Technical Research Report

Systems Research Center

Supported by the
National Science Foundation
Engineering Research Center
Program (NSFD CD 8803012),
Industry and the University

Cell Controllers: Analysis and Comparison of Three Major Projects

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TR 90-66

CELL CONTROLLERS : ANALYSIS AND COMPARISON OF THREE MAJOR PROJECTS

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August 1990

ABSTRACT

There is a critical need to achieve Computer Integrated Manufacturing, to link the factory-level functions (Product Design, Process Planning and Manufacturing Resource Planning) with the manufacturing functions (Parts Manufacturing, Product Assembly, and Quality Control). The primary functions performed by this link for all jobs issued to the shop floor, (i.e. all the parts to be manufactured in a specified period of time) include :

i) the allocation of resources (machines, material handling devices, etc), and
ii) the scheduling of tasks (manufacturing operations, material transfers, etc)

This paper defines these functions and presents the different methods that have been proposed to solve the associated problems. It provides analysis and a critical comparison of the current research at the National Institute of Standards and Technology (NIST, formerly NBS), European Strategic Program for Research and Development in Information Technology (ESPRIT, Project 932), and Computer Aided Manufacturing International (CAM-i) concerning Planning, Scheduling and Control at the Shop-Floor level.

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INTRODUCTION

The principal objective of Computer Integrated Manufacturing is to integrate the production system as a whole across the entire enterprise. Extensive research has been performed on flexible manufacturing cells, robotics, and other fabrication and material handling devices, towards the integration of the manufacturing functions that are performed at the equipment level of a shop. An attempt to integrate the different functions at the strategic factory level is also underway [19,20]. It is based on the development of a knowledge based system that manages the interface between Computer Aided Design, Computer Aided Process Planning and Manufacturing Resource Planning, the last being the coordinator and controller at the operations level.

A further step towards integration of the production system would be to bridge the gap that exists between these two integrated levels through a shop floor controller. This system will plan and schedule the jobs issued by the MRP system from the factory level, and control their execution by the automated manufacturing system at the shop floor level.

In order to incorporate the Shop Floor Control system, the missing link between the factory level and the manufacturing level, the first step has been to review and critically compare major research projects focused on the shop floor level. This will enable us to define shop floor decision making and the control architecture needed to extend our integrated factory level system into an enterprise-wide production system.

Following the trend in recent research in Production Control, we look at the planning and scheduling functions as part of a hierarchical production system. Although several hierarchical planning and scheduling systems have been proposed [32] , very few of these hierarchies define in detail the decision making and control processes of the shop floor activities. Production planning becomes a crucial problem when it comes to the scheduling task. Although a lot of scheduling algorithms exist, there has not been extensive research to incorporate real time control in schedule execution, to provide corrective action in case of schedule upsets, due to unexpected events.

This study will focus on the analysis of three, well defined cell-controller architectures that address real time solutions. All three systems fit in similar Hierarchical Production Management Systems established by the NIST (formerly NBS), CAM-i and the ESPRIT project 932.

The first part of the paper is a brief review of the definition of the major production-related functions, such as planning, scheduling, and control, performed at the shop floor level. In the second, third and fourth parts, we present respectively the objectives, the cell controller architectures, and a critical review of each of the three systems: NIST, ESPRIT-932 and CAM-i. Finally, the fifth part is a critical comparison of these three systems highlighting those characteristics that can serve as selection criteria for industrial applications. A comprehensive list of references is also provided for in-depth study of specific topics in shop floor control.

1 DECISION MAKING AT THE SHOP FLOOR LEVEL

1.1 Manufacturing Systems - Hierarchical Approach

Every manufacturing system in a large scale discrete production environment is subject to both, endogenous and exogenous uncertainties and disturbances. Hierarchical decision making is perhaps the only way to address the complexity associated with such a large dimensional problem. An important benefit of hierarchical decision making is when the system is subject to random events and uncertainty. Decision making with uncertainty could lead to frequent recomputations; monolithic models would require the entire problem to be resolved, while a hierarchical approach can gradually absorb random events without the need to resolve higher level problems. This results in large savings in computational burden, apart from added stability to the overall control.

Traditionally, three to five levels are defined. The top level is the strategic corporate planning level, below that is the tactical factory planning level; Computer Aided Design, Process Planning and Manufacturing Resource Planning are the principal functions performed at this level. Below the factory level is the shop floor. It consists of a group of processing stations or production cells (usually NC machines) connected together by a materials handling system. Parts flow through the shop, following different routes. The shop floor receives requirements from the factory-level, such as manufacturing plans (for instance output by an MRP system) for a set of jobs with associated due dates and data such as process plans, NC part programs, etc. The lower levels then coordinate and control the machines and other resources on the shop floor in order to satisfy all requirements at the right time.

The problem that we focus on, the cell controller, is the dynamic planning and scheduling of production, spanning over a time horizon of a few days down to the real processing time. The interrelationships between the parts being manufactured make the problem extremely complex. Also, this problem cannot be isolated from the global enterprise planning problem. Indeed, the global planning problem is broken down into a series of sub-problems which are sequentially solved, in the sense that the solution of a problem imposes constraints on the next lower level; the global solution is obtained when all the problems are solved.

More information regarding hierarchical production planning systems can be found in [1,27,28,29,30,32,35,39,40]. This study focuses on the analysis of the planning functions being performed at the shop floor level and downloaded to the equipment or machine level.

1.2 Cell Controller Functions

As mentioned above, the job shop is considered as a set of cells. Each cell includes processing equipment such as NC machines , robots and other material handling devices, and storage facilities.

The cell controller is responsible for:

i) transforming the manufacturing plan into a sequence of work orders with start and finish times for each workstation and each material transfer system within a short time horizon,
ii) monitoring the progress of these work orders, and
iii) taking corrective action, if any orders cannot be completed within the defined time limits.

Various definitions of these functions are presented below. A more detailed description of the functions occurring at the shop floor level can be found in [2,34,39].

1.2.1 Production Planning and Scheduling

1.2.1.1 Definitions

Planning is defined as the allocation of resources of an enterprise to various tasks to meet its objectives. It consists of a variety of interrelated functions, such as business planning, production planning, material requirement planning, and process planning. The objectives of planning depend upon the level of the hierarchy at which the plan is developed; for example, at the factory level planning is usually undertaken to determine what the company expects to manufacture and it is expressed in specific configurations, quantities and due dates, using Master Production Scheduling systems.

The distinction between planning and scheduling at the shop floor level is fuzzy and the terms are used quite interchangeably as defined by O'Grady [39]. As per Bourne and Fox [2], scheduling involves the selection of a sequence of operations (a process routing), to complete an order, and the assignment of times (for example, start and finish times) and resources to each operation. It is noted that an operation defines the resources required, the machine setup time, the machine run time, and labor requirements. Typically the process routing selection is considered as a planning activity and hence a part of the planning function, whereas the assignment of times and resources is a scheduling activity. However, the choice of a routing cannot be made without generating the accompanying schedule. The admissibility of a process routing is determined by the feasibility of each selected and scheduled operation. An operation is feasible when its resource requirements can be satisfied during the scheduled time of the operation.

In this study scheduling and planning include :

i) determining the allocation of production resources to jobs

ii) setting up the processing sequence for all jobs in queue at a machine, and

iii) determining the start and finish times for each job on each machine on which it must be processed.

1.2.1.2 Real Time Approaches

For most production environments the scheduling problem is stochastic, since the processing time for each operation is a random variable due to unpredictable events. Furthermore, job-shop scheduling is a NP-hard problem, i.e., its complexity increases exponentially with the number of variables involved. Mathematical algorithms cannot be used to solve this problem in real time and therefore, it does not allow any real time control. Interesting reviews of off-line scheduling algorithms can be found in [17,18].

To solve the scheduling problem in real time, various heuristics are used. These are methods that use the specific nature of the problem to simplify decision making, and yield acceptable, although suboptimal, solutions. Many of these heuristics are based on temporal and/or spatial decompositions of the problem. For example, a scheduling task can be simplified by aggregating products into families and machines into cells, based on part production routings: this is a spatial decomposition. The temporal aggregation groups products according to planned manufacturing start time or due date. It is then possible to schedule the aggregate items. The difficulty encountered using such a method concerns the disaggregation process. The disaggregation of an aggregate schedule is not always feasible. For example, if a family of parts has been scheduled for manufacturing on a given date, it is not always possible to derive the exact starting time for each individual part. These problems are discussed extensively in [9,10,11,28,38].

Finally, other popular heuristics rank jobs queueing up for a machine on the basis of some simple measure. When the machine or process becomes available, the job at the top of the list is chosen.

Here are some examples of the most popular heuristics:

i) Shortest processing time (SPT) :

It considers the shortest processing time for the next operation as having the highest rank. It is very effective in reducing average throughput time but does not take into account the required due date.

ii) Slack sequencing :

It considers jobs with the smallest difference between the due date and the total operation time as having the highest priority.

iii) Due date sequencing :

Jobs with the nearest due date are sequenced first, but no allowance is made for the expected operation time.

iv) Set up time sequencing :

It sequences jobs at a workstation by minimizing the total set up time, i.e., following the solution of the "traveling salesman problem".

An excellent survey of all these sequencing and scheduling methods can be found in [16].

1.2.2 Control

According to Bourne and Fox [2] " the monitoring and control of work is an extension of planning and scheduling, because it alters plans and schedules in reaction to changing environments. This requires the acquisition of status information from the factory floor, by comparing expectations with actual data, and by determining the minimum change which keeps schedules close to original schedules to maintain production stability. " A study on existing cell control hardware and software is presented in [31].

Based on this study, it is assumed that 80% of the "cell controllers" in industry only perform monitoring functions. These are standard control software systems that monitor the inputs of each machine (NC programs, etc), download orders, collect output data and generate alarms in case of conflict. Auto-Cell by Thesis Group, Cell-Pac by Arthur Andersen and CELLworks by Fast Tech Integration, Inc. are a few examples of such systems.

True " cell controllers " are customized software systems that act in the way a foreman would manage the cell. They are responsible for the coordination of the machines within a cell. Response times have to be in the order of hundreds of milliseconds to satisfy real time cell operations. American companies developing such extensive software systems include

Motorola's Computer X, Allen Bradley, Measurex Automation Systems, IBM, and AT&T. Digital Equipment Corp. and IBM are the leading suppliers of cell computing softwares. Other significant products are the Yokogawa's YEWMAC line of cell controllers, supplied by Johnson Controls, Inc. and Allen Bradley's Pyramid Integrator (PI).

2 NIST / AMRF

2.1 Objective

The Automated Manufacturing Research Facility has been established at the National Institute of Standards and Technology. It was developed to address the need for standards and measurements for the factory of the future. A control and decision-making hierarchy is proposed to control the various production and support activities required to drive this prototype factory. It is composed of a five level hierarchy :

i) Facility : business and strategic planning,

ii) Shop : production coordination,

iii) Cell : dynamic production control,

iv) Work Station : generation of production schedules,

v) Equipment : monitoring of the execution of production tasks.

One of the main issues addressed by this hierarchy is the real time scheduling which is performed at both the cell and the work station levels. The cell level is defined as a collection of machines forming a virtual cell [33], which allows for improved efficiency by using a set of machine tools and shared setups, to produce a family of similar parts. The virtual cell is a dynamic production control structure and not a real manufacturing cell which is defined by a fixed grouping of equipment on the shop floor. The workstation level directs and coordinates the activities of small integrated physical groupings of shop floor equipment.

2.2 Production Scheduler [12,13,14]

The scheduling function is performed into a two level hierarchical structure. At the first level, known as the Inter-Process Coordinator level, the inputs of the system, issued from the shop floor to the cell, are a list of jobs with associated due-dates, precedence relationships and a set of evaluating criteria. Based on the latter the system proposes start and finish times for each job at each workstation (process). At the lower level, the Process Controllers decompose the job schedules for every operation at every single equipment of the workstation, based on a similar structure.

The scheduling function is formulated as an optimization problem with the following objective function:

$$W[f_1(E_{111},\ldots,E_{kjn};L_{111},\ldots,L_{kjn}),\ldots,f_R(.)], \qquad (1)$$

where, E_{kjn} and L_{kjn} are the earliest start time and latest finish time of the k-th task (operation) of job j to be performed on process (machine) n. f_r, for $r = 1,\ldots,R$ represent the criteria to be considered, such as minimizing tardiness, maximizing production throughput, maximizing process utilization, etc. A job is a batch order of a specific part. In order to be manufactured, this part needs to be processed on a series of different machines or processes. On each of these machines, a set of operations or tasks is performed.
The constraints of the problem include the job due dates, material handling and resource availability, precedence constraints, and alternate routings.

In this system, all information necessary for schedule execution is contained in the state of the system. It comprises of status information about the processes, buffers, jobs currently on the shop floor, current schedule, and information about new jobs to be added to that schedule.

Figure 1 shows the Interprocess Coordinator structure, which addresses both the planning and controlling functions. It is noted that this structure can be duplicated at any other level.

(Figure 1. Detailed schematic for the production scheduler.)

The Scheduling function at each level, is divided in four steps, as described below :

Step 1 : CANDIDATE RULE SELECTION

It provides for both the selection of the scheduling rules and the associated evaluation criteria. The evaluation criteria are a combination of goals related to the performance of the entire manufacturing system, processes and jobs. They are often fixed. No reliable methods are available for choosing the appropriate criteria as a function of the system under consideration. The scheduling rules are a combination of preselected job release strategies, queueing strategies, material handling strategies. These rules can be fixed or can vary with the state of the system. They can be selected using algorithmic approaches or heuristics.

Step 2 : SIMULATIONS

Each trial is initialized to the current state of the manufacturing system. A number of simulation trials (K) are performed for each scheduling rule. For each rule, each of the objectives is evaluated (tardiness, production throughput, process utilization...)

Step 3 : STATISTICAL ANALYSIS

For each objective and scheduling rule an empirical probability density function is developed. Mean, sample variance, minimum and maximum are then computed.

Step 4 : COMPROMISE ANALYSIS

The best compromise scheduling strategy is chosen. It is noted that methods for making this choice in a stochastic, multi-criteria, decision making framework are currently being developed.

The control function is performed by the following modules :

LIST GENERATION

An additional single pass of the simulation is made to obtain the event list E.

$$E = [\, E_{11}L_{11}, \ldots\ldots, E_{jn}L_{jn} \,] \qquad (2)$$

The event list is then sorted into three other lists

i) chronologically into a master schedule,

ii) by job into a scheduling list (to track each job at any given time), and

iii) by process (to predict the status of a given process at any time).

COORDINATION

It coordinates the activities of the next lower level, which in case of the shop controller are the cells, and in the case of the cell controller are the workcenters within the cell. It also provides feedback status to the next higher level of the hierarchy on job completion.

COST ANALYSIS

This function has not been defined yet. It will be added to the system in the future. It is to evaluate the cost of the generated schedule.

CONFLICT RESOLUTION

It determines the impact of the discrepancy on the current schedule. If the scheduling rule is still realizable, the estimates for the anticipated durations are simply updated and new lists are generated. If the scheduling rule is no longer valid, then the entire exercise must be performed again.

2.3 Critical Review of the NIST/AMRF System

In the NIST model, the cell controller has a high degree of autonomy, since only the broad goals for the production period are transmitted down to the cell from the level above. Using a distributed scheduling approach across the different levels of the hierarchy the NIST system can :

i) quickly analyze alternatives at a given level,

ii) perform contingency planning at each level,

iii) resolve conflicts that arise between decisions at different levels.

The scheduling algorithm proposed is based on running parallel on-line simulations. Significant advantages offered by this approach include; decomposition of the overall problem into simpler subproblems, and the use of well established heuristic scheduling rules. Thus, production schedules are generated to optimize some utility function that could include more than one criteria, such as minimizing tardiness, maximizing production throughput, etc. This is accomplished by considering a number of different typical dispatching rules like Shortest Processing Time (SPT), or Last Come First Served (LCFS), etc., for each scheduling run.

While the NIST approach offers the advantages described above, it also has some limitations in its present implementation. One of these limitations is that the system does not provide for a true real-time implementation by taking into account the dynamic nature of the problem. The on-line simulation procedure requires that each of the "K" simulations be initiated from a known, invariable state, which is tied to the initial state of the manufacturing system. The underlying assumption is that the optimal value that corresponds to this initial state remains optimal, although the state of the manufacturing system has already evolved.

To date, the NIST published research has been based on the assumption that all trials must be initiated from the exact same state. Further work is required to study the implications of relaxing this assumption and thus considering a true "real-time" approach. The impact of this relaxation will have to be investigated in terms of the definition of the input and output data structures and the statistical analysis.

Another limitation inherent in any simulation approach for a production system, as opposed to one for a research test-bed, is the power of the computing technology available today. The AMRF test-bed for the NIST model uses an Intel 80286 based Personal Computer to run the concurrent simulation trials. One of the alternatives under consideration at NIST is to network a number of Personal Computers, for each candidate rule in order to increase the speed of the concurrent trials. However, there are some questions as to whether this approach will provide the speed required to support an industrial implementation. Furthermore, the required temporal aggregation of the simulation output from a network of personal computers is not yet feasible, since the state of the art in concurrent simulation technology has not progressed far enough.

Another area that has not been completely addressed by the NIST research effort is the issue of Conflict Resolution. In case that a job is not completed at its scheduled time, the event list (E) is no longer valid and must be updated. Thus the controller must update its solution, in real-time, to restore feasibility. This involves an interaction within decomposition that has not been extensively explored [12].

Finally, it must be noted that some of the techniques required to carry out compromise and statistical analyses for the concurrent simulations, including detailed coordination rules under which the workstation controller can modify the cell controller solution, still need to be developed.

3 ESPRIT, Project 932

3.1 Objective

The European Strategic Program for Research and Development in Information Technology (ESPRIT), involves both European industry and academia. Esprit project 932 (Knowledge-based real-time supervision in CIM - The workcell controller) was initiated in 1986 and is currently underway. It involves 4 European countries represented by manufacturing industries, universities and software companies participation.

The goals of this project are [37]:

" To define a methodology for the analysis, design, and implementation of Artificial Intelligence based software modules for Production Planning, Quality Control and

Preventive Maintenance (large and small batch oriented); to propose an extension of the hierarchical NIST factory reference model towards a distributed intelligent controller model ; to propose a methodology of analyzing and designing the heart of a CIM system, an intelligent workcell controller. "

Such a controller has been implemented as a prototype at Philips, Wetzlar (Germany) and at BICC, London (England).

The Factory Reference Model is derived from the NIST factory model and incorporates the hierarchical control strategy proposed by the GRAI method [15,24]. GRAI is a structured approach for the analysis and the design of the production system which combines the concept of time horizons (time interval for which commands are sent down to the lower level) and planning periods (time interval in which these commands are updated) with the hierarchical control levels of the factory. The horizontal decomposition is based on functional criteria (basic functions of production such as planning, maintenance, quality assurance, etc.).

Decision making at each level is performed by a " CIM Controller ". Each controller consists of sub-controllers, or decision making units, each responsible for a specific function of the area under control. The main coordinating controller is the production controller (planning, P) which controls sub-functions, such as quality control (Q) and maintenance control (M). However, each sub-controller has the same internal structure, as shown in figure 2, and includes an interpretation, diagnostic and action planning (planner) expert system, which are supported by a static model to represent the static informations of the area under control and a dynamic model to simulate the production system. The action-planning part of each module receives decision frames from a superior module and generates a set of decision frames for the action-planning part in inferior modules, depending on its world knowledge. The interpretation/diagnosis module receives feedback concerning the effects of its decision frames, informs its superior interpretation/diagnosis part about them, and updates its world model. This leads to a closed command-feedback loop.

The production controller design at the workcell level is addressed in this paper. Furthermore, the controller implementation at Philips is presented.

3.2 The Production Controller at the Workcell level

3.2.1 Purpose

The principal function of the workcell controller is to provide an interactive tool which can be used in real time, either for the generation of plans at the beginning of a shift, or after major breakdowns for replanning. Its goals [37] are :

1) Create a daily plan for each workstation :
This is developed by considering the weekly plan (e.g. MRP plan), the availability of the workcells and/or workstations, the performance of each workcell/station, the manpower resources available, and the product routings. This daily schedule serves as an advice to the planner who confirms it.

2) Update daily plans according to the current state of the manufacturing system :
This requires the controller to monitor each machine's status, to interpret the status variables, the predicted production rates, the predicted machine breakdowns, the lack of material, to consider the shortage of manpower, and the predicted maintenance time. By considering the daily plan and each machine's loading, the controller modifies the schedule of work for each machine, and offers it as an advice to the planner.

3.2.2 Controller Architecture

The controller has the same structure at all levels and includes several sub-modules, each representing an expert system (XPS) that solve special control tasks as illustrated in Figure 2.

(Figure 2. Controller Architecture [36,37,40])

Expert Systems (XPS)

- Int — Interpretation XPS
- Dia — Diagnosis XPS
- Act — Action Planning XPS

Data and Knowledge Bases

- DB — Real-time database
- SM — Static World Model (KEE)
- DM — Dynamic World Model (Simkit)
- CB — Control Knowledge Base (Meta knowledge)

Information and Decision Flow

- C — Plan from upper level
- C_1-C_p — Commands to lower levels
- S — Status Report about plan execution to upper level
- S_1-S_m — Status signal about command execution from lower levels
- E — Interpreted status of resources to upper level
- E_1-E_n — Status signals from lower level equipment
- I — Global information from upper level

3.2.3 Expert Systems and Knowledge Base Specifications

The Interpretation XPS is the link between the observation of the real world and the model that describes that world. Its main purpose is to initialize the static and dynamic models prior to the start of the production planning. This system observes the performance of lower level equipment, including tools and movements of materials and products, and converts the data stream (E_{1n}, S_{1m}, I) from the lower and upper levels into understandable and relevant information for the upper level (E), the action planning XPS, and the diagnostic XPS.

The Diagnostic XPS explains the divergence between the actual and the required states. For example, it determines the causes of late orders or the reductions in capacity. It checks whether the presence or movement of materials, tools and products are according to the original plan, and whether equipment is operating properly. It also monitors the product quality.

The Action Planning XPS is a decision process which optimizes a set of decision objectives while respecting :

i) the constraints given by the decision frame (restriction of the solution space issued by a higher level controller),

ii) the requests (restriction of the solution space issued by a controller of the same level), and

iii) the function specific model (structure, parameters and state of the model).

The XPS takes corrective actions if planning cannot be realized, when, for example, a lower level workstation fails (replanning). It selects the algorithms to be used for the distribution of work orders (C_{1n} in figure 2); i.e. to determine the sequence and mix of products, etc. Finally, it suggests preventive maintenance actions if evidence of failure is shown. It also sends a status feedback (S) to the higher level about the execution of the command (C).

The Planning Module releases the optimal plan to the lower level, i.e. it distributes sub-commands C1n to the workstations to fulfil command C.

The Static World Model represents the static information needed during a production planning run. Such information includes the product model (type classes), the resource model (workstation type classes, mean breakdown times), and the process model (interrelation between product and resource model, i.e. routings, cycle times, set-up times, status of order completion).

The Dynamic World Model simulates the production for a set of values of the decision variables and uses the simulation results as a basis for the calculation of the evaluation functions.

The function of the controller described above will be illustrated by describing a real-life application of the system below which was implemented at a production shop that manufactures surface mounted electronic devices in a Philips appliance factory.

3.3 The Philips Workcell Controller Implementation

The prototype workcell controller was implemented at a production shop containing four workstations for wire connection, axial component insertion, radial component insertion and insertion of surface mounted device components.

The controller plans for :

- 10000 printed circuit boards per day
- 10 different orders per day
- 50 different products, and
- 20 physical machines

3.3.1 Inputs and Outputs of the Controller

The inputs of the workcell controller are issued from the shop level and include:

i) manufacturing orders (product type, quantities and due dates) in the form of a weekly MRP production plan. This is mainly based on customer orders and does not take into account available capacities on the shop floor,
ii) a list of planned maintenance intervals, and
iii) a list of urgent and short-dated orders.

The decision frame, which is a set of decision variables, specifies the production for the next two weeks (horizon). It is generated by the workcell controller and is passed down to the shop daily (period). It consists of: the sequence of orders per workstation, the absolute start date of the first order, and the planning window width, that is, a fraction of the time horizon in which the sequences of orders are optimized. The results of the simulation performed by the dynamic model are employed to obtain approximate values for the start and finish times of the orders for each workstation.

3.3.2 Planning Steps

The Planning steps are as follows [36] :

i) Determine Planning horizon and planning windows,

ii) Assign the orders for the bottleneck workstation to the appropriate planning windows assuming that each order can start and finish within the corresponding window;

iii) Determine an optimal sequence of these orders per window, the most important objective being to minimize the total set-up time;

iv) Determine the load of the bottleneck workstation per window using the computed sequence. Carry orders to the previous window, if capacity has been exhausted;

v) Schedule the orders that finish at the bottleneck workstation backward (forward) to all other workstations involved;

vi) Test the derived plan in terms of capacity;

vii) Validate the derived plan through simulation;

viii) Change the parameters of the planning model and restart from the first step.

It is noted that:

Planning window, time buffer size, batch size and mix can be adjusted.

Due dates, planning horizon and product quantities are fixed.

Maintenance times and set-up times are minimized.

More details on the planning steps outlined above can be found in [22,23,24,25]

3.4 Critical Review of the ESPRIT Project 932 System

The ESPRIT Project 932 provides a methodology to analyze the entire Production System. Using a tool, such as GRAI, a detailed decision making architecture is designed. Such a hierarchy may be applied to a large class of production systems by appropriately adjusting the time horizon and the planning period lengths. It is noted, however, that the heuristic selected by the system to solve the scheduling problem may differ from one application to another.

A sophisticated procedure is proposed for the scheduling optimization problem. Simulation is used both as a validation tool to calculate the evaluation functions and to obtain the start and finish times of the manufacturing orders at each workstation.
Although the procedure used is not obvious, the generation of the decision variables to be simulated seems promising. A conceptual network is used that represents the relationship between the rules (procedures) and the objectives [21].

The production objectives taken into account are:

i) respecting due dates;

ii) minimizing loads;

iii) minimizing throughput times;

iv) maximizing the utilization of resources.

These manufacturing objectives are weighted and their related evaluation functions have been derived for the specific area under control (one production function at a specific level of the hierarchy). It is assumed that maximizing the utilization of resources is the least important objective. Nonetheless, we believe that it has often an important influence on production cost, and therefore, should not be neglected. Furthermore, the problem of considering non-mutually exclusive objectives has been addressed. It has been shown that using the weighted sum of the objective functions can be misleading [26]: a weighted sum of functions can be minimized by an over-proportional reduction of a low weighted objective while a high weighted one has increased. To avoid this problem, thresholds are assigned to the most important evaluation functions. It is, for example, necessary to bind the percentage of tardy orders.

The controller structure proposed by ESPRIT is modular. Each task is well defined and is assigned to a specific module. For example, the state of the system takes into account both the static and the dynamic world and is controlled by the interpretation expert system.

It must be emphasized that, in the current version of the controller, scheduling is not performed in real time. It is only used as an advice to the planner at the beginning of each shift or in the event of a major breakdown. However, there is no fundamental reason that forbids the automation of the schedule release. Both, the generation and validation of the schedule can be accomplished in real time, since heuristics and fast simulations are used, respectively.

Despite this weakness, the production control functions have been analyzed in considerable detail.

4 CAM-i / MADEMA

4.1 Objective

CAM-i proposes a hierarchical decision making architecture for the manufacturing system. It is a structure with four distinct levels of control. The physical levels are the factory level, the job shop level, the work center level and the resource level. MAnufacturing DEcision MAking (MADEMA) was developed at MIT, under contract to CAMi's Intelligent Manufacturing Management Program. It addresses the assignment of resources such as machine tools, robots and materials handling devices, etc, to production tasks. MADEMA is active at the work center level as shown in figure 3 below :

(Figure 3. MADEMA Hierarchy)

It attempts to overcome the inflexibility inherent in traditional scheduling techniques which usually optimize a single criterion. Such an approach requires all aspects of the system to be reduced to one criterion in a pre-determined manner. This assumes that the manufacturing environment is static, while in reality, priorities, requirements and conditions are constantly changing. Extensive simulation and iterative modeling is often required to enable the models to reflect the actual production environment, thus making the system too complex to respond quickly to changes in the manufacturing environment.
The decision system based on MADEMA makes the assignment of resources to production tasks that is based on a multiple criteria decision making technique, suitable for flexible manufacturing.

Details on the decision making hierarchy and MADEMA are found in [3,4,5,6,7,8].

4.2 Methodology

MADEMA focuses on modeling the decision making process at the workcenter level. The workcenter refers to a cluster of production resources such as machine tools, transport equipment, robots, etc. It has responsibility for the

i) decomposition of the job orders into task orders,
ii) assignment of the task orders, and
iii) coordination of various resources.

MADEMA uses a five step approach. This approach accommodates the dynamic structure of the decision environment by considering several alternatives for the execution of a production task. The choice of one alternative over another is made by evaluating relevant criteria, or attributes in a decision matrix as illustrated in Figure 4.

(Figure 4. Decision Matrix [5])

The five consecutive steps used to reach a decision are:

Step 1. Determine alternatives (AL_1,........,AL_m)

Step 2. Determine attributes (AT_1,.........,AT_n)

Step 3. Determine consequences (a_{11},.........,a_{mn})

Step 4. Apply decision rules

Step 5. Select best alternative.

When assignment of resources to a production task must be made, one or more of the aforementioned steps must be executed in order to arrive at the proper decision. Additionally, the implementation of MADEMA requires :

i) a simulated manufacturing environment for testing the response of the manufacturing system, and,

ii) a database that provides the data needed for the decision making process.

An explanation of the decision making modules follows. Figure 5 shows the relationships between them as well as the information flow during the decision making process.

X-DAL:

Experimental determination of alternatives has been developed to enumerate the feasible alternatives. An alternative is defined as a possible set of resource assignments to specific tasks, i.e. a list of task (TO_j)-resource (R_k) pairs is one alternative,

$$AL_i=\{TO_1R_1,TO_2R_5,...,TO_jR_k,...\} \quad (3)$$

The alternatives are subject to the following constraints,

i) technological feasibility. The technological feasibility of the resources is determined by a process planning system via an adequately structured process planning interface,
ii) resource availability,
iii) resource idleness should not occur as long as an unprocessed task remains in the work center,
iv) no more than one assignment per resource is allowed,
v) no preemption.

X-DETA:

An experimental determination of attributes has been developed to determine the decision criteria such as quality, flow-time, operation cost, tardiness and waiting time.

Decision Matrix Generator:

It takes the list of available alternatives from X-DAL, the criteria determined by X-DETA, and additional information from the database, namely the evaluation of the alternatives with respect to the criteria. The output is arranged in a matrix format in which the rows correspond to alternatives, the columns to attributes, and the entries correspond to the "consequences" or the values of the attributes for the different alternatives.

X-EVA:

This module is used to select an alternative based on a decision rule, i.e. to implement step four of the MADEMA approach. The function of X-EVA is to convert the different values of the criteria associated with each alternative into a metric that can be used to rank the alternatives. This is done by first normalizing the decision matrix and then assuming a value function in which the variables are the optimization criteria. The decision rule can be the combination of attributes that indicates which alternative has the greatest likelihood of producing a higher utility value.

The resultant decision is passed on to the module *Get Best Choice* which generates a decision that is, in turn implemented within the module *Task Resource Assignments* (see figure 5).

(Figure 5. Implementation Structure of MADEMA)

DATABASE:

A manufacturing database is used to provide the data regarding the consequences of each alternative with respect to the relevant criteria. In order to assure technological feasibility, process planning information is provided. This is obtained via the process planning interface system, that transforms raw machine feed and speed data into time information, such as expected processing times. In addition, the database receives continuous feedback from the manufacturing environment concerning the availability of resources, the status of task orders, the congestion at work centers, etc.

The MADEMA decision making process is triggered whenever there is an idle resource present in the system. The points in time at which a decision is required are set by the choice of the decision horizon which, in this implementation, is variable and is determined by the completion of a task order by a resource.

4.3 System Performance

The performance of this system was studied with a simulator called X-EMA, built using LISP structures and used for modeling the operation of the manufacturing system.
X-EMA controls the simulation by maintaining a continuous clock time. Each time the clock is incremented, X-EMA calls procedures which alter the fields of the data structures, based on previous decisions and user defined characteristics of the manufacturing environment. At pre-designated decision points, MADEMA is called upon to make new assignments which are released to the manufacturing environment. This process is depicted in the flowchart of figure 6. It comprises of the following steps:

step 1: "Simulation complete?" :
At the beginning of each clock cycle, X-EMA determines whether or not all job orders have been completed.

step 2: "Load job orders" :
A set of specific job orders is introduced into the system when the arrival times are characterized by a probability distribution.

step 3: "Cycle job orders" :
Every job order is decomposed into task orders which are then assigned to the work centers. All work centers are then updated by checking the status of each resource and if a decision is required, X-EMA calls upon the appropriate decision modules to make the assignment.

step 4: "Increment current time" :

Once the above described cycle is completed, the clock is incremented and the simulation returns to the beginning of the simulation cycle.

(Figure 6. X-EMA Flow Chart [4])

At the end of the run, the statistics describing the overall performance of the system are printed or output on the screen. These can include, the number of late jobs, the cost of execution, average work in progress, etc.

4.4 Critical Review of the MADEMA System

The MADEMA approach utilizes a combination of the rigorous analysis of scheduling and decision making theory, with some Artificial Intelligence techniques, such as rule-based expert systems. This approach tends to overcome some of the limitations that arise from traditional scheduling techniques and purely analytical modeling methods which, generally superior to simulation methods, are slow and therefore, do not appear to be very practical in the implementation of commercial CIM systems. The MADEMA approach offers a number of significant advantages :

1. The formulation of the problem with decision matrices allows flexibility in the selection of criteria to be evaluated. Rather than utilizing a static and rigid model, a class of algorithms can be used, depending upon the current status of the objectives and goals of the organization. This approach allows one to consider criteria such as quality, and operational cost, which cannot be addressed by traditional techniques.

2. It provides a strong link to process planning, through the use of a process planning interface X-MAG, to the process planning system XPS-1, developed by CAM-i. This is a strong technologically oriented function, since X-DAL must consider the technical feasibility of the different resources while determining the possible alternatives. This allows the process planning information to be evaluated concurrently while scheduling is being accomplished.

A limitation of this approach is that, as the size of the problem (the number of jobs to be scheduled) increases, the computational requirements to enumerate the feasible alternatives can increase exponentially, thus limiting the implementation to a problem size that can be computationally efficient. The technique used to limit the number of alternatives is to select a fixed decision horizon, that takes less time to complete than the shortest task. This results in the assignment of one task to each resource, thus reducing the computation time required. Additionally, the estimation of the default values for unassigned tasks is not very accurate and this can lead to selection of assignments which are sub-optimal in their performance with respect to the selected criteria. Improving performance by a more accurate estimation of the default values and an elongation of the "look-ahead" period can, again, lead to a substantial increase in the computation time.

Another issue of concern appears to be in the formulation of the utility function by assigning an additive weighting to the various optimization criteria. Since a single objective function that contains multiple criteria can also include conflicting ones such as operational cost and quality (which may be mutually exclusive), the utility function may not retain its validity. This is an issue that needs to be explored further.

One area that is not clear, is how alternative routings are handled in the determination of alternatives. While all possible and technically feasible alternatives are considered, the rules used to sequence the tasks when alternative routings are encountered are not explicitly stated.

Finally, the interaction between the scheduler at the work center level and its higher level, in terms of resolving conflicts, i.e., in those cases for which the schedule is violated and made infeasible by machine breakdowns or by "rush jobs" being introduced into the system; has not been clearly defined. However, since MADEMA has been implemented commercially, it is possible that conflict resolution has already been addressed.

5 COMPARISON OF THE PERFORMANCE OF THE THREE CELL CONTROLLERS

An attempt to compare the three approaches described in the previous sections is made in this part. The comparison considers flexibility, real time performance, modularity and portability, reaction to perturbations, and extend of implementation. It is noted that this study is only qualitative. The results are given hereunder.

Flexibility- Adaptability

Of the three systems considered, the NIST system is the most flexible since the parallel simulation structure considers a wide variety of scheduling algorithms. This allows the selection of the scheduling algorithm that is best suited to the production environment.

Real-Time performance

Although, all three system architectures are designed as real time controllers, no real time implementation has been done as yet.

Reaction to Unplanned Events

This is one of the most critical issues that determines the capability of the system to be able to provide a true real time schedule. Each of the systems considered can handle minor perturbations and readjust the schedule accordingly. In all cases the algorithm is rerun every time that the schedule can not be met. In ESPRIT, however, the link of the planning system with the quality control and maintenance modules allows the system to handle some predictable events, such as minor breakdowns and maintenance times.

Modularity and Portability

All three systems are modular and their modules can be upgraded independently. In the case of ESPRIT some modules have already been updated because of the availability of more powerful tools. Based on their modular structure, the systems should be inherently portable. However, the complexity of the information required, or generated by each module make true portability across various application areas difficult to achieve.

Speed

Speed is an important criterion to consider; However, no pertinent data are available to do so. Since all systems include some sort of simulation, it is expected that their efficiency decreases when the size of the scheduling problem increases.

Extend of Implementation

From an operating management point of view, it is important to note the degree of maturity and implementation of each approach:

NIST is still under development; ESPRIT has been tested in industry, however, since its architecture is application specific it has not been commercialized yet; MADEMA is fully implemented and tested in practice.

6 CONCLUSION

The functions required for the control of shop floor activities have been identified in this study. It appears that real time shop floor scheduling in a discrete manufacturing environment is only at the research stage. Since the classical control theory cannot be applied, simulation, heuristics and expert systems are the most common tools used for scheduling production in real time. The present paper has presented a review of the three most promising approaches to shop floor control in an attempt to provide management with some criteria for future implementations.

It is noted that hierarchical architectures, based on hierarchical systems theory seem to be appropriate for the decomposition of production planning.

To this direction, the CIM Laboratory at the University of Maryland is in the process of initiating a major research project on Hierarchical Production Management Systems (HPMS) in collaboration with the French National Institute for Research in Information and Automation (INRIA).

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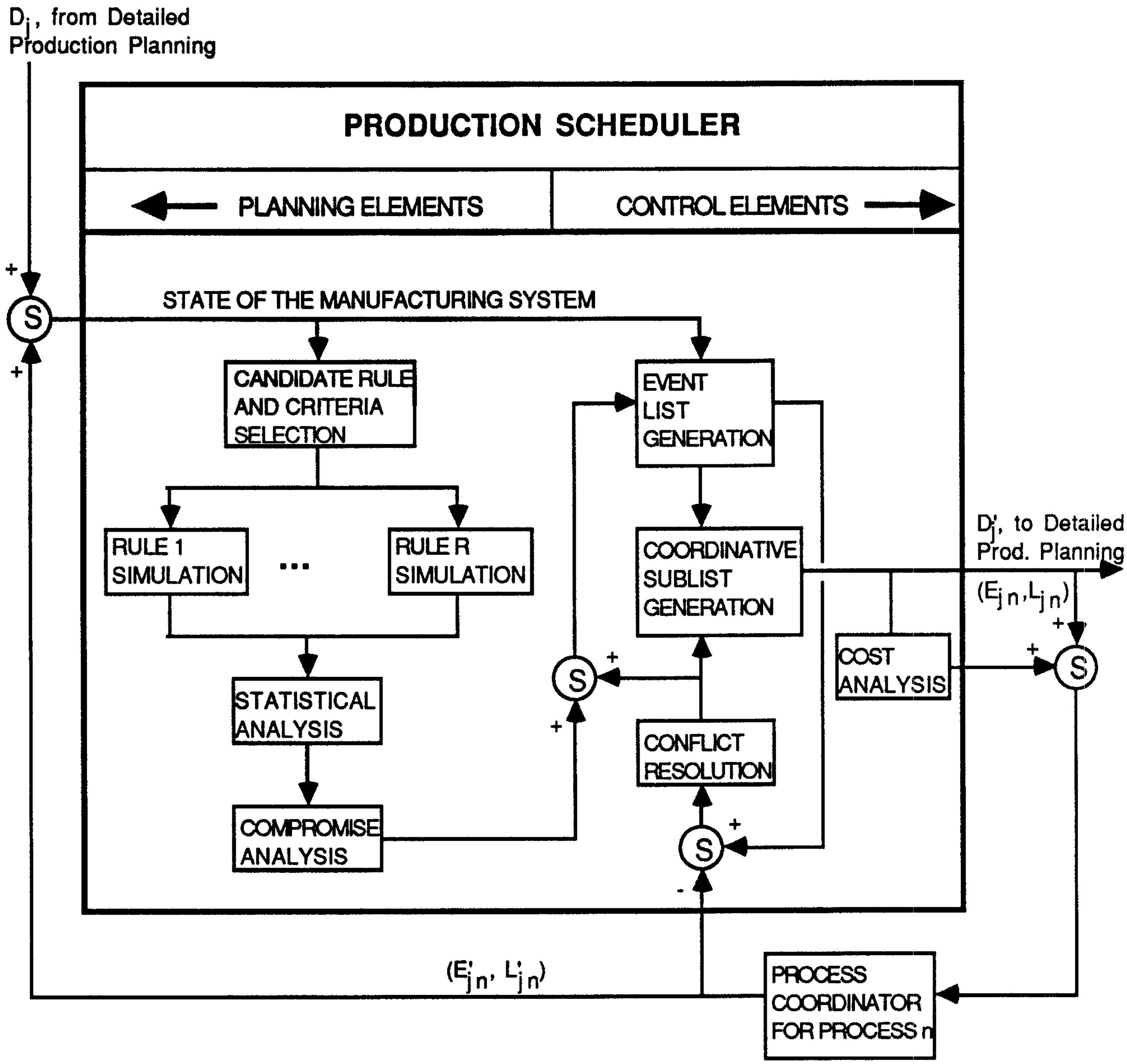

Figure 1. Detailed schematic for the production scheduler.

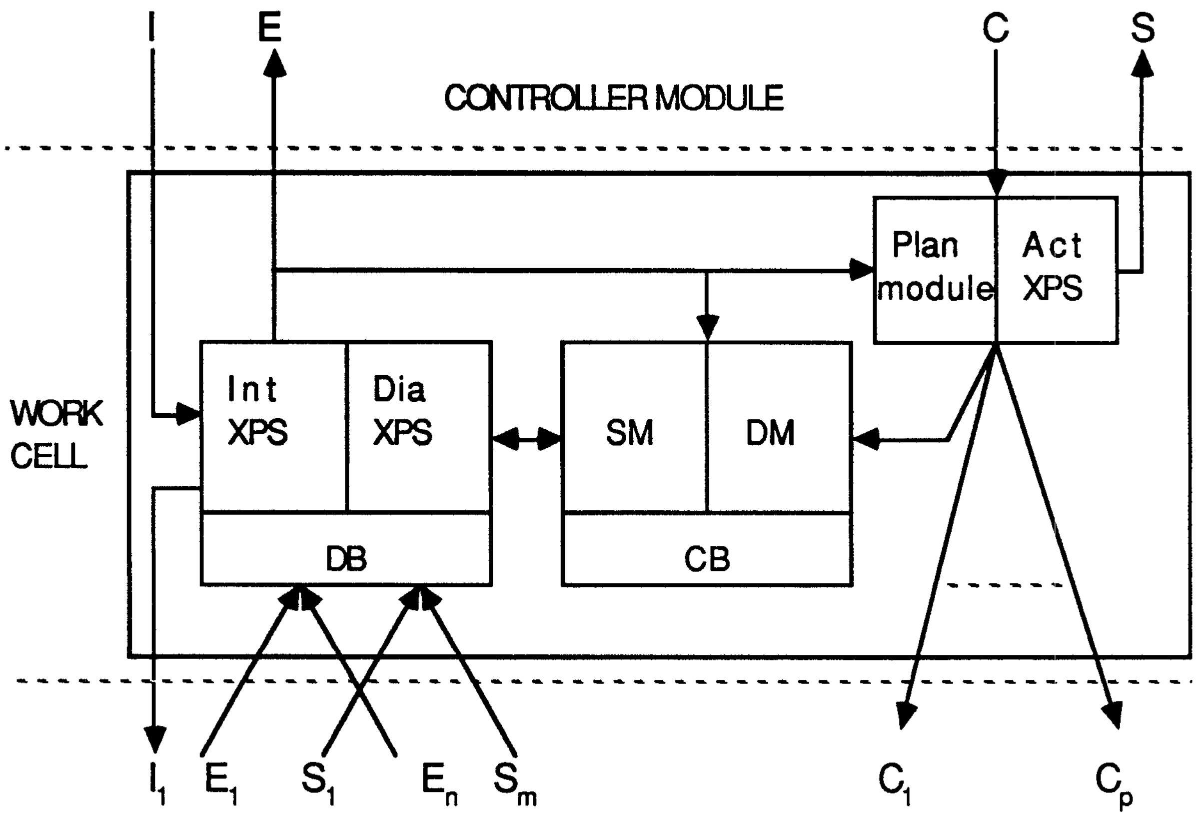

Figure 2. Controller Architecture [36,37,40]

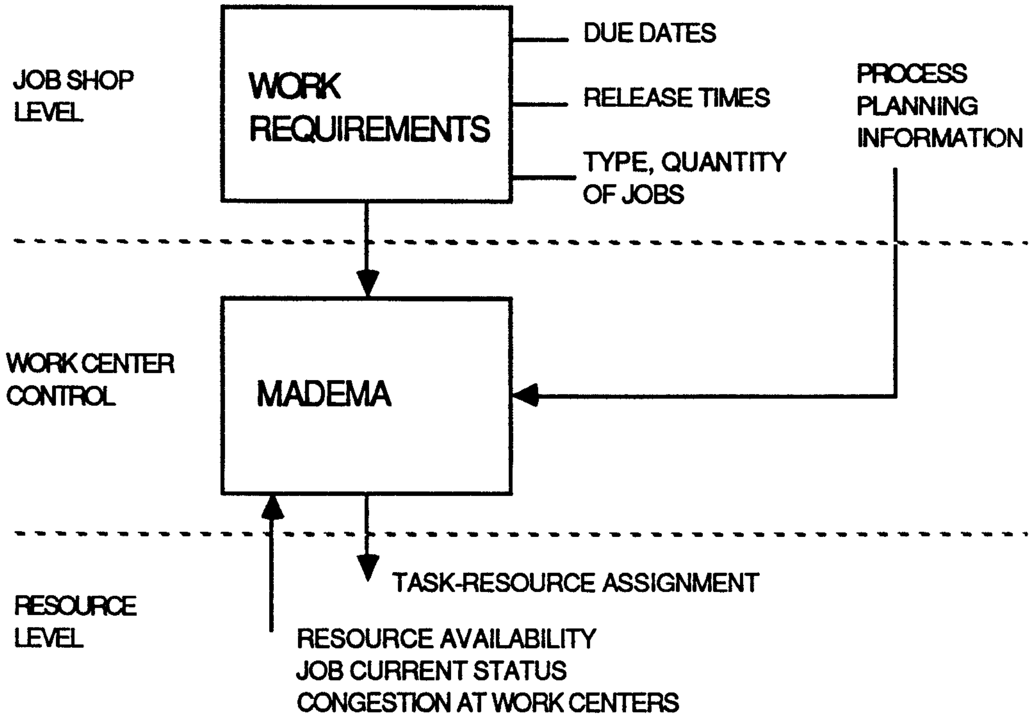

Figure 3. MADEMA Hierarchy

Attributes / Alternatives	AT1	AT2	AT3	. . . .	ATn
AL1	a_{11}	a_{12}			a_{1n}
AL2					
AL3					
.					
.					
.					
.					
.					
ALm	a_{m1}	a_{m2}			a_{mn}

Figure 4. Decision Matrix [5]

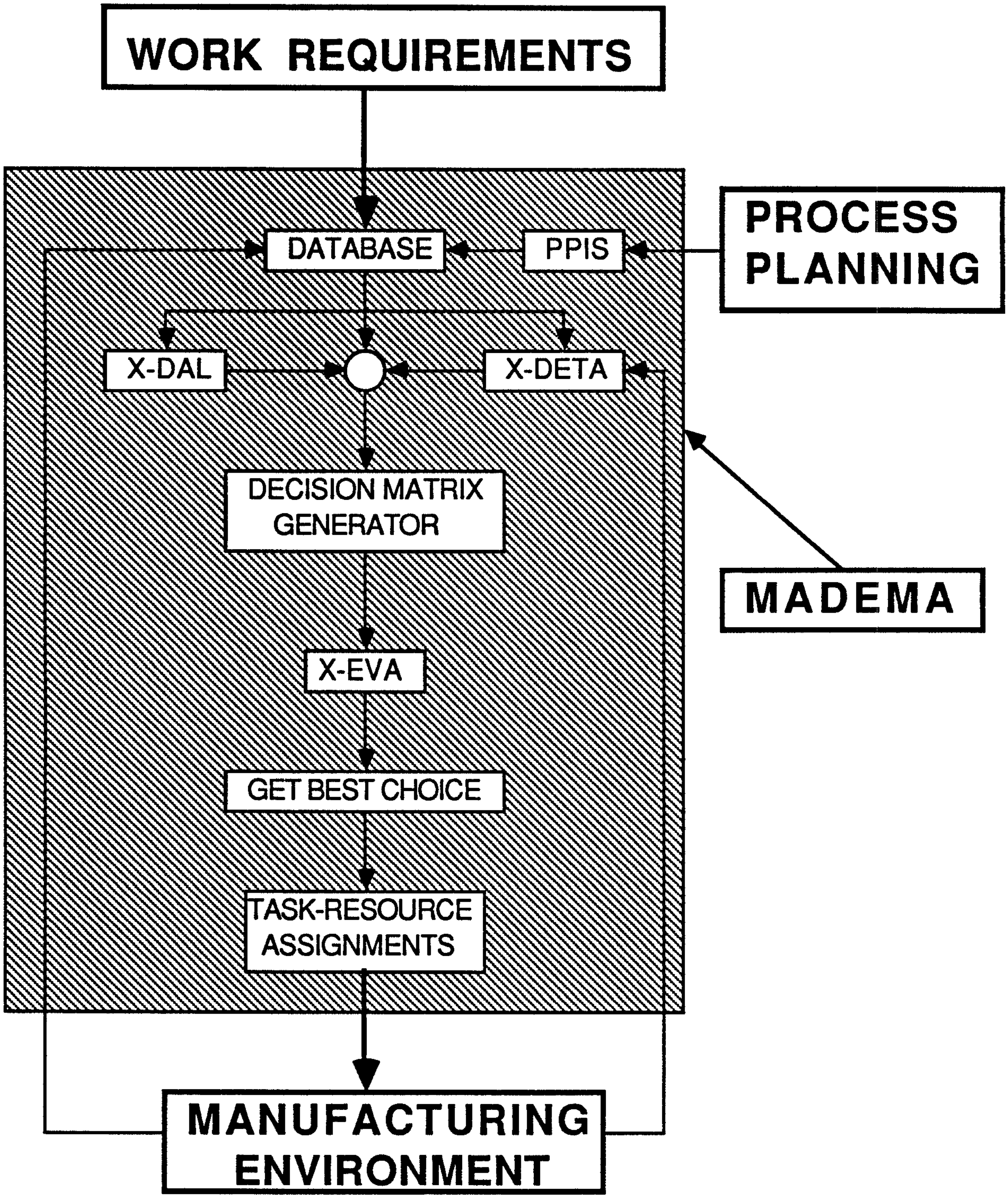

Figure 5. Implementation Structure of MADEMA

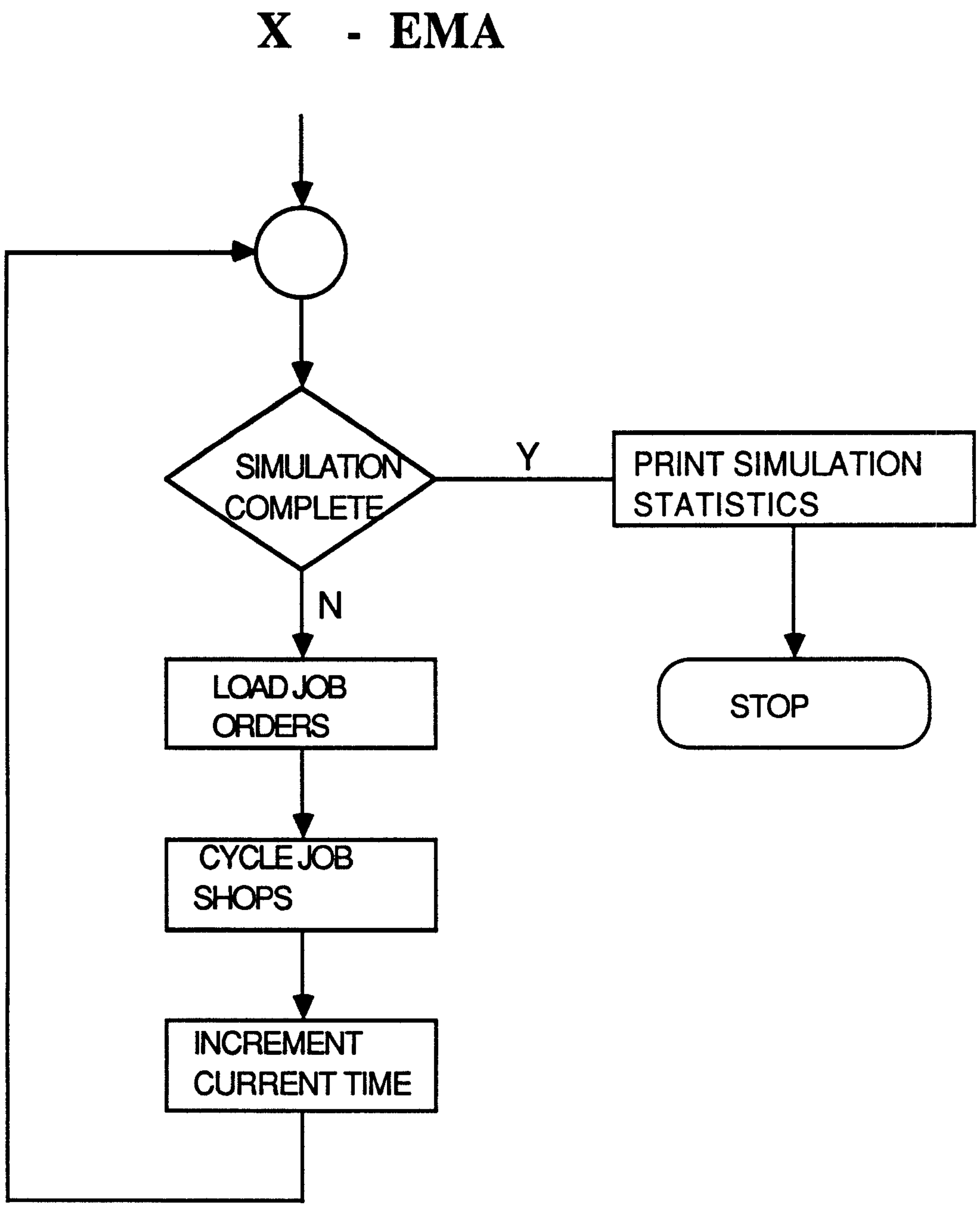

Figure 6. X-EMA Flow Chart [4]