ON THE USE OF GPSS TO MODEL HIERARCHICAL CONTROL SYSTEMS IN A MANUFACTURING ENVIRONMENT

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ABSTRACT

The concept of hierarchical, multilevel control systems is reviewed in the context of manufacturing systems, and the strata typically composing such control systems are discussed. The possibility of building simulation models of hierarchical systems, using FORTRAN routines to represent the higher-level strata, and GPSS to model the actual manufacturing steps themselves, is introduced. A hypothetical, nine-product toy-manufacturing system is described, and some of the specific features of a GPSS-FORTRAN package which successfully models this system in accord with hierarchical control principles are indicated. The relative ease of constructing the GPSS-FORTRAN model suggests that there may be substantial potential in this approach for assessing the properties of specific proposed hierarchical control systems. Such models can be used initially to investigate the relative goodness of various control algorithms which are candidates for use in these systems; then, after selection of a specific control algorithm or combination of algorithms, the models can be used further to test and evaluate the control software and data bases created to support the operation of such systems.

INTRODUCTION

It has been recognized for quite some time that in order to improve the efficiency of manufacturing systems, a higher degree of integration and control among the various activities within such systems is needed. Here are some of the things motivating development of integrated control systems in a manufacturing setting:

(a) Size, complexity, and diversity

A large manufacturing operation may at any one time involve hundreds and even thousands of kinds of raw materials, parts, subassemblies, etc., which are currently planned for, or are in inventory, or are being processed to fill hundreds of different orders. In such a setting, information processing, supervision, and control present formidable problems for all concerned, from high-level plant management right on down to clerks and operators. The use of integrated control systems in this environment is attractive, and has a high potential payoff.

(b) The gap between planning and operation

To maintain and/or improve their competitive position, many companies are using computers as information-handling and decision-making tools. In particular, the production objectives of manufacturing systems are often determined at a high level with the aid of computer simulations based on market analysis and linear programming models of the production process. At a much lower level, computers are also sometimes used in manufacturing contexts to control physical production processes, as for example in direct digital control of machine tools. Between these two levels, however, supervisory and control functions frequently are performed by supervisory personnel and production workers without benefit of the real-time information which an appropriate information and control system could make available. It is natural to try to close this implied gap in computer use by providing integrated control systems which span manufacturing activities all the way from the preparation of master production schedules on down to whatever degree of machine-tool control may be appropriate.

(c) Response to environmental changes

Integrated control of manufacturing systems provides a mechanism for fast response to changing market and other environmental conditions. In large manufacturing complexes where a great variety of products are produced, timely adaptation to such things as shifting market conditions and other environmental trends can make it possible to take advantage of opportunities for increased profits, and correspondingly can help minimize losses.

Integrated control of a manufacturing system involves linking together each of the system's information and control functions within a unified whole. Everything from customer orders, market forecasts, and inventory control procedures right on down through machine operations is taken into account in such an integrated control system. The result is both a physical and a logical link between production planning, resource allocation, plant floor control, and operation. Such a link can be of high utility throughout a manufacturing organization, both in terms of the managerial process and of the production process.

THE THREE STRATA OF AN INTEGRATED MANUFACTURING SYSTEM: PLANNING, COORDINATION, AND CONTROL

Figure 1 shows a block diagram intended to represent an arbitrary manufacturing system viewed as an integrated, multilevel system. As suggested in the figure, the tasks of managing the plant's ongoing operations are spred among three strata: planning; coordination; and control.

The highest stratum - planning - determines product requirements from customer orders and sales forecasts, then groups and arranges these requirements so as to improve or maximize the profitability of production within the constraints imposed by resource availability and delivery-time requirements. The output from this level takes the form of master production schedules. Weekly production schedules are typically prepared several weeks in advance, with fine adjustments being made later, on the basis of current information about plant operations in terms of what has actually been accomplished in the intervening period.

Budget planning also takes place at the highest stratum. A budget is a vital component in any organization's planning and control cycle. On the planning side, it is a detailed test of the consistency and feasibility of production decisions; on the control side, the budget provides a benchmark for evaluation of production performance.

The intermediate stratum - coordination - accepts the master schedules from the planning stratum and extracts from them the information needed by individual subsystems. This coordination function ideally should be continuous and timely to whatever extent is necessary to avoid bottlenecks, unnecessary slowdowns, and outright waste in the production process.

The MATERIALS REQUIREMENTS planning activity within the intermediate stratum encompasses time phasing, order planning, and raw-materials inventory control. Time phasing involves taking steps to provide parts and raw materials so that they will be available at the manufacturing facility in time to meet the requirements of the master schedule. Order planning takes aggregate demand into account to determine economic order quantities, adjusting these quantities for possible losses in scrap and/or rounding them for lot sizes, price breaks, car loadings, etc. Raw-materials inventory control addresses itself to maintaining raw-materials inventories at levels which minimize possible production delays due to problems in shipment, strikes, etc., balancing this objective against that of achieving low inventory carrying costs.

The PRODUCTION COORDINATION portion of the intermediate stratum in Figure 1 concerns itself with such things as overall scheduling, work-center scheduling, line balancing, and the control of work-in-process inventory. Using inventory, production, and quality-control data, the objective of the various scheduling activities is to have actual production meet the requirements of the master schedule. The amount of work-in-process is controlled to seek an optimal trade-off between the cost of capital tied up in inventory, and the cost of having inadequate work-in-process to buffer against temporary breakdowns and irregularities in the scheduling process.

The SALES activities in the Figure 1 intermediate stratum provide sales forecasts based on incoming orders and sales-force estimates. These activities also include analysis of customer service levels, with the objective of providing satisfactory service while minimizing investment in finished-goods inventory. Contributing importantly to customer service levels is the physical distribution system used to deliver finished goods to customers. Such a system includes warehouses and transportation networks connecting the warehouses with manufacturing facilities and with one another, as well as with customer receiving points. In addition to investment in finished-goods inventory, then, facilities maintenance and transportation costs must be taken into account while striving to maintain acceptable service levels.

The lowest stratum in Figure 1 - control - is concerned with the manufacturing process itself. This stratum controls the activities taking place at the various production points within the plant. Among the control stratum's responsibilities are such things as supervisory control of assembly lines and the actual operation of machines, including direct control of machine tools, where applicable.

As suggested by the specific example in Figure 1, then, an essential characteristic of a hierarchical system is that it is composed of a vertical arrangement of its component subsystems. A feature of the hierarchical arrangement is that higher-level subsystems have the right to intervene in the operation of lower-level subsystems. At the same time, what takes place within the higher subsystems is conditioned on the performance achieved within the lower subsystems. Although such a structure seems simple and reasonable enough, it has wide-ranging implications. A complete treatment of the theory of hierarchical, multilevel systems can be found in [3]. Some specific applications of the general theory can be found in [1], [7], [8], [9], and [10].

THE USE OF SIMULATION IN MODELING HIERARCHICAL CONTROL SYSTEMS

It is clear from the preceding discussion that hierarchical control systems are characterized by a high degree of interlocking detail. This poses considerable problems for the designers of such systems. Among the major problems that arise is that of evaluating alternative proposed designs prior to the actual implementation of one of them. Under certain conditions, proposed designs can be evaluated via analytical modeling. More often than not, however, the conditions under which analytic evaluation is feasible are restrictive to the point that the analytic approach is ruled out. In these cases, simulation modeling provides a feasible alternative.

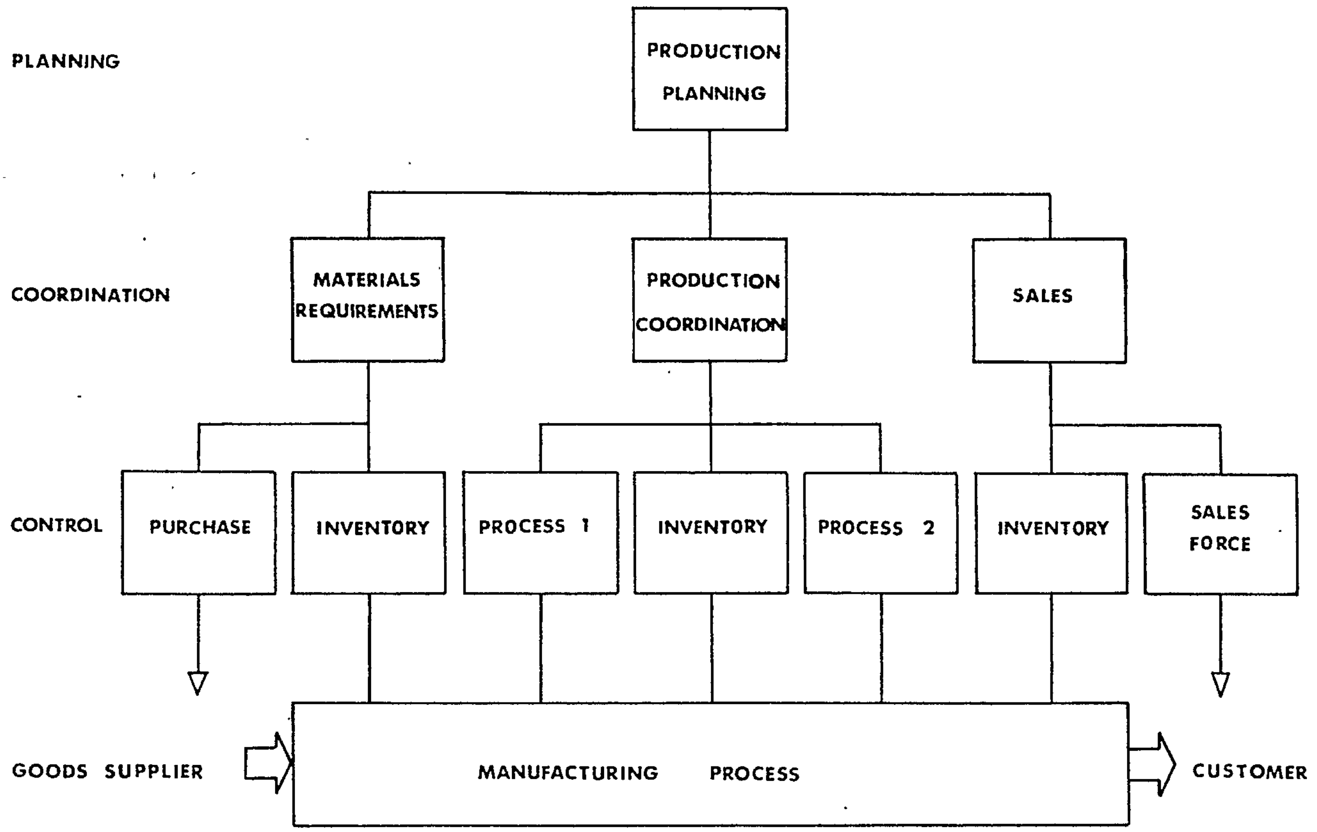

FIGURE 1. BLOCK DIAGRAM OF AN INTEGRATED MANUFACTURING SYSTEM

Assuming that a given hierarchical control system is to be modeled via simulation, a decision must be made as to what language or languages to use in implementing the model. Referring again to Figure 1, the activities within the planning, coordination, and control strata shown there would seem to lend themselves to representation in any conveniently available procedural language, such as FORTRAN or PL/I. Simulation of the MANUFACTURING PROCESS portion of Figure 1 may be another matter, however. In general, the manufacturing process likely involves a highly complicated flow of materials through a variety of men-and-machines resources. Furthermore, the times required to perform various steps in the manufacturing process may be random variables. The complex, queuing-like activities making up the manufacturing process are most easily modeled in a language which makes explicit provision for representation of queuing situations. The leading language which comes to mind in this regard is GPSS. (It should be noted, however, that a "processes and resources" capability has been installed in GASP recently [4], [11], and will be an integral part of the forthcoming GASP VI release. Some work has also been done toward providing SIMSCRIPT II.5 with processes-and-resources features [5].) Furthermore, GPSS/360, Version 2, is capable of interfacing with FORTRAN subroutines [2], and GPSS V can be interfaced with the user's choice of FORTRAN routines or PL/I procedures. A distinct possibility for modeling hierarchies of the Figure 1 type, then, is to take a GPSS-FORTRAN approach.

Following the reasoning outlined above, it was decided to investigate in finer detail the GPSS-FORTRAN modeling of hierarchical control systems by building such a model for a specific manufacturing system. The toy-manufacturing system chosen for this purpose will now be described.

DESCRIPTION OF THE TOY-MANUFACTURING SYSTEM

The toy-manufacturing system modeled here performs a series of three operations on various combinations of four inputs to produce nine outputs. The nine outputs, consisting of toy autos, toy trucks, and toy trucks-with-covers, are shown in Figure 2. (Only three distinct products are shown in Figure 2; each product is made in three different colors, however, which leads to nine different products in total.)

Three of the four inputs to the system take the form of raw materials: black, blue, and red plastic "powder" from which plastic parts can be molded. The

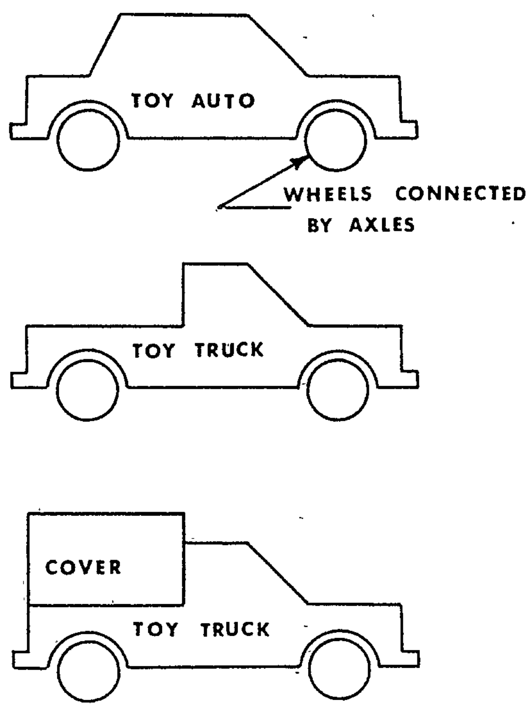

FIGURE 2. TOY-MANUFACTURING SYSTEM OUTPUTS

fourth input consists of axles sourced by an external supplier. One and the same type and color (black) axle is used for each of the nine products.

Of the system's three operations, one consists of using a plastic injection molding machine to produce ten distinct parts from the three plastic-powder raw materials. This operation is shown in Figure 3. There is assumed to be only one injection molding machine in the factory, and one machine operator. The molding machine can be used to mold parts in any sequence. For example, a blue auto body might be molded, then a red truck body, then one or more black wheels, etc. The wheels are black in all cases, whereas auto bodies, truck bodies, and truck covers can be red, blue, or black. It is assumed that the efficiency of the molding operation is not affected by the molding sequence. In other words, no overhead is involved in switching from one color to another, or from one type of mold to another.

The other two system operations involve assembly of parts. One of the operations, performed by a single worker, is that of attaching wheels to axles. The other operation, also performed by a single worker, consists of attaching two wheel-axle units to an auto body, or to a truck body; or of attaching two wheel-axle units and a cover to a truck body. The finished goods pictured in Figure 2 are the output of this last operation (autos in each of three body colors; trucks in each of three body colors; and covered trucks with the cover and body both red, or both blue, or both black).

A Gozinto graph for the assembly operations is shown in Figure 4. Among other things, the graph illustrates various assembly possibilities in terms of interchangeability of parts.

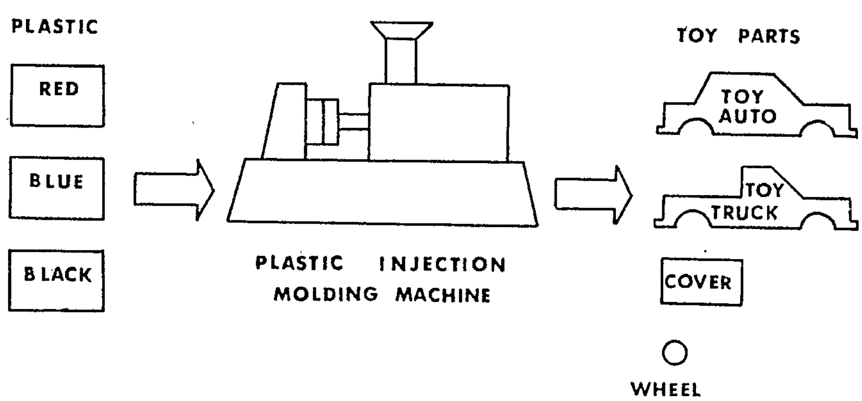

FIGURE 3. OPERATIONS AT THE PLASTIC INJECTION MOLDING MACHINE

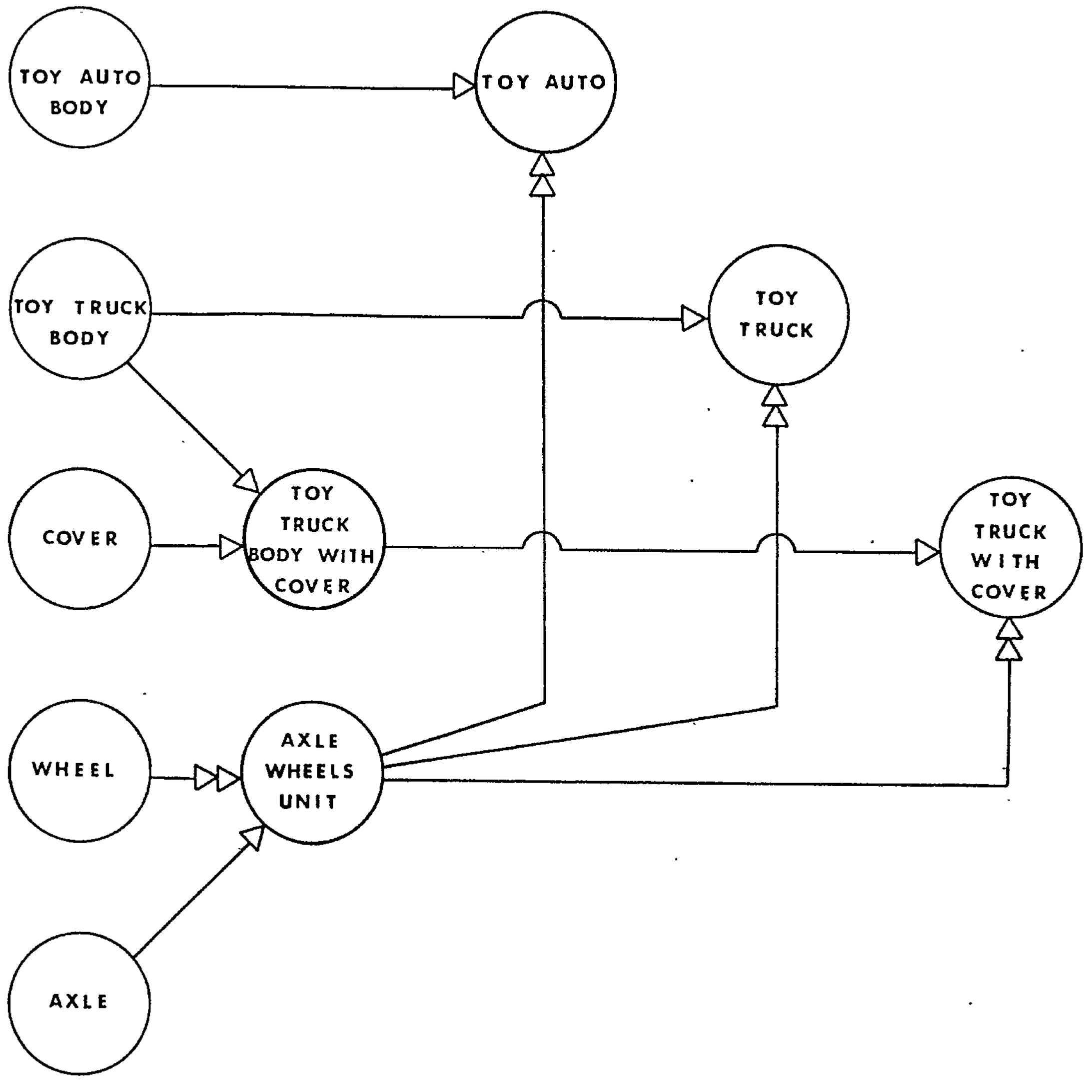

FIGURE 4. GOZINTO CHART FOR THE ASSEMBLY OPERATIONS

The three workers in the system are restricted to performing the single operation for which they have been hired. For example, the molding machine operator cannot help attach wheels to axles at times when he is otherwise idle, nor can he help attach wheel-axle units to vehicle bodies, etc.

DESCRIPTION OF THE GPSS-FORTRAN MODEL

The principal ingredients of the GPSS-FORTRAN model for the toy-manufacturing system are best understood by referring to Figure 5, which illustrates production flows in the system. The MOLDING-MACHINE station shown in Figure 5 is simulated with a self-contained GPSS model segment through which a single Transaction (representing the molding-machine operator) circulates. (A detailed discussion of the GPSS language itself can be found in [6].) Similarly, the ASSEMBLER 1 and ASSEMBLER 2 stations shown in Figure 5 are each simulated with self-contained GPSS model segments through which single Transactions (representing the respective assemblers) circulate.

Because similar logic is contained in each of these three segments, only the logic of the molding-machine segment will be outlined in detail here. When the molding-machine operator has finished molding a given part, he receives instructions about which color-and-part combination to mold next by entering a HELP Block, thereby passing control to a particular FORTRAN subroutine. This coupling of the molding-machine segment with the appropriate FORTRAN subroutine is represented in Figure 5 by the FLOW OF INFORMATION ON-LINE path labeled 1. The FORTRAN routine then examines the day's production schedule (taking into account any backlog from earlier days, and remaining work to be accomplished to meet the day's objectives) and, also taking into account the raw-materials inventory, passes back a coded value telling the molding-machine operator which color-and-part combination to mold next. If there is no work to be done (either because the day's objectives have been met, in terms of the molding-machine operator's tasks; or because plastic powder of the right color isn't on hand), the Transaction simulating the molding-machine operator is passed back a code instructing it to go onto a User Chain, where it remains idle until either the next workday begins, or more raw materials arrive so that work can be resumed in terms of fulfilling objectives as yet unmet. (The Transaction in question comes off the User Chain under instructions from some other Transaction. The other Transaction, contained in one or another of two other GPSS model segments as mentioned below, either is triggering the start of a new day's activities, or is updating raw-materials inventories in response to receipt of a replenishment order from the supplier of raw materials.)

The basic logical pattern just described for the molding-machine operation also applies to the activities of Assemblers 1 and 2. The Figure 5 FLOW OF INFORMATION ON-LINE paths labeled 2 and 3, respectively, represent the coupling of the Assembler 1 and Assembler 2 stations with appropriate FORTRAN routines which use real-time information to determine optimally which of the candidate activities the corresponding Assemblers should perform next. This optimal next-task determination could of course key on arbitrarily complicated algorithms in the general case; for simplicity here, the determination is based on a pre-ordered, first-needed first-made scan over the day's yet-unmet production objectives, coupled with the status of work-in-process inventory.

The only FORTRAN routines included in the exploratory modeling being reported here are the three routines which issue real-time orders to the molding machine operator, and to Assemblers 1 and 2. This reflects the fact that the focus of the exploratory modeling was on the GPSS portion of the overall model, and the interfacing of the GPSS segments with their controlling FORTRAN routines. The GPSS-FORTRAN interfacing featured the sharing of information via matrices which were used, in effect, to simulate the system's data base(s). Next-task codes were passed from the FORTRAN routines to the worker-Transactions via a worker-Transaction Parameter. This GPSS-FORTRAN interfacing took a highly natural form conceptually, and was easy to implement, posing no significant problems of any kind.

In addition to the three self-contained GPSS model segments just described, three other GPSS segments were used in the overall model. One of these other segments handles the placement and receipt of raw-materials replenishment orders; one initiates each new day's activities, setting the day's objectives (based on backlogged work, if any, plus other work originally called for that day); and one updates the finished-goods inventory to reflect the day's finished-goods shipments. In each of these cases, however, actions taken in these additional GPSS segments are dictated by information pre-stored in matrices. This means, for example, that such things as the master production schedule, the parts-explosion matrix, and the planned replenishment-ordering schedule were determined by hand for a given time frame, and were built into the model vis GPSS INITIAL declarations, and/or via FORTRAN DATA declarations. In an expanded version of the model, information in these matrices would be supplied dynamically via FORTRAN routines implementing procedures, practices and policies in effect within the higher-level strata in Figure 1. It is estimated that model enhancement along these lines would introduce no problems of conceptualization or implementation that could not be handled easily.

The roles and relationships of the GPSS model segments and the FORTRAN routines (or their pre-stored matrix analogs) for the toy-manufacturing system are summarized in Figure 6. There, the WORK IN PROCESS box represents the GPSS segments simulating the molding machine, and assembler stations 1 and 2 in Figure 5. The Figure 6 line between WORK IN PROCESS and PRODUCTION COORDINATION COMPUTER represents the FLOW OF INFORMATION ON-LINE links labeled 1, 2, and 3 in Figure 5. The various disk shapes in Figure 6

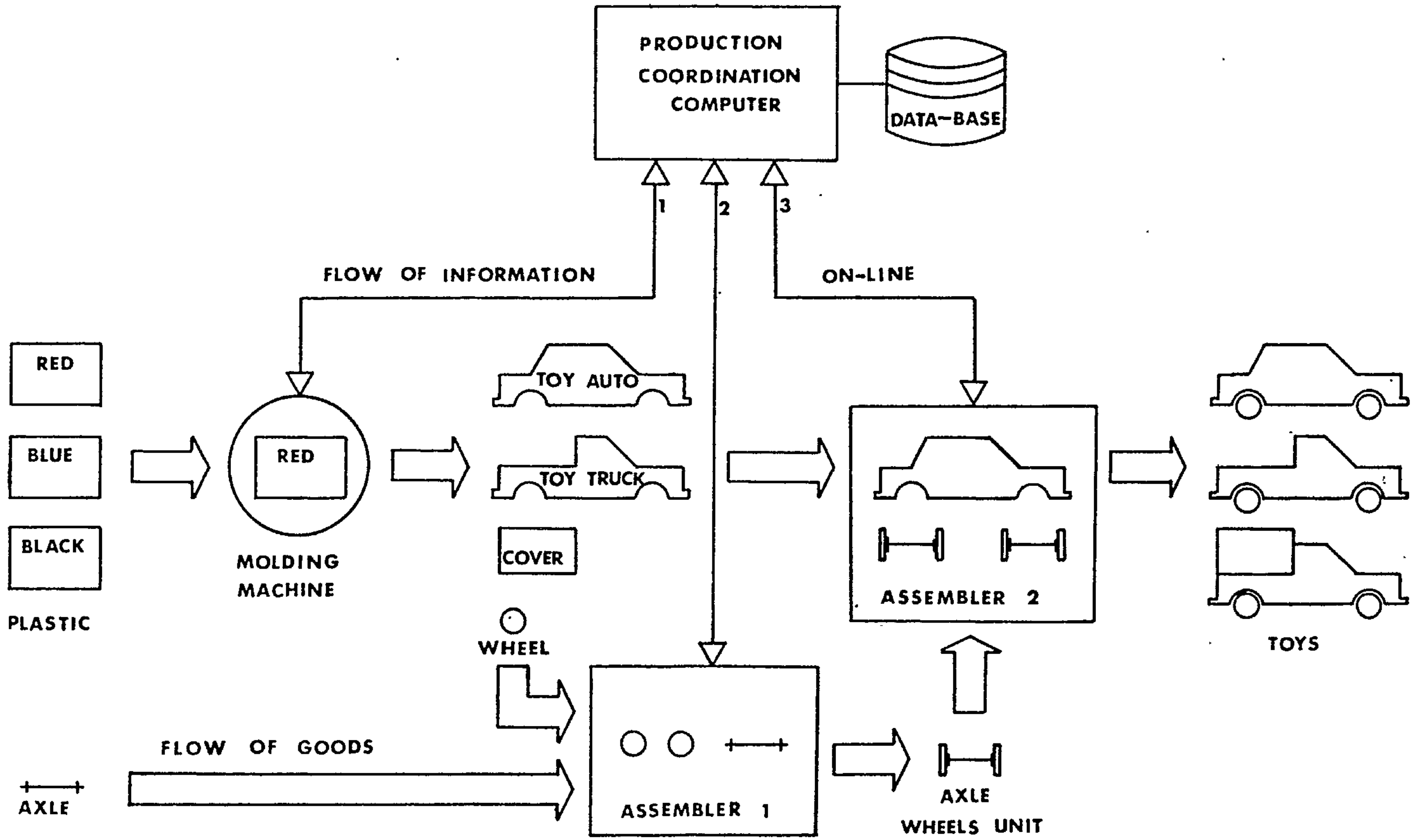

FIGURE 5. PRODUCTION FLOWS IN THE TOY-MANUFACTURING SYSTEM

represent pertinent data bases simulated in the exploratory work with pre-stored matrices. The use of FORTRAN routines to load pertinent matrices dynamically over time, as an alternative to pre-storing their values, amounts to providing FORTRAN-based logic for the boxes labeled MATERIALS REQUIREMENTS COMPUTER, SALES COMPUTER, and PRODUCTION PLANNING COMPUTER in Figure 6. Of interest here is the fact that a functioning GPSS-FORTRAN model of the toy-manufacturing system was built without providing special algorithms for materials requirements, sales, and production planning as an integral part of the model. This suggests that a "crawl before you walk, then walk before you run" approach can be taken conveniently when building simulation models for hierarchical control systems. Put differently, this means that the simulation-based design of a hierarchical control system can proceed through a series of stages of ever-increasing refinement, with gradual replacement of relatively macro (or even "unintelligent") system modules with corresponding modules which reflect finer and finer degrees of detail.

SUMMARY

The feasibility of using combined GPSS-FORTRAN models to simulate hierarchical, multilevel control systems in a manufacturing environment has been investigated and established. The ease and naturalness of working with such combined models indicates that this approach offers significant potential for experimentally investigating the properties of proposed hierarchical control systems. Such investigations are of importance for one or more of a number of reasons, namely:

...the relative goodness of various control algorithms which are candidates for use in these systems can be assessed;

...so-called top-down, bottom-up, and inside-out designs of hierarchical systems can be performed, replacing relatively macro model modules with a series of successively refined modules, reflecting ever-increasing degrees of finer detail as the design process converges on a finalized result;

...the potential benefit of real-time control of manufacturing operations, as contrasted with more conventional procedures, can be estimated in specific contexts;

...and the hierarchical control models can be used to test and evaluate the actual control software and data bases (as well as data base management systems) proposed for use to support the operation of such systems.

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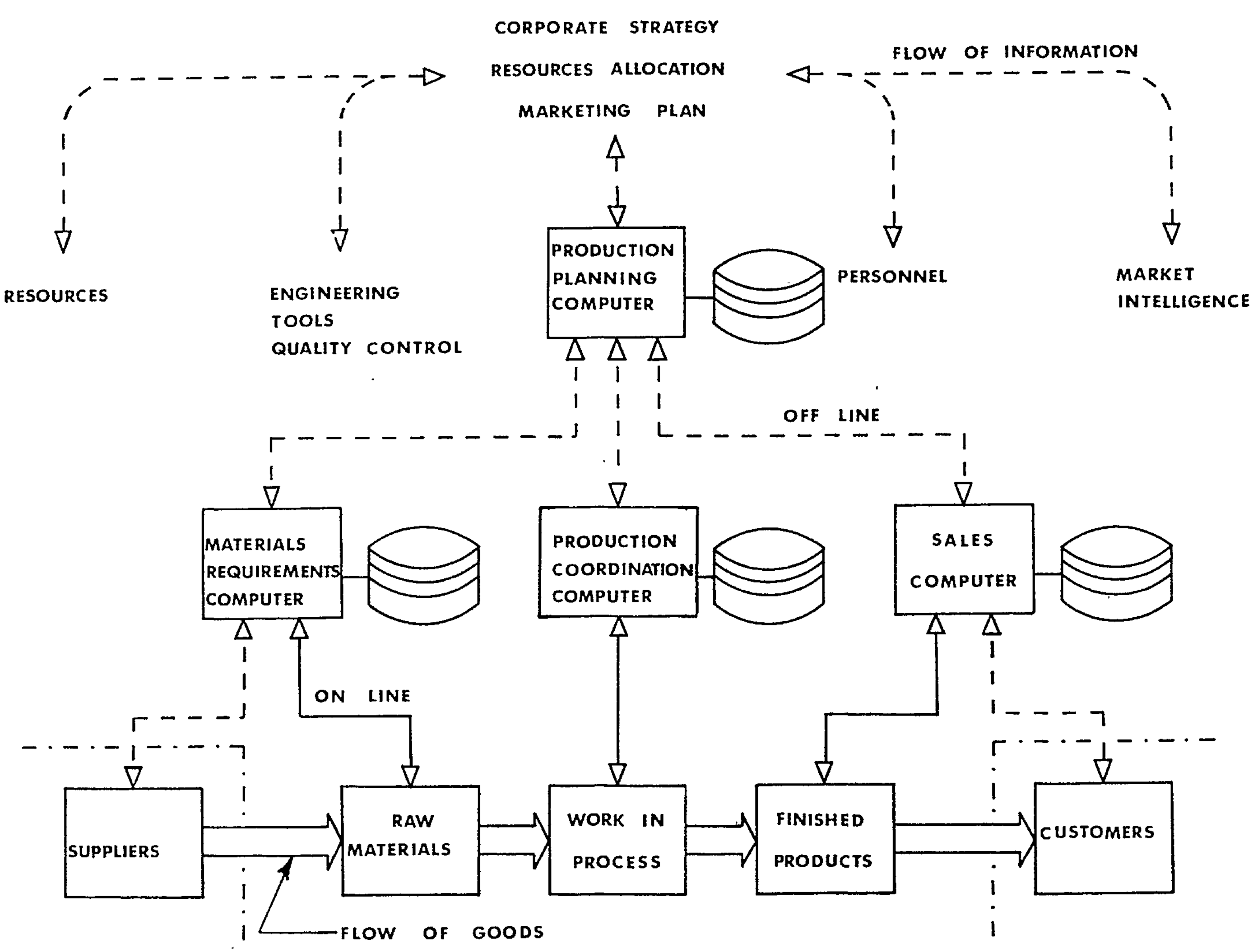

FIGURE 6. THE HIERARCHICAL, MULTILEVEL CONTROL STRUCTURE IN THE TOY-MANUFACTURING SYSTEM