A generalized methodology for computer simulation of numerically controlled production systems

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INTRODUCTION

Numerical control (N/C) is generally acclaimed as the largest single advance made in the techniques of industrial production in the last decade. It represents a key technical innovation that has significant effects on productivity, engineering design, product marketing, factory organization, employment and industrial relations.

The basis of these new types of production systems is the numerically controlled machine tool. In most types of metal-working operations the cutting or forming tool is told exactly what to do by means of a pre-recorded program. The direction in which the tool moves, its speeds and feeds, type of machining operation, together with auxiliary machine tool commands, are directed by digital instructions read from a punched tape or a magnetic storage. The N/C concept, as it applies to machine tools, emphasizes the significance of this new form of automation: the merging of information handling systems with production facilities.

Numerically controlled machine tools can be looked at primarily as information utilization devices which operate at the periphery of a digital computer. Their function is the utilization of information to give output in the form of finished physical parts. Computing power is necessary to prepare and organize the machining instructions which, when fed to the machine tool, represent a "fixed logic" program describing product dimensions, machine member direction, speeds, feeds and other process control data.

At present, a variety of numerically controlled machines are encountered in various industries, all of them requiring data processing services of various complexity and frequency. In the metal-working machine tool area, N/C machines such as turret drills, jig borers, lathes, multi-axis milling machines, engine lathes and multi-purpose machining centers are most common in large manufacturing companies but are also found in medium and small machine shops. Other numerically controlled devices that are being used extensively are drafting machines, flame cutting machines, riveters, tube benders, welding machines, and inspection machines.

Figure 1 shows a general-purpose N/C machine tool considered in the simulation model discussed in this paper.

The concept of computer-based numerical control is not relegated to the machine tool itself but can embrace the full spectrum of N/C production in an engineering and manufacturing company. Indeed, the entire process may go from functional specifications of the piece-part through production control, individual part manufacture, assembly testing and follow-on statistical performance evaluation. In addition, there is a definite trend for computer support in N/C manufacturing for part selection, machine center loading and scheduling in order to improve N/C/machine tool utilization. Information processing for numerical control is carried out in all three of the major phases required in the production of a part. Phase 1, information generation, constitutes the process of defining
a part. This process aims at arriving at some specific and detailed specification of the configuration of the part to be produced and at its method of machining. Phase 2, machine tool program generation, has the objective of providing the computations required for the production and verification of the complete set of machine tool instructions. Phase 3, information utilization, covers the final phase where the instructions in the machining program are used at the machine tool site for actual production of the desired part as visualized in the part design. The main objective in programming an N/C machine tool is the solution of the overall machining problem, i.e., the optimum application of an automated machine tool to a given piece of work according to predefined geometry and the attainment of the highest speed in the machine operation compatible with machine dynamics and efficient metal-working techniques.

Computer-based programming systems for numerical control remove the part programmer from direct contact with detailed machine tool coding and allow him to define the machining problem in broader and more meaningful terms. He can describe his problem and procedures with a symbolic or graphical language which is problem oriented and has little relationship to the computer itself. The data coming out of the computer are in the language that the machine tool director can understand. A symbolic-type manufacturing language (APT) with English-like terms can be used by production people to “talk” to the computer. In this language, which should be easy to master, the part programmer may describe the profile, surfaces or hole patterns which define the part to be machined, and specify the sequence of required tool motions to generate the desired geometry in metal forgings or castings.

As shown in Figure 2, the present state of the art in the use of general-purpose computers in machine tool programming reflects the recent advances reached in computer technology in general. Experimental graphical part-programming systems are in existence today that permit, through the use of a cathode-ray tube display equipped with a light-pen device, the definition of the part, and subsequently, of the machining problem. The part programmer can immediately see the results of the process as the solution of the problem progresses.

These programs can also produce true perspective pictures of any curvilinear segment of series of lines including coordinate axes, and provide the part programmer with an added degree of flexibility in controlling what he sees on the scope. By manipulation of console switches, the operator may rotate the three-dimensional view of the part being shown about many axes and thus observe it from various aspects as an aid in deciding if it has correctly defined the part configuration. The graphic communication capability is expected to increase part programmer efficiency and decrease the preparation time of verified N/C tapes.

**Formulation of the generalized model**

The formulation of a generalized model for N/C production stipulates parameters that provide the prime operating modes of the production system, and describes means for evaluating alternative design solutions.

A simulation methodology in numerical control requires the definition of a framework achieving integration of physical processes and information handling processes. Figure 3 shows a simplified representation of such process integration. There are essentially four component systems or subsystems considered in the modelling philosophy presented here. There are the N/C Data Processing System, the Physical Processing System, the Emergency Repair Support System and the Production Information System.

The Numerical Control Data Processing System has the function of generating machine tool control informa-
tion from engineering drawings and process planning data.

The Physical Processing System covers the production processes carried out by the N/C machine tools and the Emergency Repair Support System provides the services needed for repair of machine tool breakdowns.

The Production Information System encompasses all the activities of the three principal systems mentioned above. Sensing elements report to this information system events that take place in the subsystem. The end result of the information arriving at the Production Information System is a series of images that describe the activities within the subsystems.

The generalized model treats the numerical control plant as a man-machine system of discrete-type production and it makes use of feedback links within each subsystem and between the subsystems themselves. The production system may be composed of procedures, equipment, information, methods to compile and evaluate the information, as well as the people who operate and use the information. The basic schematic model of the generalized N/C production system is shown in Figure 4. The model is a detailed representation of the operations and flows illustrated in elemental form in Figure 3.

The flows as indicated in the diagram are of four distinct types. The solid-black line network shows the materials flow from raw material storage to finished part storage, going through the numerical control machining operation. The double-line network provides the carrier for all information issued from the arrival point of the engineering drawings to the issuance of numerical control tapes for the production process, going through various points for processing of the numerical control programs. The broken lines identify information flow for machine repairs. The thin-line network links all the other three networks and their work stations to an information center designed for the measurement of system performance during the simulation.

Shop orders are treated as purely exogenous inputs, accompanied by engineering drawing releases and process planning data. These orders represent the transactions which go through the system in a stochastic flow. Based upon decisions on the extent to which plant capacity is used, the model allows incoming orders to

Figure 4—General model for N/C production systems—Complete model diagram
enter the system or to be routed to "sinks" which represent subcontracting functions. Orders entering the system are routed to the numerical control part programming function which handles all the operations necessary to code, process, validate and machine-tool test the information necessary to run the N/C machines. The computer processing operation simulated in the model produces families of N/C tapes to be used in the major routings considered in the model. The machining programs are released to the machine centers for tape proofing prior to the final release to production.

The highly aggregated function blocks shown in the general schematic, as well as the various linkages of direct flow and feedback loops, may be broken down to a much greater level of detail through the use of the General Purpose Systems Simulator (GPSS) language. GPSS is the computer simulation language which was used in the experimentation connected with the development of this methodology. Flows through the numerical control parts programming function, for example, can be described with a finer resolution when put through the subfunctions of Part Programming proper, Computer N/C Processing, Graphic Verification and Control Tape Proofing. Within the Breakdown Repair function boundary logical blocks are introduced representing sources of machine breakdown events, together with blocks representing repair functions and termination of repair operations.

The Numerical Control Machining Centers may have one or more machine tools of the same type operating in the center. Parameters affecting the machining center operations are the number of working shifts per day, the length of the individual shift and the number of working days per manufacturing week. Wide flexibility exists in programming shifts for the various centers, including the assignment of different shifts of varied duration.

The scheduling program requires a description of available facilities per center in terms of a facility identification, number of shifts of operation, and number of machine hours of capacity. The scheduling function operates on the given job information to calculate for each job the probable number of manufacturing days needed to process the job and the manufacturing week number in which the job processing will start at the machine center. It determines the load that would exist at each machining center according to the over-all job lot processing time and to the frequency of job order and tape arrivals.

Design criteria and structure of the N/C production systems simulator

A methodology of simulation of N/C production systems requires a formulation of the various characteristics of total system components, subsystem interdependencies, system flows, and stochastic functions. The resulting structure may be called an N/C Production System Simulator, which is a computer program capable of tracing the activities of the N/C production system as they change in time.

The composition of the N/C Data Processing System and of the Physical Processing System can be described by program modules representing part programming functions, computer processing functions and machining functions. The simulation of the flow of the job orders and part programs through the production system can be achieved by transmitting "transactions," representing job orders and part programs through the network of simulated queues and processing stations. The arrangement of the queues and the processing station elements also includes information feedback loops which are required by the nature of numerically controlled operations.

Production system input characteristics

The first task in the definition of the input characteristics is to identify the various types of transactions which flow in the various information streams of the GPSS model and in its control strings. The latter are GPSS model segments operating outside of the main model, which control events taking place in the simulator, such as machine breakdowns, or control duration and number of work shifts at the machining centers of N/C data processing units.

Production orders entering a shop generally follow two main streams—new orders and reorders—flowing as transactions into the network of the model. The new orders require production planning, the definition on work routings, setups, part programming and preparation of N/C tapes. The reorders have the necessary N/C tapes already available from previous job-lot runs. These tapes are usually stored in the tool room and are treated as any other tool which may be required for setup and fabrication of the specific job lot.

Each transaction entering the model represents a production order for new parts or for additional production of parts identical to ones produced in previous orders. The transactions are assigned to certain parameters defining the production order configuration and the characteristics of the processing centers through which the order is expected to go, either for N/C information processing and/or parts fabrication. Due to the different nature of the operations carried out in the N/C Data Processing System and in the Physical Processing System, the same transaction may have entirely different parameters assigned when it goes through the two subsystems. The GPSS parameter assignment is made according to the system in which it operates or to the seg-
ment of the specific system in which the transaction is active at the moment.

An analysis of the functions and elements of the various subsystems should be preceded by a review of the assumptions made in relation to the generalized model structure, the subsystem interfaces and total system inputs. Technological constraints pertaining to the metal-working processing should also be considered.

The model represents a data processing operation used to produce numerical control tapes, which is integrated with a numerically controlled machining complex that manufactures parts. It does not recognize adjacent departments such as shipping or purchasing. Arrivals from outside the system may come from departments such as purchasing or engineering, or they may be direct customer order arrivals, as in the case of small job shops. A production order can coincide with a shop order in the context of this simulation. In practice shop orders are released 10-15 days before the first operation is scheduled to begin, since a preparation period is required to make sure that raw materials and proper tooling are available when needed. In the case of numerically controlled manufacturing this process preparation should take place concurrently with the operations necessary to produce and test the numerical control tapes for the specific job on order.

It should be noted that the model does not recognize transit times between one center and the other. The transaction that leaves one center simply joins the waiting line (if any) of the next station. During simulation of job shop operations the simulator does not take into consideration certain standing shop practices such as lap phasing, job-lot splitting and the saving of setups. Lap phasing is a form of parallel scheduling in which a lot can be simultaneously processed on at least two machines. As far as capacity is concerned, the model, once defined in its structure and mode of operation for a specific simulation run, reflects only a fixed machine tool capacity.

As discussed previously, the processing facilities are grouped in centers along specific routings. The transaction of the part program which follows a common routing in the N/C data processing system is channelled in a specific routing as soon as it reaches the physical processing system, according to part configuration and to the technology of the machining process. The differences in the machining process are primarily dictated by the geometry of the piece-part, the type of N/C machine tool, the way in which material is removed and the type of material being machined. The model takes into consideration machining centers of entirely different nature where the discrete and/or continuous process of metal removing produces parts shaped as solids of revolution (lathe operation), or bounded by surfaces machined in three-coordinate cartesian space (milling operations) or by removing metal at discrete positions as by drilling or spot facing (multi-purpose machine). No exchange of routings is allowed for a transaction in case of excessive machine loads or machine breakdowns.

There is no allowance for interaction among similar production orders at the various facilities. The possibility of accumulating jobs requiring nearly identical setups in order to save setup times is not considered. Other important assumptions concerning the shop operations are the absence of delays due to the work piece not being available at the scheduled time at the machine site, or delays due to cutting tools, holding fixtures, special tooling, and N/C tapes not available at scheduled machining time.

Rejects or scrap due to fabrication errors or machine tool programming errors recorded in the tape program are assumed impossible in the simulation. Although in the case of conventional machine shops this assumption may seem quite unrealistic, it may hold true in many cases of efficiently run numerical control shops where validation procedures in tape programming and tape testing are enforced and machine tool operator intervention is kept at a minimum. It is also assumed that machining breakdown does not cause any scrap or interruption of the machine cycle during a specific part production cycle.

In the simulation of the man-machine system described in this paper, consideration of the human element leads to the following basic assumptions. Part programmers can be assigned to any part programming job irrespective of the N/C machining process or type of N/C machine tool requiring programming. The part programmer responsible for the symbolic programming of a specific drawing also runs the drafting machine for visual verification of the part contours and tool paths and attends the first machining tool run for the tape proofing operation.

Although machine tool operators cannot be exchanged for part programmers, complete flexibility is assumed in shifting operators from one N/C machining center to another. Machine tool operators in this model need no additional training or special skills, even though the same man may run an N/C lathe or a 3-axis N/C milling machine, which in practice is a reasonable assumption. Machine tool operators and part programmers are assumed always present at processing stations as no consideration in the simulation is given to fatigue, personal time and absenteeism. Machine tool operators are expected not to intervene during the machining process, while in real life situations the operator may slow down cutting rates and feed rates due to piece-parts showing different characteristics in their raw material piece form or in the quality of the raw material.
Secondary operations are not needed as supporting machinery of conventional type is assumed not present in the system. Shop operations sometimes used in preparation of forgings and castings for the N/C process are not considered necessary or relevant for the simulation. Deburring, degreasing or heat-treat operations are not included. Part inspection is not considered in the simulation model although inspection with measuring devices mounted on the N/C machine, or use of tape-controlled inspection machines is technically feasible.

Preventive maintenance does not occur in the scheduled production work period and all emergency maintenance takes place during scheduled work time. No attempt is made to combine the two types of maintenance operations. Finally, adequate storage space is assumed available in front of machining centers and in job-lot staging areas; saturation of storage areas is not considered in the simulation in case of extreme build-up in machine center queues.

A few constraints in the simulation described in this paper are concerned with the limitations in system definition imposed by the GPSS program itself. Computer simulation programs, by necessity, have boundaries in the amount of data they can retain at any stage of the process, the number of attributes that can be assigned to transactions, the number of variables and composition of variables that can be defined in the system and, obviously, the computer time that can be economically spent on any one simulation run.

The physical processing system

The Physical Processing System represents the physical processes and the resources required to produce the end product, i.e., machined parts. To control the scale of the model built with the methodology discussed here, the physical processing facilities were limited to three multi-machine centers of different type. However, from one to four numerically controlled machine tools can be operated within each center. The organization of the machine centers is of sufficient detail to permit useful evaluation of congestion conditions in shop-order flow through the centers. It also allows the analysis of the effects of overloading in the Numerical Control Data Processing System and of the effects of intervention by the Emergency Repair Support System in case of machine breakdown at any of the centers.

Each machine tool is characterized by a capacity represented by the maximum work time period that may be allowed daily for the machine in the shop. Machine capacity is measured in minutes and makes reference to the three capacity levels set by first, second or third shift of work. Provision is made for the machines to work five days, six days or seven days per week. Flexibility is provided by the model in the number of daily shifts or duration of the weekly work period. This arrangement is quite similar to actual working situations in numerical control machining operations since numerical control machines on determined shop routings are, in practice, shut down without affecting the operation of the remaining centers. If desired or deemed necessary, machine centers can be operated independently on entirely different schedules one from the other. One of the striking characteristics of numerically controlled machinery is the consolidation of many machine tools of conventional type in one processing center.

The emergency repair support system

The simulation of breakdown repair operations in a machine shop has all the elements of a queueing situation. Machine breakdowns in the shop require repairs which are treated as jobs to be performed. The maintenance man becomes the service facility for which competition may generate when more than one machine is down at any given time. The time necessary to repair the facility represents the service or processing time.

In the N/C production system simulation breakdowns occur as a result of the intervention of a separate GPSS model, which is run concurrently with the main program to simulate the emergency maintenance operations required to repair the malfunction or malfunctions which have occurred in a single facility unit. Simulated breakdowns are classified by type of fault: i.e., electronic, hydraulic or mechanical, and by the type of machine, with faults occurring on multi-purpose machines, milling machines and lathes.

The production information system

The Generalized Model Schematic Diagram of Figure 4 illustrates the various linkages of the Production Information System. The sensing elements shown in the schematic diagram allow management to follow the flow of shop orders through the Numerical Control Data Processing System and the Physical Processing System, and the stoppage of shop orders through the Emergency Repair Support Subsystem. It is then possible to study the effects of congestion caused by the need of accessing processing stations, or caused by limitations in the capacity of sections of the network.

Corrective action may be issued to affect the operations of one or more subsystems. Changes are not issued during a particular simulation itself, but they are rather the result of decisions made in view of the output supplied at the end of the simulation, which covers a predetermined time span. Changes in scheduling procedures, manpower and machine capacities, or changes in incoming order configuration can be introduced in order...
to improve the over-all performance and to evaluate specific measures of effectiveness.

The generalized simulation methodology is designed to study the flow of job orders through the N/C production system and to analyze how the system reacts to various conditions of operation. The output data obtained from the simulation is, therefore, in terms of physical performance of the total system, its subsystems and their components. There are many measures of physical performance of the total system, its subsystems and their components, which can be generated for any given set of decision rules through the reporting function. These measures include the transit times required for an order to flow through the system or sections of the system, the number of orders in delay, the length of delay times at various points of congestion, the degree of utilization of the facilities or the utilization of manpower. The total flow time—or time from the receipt of a production order to the completion of that order for delivery to another department or directly to the customer—represents the best over-all measurement of physical performance. This measure does not provide a direct economic evaluation of performance. The measures of performance which can be obtained from the N/C Production Systems Simulator may be grouped in the five categories which follow:

I. Output Data on Queues Forming at Processing Centers
   • Distribution of queue delay times at N/C processing centers and N/C data processing centers.
   • Maximum and average contents of queues at processing centers.
   • Average length of time spent by production order in queue of specific processing center.
   • Record of queue lengths as a function of time taken at selected queues of the system.

II. Output Data on Facilities Control
    • Time covering period of operation of facilities.
    • Average utilization of each facility based on period of operation. This also constitutes the loading factor of the facility.
    • Total loading levels and capacity levels at each N/C machine center, over period of operation considered.

III. Output Data on Production Order Control
    • Total number of job-lot orders accepted and completed by system during period of operation considered.
    • Average flow time of new orders through N/C data processing system and through total production system, including physical processing system.
    • Average flow time of reorders through physical system, and average flow time of reorders and new orders combined through total system.

IV. Output Data on Operating Schedule Control
    • Number of manufacturing days and manufacturing weeks covered by scheduling.
    • Number of manufacturing days expected to process specific new order or reorder, and number of manufacturing weeks when specific new order or reorder is expected to be processed at machine center.

V. Output Data on Breakdown Repair Control
    • Distribution of queue delay times at machine center for the handling of repair order.
    • Total number of breakdowns which occurred at specific machine center.
    • Maximum and average contents of queue for handling of repairs at machine center.
    • Average time spent for repairs at machine center.
    • Average utilization of repair technicians assigned to machine center.

Experimental Investigation

The system configurations analyzed in the experiment comprised the majority of components expected to be found in an integrated computer-based N/C production system. It is felt that the type, the number and relationship of components used in the model, as well as the operating policies employed in the simulation, give a complete demonstration of the use of the methodology. The physical processing subsystem and the N/C data processing subsystem defined in the model used, have been structured to incorporate, as much as possible, the dynamic complexity to be found in numerically controlled manufacturing operations using computer-assisted programming.

The primary objective of the experiments was to determine whether significant differences in performance could result from changes in selected design aspects of the two major subsystems. The discussion of the problem which prompted the subject of the research indicated that fully integrated computer-based N/C manufacturing systems are not in wide use in industry today. Of the few in operation, integration was achieved as an evolutionary process rather than on the basis of a completely new approach to N/C production system design.

The formulation of the simulation model was based on a large amount of data on N/C machine characteristics and N/C production operations obtained from various industry sources over a period of several years. Information processing times, physical plant characteristics and actual performance factors of man-machine components of the system were obtained from aerospace manufacturers and research institutions.
The tests showed that the behavior of the model is acceptable and contained within realistic limits. During the many runs preceding the final tests, the model was manipulated over wider ranges of operations than the ones which are normally encountered in actual system operations. The effects of changes in critical design parameters were examined and the computer results compared with results obtained from a base configuration of the system structures under study.

The objectives of the experiments carried out were as follows:

1. To structure the model in such a form to adequately represent a typical N/C production system of metal-working manufacturing.
2. To set up the model in such a way as to use operating policies normally encountered in N/C job-shop operations.
3. To obtain steady-state statistics for a variety of configurations in the numerical control data processing subsystem.
4. To carry out a statistical analysis on the change of system performance and to compare statistics generated for the new system configurations.
5. To study the dynamic relationships between queuing conditions in the N/C data processing system and the physical processing system.

As to the characteristics of the particular model used in the experiments, assumptions were made on the loading of the production system and the system operating rules based on actual operating data. The generalized model is structured so that it produces a collection of statistics for later analysis and for conducting, through changes in model geometry and through operations manipulations, more experiments to obtain further statistics for comparative purposes.

The study of the behavior of the N/C production system model, carried out as part of the experimental investigation, was based on eight different measures of performance. "Flow time" was defined as the difference between the time at which an order (or transaction) arrives at the system or subsystem, and the time at which the same order (or transaction) leaves the same system or subsystem. For convenience, the term "transit time" may be used alternatively for flow time.

The first four measures of performance investigated were:

1. Flow times of new orders through the numerical control data processing system.
2. Flow times of new orders through the total production system.
3. Flow times of reorders through the physical processing system.
4. Flow times of all orders through the total production system.

The flow times of reorders relate to the physical processing system only. It should be recalled that reorders in N/C production do not require the preparation of machine tool tapes by the N/C data processing system since these N/C tapes can be made available simply by requesting them at the tool room where they are kept in storage racks after being used for the processing of previous production orders.

Although this paper does not cover the complete set of experiments performed and related analyses, one of the most interesting conclusions drawn from studying the simulation output is the behavior of the model under a configuration of the system operating with three part programmers. The flow times through the physical processing system and total system appeared to be consistently shorter when the simulation is run with three part programmers. This seems to confirm the practice in industry which aims at assigning one part programmer per N/C machine. This assignment is particularly necessary when programming jobs are of complex nature, as in the case of milling machine tape preparation. The low flow-time levels of the specific configuration investigated may also be the result of interaction between new orders and reorders when congestion develops at the part programming center. One effect of this interaction is the reduction of new order arrivals at the N/C machine centers.

Separate dynamic analysis runs were carried out for each one of the system configurations chosen for the study. The different configurations were characterized by the part programming function simulated with one part programmer, three part programmers and nine part programmers, identical to those introduced to obtain steady-state statistics. The results of dynamic behavior tests showed a high degree of interaction between the part programming operation and the machine operations at the N/C centers, with marked changes in the rate of build-up and decay of waiting lines at the various processing points. These variations seemed to be quite evident in the system configuration having three part programmers. It should be noticed that the peaks at the part programming queue were followed closely by peaks of varying amplitude at the N/C machine centers. It was apparent that the build-up of queues at the part programming center depended upon the arrival rates of new orders and the part program processing rates. The build-up was also influenced by the three feedback loops of the APT diagnostics check-out, the N/C drafting machine output check-out and the N/C tape proofing operations. It should be recalled that the part programming operation, as represented in the model, is constrained by work shifts which are dissimilar from the work shifts governing the N/C machine center operation. The different operating rules caused a
pulsing effect in the operation of N/C data processing facilities.

The physical processing system seemed to be quite sensitive to variations in the part programming center queue. The release of N/C tapes is an intermittent operation, which is paced by work shifts. It may present peaks of different intensity, according to factors such as part complexity and number of reworkings of part programming jobs. Correspondingly, build-up at the waiting lines in front of the machining centers may well depend on the size of part programs, size of job-lots, timing of N/C tape releases and on the processing rates governing the operation at the N/C machine center.

To summarize, the comparisons made for the four different measures of performance and the dynamic analysis show, both by visual comparison and by statistical test, that the simulator is highly sensitive to changes in the part programming manpower levels.

CONCLUSIONS

Numerical control is a production technology that forces management to look at a manufacturing enterprise as a whole, in the interdependency of all the steps from product conceptualization through the processes that yield the finished product. Fundamental to increasing the success of numerical control and the rate of acceptance of N/C machinery, is the systems approach to forward thinking in this new area. This mode of attack views all components of a N/C production system in the light of their interrelationships and their functional objectives. It has been applied with outstanding success in the development and operation of complex computing and communication networks, especially by the requirements of intricate and interlocking systems of military installations.

It is felt that the use of advanced techniques of digital simulation may become in the near future a major contribution to the development of a body of knowledge on application of numerical control to discrete-type production and to job-shop manufacturing systems. A purpose that may be pursued by research through examining large-scale models could be to show how N/C production and related activities, particularly decision-making and control of shop operations, can be explicitly modelled. The research should be aimed at the major goal of developing and refining a methodology for building production models embodying the new principles of N/C manufacturing through the use of computer simulation.

Finally, it can be said that the discipline of reducing production organizational concepts to precise formulations, and the requirements of specifying decision rules and procedures in a straightforward unambiguous fashion is undoubtedly an education in itself, whether for the N/C user or the the manufacturers of computers and numerical controls.

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