COMPUTERIZED MANUFACTURING SYSTEMS: A NEED FOR INTEGRATION

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1. INTRODUCTION

Computerized Manufacturing Systems have been developed in order to deal with the growing specialization of modern products. These systems provide a capability to economically produce small to medium quantities of a wide variety of parts which demand exacting tolerances. Through the minimization of human interactions, these systems have provided engineers with a much stronger influence on productivity, quality control, and reliability.

The need to combine the flexibility and ease of set up of numerical controlled machining centers with the advantages of an automated transfer mechanism has given rise to one form of computerized manufacturing systems. One of these systems is of interest because of its ability to handle very large workpieces which must be machined to extremely close tolerances. This system was built by Sundstrand for operation at the Caterpillar Company in Peoria, Illinois.

The replacement of human decision-making in this system has placed an increased burden on the computer software which controls system operation. It was desired to modify the system configuration, including software, in order to improve system operation. Experimentation with the system was not possible since production could not be disrupted. In addition, any such experimentation would need to be extensive since the interactions between the physical system and its control logic have reached a level of complexity beyond intuition. For these reasons, the improvement study used a tool of systems analysis; namely, simulation.

Numerous manufacturing facilities have been simulated during the past two decades. Flow shop simulations (12), queue-server simulations (11), and others have been developed and are currently being utilized by industries to help determine system bottlenecks (4, 5), effectiveness of line balancing procedures, optimum lot size, and part sequence impacts. They are also used for determining the effect of machine downtime and worker absenteeism. These simulations have been used to analyze existing systems to try to determine, without expensive real-time experimentation, the effect of both physical and structural changes and managerial policy changes (6, 14). They have also been used as a design tool particularly in the area of transfer lines and job shop layout (7, 9, 15).

2. DESCRIPTION OF SYSTEM HARDWARE AND SOFTWARE

2.1 DNC MACHINING SYSTEM (HARDWARE)

The simulation program described in this paper models the Sundstrand Omnicontrol DNC (Direct Numerical Control) line at the Caterpillar Tractor Company in Peoria, Illinois. The line, shown in Figure 1, consists of nine machines fully integrated with a material handling system, and a DEA coordinate inspection machine. A remotely located Digital Equipment Corporation PDP 11/20 computer and supporting equipment control the entire system on a real-time basis.

The line's metal cutting machines include four OM3 Omnimills, five-axis machining centers; three OD3 Omnidrills, four-axis drilling machines; and two G & L vertical turrent lathes. The machines are arranged on opposite sides of center rails on which two automated Conco tractor-type transporters, each equipped with two cross-traveling shuttle mechanisms, provide in-process material handling. The shuttle cars also deliver parts, as directed by the computer, to the DEA coordinate inspection machine.

The machines and the transporters are fully controlled by a Sundstrand Level One Omnicontrol computer system. Cathode-ray tube display and keyboard consoles at each machining station provide for on line system status evaluation and manual override capability.

Material input and output to the machining system occurs in the 16-station Load/Unload area located midway along the line's length. These stations also provide for in-process inventory.

The parts being machined on this line are housings for automatic transmissions. There are two different sizes, the smaller housing weighs approximately 300 pounds, the large housing weighs approximately 600 pounds. Each housing is made up of two units, a "case" and a "cover." The units arrive at the facility in rough casting form and leave as an assembled matched pair. The number of basic machining operations performed approaches one thousand, this total is divided into approximately forty operation sets per unit.

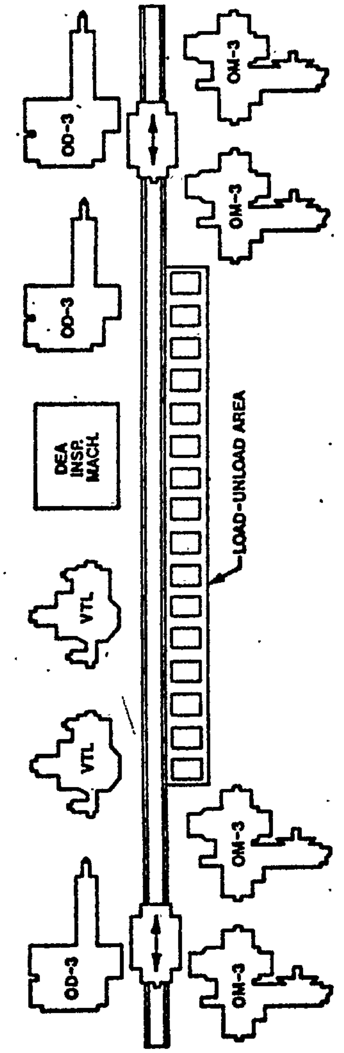

Figure 1

2.2 DNC MACHINING SYSTEM (SOFTWARE)

As mentioned above, material handling is accomplished in the system by two transporters on the same track. These cars are unable to pass each other, though each car can service any machine or station on the line. One of the functions of the system software is to provide for efficient material handling by controlling the transporters so as to minimize moves and prevent interference. Two programs are critical to the control of movement of parts through the line; namely, Line Map and Line Control.

2.3 LINE MAP

Line Map is a static program which evaluates the line configuration (i.e., which machines and cars are in operation, which parts are being produced) and attempts to assign required operations to the machines in such a way as to balance the work load on every machine.

Line Map produces a basis from which a priority assignment can be derived. The controlling logic, under which the parts are delivered to various machines, uses this priority scheme as a framework for generating the decisions which produce a job-machine sequence so as to minimize the make span of the finished part. The conceptual equivalent is the minimization of the Gantt chart for the group of part operations considered under each generation of a Line Map.

2.4 LINE CONTROL

Line Control is responsible for the actual movements of the parts on the line, i.e., which part goes to which machine at what time. It also must monitor the shuttle car movements to prevent crashes and improper operation of the positioning mechanism. Line Control is a dynamic program which allows for active intervention by the operators in order to adjust to inconsistencies such as system failures or tool wear.

In order to determine which machine will be serviced next, Line Control uses a priority system and a movement chaining concept.

The priority system is based on the magnitude of the cycle time of the machines. Highest priority is given to the machine with the longest cycle time and so on down to the machine with the shortest cycle time having the lowest priority.

The movement chaining concept is implemented in Line Control by first checking the highest priority machine which is available for machining a part. If a part is requesting any of the operation sets assigned to that machine, trying the highest priority operation sets first, then this machine is considered the center of a chain of movements. If the machine has a part on it, another machine must be found which is available (requesting) or the part must be set on one of the Load/Unload stations which is empty and available for in-process storage. This machine and the one which receives this first successor part (and so on) form the forward chain. Next an attempt is made to find a part for the machine which supplied the center machine with the first part. If such a part is found, then another attempt is made to find a part for what has become the first machine in the backward chain. This process continues until there is no appropriate requesting part. The machines identified during the successful iterations become the elements of the backward chain. When a valid chain is produced, the Line Control assigns a car to this command sequence such that the last member of the backward chain is serviced first. Then the commands are executed in sequence through the center machine and out to the last machine in the forward chain.

There are many other factors considered by both Line Control and Line Map, but the essence of what they do has been described. This system has operated under automatic control at Caterpillar for over two years. The software, including Line Control has proven to be operationally very reliable, however functionally there have been difficulties.

3. PROBLEM ANALYSIS

Because of the rules involved in the assignment of operations to the individual machines, no two machines can perform the same operation. Given that this restriction must be maintained and given that the priority scheme previously described is used as the basis for determining which part is serviced, then the control logic should service the system in such a manner that the parts move through the system in the order which was previously envisioned by the designers who wrote the Line Map.

In this instance, the concept of maximizing the through-put of the system by efficiently allocating jobs to capable machines and fixing the movements of parts through the system in a lockstep manner is a manifestation of the Gantt Chart concept of line balance which, in the absence of any breakdown conditions or rework requirements, can produce a very high utilization of the equipment involved and also a respectable level of production. Unfortunately, the reliability (or more appropriately the unreliability) is a cumulative entity. For this reason, even highly reliable components in a tightly coupled system without sufficient backup capabilities can cause the overall system to exhibit a fairly low level of reliability and, therefore, low productivity. The inappropriate restrictions of the control logic negating the functional flexibility of the hardware system.

An objective of our effort was to find those changes that could be made in the present software or human procedural systems so that a closer match could be realized between the planned sequence imbedded in the Line Map and the actual physical movement of parts as orchestrated by Line Control.

Observation of system operation over an extended period indicated at least three areas for possible improvement; namely, (1) the Line Control algorithm, (2) Load/Unload station placement, and (3) material input strategies.

The Line Control algorithm was chosen for study because certain activities, such as servicing a member of the backward chain or "by-passing" a move because of an inability to construct a feasible forward chain, inhibited the servicing of the <u>highest</u> priority machines and so could be considered as a costly constraint to the system. The following alternative control strategies allow investigation of system behavior for various degrees of such constraints.

1. Full forward and back chaining
   (This was implemented as originally designed in order to provide a standard for comparison to determine improvement or degradation.)

2. Forward chaining only

3. Forward chaining only with unloading from the origin machine possible
   (This allows what would have been an infeasible command sequence to be made feasible utilizing the temporary storage capabilities of the system.)

4. No forward or backward chaining
   (This should be the most flexible delivery mode of operation and thus the most responsive to the system's needs.)

Observation of the line indicated that the Load/Unload stations which were used as temporary storage facilities at one end of the line seemed to be highly utilized where as the ones on the other end sat idle for long periods of time. It was expected that better balance would ease congestion in that area and reduce the amount of interference conditions. Two alternative locations were:

1. Present location of the stations

2. Present sequence but with dedicated stations shifted two positions to the right.

OPERATIONAL PROCEDURES

From observing the system, it was evident that when the system requested certain raw castings, it often was not given one. This was particularly true of the covers. The reason for this practice was that the covers compete with the assemblies for several key machines and by reducing the number of covers in the system (by producing an excess and then storing them off line) the foreman could increase the line's productivity.

The following input strategies were considered as alternative practices:

1. No stock control level of any part type (the system receives parts as the pallets become available).

2. Stock control level of "1" for covers or cases. This means that after a specified start up level is achieved, the system receives a raw case or cover only after it has accepted a new raw assembly.

3. Stock control level of 5 with a "resumption of manufacturing" level equal to 1 for covers. This means when the queue of finished covers reaches 5, production of covers halt until 4 have been used to make assemblies. Cases have unrestricted input.

4. Stock control level of 10 with a "resumption of manufacturing" level equal to 1 for covers. Cases have unrestricted input.

4. THE SIMULATION PROGRAM

4.1 FLOW CHARTS

The simulation model of the Caterpillar system is written in FORTRAN using GASP IV and follows as closely as possible the real life system while still maintaining the versatility which was desired in order for it to be used as a tool for experimentation with this line and other proposed automated manufacturing facilities. The model is of the discrete-event type and there are three major events associated with system operation. These are labeled Load, Unload, and Finish. The Load event models the loading of a part onto a machine. The Load event is scheduled to occur at that time represented by: (1) the travel time from the point where the car picked up the piece to the destination machine, (2) the positioning time of the car, and (3) the actual loading time onto the destination machine. The Unloading event is similar to the Load event except that it models the removal of the part from the machine. The Finish event can be scheduled at the time of a Load since the cycle time of the operation sets are all deterministic. The Finish event puts the machine and part in "Requesting" status for whatever is scheduled to occur next. Each of these three major events are described later in more detail.

Figure 2 shows a flow chart for the logical progression of the simulation program. A program listing is shown in (Report No. 4, Ref. 8) and is available through the authors. Referring to Figure 2, the program proceeds as follows:

1. Read in system specific information

   a. Machines in operation
   b. Zones status
   c. Cars status
   d. Part to be machined
   e. An order list of operations to be performed by each machine on each part, length of time, and other specific information

2. Assign priority to each machine and to each part operation on a machine according to priority rules

3. Set up initial start up conditions, schedule initial operations to be finished, initialize part files

4. Relinquish control of the simulation package to GASP

5. GASP determines next (first) event to occur. This event calls (LINCTR) Line Control which is responsible for the movement of parts on the line.

6. Line Control checks if a chain of commands for a shuttle car can be built. If so, subroutine CHAIN is called after which subroutine COMCHA loads that chain into a file

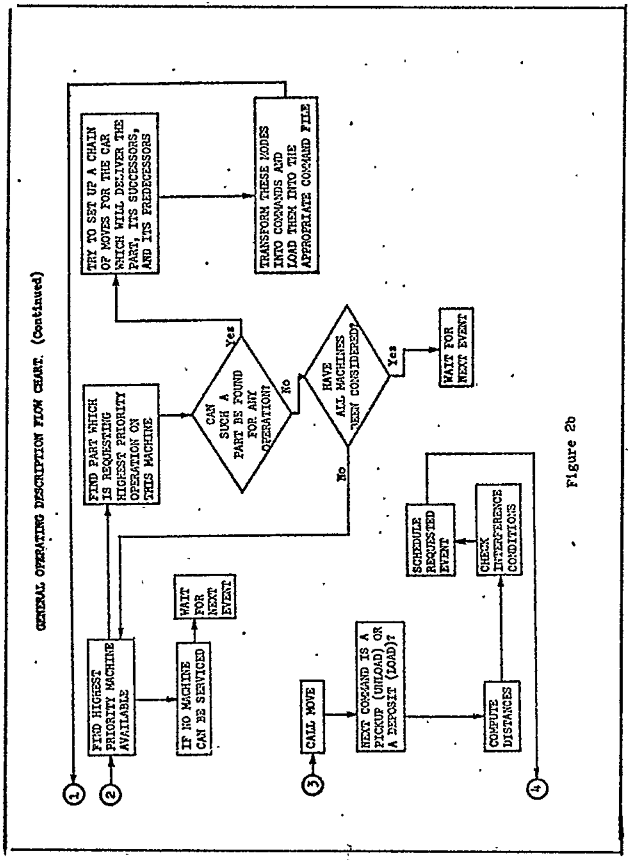

Figure 2b

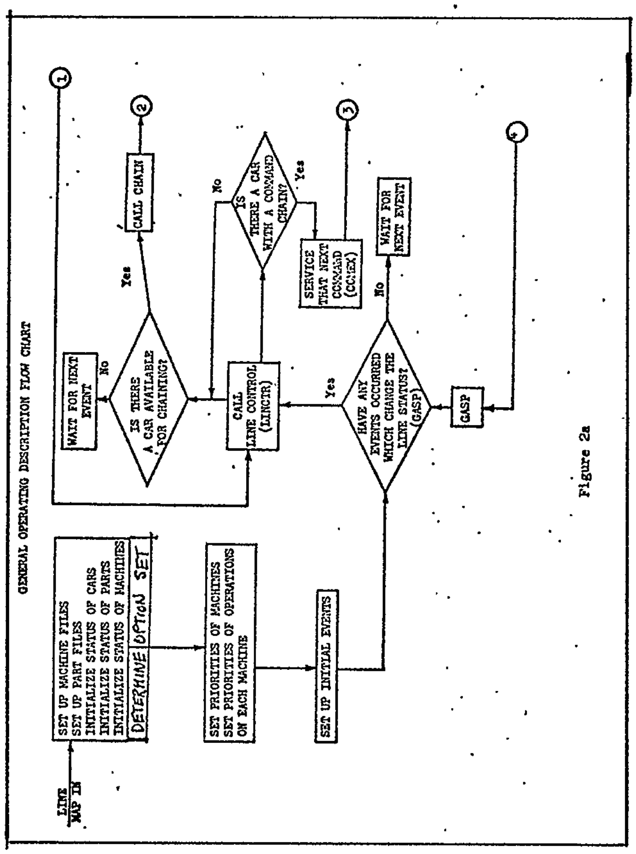

Figure 2a

so that the chain becomes the command template for the particular car around which it was built.

7. If a command chain exists for one of the cars, LINCTR calls COMEX (Command Execute) which removes the first command from the command queue and starts it processing. In order to do this, COMEX calls DISTNCE and INTFR which give respectively the distance and the destination of the car and checks for interference conditions which might exist along the way.

8. If conditions are favorable, a Load machine or Unload machine event is scheduled to occur and control is returned to LINCTR.

9. LINCTR finally checks to see if the conditions are present for a special load at the Load/Unload stations. If so, their finish is scheduled in the event file and control is returned to GASP.

10. GASP updates "TNOW" to the next event in the event file and processes that event.

11. When "TNOW" = "TTFIN" (end time), GASP prints a summary report which contains a snapshot of the file contents for each file as well as the results of the statistical data collection routines (i.e., for each observed variable the mean, maximum, minimum, standard deviation of the mean, and the total number observations made). Finally, the plot of production is output for each part type as well as graph of the time in the system for each part type.

4.2 VALIDATION AND VERIFICATION

In order for the simulation model to be a credible tool for system analysis, the model was subject to the processes of verification and validation. Verification (establishing that the model indeed behaves as the experimenter intends) was accomplished by tracing the cart movements, the progression of operations on specific parts, the entrance and exit of parts, and the formation of command chains, etc. These activities were checked and verified to be occurring according to the current operating practices at Caterpillar. Validation (establishing that the output of the simulation accurately reflects the real life situation) was difficult to perform due to the lack of production data for time periods of complete automatic operation of the Caterpillar line. However, the output of one shift which, except for some rework pieces, ran under complete automatic control was available. These results show the model output for the number of operations per shift is within five percent of the actual number of operations performed by the system. Also, the average length of command chains built by the simulator corresponded closely with the actual averages observed on the physical line.

5. POLICY ANALYSIS

5.1 INTRODUCTION

The policy analysis was conducted in the context of a computer simulation experiment (13). The experiment was conducted as a full factorial experiment. Thus every level of a factor was combined with every level of every other factor. The main advantage to this approach is the ease in identifying the factor interactions over a wide range of levels. It is also relatively easy to set up and execute. The purpose of the factorial design is to provide a means for establishing which independent factors have significant effect. Ultimately we want to identify which levels of a particular factor are significantly better than other levels of that factor.

The dependent variables (response variables) were the number of operations per day and the number of finished pieces per day. These measured factors were chosen since they provide an easily understood and widely used performance measure for analyzing manufacturing systems.

5.2 STRUCTURAL MODEL

The controlled factors involved in this experiment can be classified as either fixed quantitative or fixed qualitative. The Line Control Policies and the Load/Unload positions are fixed qualitative factors. The Input Policies are fixed quantitative.

As indicated, the experiment was designed as a 4x2x4 full factorial experiment with all factors fixed as follows:

FACTOR 1: Line Control Policies

Level 1 - Full forward and backward chaining
2 - No backward chaining, full forward chaining
3 - No backward chaining, full forward chaining with offload from origin machine
4 - No forward or backward chaining

FACTOR 2: Load/Unload Position Policy

Level 1 - Present position
2 - Proposed balanced with respect to usage location

FACTOR 3: Input Policies (of raw castings)

Level 1 - No stock control
2 - Stock control with cut off level of one
3 - Stock control with cut off level of five
4 - Stock control with cut off level of ten

The mathematical model for the 32 treatment combinations with one experimental unit per combination is:

$$Y_{ijk} =$$

$$u + C_i + P_j + CP_{ij} + I_k + CI_{ik} + PI_{jk} + (ijk)$$

$i = 0,1,2,3 \quad j = 0,1 \quad k = 0,1,2,3$

where Y_{ijk} = Response variable measured (number of operations/shift or number of parts/day)

u = Overall mean

C_i = Effect of the Control Policy

P_j = Effect of the Position Policy

I_k = Effect of the Input Policy

CP_{ij} = Effect of interaction of C_i and P_j

CI_{ik} = Effect of interaction of C_i and I_k

PI_{jk} = Effect of interaction of P_j and I_k

The reason that the interaction term C_i and P_j and I_k is assumed to be zero is that with one observation per cell, this is a necessary assumption in order to test on row and column effects.

5.3 FUNCTIONAL MODEL

The design of the experiment detailed a complete factorial treatment combination of the independent variables. This means all possible combinations of the factors involved as defined by their levels were simulated. Thus 32 different runs were made of the simulation program. Each run was terminated when the simulated time reached 32 hours. Data was then collected from the part of the simulation output which represents the last three 8-hour intervals (shifts).

Six additional runs were performed on a group of factor sets which were chosen, by the results of the first runs, to be likely candidates for the definition of very good and very bad combinations of running factors. These runs, however, differed from the previous runs in the random number seed chosen to initialize the sampling procedure of the probability distributions which determine the stochastic elements in the model. A t-test was then performed on corresponding runs to determine whether there was any difference between the two means produced. The results of this test show that as a factor, the simulation model with different random number seeds defining different levels, has no significant effect. Because of this result, a complete factorial experiment without replications was justified.

Analysis of the measure of steady state (a time averaged mean number of operations per shift) shows that the operating policy of using forward and backward chaining is unacceptable as an operating procedure. Under this Line Control strategy the system never reaches a steady state condition and eventually decays to a degenerate (dead-locked) state. For this reason, this cannot be compared with the other effects in a meaningful manner.

Thus eight of the runs were discarded.

5.4 ANALYSIS OF RESULTS

The results of the 24 accepted computer runs for the full factorial experiment for both response variables were analyzed using standard statistical packages on the Purdue University CDC 6600 System.

The ANOVA for the response variable "number of operations per day" in the notation developed previously to present the mathematical model, the calculated 'F' values $\left(\frac{MS_{factor}}{MS\ error}\right)$ are greater than the critical F values at the .05 confidence level for the following factors and interactions:

- C - Control Policy
- P - Load/Unload Position Policy
- I - Input Policy
- CI - Interaction of the Control Policy and Input Policy
- PI - Interaction of the Position Policy and Input Policy

These factors can be said to have a significant effect on the output of the system with respect to the number of operations per day.

The Tukey test indicated that for Factor 1 (Control Policy) level 4 was significantly higher than level 2 and level 3. There was no significant difference between level 2 and level 3.

Similarly for Factor 2 (the Load/Unload Positions) the test shows that level 2 is significantly better than level 1. Finally, for Factor 3 (Input Policies) the Tukey test shows that levels 2, 3, and 4 are not significantly different from each other but all of them are significantly better than level 1.

The ANOVA for the response variable "number of completed assemblies per day" in the notation of the mathematical model indicates that at the 5 percent confidence level the following factors and interactions have a significant effect on the number of finished assemblies per day:

- C - Control Policy
- I - Input Policy
- CI - Interaction of Control Policy and Input Policy

The results of the Tukey test show that for Factor 1 (Control Policy) level 4 is significantly higher than level 2 and 3. There is no significant difference between levels 2 and 3. Since the ANOVA test indicated that Factor 2 (Load/Unload Position Policy) did not have a significant effect on the number of assemblies per day, no range test was needed. Finally, for Factor 3 (Input Policies) the Tukey test shows that levels 2, 3 and 4 are not significantly different from each other but all of them are significantly better than level 1.

6. CONCLUSIONS

6.1 CONCLUSIONS FROM THE EXPERIMENT

Analysis of the results of the output indicate that for the operating criteria measured, the following levels of the significant factors produce the best results:

FACTOR 1	FACTOR 2	FACTOR 3
Level 4	Level 2 (for the response variable "number of operations per day")	Level 2 Level 3 Level 4

This indicates that the Caterpillar system with its fixed routing and single track transporter system operates best when the Control Policy for controlling the movement of parts is as flexible as possible. This flexibility allows the system to constantly monitor the status of the system and prevents it from locking into a chain of commands which force interference and deadlock conditions. This flexibility also gives the control system the ability to respond quickly to changes in the physical system configuration which cannot be predicted.

The preference of Level 2 of Factor 2 for one of the response variables indicates (according to design expectations) that the position of the Load/Unload stations which are dedicated to refixturing of parts can be rearranged to provide more in-process storage capacity in a congested area, and in relieveing the bottleneck help to increase the utilization of the machines.

Finally the results of the examination of the effects of the input factors suggest that the operational balance on the machines does not, in fact, deal adequately with the disproportionate machining time required by the different parts. The results also indicate that the production capacity, with respect to producing finished assemblies, is very sensitive to the part mix on the line. This part mix, it appears, can very adequately be controlled through the use of experimentally derived input rules. In short, the existence of some stock control policy is much preferred over none at all, and it appears that, within the limits tested, the restrictiveness of this policy has little effect. Because of this last fact, probably the best Input Policy to use would be the most restrictive one which only allows an in-process stock storage level of one, since this would contribute to the reduction of inventory costs.

6.2 BENEFITS OF THE SIMULATION EFFORT

The development of the simulation model was done in conjunction with both Caterpillar and Sundstrand personnel. Thus, the total benefit of the simulation effort does not derive solely from the model output. However, the simulation results can be credited with increasing the confidence of the production management that certain modifications would be beneficial. As a result, the Line Control algorithms used by the Caterpillar system were modified as suggested by the simulation results (i.e., elimination of backward chaining). An increase of 10 percent in number of operations was obtained after this change. Other changes suggested by the simulation output are now in the process of being implemented.

6.3 HINDSIGHT

One of the major benefits of the user (or customer) in any simulation effort is a result of the problem analysis which must occur in order to develop the computer model. The rigorous decomposition of the systems functional, data, and activation requirements with a general viewpoint of productivity enhancement and a specific focus on the understanding of the causal relationships in the resulting structure to specific problem symptoms, produces an understanding of the problem which is logically structured and more easily communicatable. However because this procedure is generally informal and the customers requirements often poorly understood, there is a need to utilize more formal techniques in the information gathering and requirements definition.

Inspection of the current simulation model indicates a particular level of abstraction which is a representation of the author's concept of the functions of the system which were necessary to model the decisions and activities determined to be critical to resolve the problems identified during the physical system analysis phase. The procedure for:

1. formulating the concept of the system as it exists in reality
2. determining the causal relationships which are most likely the explanation of the problem symptoms which precipitated the need for analysis.
3. Designing a system which adequately reflects both the causal relationships and the actual physical system functions and data flows as they are required to define those relationships.
4. Designing and constructing a software system which incorporates a machine to manipulate with reference to an incrementing factor (time and parts in this case) to provide an efficient technique for investigating the effect on specified measures of a large number of events being processed through the system.
5. Verifying that the software system is consistent and correct with respect to coding areas.
6. Validating that the software system actually meets the requirements specified in phase (3).
7. Designing an experiment which used the software system and the machine on which it operates.

8. Performing the experiment according to the design developed as software system is capable of correctly being configured.

9. Analyzing the results via statistical techniques appropriate to the particular design and configured by the specific experimental procedures and results.

10. Extrapolating the conclusions of the experiment to the "real life" system via the initial causal relationships and problem conceptualization.

Is a discipline (or black art depending on the particular point of view) enhanced by experience and augmented by developing mathematical techniques or tools. Communicating these concepts and designs and their implications to the customer and insuring that the assumptions made in order to abstract do not conflict with any "important" details (of which the user is very familiar) is the ultimate responsibility of the systems analyst. If major advances are to be made in the application of this discipline to benefit the decision maker in manufacturing more refined techniques for communicating consistently and and logically between each of these activities and to the customer* are required. Common language is not precise enough and computer code (even higher order languages) are too restrictive and cumbersome. What seems appropriate is a combination of Case (16) Standard Natural language terms and a graphical/symbolic technique for description and structure respectively which is both logically consistent and human engineered.

There have been techniques developed and used in the area of software and systems engineering which address these problems. Investigation is currently underway to evaluate the usefulness of these techniques and the development of enhancements to their implementation.

* customer or user is defined to mean whoever or whatever uses the output of this process to influence a decision making process.

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