Functional Design, Modeling and Analysis of a Facility-Level CIM System

by

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ABSTRACT

There is a critical need for establishing CIM at the facility level, to complement the research done in manufacturing integration, which has concentrated so far on flexible manufacturing cells, robotics and other material handling devices. This paper identifies the application modules that clearly lend themselves to an integrated information flow in a controlled manner: Computer aided design and computer aided process planning consist the product and process design centers of the proposed system respectively. Manufacturing resource planning undertakes the management of production plans to satisfy the market demand. The functional design of the system is derived from expertise in manufacturing management. The modeling and analysis are now formalized with the use of generalized Petri-Nets. The implementation strategy recognizes the existence of application tools that must be retained and subjected to synergism. Hence, a database interoperability language is in its final development stage, to enable the construction of the knowledge-base that will control the system. Extensions of this work include the incorporation of a shop floor control module, to interface with the factory level.

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1. INTRODUCTION

Two decades ago a technical discussion on integrated manufacturing would most likely have been viewed as an intrusion by the technologist into the activities of the manufacturing community, an intrusion that was neither needed nor wanted. But events have changed those attitudes. The evolving world economic system has demanded new responses. The resulting challenge to U.S. firms is severe. As a consequence " the whole manufacturing enterprise is undergoing fundamental change. It is becoming more science driven and both uses and produces sophisticated technology... We need to look at manufacturing as an integrated system and optimize it as a total process", (Anonym 1987). The technical tools used to design both the product and the manufacturing system will be increasingly critical to achieving the desired competitiveness. Creating these tools, however, requires a thorough understanding of the principles of the manufacturing process as a system. It is an unfortunate commentary on the state of development of manufacturing technology that this basic understanding has yet to be achieved. Traditionally, the first step in treating the system as a whole has been to start from considering specific independent sub-systems, that fall within one's specialty, such as design, processes, materials handling and the like. Clearly, this approach has been successful in creating stand-alone modules with little to no synergism.

Adopting reasoning by analogy, one can point out that the

flow of material in a manufacturing system has many similarities to the flow of data in an information system; both material and data move in discrete units over preexisting paths that are not completely predetermined in structure. Both require storage and access. Although modularity in the design of hardware may be (and has been) as useful as it is in computer software, it creates interfaces that can inhibit the flow of goods, just as it can inhibit the transfer of data or the exchange of information. Old patterns of limited interaction between elements of the manufacturing enterprise must give way to new patterns emphasizing communication and teamwork. We can no longer afford the disruptions and the severe inefficiencies resulting when one unit throws a design, analysis, or test "over-the-wall" to another unit.

We therefore conclude that there is a critical need for more powerful and comprehensive tools for addressing the total system, without losing the important details of the elements - tools that would synthesize the elements. The objective of this paper is to design a model and develop tools for the synthesis of sub-systems, including considerations of tooling, material flow and utilization, fixtures, machines, inventory, product, and process.

Given that the high cost of pilot-scale manufacturing systems often precludes the pilot operation and testing of alternative designs for manufacturing systems, the validity of new system designs becomes critically dependent on the adequacy of the models and the consistency of data. Therefore, a critical

need exists for developing and sharing data from a variety of sources. In recognition of the severe lack of such a mechanism, this paper presents the functional design of an integrated facility-level manufacturing system, involving three well defined and tested modules: Computer Aided Design, Computer Aided Process Planning, and Manufacturing Resource Planning. The modeling and analysis of the system has been effected by using Petri Nets, a proven technique, long used for hardware configurations. We also present the implementation tools, involving a data base interoperability language, which provides for data retrieval and updates in a consistent manner. Sample scenarios are also presented, through simulated runs of the model.

2. APPLICATION SYSTEMS - MRP II, CAD, CAPP

As indicated in the introduction, our philosophy aims at employing existing and well established software application tools, put together in a way that satisfies the requirements of our CIM system. An outline of the main feature and characteristics of the tools dealt with so far is provided in this section.

Manufacturing Resource Planning (MRP II) is an integrated system by itself, consisting of several functional modules surrounding a common database, and apparently becomes the information center of CIM, (Bohse and Harhalakis 1987). The typical MRP II architecture is shown in figure 1, (Harhalakis 1986). At the highest level, the Master Production Schedule (MPS)

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establishes and monitors the production goals of the organization by using the independent demand, in the form of customer orders and/or sales forecasts, as determined by the marketing department. Moreover, "rough-cut" capacity is explored at this level, in order to identify the potential bottlenecks before they occur.

Once established, the master production schedule is executed by the other modules of MRP II. Material Requirement Planning translates gross requirements for end products (i.e. independent demand) into time phased net requirements for subassemblies and individual parts (i.e. dependent demand), by using the information from the Bills of Material/Routings and the Inventory Control modules. The result of an MRP run are a series of purchase and manufacturing orders, which then are handled and monitored separately by the Purchasing and the Shop Floor Control (SFC) modules respectively. Purchase orders are firmed, released, and tracked by Purchasing, while in the SFC module a rough production schedule is produced for manufacturing orders by using routing information, in order to examine the capacity in greater detail than the rough-cut check at the MPS level. Orders are then tracked through the Receiving/Quality Control modules for purchased parts, and through work centers, to the delivery of manufactured parts, all the way up to the final product. Since its first appearance in the late 1950's and early 1960's, MRP II has become a highly sophisticated closed-loop manufacturing information system, (Bohse 1987).

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Because of its integrated architecture, MRP II is considered being the "Hub" of the proposed system, providing a modular capability for integration, so that the full CIM system at the facility level can be achieved.

Computer Aided Design (CAD) can be defined as the set of sub-modules that assist the designer in drafting, analyzing, and optimizing a part design. For the purposes of the proposed system, we concentrate on data identifying parts, and relationships between parts and their components in various assembly configurations. These data are then used to automatically generate part master records and bills of materials in the MRP II module. All other data initiated and maintained in a typical CAD application (eg. part geometry, surface finish, dimensional tolerances etc.) are outside the scope of this work.

Computer Aided Process Planning (CAPP) can be defined as the set of sub-modules that transform part design specifications into manufacturing instructions required to convert a part from a rough state to a finish state. It selects tools and machines, determines operation sequences, calculates operation and setup time, and identifies any jigs and fixtures needed for fabrication or assembly work. This information is basically used to automatically generate routings in the MRP II module.

In short CAD and CAPP are the centers for product and process design, while MRP II coordinates and executes all of the production tasks to satisfy the independent demand. In order to develop a generic model and to demonstrate its feasibility in a

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wide variety of applications, we deliberately avoided the employment of specific applications available commercially. Instead, we have replicated their features and characteristics that are of interest to the proposed system, and we have simulated their functioning so as to keep away from any "module-specific" solutions.

3. PREVIOUS WORK

CIM with conventional technology has started to make an impact on the direct labor in the shop floor area. However, the impact of CIM at the overhead area still falls short of expectations. By taking advantages of the existing information systems and the advent of intelligent systems, CIM may be brought closer to reality and provide real business solutions. For better implementation, new ways of integrating existing CIM tools must be developed and further improved, (Tseng and O'Conner 1986).

There have been some efforts made in this area for the integration of CAD, MRP II and CAPP or CAM through different database management system approaches. The Integrated Computer Aided Manufacturing (ICAM) Program, (Anonym 1983), sponsored by the United States Air Force, was established to develop systems for effectively managing information through four areas: system development, information management, planning and control, and product and process definition. Under this program, the Integrated Information Support System (IISS) was developed to

demonstrate integrated applications, advanced information management concepts and the transfer of ICAM technology. The IISS adopted the approach of using a common database model, which isolates data from the application systems and attempts to resolve conflicts, to rebuild databases, and to put all data in one computer as the CIM systems become more and more complex. The ICAM Definition (IDEF) methodology was developed as the primary tool of system design and modeling, which includes three modeling techniques: IDEF0 function modeling, IDEF1 information modeling, and IDEF2 dynamic (simulation) modeling. The IDEF0 and IDEF1 provide a complete static modeling method for production control and CIM systems. However, the IDEF2 dynamic model, used in simulation and performance evaluation, is not yet clear and adequate for CIM analysis and simulation purposes. This program and the Integrated Information Database Administration System (IMDAS) developed by the National Bureau of Standards, (Su 1986), which provide some useful tools for research in CIM, emphasize on extending the traditional database management technology to synchronize the data processing through each module of the CIM system but do not involve any use of expert systems.

A knowledge-based expert system can be the heart of CIM, since it can accommodate a lot of rules and constraints based on manufacturing expertise. Building high-performance knowledge-based expert systems for advanced manufacturing and automation is now the most active research subject within CIM and AI. Therefore, there is a lot of research work going on in developing

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various such systems for different manufacturing applications around this country, such as the Laboratory for Manufacturing and Productivity at MIT, (Kim 1986), State University of New York at Buffalo, (Wang and Wysk 1987), and the Knowledge-Based Engineering Systems Research Laboratory at University of Illinois-Urbana-Champaign, (Lu 1986). Recently, a manufacturing information management design method was developed at Rensselaer Polytechnic Institute, (Hsu et al 1987), which used a two-stage entity relationship (TSER) modeling method and a knowledge-based control methodology in a metadatabase framework. This work, however, only provides the design concept and the necessary methodologies for it, but is not intended to implement the integrated system with AI technologies. To implement a CIM system, a formal language based on AI is needed, in order to define the rules and constraints for the data integrity in a manufacturing environment. A good sample specification of a CIM architecture for a workcell, comprising simple workstations, focuses on the shop floor level, and was implemented at the Phillips CAM center, (Biemans and Blank 1986), in the Netherlands. It uses LOTOS (Language for Temporal Ordering Specifications) developed by the International Organization for Standardization (ISO).

In contrast to these efforts, which mainly concentrate on the integration at the shop floor level, our CIM system resides at a higher level-the facility level. It is, therefore our belief that our work indeed complements the total CIM architecture,

using the proposed "top-down" approach. Also in contrast to database integration for the single database CIM systems, we propose a database interoperability approach, that has already been used in developing an knowledge-based MRP II/CAD integrated system, (Harhalakis et al 1987), at the Department of Mechanical Engineering, of the University of Maryland. It takes into account the diversities of hardware and software produced by different manufacturers, and the possibility of adding to existing computer facilities rather than replacing them.

A powerful modeling tool, Petri-Nets, is currently used in this work for modeling our system dynamically, with concurrent processes. It was initially developed and used mainly for advanced computer integrated systems design, both in hardware and software, such as artificial intelligence in network systems, (Courvoisier et al 1983), and for flexible manufacturing systems, (Crockett and Desrochers 1986). Most recent applications of Petri-Nets in manufacturing systems are focusing again on the shop floor level, with large numbers of work stations, robots, and transportation systems, to be handled by a central controller. Timed Petri-Nets are primarily used for scheduling and sequencing, (Ravichandran and Chakravarty 1987), (Merabet 1987). Several reduction algorithms have also been developed for analyzing very complicated systems, (Hollinger 1986), and we are planning to exploit some of them.

Finally, our implementation tool for the proposed system is the Update Dependencies language, (Mark and Roussoupoulos 1987),

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developed at the Computer Science Department, of the University of Maryland, which has been used successfully for data retrievals and updates in the MRP II/CAD integrated system mentioned before.

This is the first time that Petri-Nets are used to model a CIM system at the facility level. The use of Petri-Net theory for a dynamic modeling of the MRP II/CAD/CAPP integrated system will be discussed later.

4. FUNCTIONAL DESIGN OF THE SYSTEM

The functional model of MRP II/CAD/CAPP integrated system is based on the similarity of functions and the commonality of data among these three application modules. More specifically, the common elements identified and dealt with are as follows:

-- Common elements in MRP II, CAD, and CAPP
   * Part Specification
   * Bills of Material
   * Engineering Changes
-- Common elements in MRP II and CAPP
   * Routing Records
   * Work Center Records

As mentioned before, the model is not based on any particular MRP II, CAD, CAPP package, but instead is intended to be generic enough to be applied to any set of fairly well-designed application modules. The model includes the sharing of

part specification, product structure, routing and work center information, and engineering change data. It is intended to operate in a discrete parts, make-to-stock environment.

The detailed common data records maintained in each system are listed below.

PART RECORD

CAD	MRP II
Part Number	Part Number
Drawing Number	Drawing Number
Drawing Size	Drawing Size
B.O.M. Unit of Measure	B.O.M. Unit of Measure
--	Purch./Inv. Unit of Measure
--	U.O.M. Conversion Factor
--	Source Code
--	Standard Cost
--	Lead Time
Supersedes Part Number	Supersedes Part Number
Superseded by Part Number	Superseded by Part Number

PART REVISION RECORD

CAD	MRP II
Part Number	Part Number
Revision Level	Revision Level
Effectivity Start Date	Effectivity Start Date
Effectivity End Date	Effectivity End Date
Status Code	Status Code
Drawing File Name	-

ROUTING RECORD

CAPP	MRP II
Routing Number	Routing Number
Part Description	Part Description
Unit of Measure	Unit of Measure
Operation Number	Operation Number
Operation Description	Operation Description
Work Center ID Number	Work Center ID Number
Set Up Time	Set Up Time
Machining Time	--
Handling Time	--
Run Time	Run Time
Feed	--
Speed	--
Depth of Cut	--
Number of Passes	--
--	Resource Code
--	Begin Date
--	End Date
Status Code	Status Code

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WORK CENTER RECORD

MRP II	CAPP
ID Number	ID Number
Description	Description
Department	Department
Capacity (HR.)	--
Rate Code	--
Resource Capacity	--
Dispatch Horizon	--
Effectivity Start Date	Effectivity Start Date
Effectivity End Date	Effectivity End Date
Status Code	Status Code
--	Horse Power
--	Speed Range
--	Feed Range
--	Work Envelope
--	Accuracy
--	Tool Change Time
--	Feed Change Time
--	Speed Change Time
--	Table Rotation Time
--	Tool Adjustment Time
--	Rapid Traverse Rate

4.1 Status Code

To represent the functioning of the model, status codes for each entity are used to control the information flow and the status changes. The entities in question are part revision, routing, and work center, and are shared between MRP II, CAD, and CAPP. These status codes are listed and explained below:

-- PART REVISION STATUS

CAD

W - "Working" : At a conceptual or preliminary stage, prior to approval, and not transmittable to MRP II.

R - "Released" : An active part, whose design has been finalized and approved.

H - "Hold"   : Under review, pending approval, possibly with a new revision level. The part should not be used by any system.

O - "Obsolete" : The part is obsolete.

MRP II

R - "Released" : An active part, whose purchase or manufacture can be initiated in MRP II.

H - "Hold"   : Under review, not to be used by MRP II.

CAPP

W - "Working" : At a conceptual or preliminary stage, prior to approval.

R - "Released" : An active part, whose design has been finalized and approved.

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H - "Hold"        : Under review, pending approval, possibly with
                    a new revision level.

O - "Obsolete"    : The part is obsolete.
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-- ROUTING STATUS

CAPP

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W - "Working"     : At a conceptual or preliminary stage, prior
                    to approval, and not transmittable to MRP II.

R - "Released"    : An active routing, whose process design has
                    been finalized and approved.

H - "Hold"        : Under review, pending approval, possibly with
                    a new revision level. The routing should not
                    be used by any system.

O - "Obsolete"    : The routing is obsolete.
```

MRP II

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R - "Released"    : An active routing, which is able to be passed
                    down to the shop floor by MRP II.

H - "Hold"        : Under review, not to be used by MRP II.
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-- WORK CENTER STATUS

MRP II

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R - "released"    : An active work center.

H - "Hold"        : Not to be used by MRP II.

D - "Delete"      : A work center deleted from the system.
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CAPP

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W - "Working"     : At a preliminary stage, work center details
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need to be entered in CAPP.

R - "Released" : An active work center, able to be used in process plans.

H - "Hold"   : Under review, not to be used for process plans.

O - "Obsolete" : The work center is obsolete.

4.2 System Model Description

By using these status codes and human expertise, many scenarios were derived and formed a constraint based management system. A typical scenario (Creation of a new part in CAD) in this system is illustrated below. CAD controls the creation and modification of design data, originating engineering changes, and is one of the centers from which new parts are introduced. It is considered that all part numbers are assigned solely by CAD for consistency.

A new part is first developed in CAD with the following management type of data needed by the integrated system.

PART RECORD	REVISION RECORD
* Part Number	* Part Number
* Description	* Revision Level
* Unit of Measure	* Drawing File Name
	* CAD Status Code

With these data, the system performs a series of consistency checks to ensure that the part number has not yet been assigned by CAD to another part. Initially the CAD part revision status

code is set to "W". The effectivity dates are left unknown to be decided by MRP II users. The moment the record of the new part is created within the system, a skeletal routing record is automatically created in CAPP. This will let CAPP know that this part is being worked on, and CAPP will be called upon to contribute to the design shortly, in terms of clearing the design from the point of view of manufacturability and finalizing the product structure (for assembly parts). After CAD and CAPP work on the part, and the design is ready in every aspect, it can be released in CAD.

As soon as CAD releases the part, several actions are initiated. A skeletal part master record for the new part is automatically established in MRP II. Those data fields maintained in MRP II, but not in CAD, are initiated as unknown until supplied by MRP II users. Second, a revision record is also established in MRP II by using the part number and revision level from CAD revision record. The status of MRP II revision is set to "H", since many of the fields required by the MRP II system have been initialized to unknown, and have to be completed before MRP II can consider the part to be active. MRP II also has to wait for CAPP to release the routing to generate lead time information for manufactured parts. CAPP can release the routings only after CAD releases the part, because finalized process plans are normally completed only after the design is finalized. Also, MRP II must have the part established in its part master record before it can accept the routing from CAPP. Third, CAD checks for

a value in the "supersedes part number" field of the CAD part record. If it finds a valid part number in this field, the part number of the new part is inserted into the "superseded by part number" field in the part record of the superseded part. The MRP II part master record is likewise modified to reflect the supersession. The latest revision of the part being superseded, which may have a released status, or which may be on hold, is then made obsolete. If all the preceding steps are successful, the status of the new CAD revision is changed to "R".

MRP II now starts working on the part record of the new part in the system. It fills in whatever information required is available, including lead time, by using either the production routing information from CAPP or the vendor information from the purchasing module.

When CAPP finalizes its process plan, the routing record is given a released status. Once again a series of consistency checks are initiated before the release can be successful. First, a check is made to make sure the part for which the routing is to be released has a released status in CAD. If it does not, a message to this effect is generated in CAPP, and the release is not possible. Second, a check is made to make sure that the effectivity dates of all the work centers used in the routings are at least six months (or some other applicable time period) ahead. This ensures that the routings are still applicable when the product must be produced. Third, it is checked that all the data fields in the CAPP routings file are complete. If all these

checks are successfully made, then the routing is assigned an "R" status, and is immediately transferred to the routing module of MRP II with a status of "H".

The final step in this chain of events is that MRP II releases the part record and then the routing record.

The complexity of this system grew very rapidly as more and more scenarios were developed, which made the continuation of the work very difficult. Therefore, the need for an appropriate modeling method was critical at that point. In the next section, two modeling attempts initially used are presented and discussed.

5. PREVIOUS MODELING ATTEMPTS

Our first modeling attempt employed status diagrams, as shown in figure 2, which illustrated the information flow and status changes of entities among MRP II, CAD, and CAPP. Entity statuses are represented with a two-character code. The first character is a number which indicates the entity being dealt with, and the second is a letter, to identify the current phase the entity in question is going through.

When a brand new part is first created under a design process in CAD (1a), a skeletal routing record is automatically created in CAPP (1b). Once the new part is released in CAD (1c), a skeletal part record and a skeletal revision record are automatically created in MRP II (1d). At the same moment, the superseded part becomes obsolete (2c) whether from released status (2a) or from hold status (2b). After the routing for the

new part is released in CAPP (1e), the routing information is transferred to CAD and a routing record is created (1f). The revision record cannot be released in MRP II (1h) until the routing record is released to MRP II (1g) from CAPP. The revision record of the new part is completed with an effectivity start day after the part was released in MRP II.

By using this status diagram, the text needed to describe the functions of the system can be reduced, and errors within the functional design can be detected earlier. The main drawbacks of this modeling tool include failure to provide information about the sequence of events occurring between the new part and the old part (parallel processing), and inability to reveal conflicts in the logic.

Another modeling method used in the MRP II/CAD integration was precedence Gantt charts, which manage to express more clearly the timing of the events in the system, as shown in figure 3. The sequence of events along parallel lines and between adjacent lines can be clearly shown from the figure. However, it is still cumbersome to clearly reflect precedence of events between any other two lines, and also it presents difficulties in handling large systems with complex interrelations between events.

6. PETRI-NETS

6.1 Introduction

Since the pioneering work of Petri who originated his nets in his dissertation "Communication with Automata", (Petri 1962),

Petri-Nets have been increasingly developed and used for modeling a wide variety of systems. This paper provides another illustration of their modeling capabilities in the field of Computer Integrated Manufacturing (CIM).

6.2 Basic notions of Petri-Nets

The structure of a Petri-Net is a bipartite directed graph consisting of two types of nodes called places and transitions, (Peterson 1981). Places and transitions are joined by directed arcs. Input (resp. output) places of a transition are places connected by incoming (resp. outgoing) arcs of the transition. In order to simulate the dynamic behavior of a Petri-Net, each place is marked with a non-negative number of so-called tokens. We may think of tokens as representing data item or as holding some conditions represented by places. A transition is said to be enabled if each of its input places is marked with at least one token. An enabled transition may be chosen to fire. The firing of a transition consists of removing one token from each of its input places and adding one token to each of its output places. We may think of a firing as an event which may take place if certain conditions are satisfied. Each firing will cause the old conditions to cease and new conditions to hold, and the total number of tokens in a Petri-Net may change after each firing. A firing sequence is a sequence of successive firings of transitions. A marking is said to be reachable from an initial marking (i.e. an initial distribution of tokens), if there exists

a firing sequence that transforms the initial marking into this new marking. The set of all reachable markings (states) is described by the reachability tree.

Notations

(1) $P = \{p_1, \ldots, p_n\}$ denotes the set of places (represented graphically as circles)

(2) $T = \{t_1, \ldots, t_m\}$ denotes the set of transitions (represented graphically as bars)

(3) A marking is represented by a n-vector of non-negative integer $M = [m_j]_{n \times 1}$, where the j-th component m_j denotes the number of tokens on place p_j. M^o denotes the initial marking.

6.3 The Model

The system caters for numerous scenarios. In this section, however, a typical scenario of creating a new part in CAD, previously represented with a status diagram (figure 2) and a precedence Gantt chart (figure 3), is modeled using Petri-Net theory, as shown in figure 4. The modeling of this scenario involves a mapping of the logical rules which regulate the data flow between the three application modules, onto a Petri-Net. It is a transformation of logic expressed in written words into a graphical and mathematical form, suitable for analysis. Obviously, the value of the analysis will depend on the correctness of this conversion, so it is important there be a formal means of verifying the accuracy of the mapping. It will be

shown in section 6.4.1 how net invariants can be used to accomplish this task.

The Petri-Net graph, shown in figure 4, is composed of 33 places and 16 transitions grouped into three sections, corresponding to the three application modules. This physical layout provides a clear graphical representation of the dependencies and relation between the three systems.

In addition to the graphical representation of the Petri-Net, the structure of the net can be expressed in the form of a matrix called an incidence matrix, as shown in figure 6. It is defined as follows:

$$C = [C_{ij}]nxm \quad \text{where} \quad \begin{array}{l} C_{ij} = -1 \text{ if } P_i \text{ is an input place of } t_j \\ C_{ij} = 1 \text{ if } P_i \text{ is an output place of } t_j \\ C_{ij} = 0 \text{ otherwise} \end{array}$$

The interpretations assigned to the places and transitions are given in figure 5. For each of the three modules, either one or two places have been used to represent the various status codes (working, released, hold, obsolete). The set of places $\{p_3, p_4\}$ is an example of the use of two places for representing a status code. Both of these places represent the working status in CAD but, in addition, p_3 indicates that a part design is still in progress, while p_4 indicates a completed and approved part design. The use of two places in some cases was necessary in order to represent precedence constraints. For example, before process plans can be completed in CAPP (t_{15}), the part must be finalized and approved in CAD (t_2). This event, finalizing the

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part in CAD, occurs while the new part has a working status in CAD.

The marked Petri-Net graph shown in figure 4 indicates one of the possible initial states of the integrated system. Notice that the only enabled transition in this marking is t_1 (Insert a new part in CAD). This event can occur only if the user has and is ready to key in the essential part data, such as part #, description, BOM unit of measure, revision level, and drawing filename (p_1). Also, the part number being added must not already exist in CAD (p_2). After the new part has been successfully established in CAD, the CAD revision record will have a working status (p_3) and transitions t_2 and t_{14} will be enabled. As stated previously, t_2 represents the completion and approval of the new part in CAD while t14 is interpreted as the creation of a "skeletal" routing record in CAPP. Ideally, once the part record is created in CAD, a "skeletal" routing record is immediately created and set to working status in CAPP, but problems might arise that would cause this event (t_{14}) to occur either before, during or after the part design is completed (t_2).

Once the part has been completed and approved it is then ready to be released (p_4) and either t_3, t_4, or t_5 (release part in CAD), will be enabled. Which particular transition is enabled will depend on the status of the superseded part, if one exists at all. Note in figure 4, in this particular case, the superseded part has a released status in CAD (p_9). Alternatively,the superseded part may have a hold status (p_{11}) or the new part may

not be superseding another part (p_5). Similarly, in the MRP II system, the initial marking will indicate a token in p_{14}, p_{16}, or p_{19}, depending on the status of the MRP II part revision record. This status may or may not correspond to the status of the superseded part in CAD. There are two other sets of places used to represent status codes in MRP II. The sets {p_{15}, p_{18}, p_{22}} and {p_{25}, p_{27}, p_{28}} represent the possible statuses of the new part revision and routing records respectively. In CAPP, the set of places {p_{30}, p_{31}, p_{33}} represents the possible statuses of the routing record. The final place specified in the initially making is p_{32}. This indicates that effectivity end dates of all the work centers in all routings are at least six months ahead.

As a way of performing checks or maintaining the precedence of activities, additional places have been included in the net which duplicate the interpretation of other places. This was done in order to properly reflect the logical rules, by imposing further preconditions on certain events before they can occur. For example, the release of the new part in CAD (t_3, t_4, or t_5) must precede the release of the routing record in CAPP (t_{16}). Therefore, p_7 (the input place to t_{16}) has been given the same interpretation as p_8 (released status in CAD), and must contain a token before t_{16} can be fired. An alternative method of performing this check is to use a self-loop for t_{16}. A self-loop is a transition which has an input and output from the same place but a major drawback is that self-loops cannot be represented in the incidence matrix.

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6.4 Results

After modeling the system with a Petri-Net, the Petri-Net was analyzed in order to validate the model and to gain insight into the behavior of the modeled system. The use of three analysis techniques (invariants, reachability trees, and behavioral nets) will be described below.

6.4.1 Invariants

Net invariants have been useful in analyzing the Petri-Net model in terms of verifying system properties and locating modeling errors, (Memmi and Roucairol 1980), (Martinez and Silva 1982). An invariant is formally defined as a n-vector, X, of non-negative integers such that:

$$X^T C = 0 \qquad (1)$$

where C denotes the incidence matrix and T denotes the matrix-transpose. The set of places whose corresponding components in X are strictly positive is called the support of X and is denoted by $||X||$.

The fundamental property of invariants is the following: X is invariant if and only if for any initial marking M^O and for any reachable marking M:

$$X^T M = X^T M^O \qquad (2)$$

The interpretation of (2) is as follows: the total number of tokens in the set of places $||X||$ (weighted by the components of X) is invariant by any transition firing.

A total of 76 invariants were obtained from the Petri-Net

model of the CAD/CAPP/MRP II system. By examining these invariants, the accuracy of mapping the initial logic on the Petri-Net was checked. The initial logic specifies that every part and routing record be assigned a single status code. This would require that the places of the Petri-Net, which represent the possible status codes of a record, be mutually exclusive. An invariant containing these places would verify this property. For example, in CAD, a new part record is permitted to have a status of working (p_4) or released (p_8) but not both. This was proven to be a property of the Petri-Net model by the invariant i_1 shown in figure 6, which denotes the set of mutual exclusive places {p_1, p_3, p_4, p_8, p_{10}}. Invariant i_2, as shown in figure 6, indicates that the part to be replaced by the newly created part have a status of either released (p_9), hold (p_{11}), or obsolete (p_{12}) and thus, correctly matches the initial logic. Similarly, invariant i_3 verifies the mutual exclusiveness of the places representing the possible status codes for the superseded part record in MRP II. Any inconsistency between the initial logic and the invariants would have indicated an error in the modeling process or in the initial set of logical rules.

6.4.2 Reachability tree

Another method used to analyze the Petri-Net, was the construction of the reachability tree as shown in figure 7, The nodes of the tree represent the reachable markings (states) of the Petri-Net while the arcs represent the firing of transitions

between the markings. The numbers contained in the nodes of the tree identify the places in the net which are marked with a token. For example, the node at the top of the tree, $(1,2,9,19,32)$, indicates that each member of the set $\{p_1, p_2, p_9, p_{19}, p_{32}\}$ is marked. Beginning with this initial marking, the reachability tree was generated by successively firing the enabled transitions until either no further transitions were enabled or a marking identical to another node was reached.

The reachability tree provides a means of discovering logical conflicts in the system. These logical conflicts can cause blockages in the tree which prevent the branches from properly terminating in the desired final state. For this scenario, the desired final state consisted of the following:

(1) New Part in CAD has "R" status and effectivity start date (p_{10})

(2) Superseded part in CAD had "O" status (p_{12})

(3) Part in MRP II has "R" status (p_{22})

(4) Superseded part in MRP II has "R" status and an effectivity end date (p_{20})

(5) Routing record in MRP II has "R" status (p_{28})

(6) Routing record in CAPP has "R" status (p_{33})

If the newly created part does not replace an existing part, then the desired final state would consist of all of the above with the exception of the second and fourth items. Blockages

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discovered in the process of constructing the tree were removed by either adding missing conditions or changing the dependencies between existing conditions.

In addition to providing an overview of all the reachable markings of the net, the reachability tree shows how the final marking can be reached by executing any one of a number firing sequences. Two such firing sequences are $(t_1-t_{14}-t_2-t_{15}-t_3-t_{16}-t_{11}-t_6-t_8-t_{12}-t_{10}-t_{13})$ and $(t_1-t_{14}-t_2-t_3-t_{15}-t_{16}-t_{11}-t_6-t_8-t_{12}-t_{10}-t_{13})$. Notice that they both contain the same transitions, but arranged in slightly different orders. A number of firing sequences are obtained because the events that can occur concurrently have an unspecified order of occurrence. For example, transitions t_3 (release the part in CAD) and t_{15} (complete the routing record in CAPP) are both enabled in the marking M = {4,6,9,19,30,32} and the decision on whether they fire concurrently or whether one fires before the other is arbitrary.

6.4.3 Behavioral net

The final analysis tool used was the behavioral net, as shown in figure 8. This net is a transformation of the Petri-Net graph (based upon the initial marking) into a form which clearly distinguishes the transitions which fire concurrently from the ones that fire sequentially. In this form, possible redundancies in the logical rules were revealed by finding the redundant places and/or links between transitions and places of the

behavioral net.

The behavioral net was constructed in the following manner: Let P_1, (P_1 = {p_1, p_2, p_9, p_{19}, p_{32}}), be the set of places which are initially marked and let T_1, (T_1 = {t_1}) be the set of transitions that are enabled by the places of P_1. We assume that all transitions of T_1 fire once and let P_2, (P_2 = {p_3, p_9, p_{19}, p_{29}, p_{32}}), be the new set of marked places. Likewise, T_2, (T_2 = {t_2, t_{14}}), is the set of transitions that are enabled by the places of P_2 and P_3, (P_3 = {p_4, p_6, p_9, p_{19}, p_{30}, p_{32}}), is the new set of marked places once all transitions of T_2 have fired and so on until the process stops when all enabled transitions have fired. In the transformation described above, the net is said to be unfolded.

Apart from simulation purposes, the behavioral net helped in analyzing and validating the process logic. In the net shown in figure 4, t_{12} (complete the routing record in MRP II) is enabled if p_{25} (unfinished routing record with hold status in MRP II) and p_{26} (completed part record with hold status in MRP II) are marked. However, given the initial state and the corresponding behavioral net (figure 8), it appears that p_{25} is always marked if p_{26} is. Hence, the condition that p_{25} be marked to enable t_{12} is redundant, under the condition that p_{26} be also marked. It means that, from a logical point of view, the outgoing arc from p_{25} to t_{12} and the incoming arc from t_{11} to p_{25} can be suppressed. However, in the interest of obtaining more information on the state of the system, it was decided to

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maintain this redundancy. Similarly, the condition that p_8 (part record with released status in CAD) be marked to enable t_{10} (release part record in MRP II) is redundant with the condition that p_{18} (completed part record in MRP II) be also marked. Nonetheless, this redundancy was also retained.

7. DISCUSSION

While Petri-Nets have been traditionally used in modeling and analyzing computer systems (hard/software), the application discussed in this paper represents the first time they have been used in the study of CIM at the facility level. In this area, they have proven to be a powerful modeling tool for the CAD/CAPP/MRP II integrated system and are superior to status diagrams and precedence Gantt charts in a number of ways. Unlike these previous modeling attempts, the use of Petri-Nets made it possible to properly model the various activities in the system that were capable of occurring concurrently, such as releasing the new part in MRP II (t_{10}) and completing the routing record in MRP II (t_{12}). In addition to being able to model concurrence, another strength of Petri-Nets is their ability to represent conflicts. A conflict occurs for example when two transitions are enabled and the firing of one of them disables the other. Although this was not used in the present model, it is foreseeable that this capability will be useful for modeling other scenarios of the system that involve making revisions to existing parts.

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Unlike the previous informal modeling attempts, Petri-Net theory is a formal modeling tool with analysis techniques such as invariants, reachability trees, and behavioral nets. Net invariants were useful in verifying that certain places in the net actually represented mutually exclusive conditions, as specified by the logical rules. These invariants were obtained by using a very efficient algorithm that calculates all the minimal support invariants of a generalized Petri-Net, (Martinez and Silva 1982). The construction of a reachability tree simulated the dynamic behavior of the system and revealed blockages in it. From the behavioral net, redundant places and arcs were exposed. It was possible to manually construct both the reachability tree and the behavioral net for the present model due to their relatively small sizes. But, as the modeled system becomes more complex, the use of software tools designed to construct, edit, and analyze Petri-Nets will become necessary. There will also be a need for efficient algorithms to enhance the power of these tools.

Another advantage of Petri-Nets is how the graphical representation made the integrated system easier to understand, by providing a clear structural view of the model. The Petri-Net graph makes it possible to quickly identify the status codes of all the part and routing records by the current locations of the tokens. Also, all the consistency checks which take place in the CAD/CAPP/MRP II system are explicitly expressed on the Petri-Net graph, unlike in the status diagrams and precedence Gantt charts.

One final major advantage of Petri-Nets is their hierarchial modeling capability. They can be used to describe the system a different levels of abstraction and detail. For modeling at a more abstract level, subnets can be replaced with a simple place or a simple transition, and for more detailed modeling, a place or transition can be replaced with a subnet, (Lee and Favrel 1985). This procedure will be helpful in analyzing the model as it becomes more complex when other scenarios are considered.

8. EXTENSIONS AND CONCLUDING REMARKS

The modeling and analysis of the "Creation of a new part in CAD" scenario using Petri-Nets has provided a good foundation for additional work. One area which will be carefully investigated deals with the modification of the current Petri-Net model to include the handling of multiple parts. This enhanced Petri-Net model would then be able to represent the situation where a CAD user enters a new part into the system while there is another part already in the system.

Another area of future work involves the design and specification of other scenarios. The "Creation of a new part in CAD" is only one of the many operations needed for controlling data exchange and update in the CAD/CAPP/MRP II integrated system. Others that will be investigated include the following:

Parts

(i)   New purchased product part from CAD.

(ii)   New manufactured tool part from CAPP.

(iii) New purchased tool part from CAPP.

(iv)   New purchased supply part from MRP II.

Routings

(i)   Generated in CAPP.

(ii)   Revision of routings.

Work centers

(i)   Installation of a new work center.

(ii)   Deletion of work center.

(iii) Reviewing a work center in CAPP.

(iv)   Reviewing a work center in MRP II.

Revisions

(i)   Revisions of manufactured product parts from CAD.

(ii)   Revisions of purchased product parts from CAD.

(iii) Revisions of manufactured parts from CAPP.

(iv)   Revisions of purchased parts from CAPP.

(v)   Revisions of purchased supply parts from MRP II.

(vi)   Revisions of purchased as well as manufactured product parts from MRP II.

Once all these scenarios have been developed and modeled using Petri-Net theory, the next step would be to systematically combine them to form a complete CIM system model at the facility level. This will be possible since Petri-Nets are synthesizable.

After the combination of these scenarios, the next step would be to emphasize on the study and application of reduction methods for the much more complicated model of the whole system. The goal would be to transform the Petri-Net to a reduced net while retaining some desirable properties of the original net, (Lee and Favrel 1985). Information about the highly complex CAD/CAPP/MRP II integrated system can still be obtained by analyzing the reduced net. There have been some reduction methods proposed for different applications, (Kwong 1977), (Grislain and Pun 1979), (Lee and Favrel 1985) and all of them will be carefully reviewed to develop an appropriate reduction method for the CIM system, in an attempt to reduce the complexity of a fully automated manufacturing environment.

Programming will be the final step, once an accurate model of the CAD/CAPP/MRP II integrated system (including all scenarios) has been constructed. The functional specifications of the model will be programmed in the Update Dependency Language, which is currently under development in the Department of Computer Science at the University of Maryland, as a tool for achieving interoperability, (Mark and Roussopoulos 1987). A rule set is constructed for the integrated system, called update and retrieval dependencies, which controls inter-database consistency

through inter-database operation calls. This rule set will be used to implement the integrated CAD/CAPP/MRP II system, (Harhalakis et al 1987).

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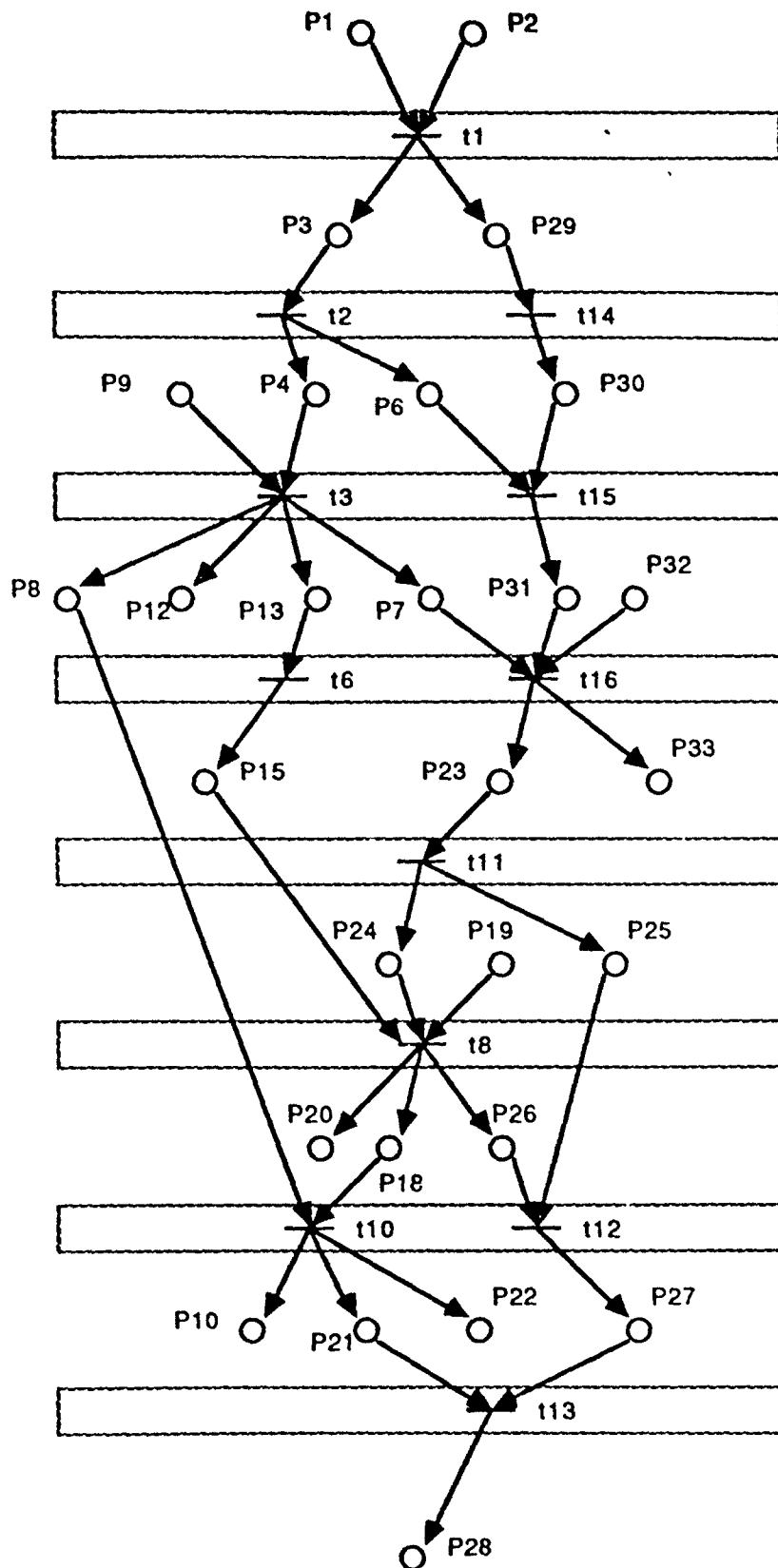
Figure 8. Behavioral net.

Figure 7. Reachability tree.

	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14	t15	t16	i1	i2	i3
p1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
p2	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
p3	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
p4	0	1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
p5	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
p6	0	1	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0
p7	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0
p8	0	0	1	1	1	0	0	0	0	-1	0	0	0	0	0	0	1	0	0
p9	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
p10	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0
p11	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
p12	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
p13	0	0	1	1	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0
p14	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	1
p15	0	0	0	0	0	1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0
p16	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	1
p17	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
p18	0	0	0	0	0	0	1	1	1	-1	0	0	0	0	0	0	0	0	1
p19	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	1
p20	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
p21	0	0	0	0	0	0	0	0	0	1	0	0	-1	0	0	0	0	0	0
p22	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
p23	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	0
p24	0	0	0	0	0	0	-1	-1	-1	0	1	0	0	0	0	0	0	0	0
p25	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0
p26	0	0	0	0	0	0	1	1	1	0	0	-1	0	0	0	0	0	0	0
p27	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0
p28	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
p29	1	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0
p30	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0
p31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0
p32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0
p33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0

Figure 6. Incidence matrix and three invariants.

TRANSITIONS	INTERPRETATION

t_1:   CAD user inserts the new part in CAD.
t_2:   CAD user completes working on the part design and completes the part record and revision record.
t_3:   CAD user releases the part.
t_4:   CAD user releases the part.
t_5:   CAD user releases the part.
t_6:   Skeletal part record and revision record is established in MRP II.
t_7:   MRP II user completes the part record and revision record.
t_8:   MRP II user completes the part record and revision record.
t_9:   MRP II user completes the part record and revision record.
t_{10}: MRP user releases the part.
t_{11}: Skeletal routing record is established in MRP II.
t_{12}: MRP II user completes the routing record.
t_{13}: MRP II user releases the routing record.
t_{14}: Skeletal routing record is established in CAPP.
t_{15}: CAPP user completes the routing and process plans.
t_{16}: CAPP user releases the routing record.

Figure 5. Interpretation of places and transitions.

PLACES	INTERPRETATION

p_1: New part is ready to be entered in CAD.

p_2: New part # has not existed in CAD before.

p_3: New part record and revision record with "W" status in CAD. Part design has not been completed yet.

p_4: Completed part design and completed part record and revision record with "W" status in CAD.

p_5: No superseded part in CAD.

p_6: Completed part design and completed part record and revision record with "W" status in CAD.

p_7: New part record and revision record with "R" status in CAD.

p_8: New part record and revision record with "R" status in CAD.

p_9: Superseded part with "R" status in CAD.

p_{10}: New part record and revision record with "R" status and completed effectivity start date in CAD.

p_{11}: Superseded part with "H" status in CAD.

p_{12}: Superseded part with "O" status in CAD and completed superseded by part #.

p_{13}: Skeletal part record downloaded from CAD.

p_{14}: No superseded part in MRP II.

p_{15}: Skeletal part record and revision record with "H" status in MRP II.

p_{16}: Superseded part with "H" status in MRP II.

p_{17}: Superseded part with "H" status in MRP II and completed effectivity end date and superseded by part #.

p_{18}: Completed part record and revision record with "H" status in MRP II.

p_{19}: Superseded part with "R" status in MRP II.

p_{20}: Superseded part with "R" status in MRP II and completed effectivity end date and superseded by part #.

p_{21}: Completed part record and revision record with "R" status in MRP II.

p_{22}: Completed part record and revision record with "R" status in MRP II.

p_{23}: Skeletal routing record downloaded from CAPP.

p_{24}: Skeletal routing record with "H" status in MRP II.

p_{25}: Skeletal routing record with "H" status in MRP II.

p_{26}: Completed part record and revision record with "H" status in MRP II.

p_{27}: Routing record with "H" status in MRP II is complete.

p_{28}: Completed routing record with "R" status in MRP II.

p_{29}: Skeletal routing record downloaded from CAD.

p_{30}: Routing record with "W" status in CAPP.

p_{31}: Completed routing record with "W" status in CAPP.

p_{32}: Work center effectivity end dates are at least six months ahead.

p_{33}: Completed routing record with "R" status in CAPP.

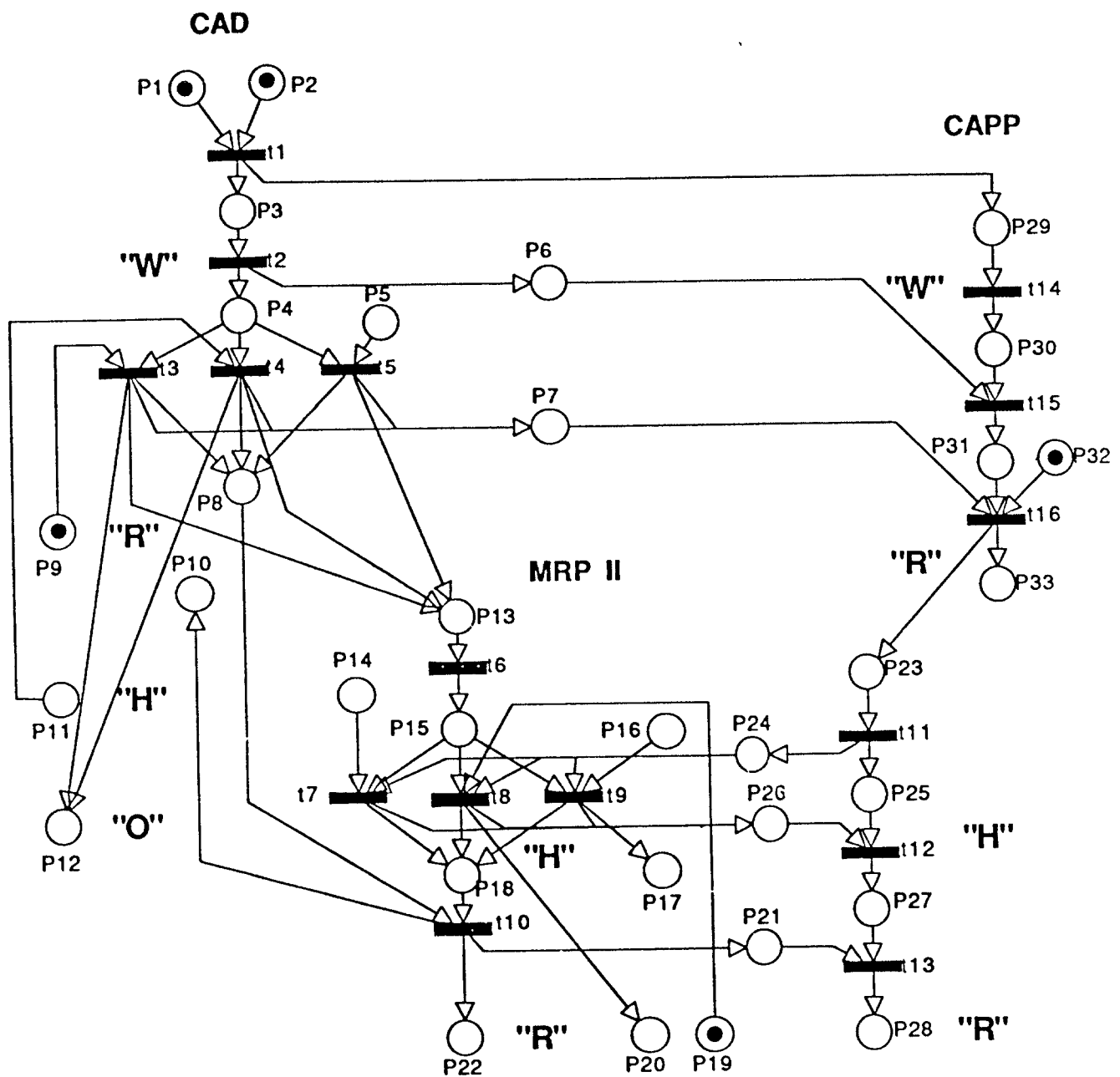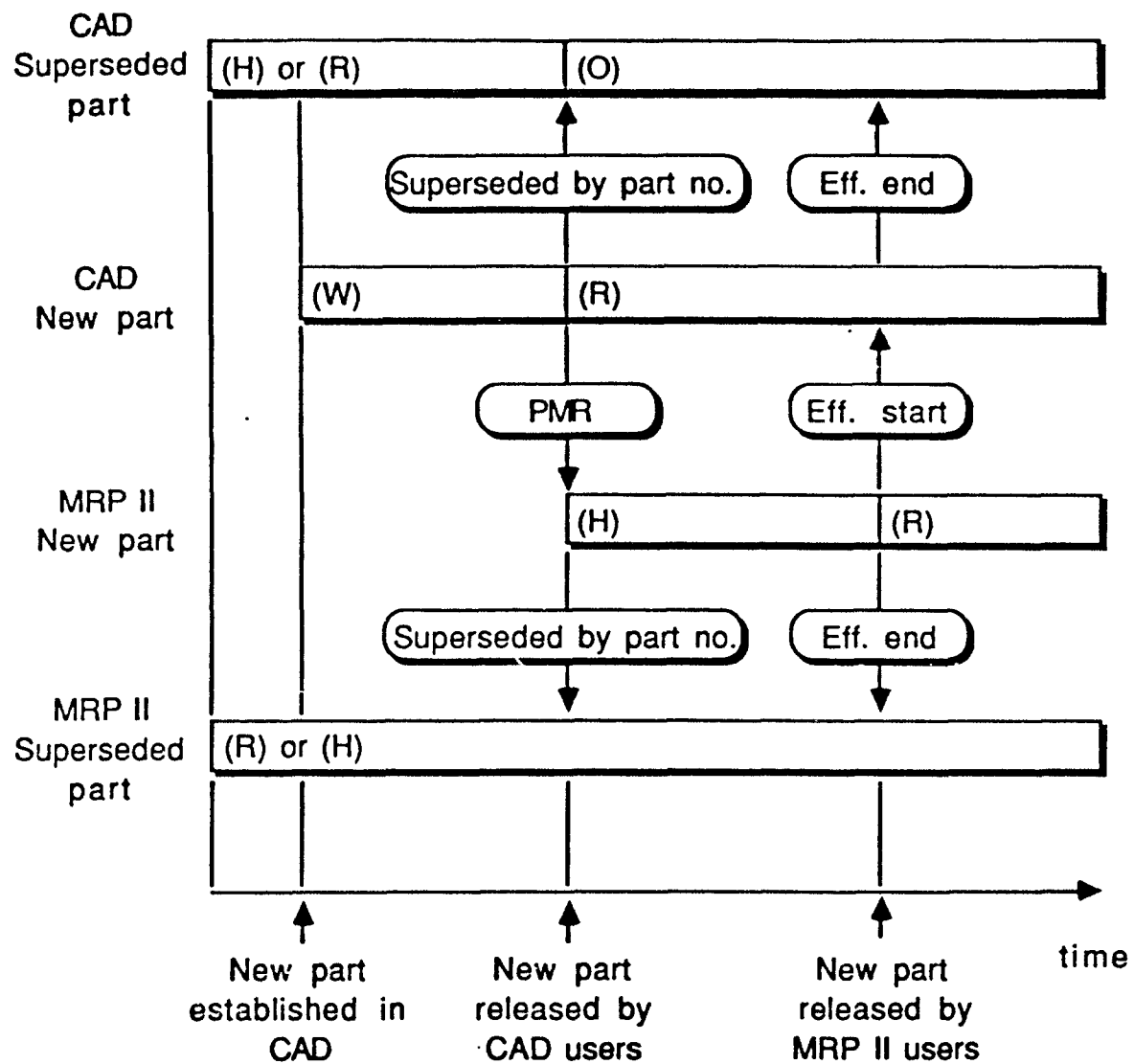Figure 4. Petri net model with initial marking.

CAD
Superseded
part

(H) or (R)   (O)

Superseded by part no.   Eff. end

CAD
New part

(W)   (R)

PMR   Eff. start

MRP II
New part

(H)   (R)

Superseded by part no.   Eff. end

MRP II
Superseded
part

(R) or (H)

New part
established in
CAD

New part
released by
CAD users

New part
released by
MRP II users

time

Figure 3. Precedence Gantt Chart - Creation of a New Part via CAD.
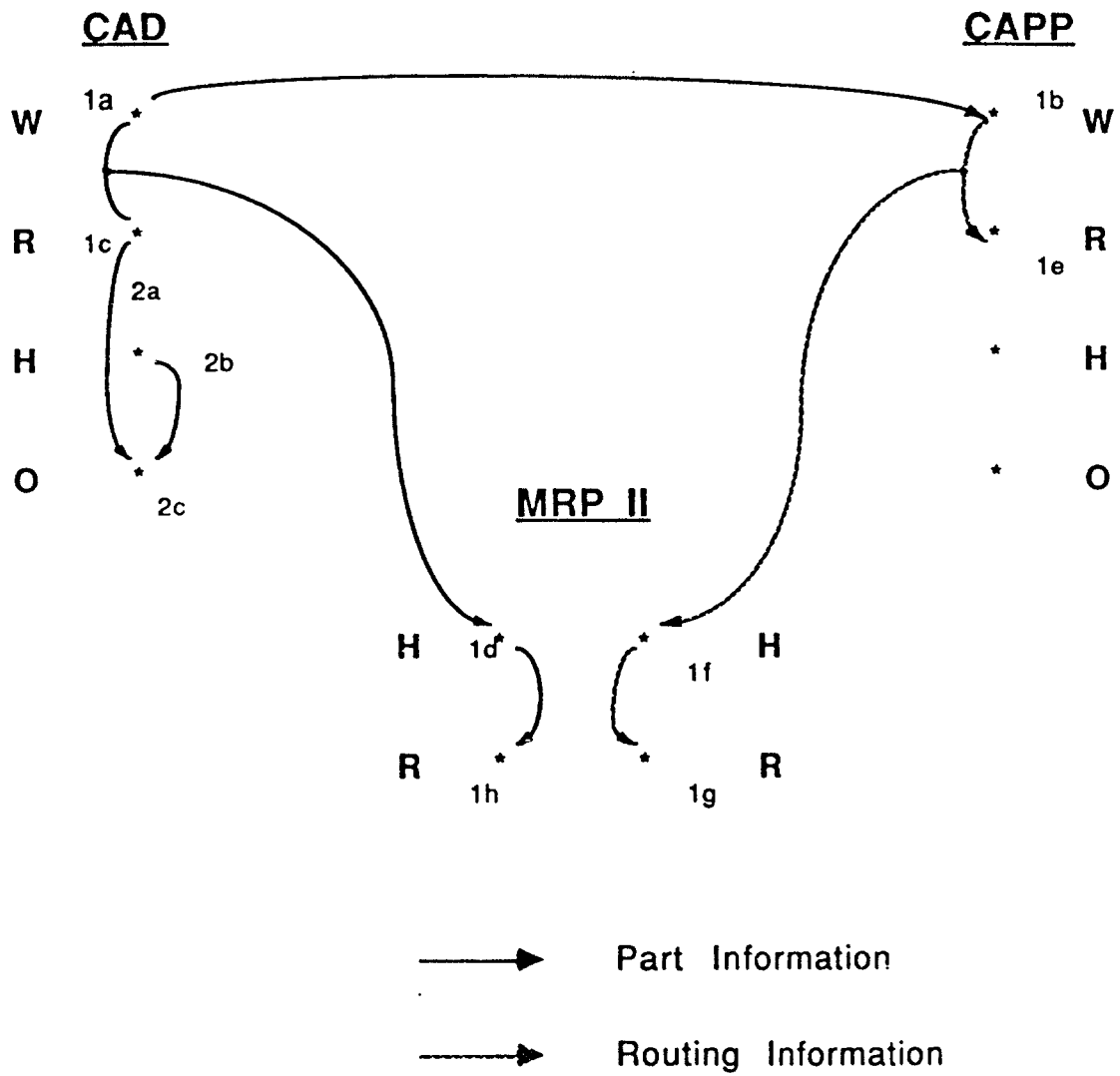
Figure 2. Status Diagram – Creation of a New Part via CAD.
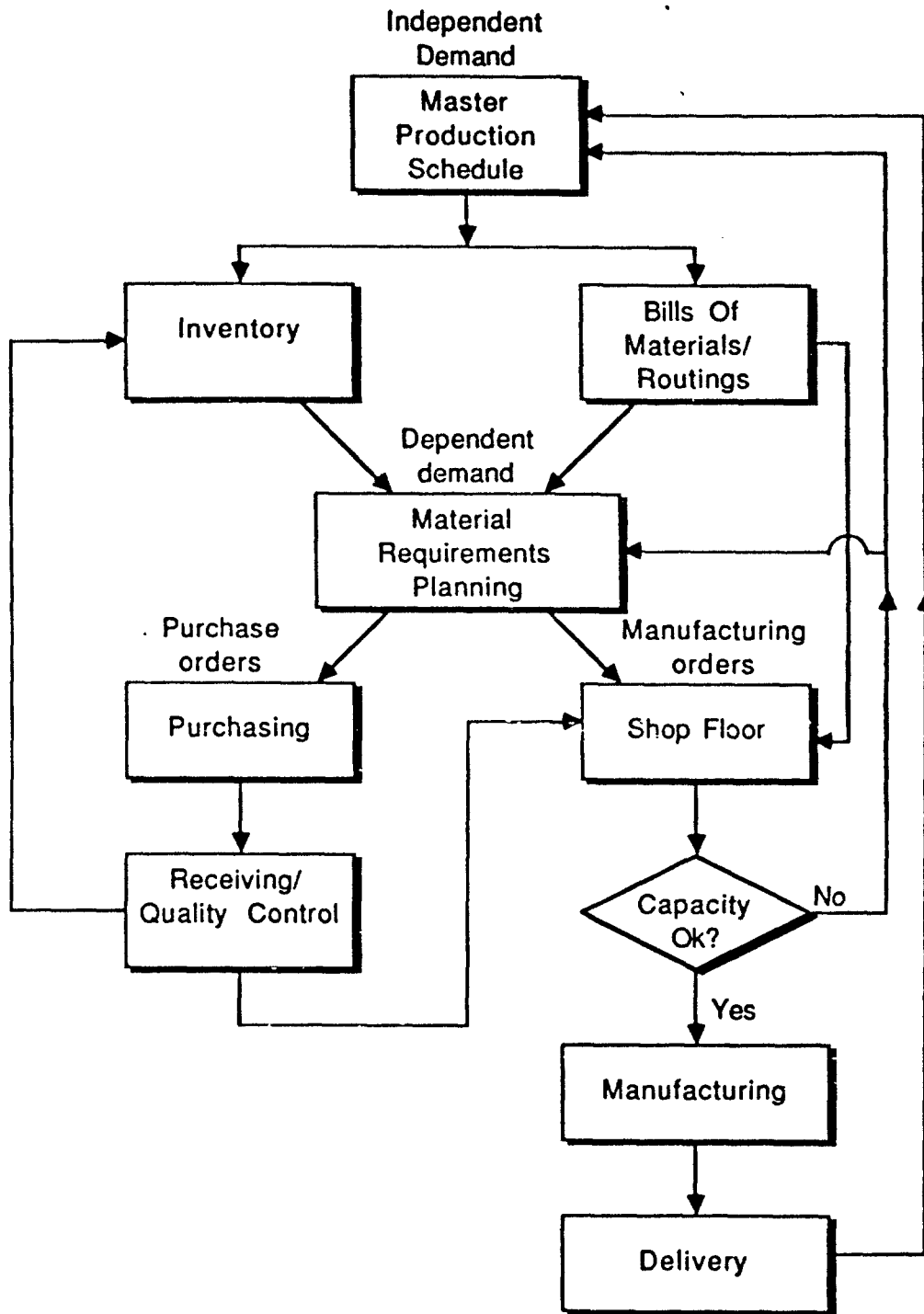
Figure 1. Typical MRP II Architecture.

LIST OF FIGURES