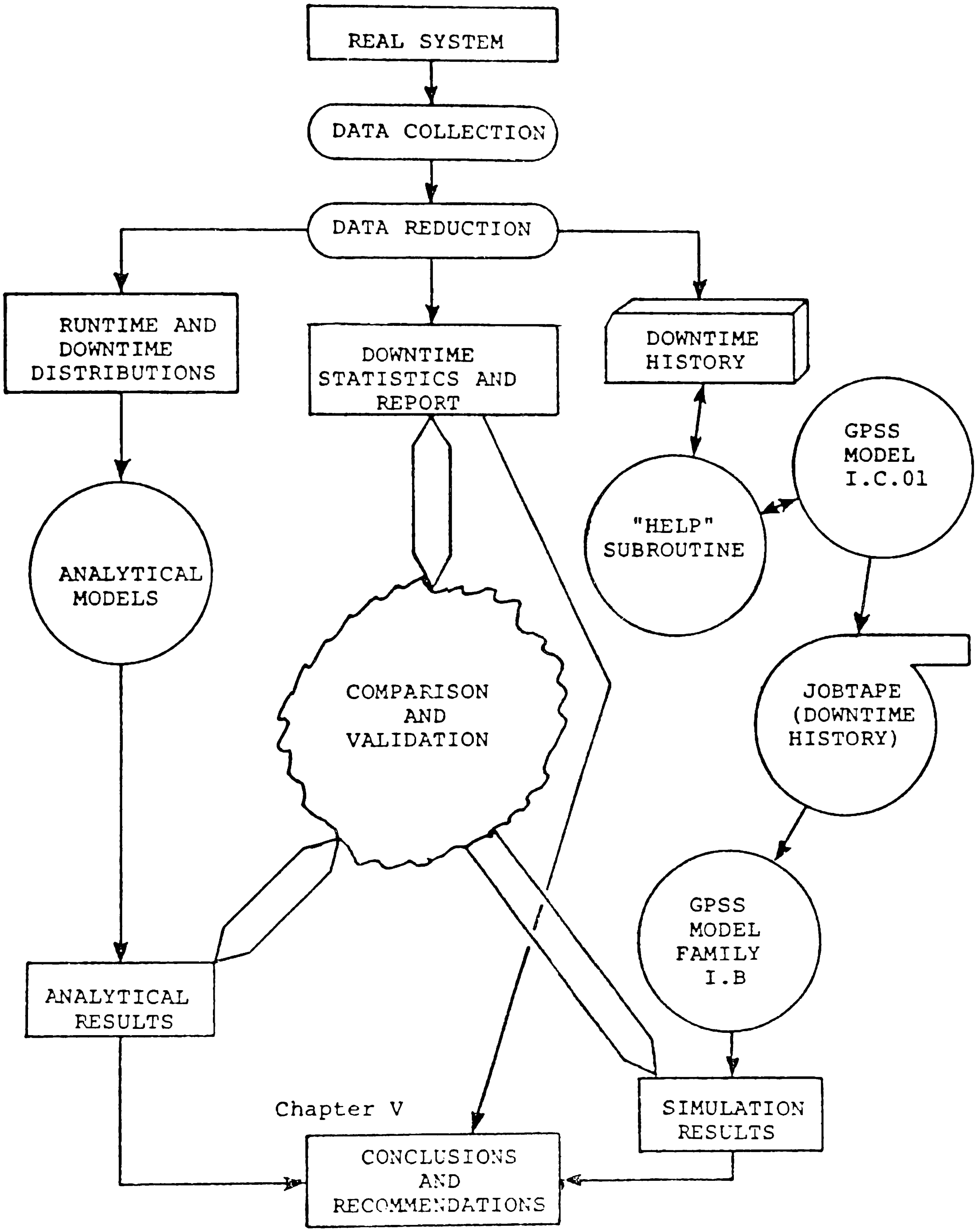


Figure 2 - Project overview

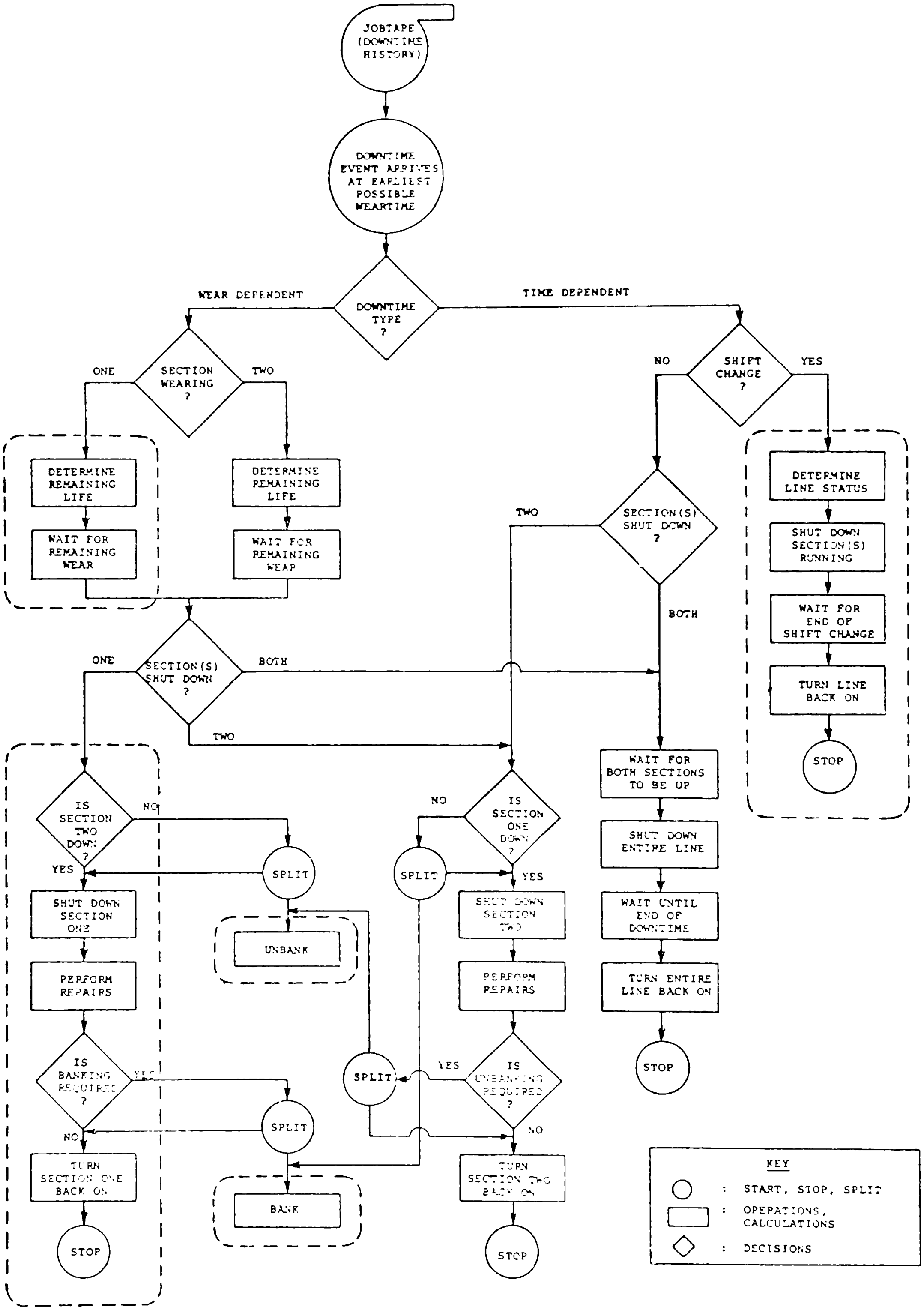
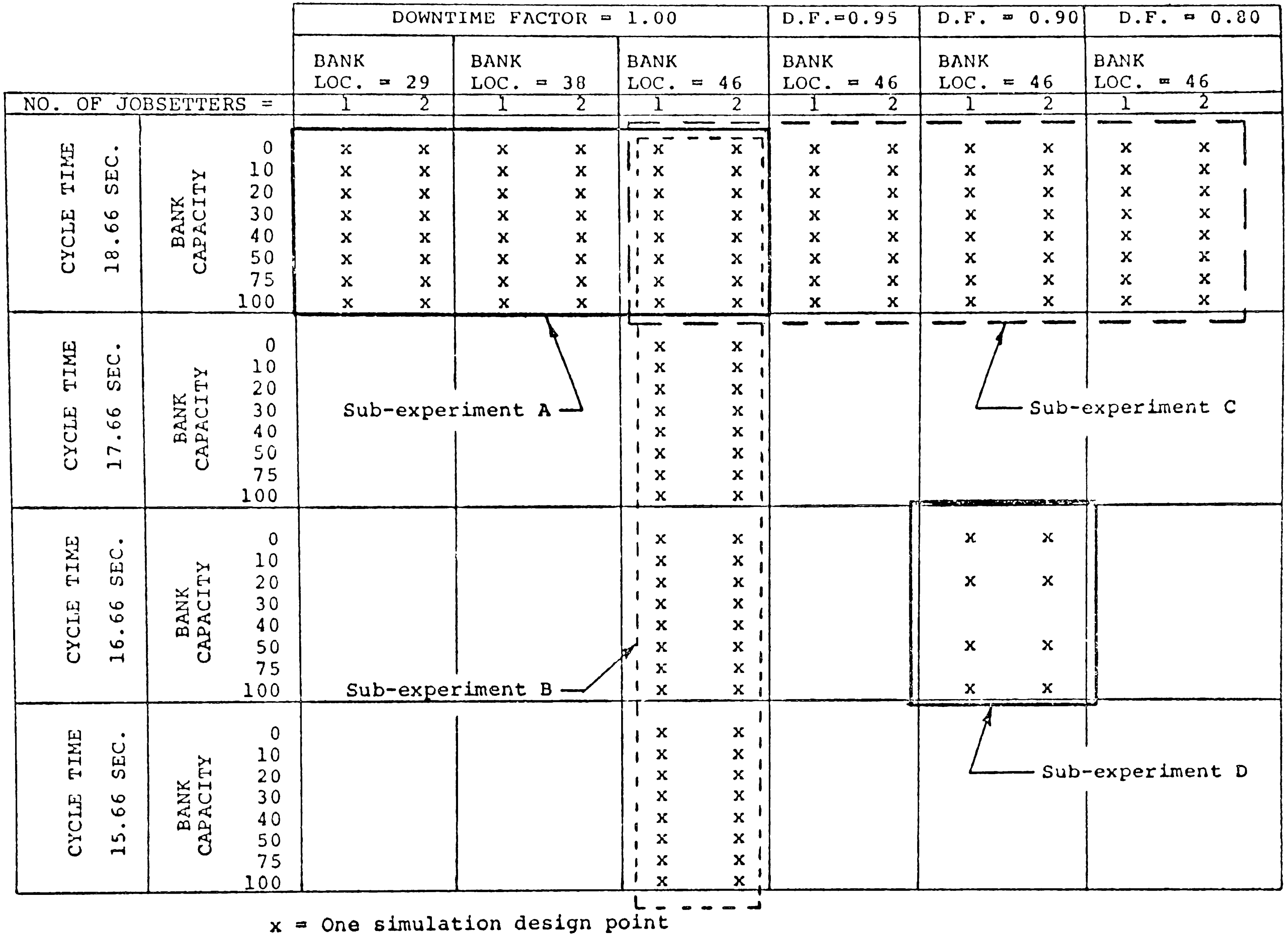


Figure 3 - Simulation model logic



x = One simulation design point

Figure 4 - Simulation experiment

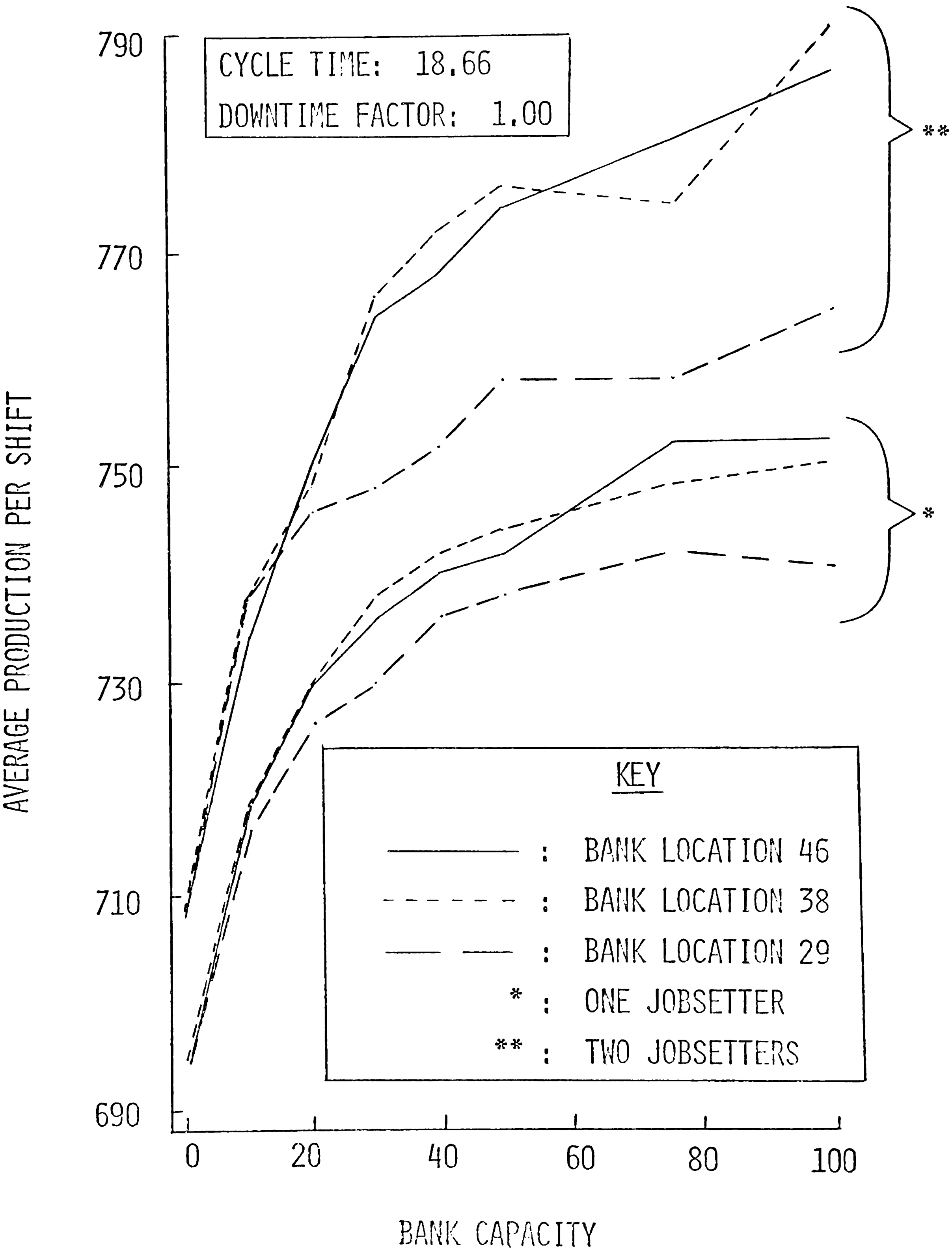


Figure 5 - Impact of bank location

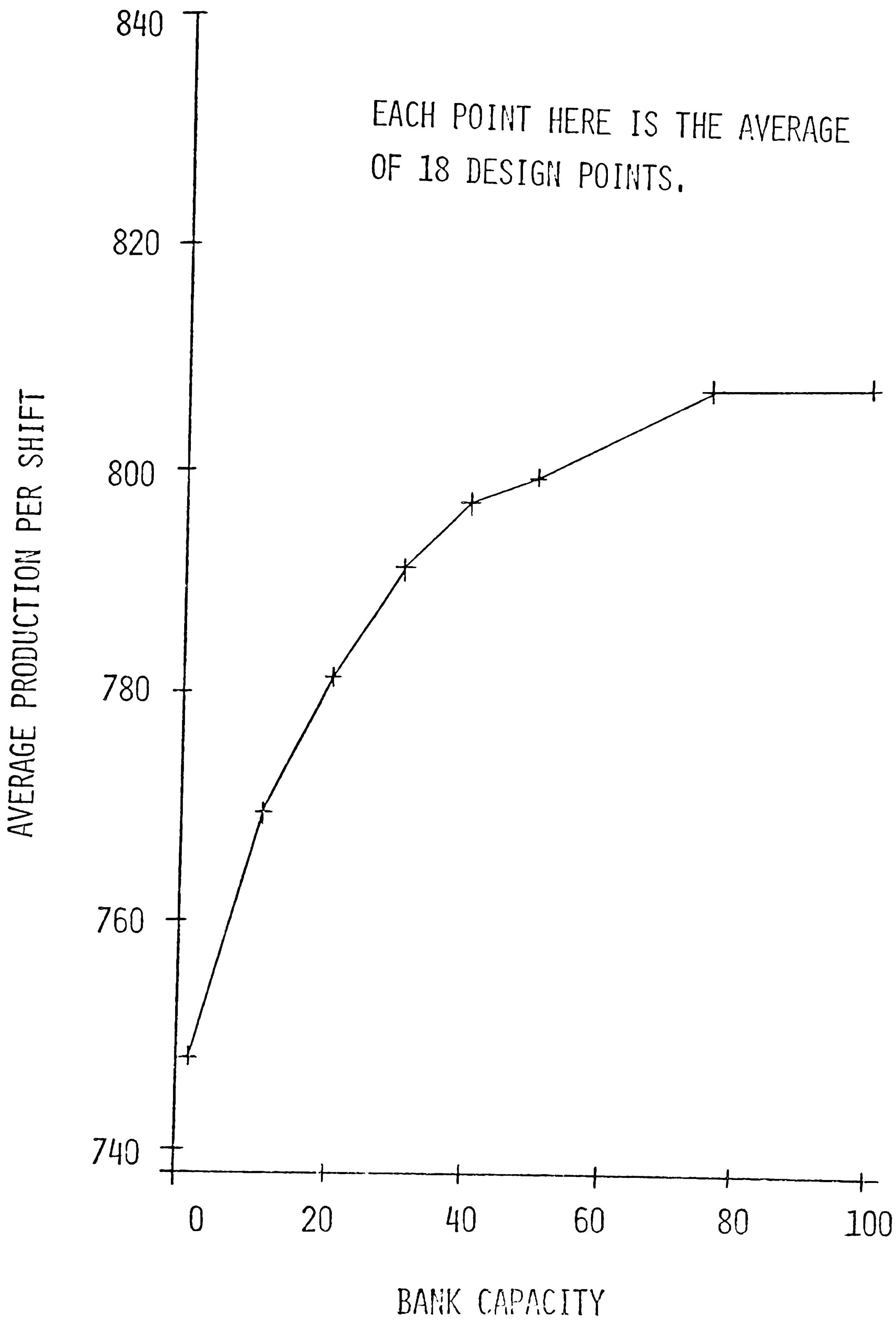


Figure 6 - Impact of bank capacity

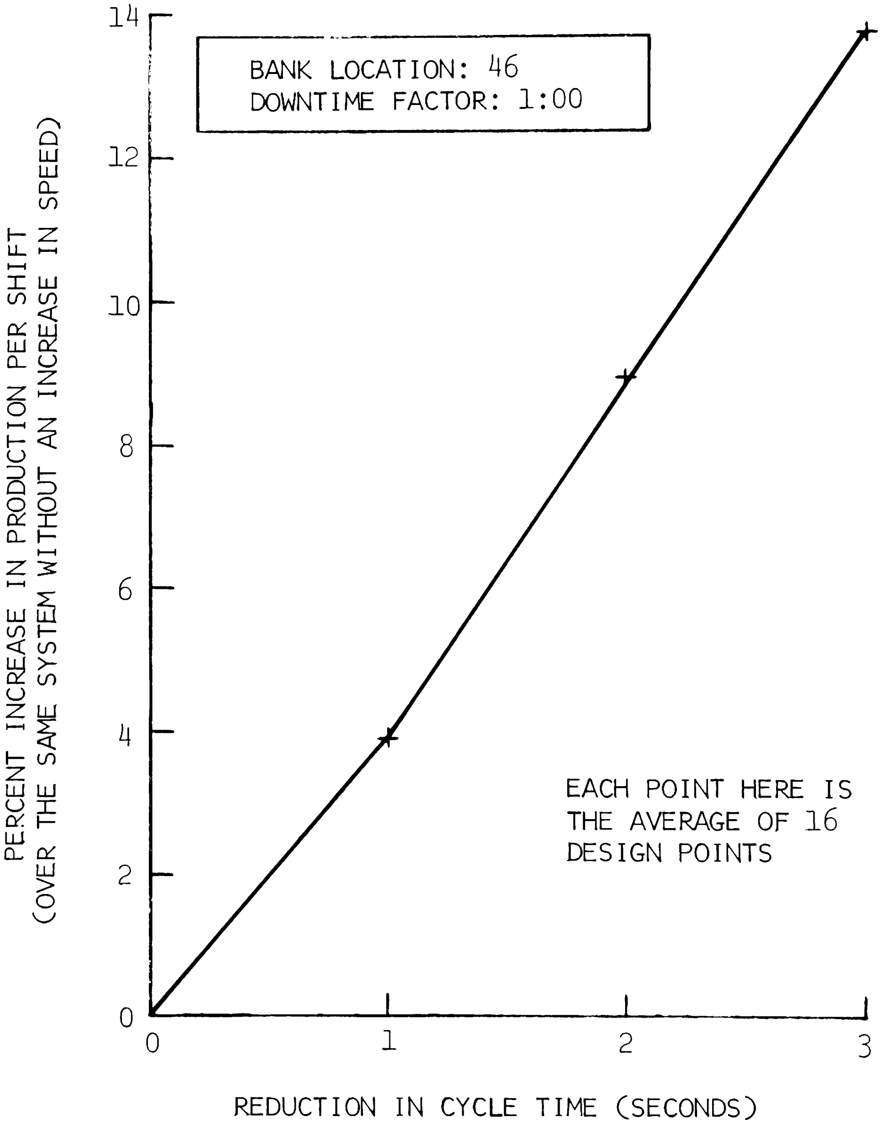


Figure 7 - Impact of reduced cycle time

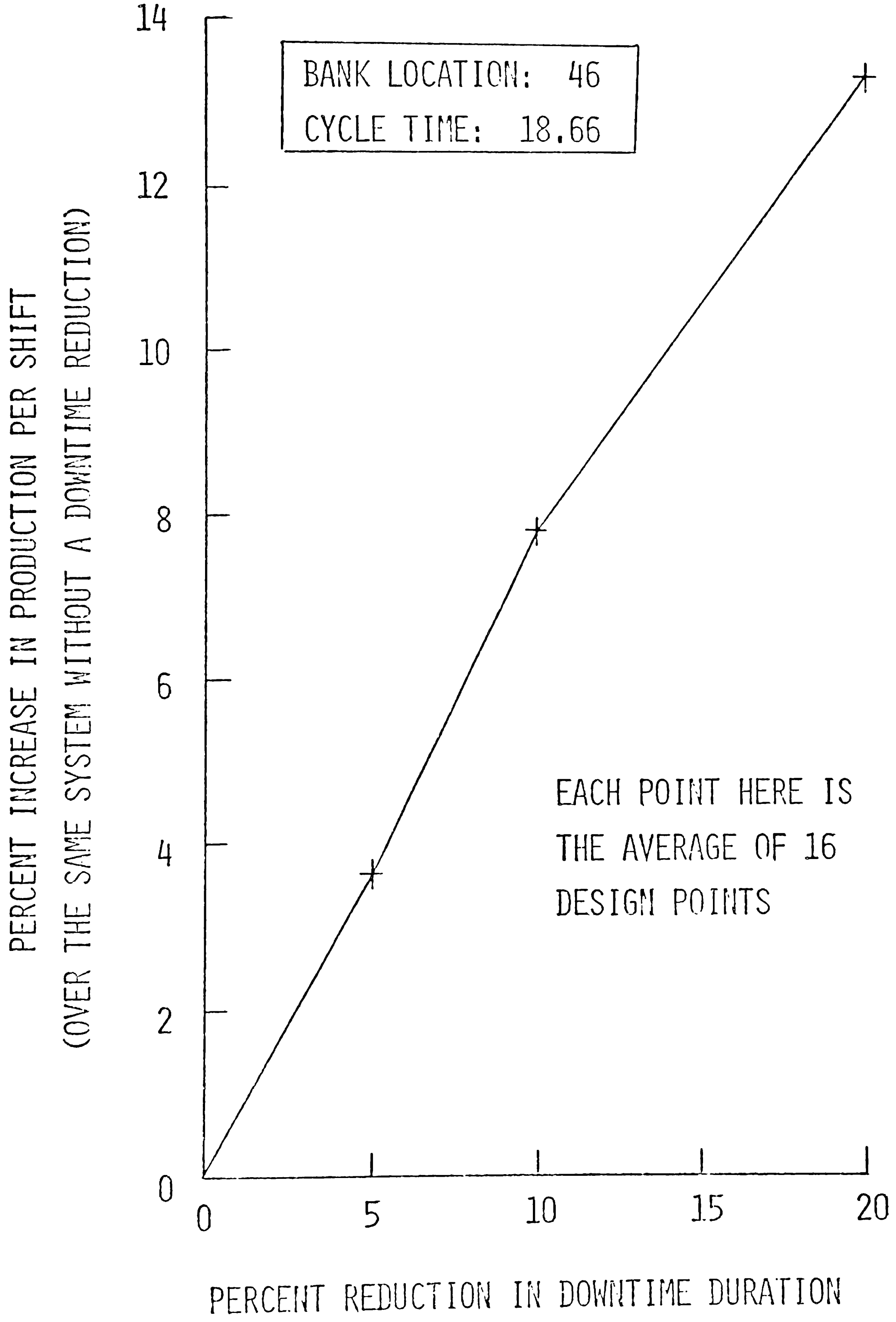


Figure 8 - Impact of reduced downtime duration

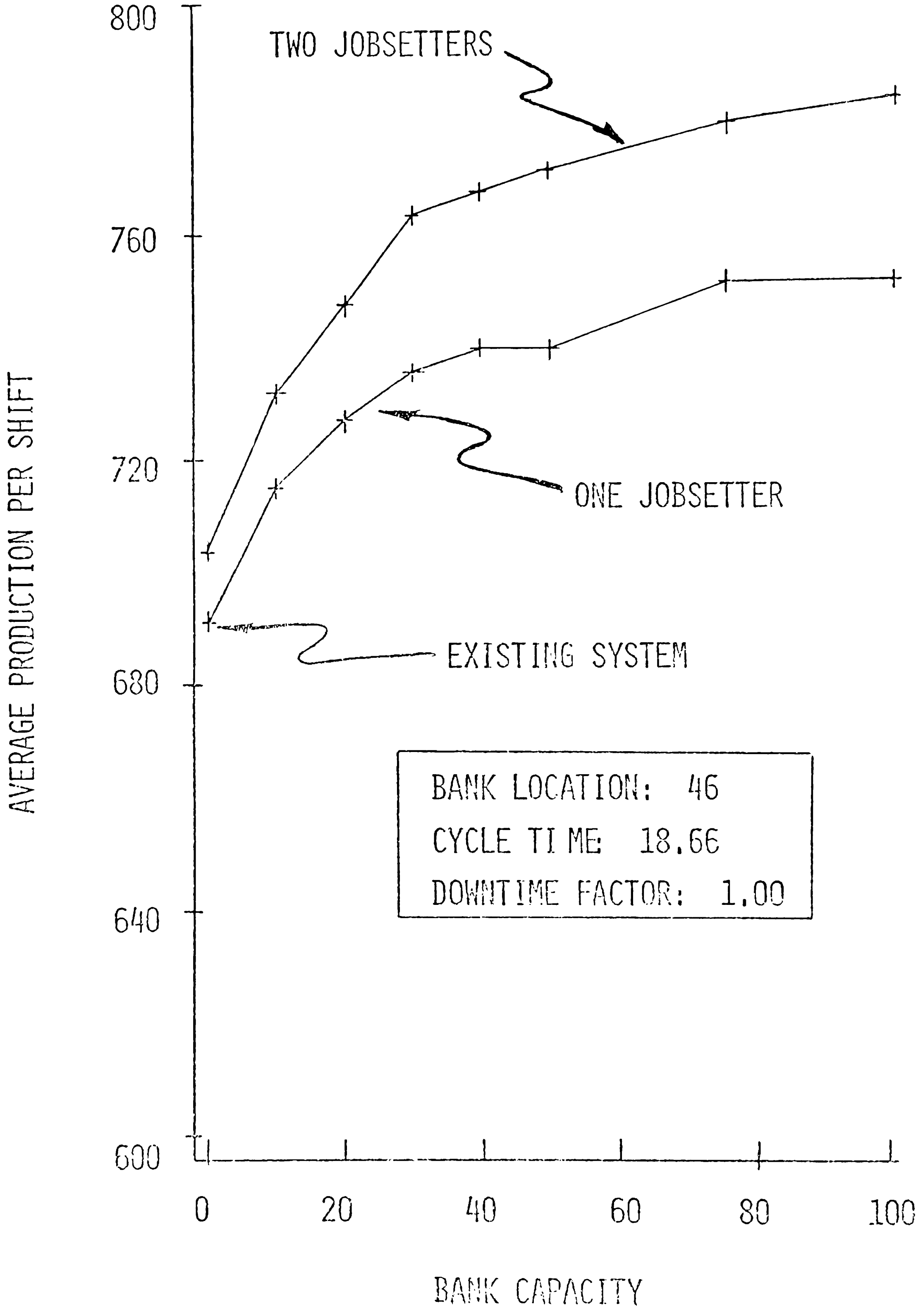


Figure 9 - Impact of second jobsetter

COMPARISON OF EFFICIENCIES PREDICTED BY ANALYTICAL AND SIMULATION MODELS

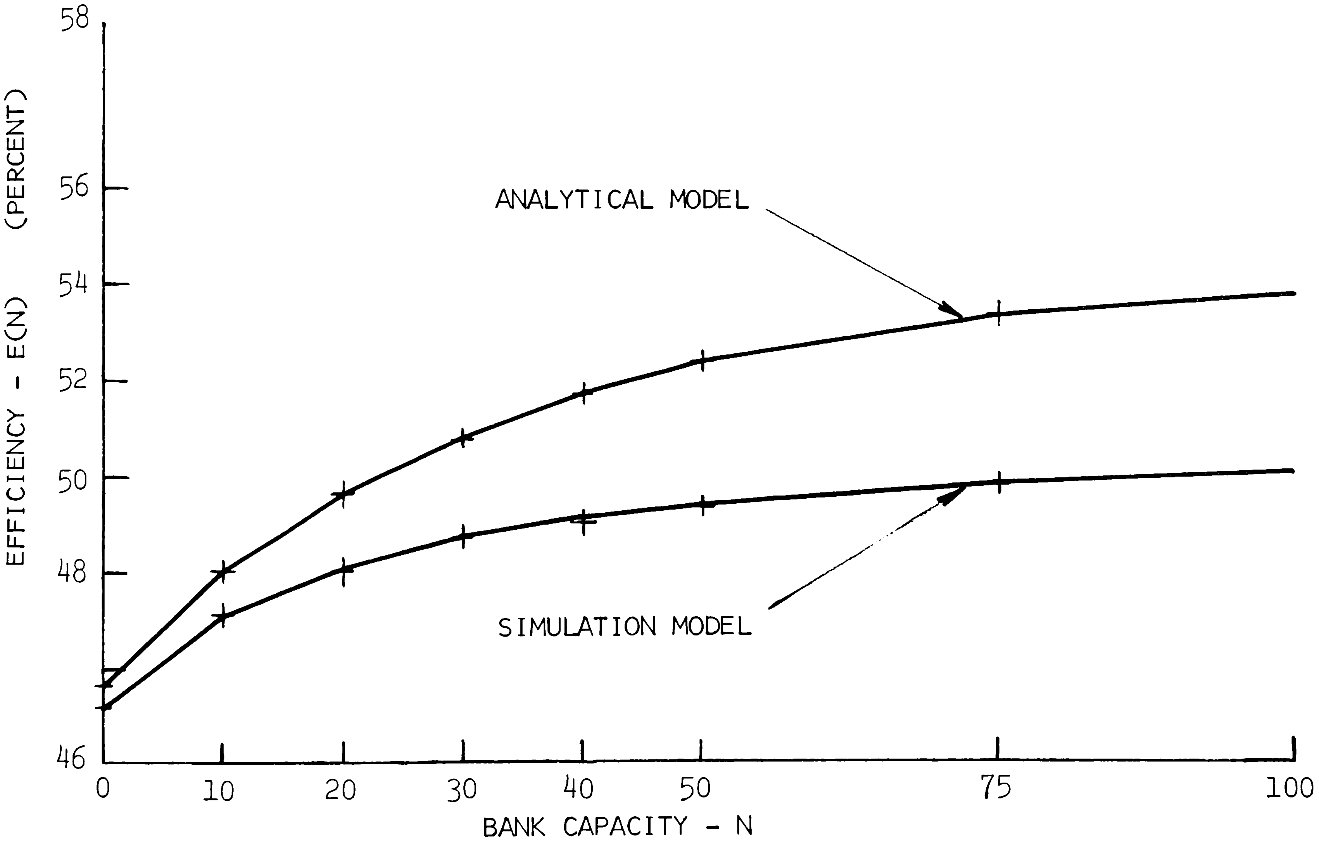


Figure 10 - Comparison of analytical and simulation models