

## A BLACKBOARD ARCHITECTURE FOR INTEGRATED PROCESS PLANNING/PRODUCTION SCHEDULING

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### ABSTRACT

As companies increase the level of customization in their products, move towards smaller lot production and experiment with more flexible customer/supplier arrangements such as those made possible by Electronic Data Interchange (EDI), they increasingly require the ability to quickly, accurately and competitively respond to customer requests for bids on new products and efficiently work out supplier/subcontractor arrangements for these new products. This in turn requires the ability to rapidly convert standard-based product specifications into process plans and quickly integrate process plans for new orders into the existing production schedule to best accommodate the current state of the manufacturing enterprise.

This paper describes IP3S, an Integrated Process Planning/Production Scheduling (IP3S) Shell for Agile Manufacturing. The IP3S Shell is designed around a *blackboard architecture* that emphasizes (1) *concurrent* development and dynamic revision of integrated process planning/production scheduling solutions, (2) the use of a *common representation* for exchanging process planning and production scheduling information, (3) *coordination* with outside information sources such as customer and supplier sites, (4) *mixed initiative decision support*, enabling the user to interactively explore a number of tradeoffs, and (5) *portability and ease of integration with legacy systems*. The system is scheduled for initial evaluation in a large and highly dynamic machine shop at Raytheon's Andover manufacturing facility.

### 1 INTRODUCTION

Over the past two decades, considerable efforts have been expended in developing integrated Computer Aided Design/Computer Aided Manufacturing functionalities e.g., Harrington (1974), Rembold and Dillman (1986) and Scheer (1991). Simultaneously, important progress has been made towards the development of integrated production planning and control solutions e.g., Orlicky (1975), Goldratt (1980), Smith (1994), and Sadeh, et al., (1994), as well as integrated sales/marketing solutions, leading to what we can view as "islands of integration" within the enterprise (Kerr, 1991). While the actual level of integration within each island can significantly vary from one enterprise to another, and important progress still remains to be made within each of these areas, building the bridges between these islands is without any doubt the next major hurdle in developing Computer Integrated Manufacturing environments capable of effectively supporting Agile Manufacturing practices.

As companies increase the level of customization in their products, move towards smaller lot production and experiment with more flexible customer/supplier arrangements such as those made possible by Electronic Data Interchange (EDI) (Lee, 1992), (Srinivasan et al., 1994), (Swaminathan et al., 1994), (Goldman et al., 1995), they increasingly require the ability to quickly, accurately and competitively respond to customer requests for bids on new products (i.e., quality, costs, delivery dates, etc.) and efficiently work out

supplier/subcontractor arrangements for these new products. This in turn requires the ability to (1) rapidly convert standard-based product specifications into process plans and machine operations and (2) quickly integrate process plans for new orders into the existing production schedule to best accommodate the current load of the facility, the status and allocation of machines, fixtures and tools, and the availability of raw materials. A key element in effectively supporting such capabilities requires bridging the integration gap between CAD/CAM and production scheduling through the development of integrated process planning/ production scheduling functionalities.

This paper describes IP3S, an Integrated Process Planning/Production Scheduling (IP3S) Shell for Agile Manufacturing. The IP3S Shell is designed around a *blackboard architecture* (Erman et al., 1980), (Stefik 1981), (Nii, 1986) and (Smith, 1994] that emphasizes:

(1) *concurrent development and dynamic revision of integrated process planning/production scheduling solutions*, using new analysis and diagnosis tools that enable efficient process plan development through early consideration of resource capacity and production constraints (e.g., taking into account the current load of the facility) and greater optimization of production activities through direct visibility of process alternatives and tradeoffs. This contrasts with existing manufacturing practice where process planning and production scheduling are treated as independent activities carried out in a rigid, sequential manner. Instead, concurrent development and revision of integrated solutions is expected to significantly enhance the ability of manufacturing companies to efficiently adapt to changing conditions and yield significant performance improvements (e.g., lead-times, due date performance, resource utilization, inventories, coordination with customers and suppliers, etc.)

(2) the use of a *common representation* for exchanging process planning and production scheduling information

(3) a *control infrastructure* for managing interactions between process planning and production scheduling activities and supporting integration with other information sources (e.g., enterprise level planning, suppliers, etc.)

(4) *mixed initiative decision support* making it possible for the user to explore alternative tradeoffs ("what-if" scenarios) by interactively imposing and/or retracting various assumptions (e.g., process alternatives with different resource requirements, alternative delivery dates, alternative resource assignments, alternative workshift assumptions, etc.) and evaluating the impact of these decisions through incremental process plan/production schedule modification.

(5) *portability and ease of integration with legacy systems*, making it possible to quickly customize the shell to support integration of process planning and production scheduling in new environments.

The IP3S Shell is scheduled for initial demonstration and evaluation in the machine shop located at the Raytheon Electronic Systems manufacturing facility (Andover, MA), an environment for which it is undergoing integration with Raytheon's IPPI process planning system (Raytheon 1993a,

1993b) and Carnegie Mellon's Micro-Boss scheduling system (Sadeh et al., 1993, 1994). With about 50 percent of incoming orders requiring the construction of new process plans or revision of existing ones and with over 150 CNC machine tools and over 100 people working over 3 shifts, Raytheon's Andover machine shop is a complex, highly dynamic, small-lot manufacturing environment that typifies many of the challenges Agile Manufacturing seeks to address.

## 2 INTEGRATING PROCESS PLANNING AND PRODUCTION SCHEDULING

Technical challenges in effectively supporting integrated process planning/production scheduling decisions in a complex and dynamic environment such as Raytheon's machine shop are multiple. From a pure process planning perspective alone, the sheer variety of parts, number of orders requiring the generation of new process plans and production of new tools, and finally the variety of machines and their various characteristics present a challenge in their own right. As in other large machine shops, production scheduling in this environment is no easy task either. Major scheduling challenges include (1) the presence of multiple sources of uncertainty, both internal (e.g., machine breakdowns) and external (e.g., new order arrivals, delays in tool production/modification or in raw material deliveries, etc.), (2) the difficulty in accurately accounting for the finite capacity of a wide array of resources operating according to complex constraints and (3) the need to take into account the multiple resource requirements of various operations (e.g., tools, NC programs, raw materials, human operators, etc.).

While considerable progress has been made with respect to software technologies for process planning and finite-capacity production scheduling, very little attention has been given to issues of integration. Except for a few integration attempts e.g., (Aanen 1988), (Iwata and Fukuda, 1989), (Khoshnevis and Chen, 1989), (Tonshoff et al., 1989), (Bossink, 1992), (Zhang and Mallur, 1994) and (Huang et al., 1995), often in the context of small manufacturing environments, process planning and production scheduling activities are typically handled independently, and are carried out in a rigid, sequential manner with very little communication. Process alternatives are traded off strictly from the standpoint of engineering considerations, and plans are developed without consideration of the current ability of the shop to implement them in a cost effective manner. Likewise, production scheduling is performed under fixed process assumptions and without regard to the opportunities that process alternatives can provide for acceleration of production flows. Only under extreme and ad hoc circumstances (e.g., under pressure from shop floor expeditors of late orders), are process planning alternatives revisited. This lack of coordination leads to unnecessarily long order lead-times, increased production costs and inefficiencies and severely restricts the ability to effectively coordinate local operations with those at supplier/customer sites, whether internal (e.g., internal tool shop) or external (e.g., raw material suppliers).

In their survey of prior efforts to integrate process planning and production scheduling, Huang et al. (1995) distinguish between three approaches :

1. Non-linear Process Planning, which generates all possible process plans ahead of time (i.e., based on static considerations) and dynamically selects between these alternatives at execution time. This is the approach taken in the FLEXPLAN system (Tonshoff et al., 1989);

2. Closed Loop Process Planning, also referred to as real-time or dynamic process planning e.g., Iwata and Fakuda (1989), Khoshnevis and Chen (1989), where process planning attempts to take into account dynamic resource availability information;

3. Distributed Process Planning, which reduces the complexity of the Closed Loop approach by subdividing integrated process planning/production scheduling decisions into multiple more localized decision phases (Huang et al., 1995).

In practice, none of these approaches totally dominates the other two, as different manufacturing environments generally entail different levels of complexity and different operational requirements (e.g., different real-time requirements). In fact, the decision flows assumed in earlier work are rather restrictive and cannot accommodate some of the complexities of environments such as the Raytheon machine shop. For instance, at the Raytheon facility, new process plans often require the production of new custom tools. As a result, evaluation and scheduling of process plans in this environment requires tight coordination with an internal tool shop. In general, coordination with suppliers, whether internal or external, has been ignored in earlier work to develop integrated process planning/production scheduling solutions. Another challenging aspect of the Raytheon machine shop has to do with the fact that it is not a single-user environment. Instead, five industrial engineers work concurrently on the generation and modification of process plans, each one of them making decisions that influence the future load of the facility. The result is a dynamic environment where it is not always easy to predict future resource loads. More generally, both process planning and production scheduling, even with the support of sophisticated state-of-the-art computer-aided process planning and scheduling techniques, remain highly interactive processes, where the user evaluates alternative decisions based on experience and knowledge that is not easily amenable to computer modeling. Rather than committing to a prespecified decision flow, as in earlier approaches, the IP3S blackboard architecture emphasizes a more versatile integration framework where the user can dynamically select between alternative decision flows and control regimes. The resulting shell provides a customizable framework capable of supporting a wide range of integrated process planning/production scheduling decision flows, including all three of the approaches identified by Huang et al. (1995) as well as a number of more complex hybrids.

### 3 THE IP3S BLACKBOARD ARCHITECTURE

The use of blackboard architectures as a vehicle for integrating multiple knowledge source modules to solve complex problems has been demonstrated in a variety of application domains (e.g., speech understanding, scene recognition, factory scheduling, etc.). Through their emphasis on modular encapsulation of problem solving knowledge in independent knowledge sources that communicate through a shared data structure (blackboard) and their explicit separation of domain knowledge (e.g., process planning and production scheduling knowledge in this case) and control knowledge, blackboard architectures offer several key advantages:

- *extensibility* of the architecture, making it particularly easy to progressively add or enhance knowledge sources (e.g., add new analysis knowledge sources to support mixed initiative planning/scheduling functionalities)
- *flexibility* of the control procedure, making it possible for the user to select between multiple control regimes (e.g., highly interactive control regimes where many decisions are made by the user versus more autonomous regimes where the user specifies high-level tasks or “goals” and lets the system figure how to accomplish these tasks)
- *re-usability* of knowledge sources (e.g., analysis/diagnosis knowledge sources) across multiple manufacturing environments
- *ease of integration with legacy systems* (e.g., existing process planning and/or production scheduling systems).

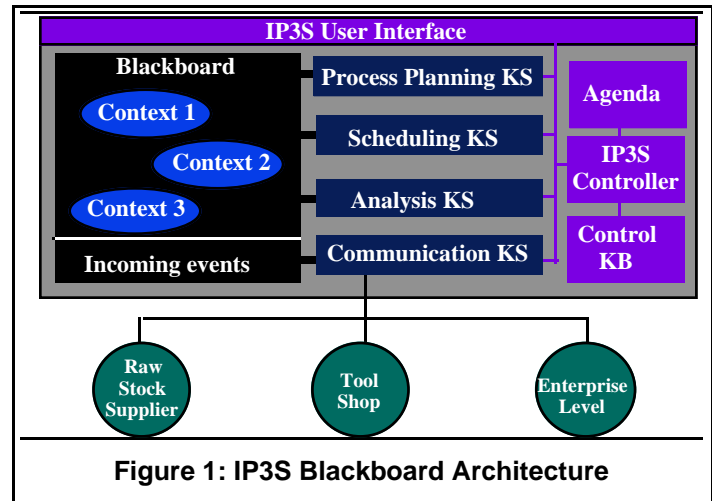


Figure 1 provides an overview of the IP3S blackboard architecture. The system consists of several *knowledge sources* (KSs), including a process planning KS, a production scheduling KS, a communication KS and several analysis/diagnosis KSs. The blackboard is the shared data structure through which KSs Both complete and partial solutions are stored on the Blackboard and are analyzed and

improved upon by the KSs. These solutions are generated through automated search, interactions with the user, or a combination of both plus knowledge source analysis results and incoming events (e.g., new orders, requests for bids, expected tool completion dates, machine breakdowns and other shop floor updates, etc.).

The IP3S *Controller* determines, either automatically or through interaction with the user, which knowledge source to activate next. The blackboard, controller and knowledge sources are being implemented using Expertsoft's PowerBroker product. Each runs as an independent process that communicates with the others using a Common Object Request Broker Architecture (CORBA) compliant protocol.

The remainder of this section describes the major elements of the IP3S blackboard architecture.

### 3.1 The IP3S Blackboard

The IP3S blackboard is organized around an arbitrary number of user-defined or system-defined contexts, each corresponding to a potentially different set of working assumptions. The assumptions for a given context reflect a specific set of orders being planned and scheduled and the set of resources available for use. For instance, upon receipt of a request for bid on a possible order, the user can create a copy of the context in which (s)he is currently working and incorporate the potential order into the order list of the new context. An integrated process planning/production scheduling solution can then be developed for this new set of orders, through incremental modification of the solution built in the original context. Using this new solution, the user can evaluate the impact of the possible order, determine a realistic completion date and decide whether or not to submit a bid. Similarly, new contexts can be created to evaluate different shift alternatives (e.g., determine if adding a shift on one or more resources could help complete some orders earlier), evaluate process

plans with different tooling requirements, compare alternative sourcing options, and perform a number of other "what-if" analyses.

IP3S contexts can store complete or partial process planning/production scheduling solutions, allowing the user to leave a particular context at any point in time and explore other, potentially more promising alternatives in other contexts. As solutions are constructed and modified in a particular context, so-called *unresolved issues* are updated to help the system and the user keep track of aspects of the solution (within the context) that are expected to require further work. The IP3S architecture distinguishes between 3 main types of unresolved issues relating to:

1. the *completeness* of the solution, such as an order still missing a process plan or an order that has a process plan but has not yet been scheduled,.

2. *inconsistencies* in the solution such as an order whose current process plan is not the same as the one used in the production schedule or a schedule invalidated by a machine breakdown;

3. potential *areas for solution improvement* such as an order that seems excessively late, a newly added shift on a bottleneck resource, or a canceled order.

In IP3S, unresolved issues can be tailored to suit the needs of a particular environment. For instance, because of the time it takes at the Raytheon machine shop to develop a detailed process plan with complete tooling information, unresolved issues in this environment differentiate between "coarse" and "refined" process plans, depending on whether tooling information is provided. This makes it possible to sometimes approximate future machine loads, without having to wait for completely developed process plans. A subset of unresolved issues developed as part of the customization of IP3S for the Andover machine shop is displayed in Figure 2.

<b>Order Related:</b> <b>Completeness:</b> Order-w/o-Default-Process-Plan Order-w/o-Coarse-Process-Plan Order-w/o-Coarse-Production-Schedule Order-w/o-Refined-Process-Plan Order-w/o-Refined-Production-Schedule Order-to-be-Canceled (existing order must be unscheduled and deleted) <b>Inconsistency:</b> Order-w/-Inconsistent-Production-Schedule (The production schedule for an order predates its process plan.) <b>Improvement:</b> Tardy_Order (parametric, user defined unresolvedissue)	<b>Resource Related:</b> <b>Inconsistency:</b> Resource-w/-Breakdown <b>Overall Solution:</b> <b>Completeness:</b> Unprocessed-Shop-Floor-Update <b>Resource Utilization Statistics:</b> <b>Improvement:</b> Outdated-Resource-Util-Statistics
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Figure 2: Examples of unresolved issues used for the Andover machine shop

### 3.2 The IP3S Controller

A key feature of the IP3S architecture is its ability to support multiple control regimes, including highly interactive control regimes where the user interactively specifies the course of action to be followed as well as more autonomous control regimes where domain-specific control heuristics decide what to do next. The IP3S Controller is the system component responsible for directing solution construction, revision and analysis, either under close interaction with the user or under more autonomous regimes. It is responsible for specifying which events to incorporate in the current working context and when, determining which unresolved issue(s) to focus on next, selecting the course of action to be followed when working on a particular unresolved issue (e.g., which knowledge source service to active next)

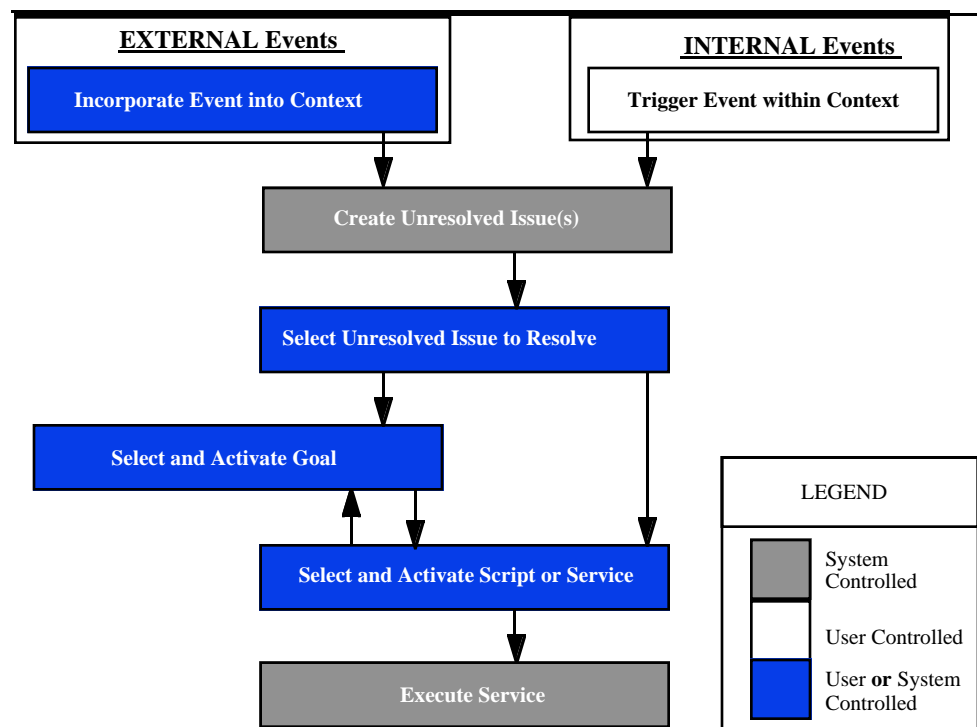
The IP3S *agenda* is a data structure used by the controller to keep track of problem solving tasks to be executed. When a particular course of action is selected, either interactively by the user or automatically by a control heuristic, one or several items are placed on the agenda, describing the tasks to be performed next by the system. The IP3S architecture supports three types of agenda items:

(1) *explicit knowledge source service activations*. Examples include activation of a specific analysis KS service, activation of a process planning KS or production scheduling KS service to expand or revise a specific solution component, activation of the communication KS to send a request to the tool shop for a completion date estimate for a new tool, etc.

(2) *scripts*, which specify a predefined sequence of knowledge source service activations and/or goals (see below) known to generally accomplish a particular task. For instance, a simple script to incorporate a new order in the current solution might include the following steps: (a) process planning KS activation to build a process plan for the new order, (b) a communication KS activation to obtain completion time estimates from the tool shop for custom tools required by the new process plan, (c) production scheduling KS activation to incorporate the new order with its process plan into the overall production schedule.

(3) *goals*, which are used to specify higher-level objectives for which multiple scripts may be available. This corresponds to situations where selection of a script is likely to depend on a number of context-specific considerations (e.g., presence of a bottleneck resource). The actual selection of a script can be performed either by the user or using domain-specific control heuristics.

Figure 3 attempts to summarize the overall decision flow within the IP3S architecture. At any point in time, the controller, either autonomously or following user directions, can incorporate new events into the current working context. This includes external events such as the arrival of a new order or user-defined ("what-if" analysis) events such as a decision by the user to see if adding an extra shift on a resource can help improve the solution. Incorporating a new event into a context results in the automatic creation, modification and/or deletion of one or more unresolved issues. For instance, incorporating a new order into a context will result in the creation of an unresolved issue indicating that this order does not have a process plan. Incorporating a reply from the tool shop will result in the deletion of an unresolved issue indicating that this context is awaiting a reply from the tool shop.



**Figure 3: The IP3S Control Flow.**

New courses of action can be selected by the user or by domain-specific control heuristics. This can be done by selecting a particular unresolved issue to focus on or by selecting goals. Scripts or KS activations specifying how to refine the current working solution.

The result is a system where the user can select between different levels of interaction and different control regimes. This includes tight interaction regimes where the user imposes low-level decisions through specific KS service activations (e.g., specific selection of a process alternative, specific sequencing of two operations on a given machine) as well as looser modes of interaction where the user interacts with the system through specification of higher-level goals (e.g., requesting the system to look for a solution where the engineering costs associated with a specific order are lower

than in the current solution or a solution where one or several orders are completed earlier, etc.), relying on control heuristics to drive the problem solving process.

### 3.3 Knowledge Sources

Knowledge sources serve as the primary problem solvers in a blackboard system. In the IP3S system, each domain-level KS acts as a server that supports a variety of services that can be activated, scheduled and invoked by the system. Each service class has an associated KS function that is called, with an optional set of parameters. When a script is activated, a service activation is instantiated for each service specified in the script. The parameters provided to a service activation serve as the stimulus units to the knowledge source called to perform the designated service.

Knowledge sources communicate their results by posting new information to the blackboard and modifying existing information. These events may generate unresolved issues within the current blackboard context that may lead to the posting of additional goals and the activation of additional scripts or services. The KS service also returns a value indicating whether it has completed its designated task successfully. This information is in turn used by the IP3S Controller KS to help determine the next course of action.

**3.3.1 Scheduling Knowledge Source** This knowledge source is based on the Micro-Boss finite capacity scheduling system (Sadeh, 1993 and 1994). Micro-Boss relies on a new set of “micro-opportunistic” search procedures that constantly monitor resource contention during the construction or repair of the schedule and dynamically redirect the system’s optimization efforts towards areas of the search space subject to the highest contention (i.e., groups of operations contending for critical resource/time intervals). These search procedures support predictive, reactive and interactive scheduling functionalities and have been shown to consistently yield significant improvements in schedule quality (i.e., due date satisfaction, lead-time and inventory performance) over multiple combinations of priority dispatch rules and release policies as well as over sophisticated bottleneck-centered scheduling techniques.

Micro-Boss is currently undergoing customization for incorporation into the IP3S architecture. This customization includes the development of the following key IP3S services:

- *Schedule Generation*: generation of new schedules
- *Schedule Repair* in reaction to shop floor updates (e.g., machine breakdowns, execution delays, etc.)
- *Dynamic order incorporation*:: dynamic incorporation of new orders/order cancellations/order modifications. Several variations of this service will be provided that differ in the amount of schedule reoptimization they perform.
- *Schedule Editing*, enabling the user to interactively manipulate a given scheduling solution
- *Goal-Driven Schedule Reoptimization Services* (e.g., a service that attempts to reoptimize the schedule to improve the completion date of one or several orders).

At the time this paper is written, only a subset of these services has been implemented.

**3.3.2 Process Planning Knowledge Source** This knowledge source is based on Raytheon’s IPPI generative process planner (Raytheon, 1993a and 1993b), a system currently in use at two of Raytheon’s Government Group divisions. A key feature of this module will be its ability to develop and revise process plans while accounting for existing and projected resource commitment information posted on the blackboard.

IPPI utilizes knowledge bases populated with raw stock configurations, process selection logic and manufacturing resource capabilities. Machine tool selection and tool path generation is done by invoking CUTTECH, a module developed by the Institute of Advanced Manufacturing Sciences (IAMS). Plans produced by IPPI consist of:

- an ordered list of machining operations including recommended tooling, feeds and speeds
- process routing information,
- bill of materials.

The Process-Planning KS (IPPI) will contain the following services:

- *Process Selection*: This service takes an order as input and accesses a feature based solid model corresponding to the part ordered. Utilizing knowledge bases that contain process, resource and raw stock information and resource loading data from the IP3S blackboard, a macro-level process plan or *ProcessRouting* is generated for the part and posted on the blackboard.
- *Operation Details*: Provided “process routing” as input, this service provides a more detailed *ProcessRouting* object. The output object contains tooling and fixture requirements, and estimates of time to setup each machine in the routing and the duration of each operation.
- Other services will include: *Raw Stock Selection*, *OperationOrderingOptimization*, *Cost*

### 3.3.3 Analysis / Diagnosis Knowledge Sources

The IP3S approach is based on the general premise that the complexity of the combined process planning/production scheduling search space can effectively be reduced and solution quality enhanced by using process planning considerations to help focus search within the scheduling sub-space and, conversely, by taking into account scheduling considerations to quickly identify promising alternatives within the process planning sub-space. Analysis/diagnosis knowledge sources are central to achieving this integrated search behavior. They help identify sources of inefficiency in the current solution and determine how the solution can most effectively be improved (e.g., whether to generate an alternative process plan for a given part, to modify its current tooling requirements, reschedule operations on a critical machine, reallocate NC programmers to different machines, etc.). Analysis results are summarized on the blackboard, where they are accessible to the user and IP3S control heuristics to determine how to proceed.

An example of a key IP3S analysis KS is the *Resource Utilization KS*. This KS estimates resource contention, by accounting for both current reservations and projected demand of orders that still need to be scheduled. These statistics, which are computed for one or several groups resources over prespecified time buckets (e.g., weekly buckets in the case of the Andover shop), are posted on the blackboard and can be accessed by the Process Planning KS to help identify promising process alternatives.

Examples of more complex analysis/diagnosis KSs currently envisioned include:

- *KSs to Identify Solution Inefficiencies/Opportunities for Solution Improvement*: These KSs will be specialized in the identification of specific inefficiencies/opportunities for improvement in the solution (e.g., a late order, an order whose lead-time seems particularly high, an order whose engineering costs seem particularly high, an underutilized resource, etc.)
- *Solution Improvement KSs*: Given a specific solution inefficiency, such a KS will help identify promising ways of improving the current solution. For instance, in the case of an order whose completion date is delayed due to contention for a bottleneck machine, a specialized KS could be called to explore alternative ways of improving the existing solution, e.g., modifying the critical order's process plan, freeing the bottleneck resource by modifying process plans of competing orders, etc. The KS will evaluate how attractive each one of these alternatives appears and post its results on the blackboard, where they can be used by the IP3S control heuristic or the user to decide which alternative to try first.

**3.3.4 Communication Knowledge Source** The Communication KS facilitates communication between the IP3S system and the various external component systems, such as the enterprise-level planning system, the raw stock suppliers, the tool shop and the user. Its responsibility is to formulate the outgoing messages transmitted to members of the outside environment.

The Communication KS is equipped with the necessary knowledge to construct messages for conveying specific kinds of information to the various external system components. It passes information in a particular format as determined by the destination and the type of information being communicated. Messages to the enterprise-level planning system have different characteristics than those intended for the tool shop, suppliers, or the user. Each intended destination and message type will need to be supported by this KS.

## 4 SUMMARY AND CONCLUDING REMARKS

A key requirement to supporting agile manufacturing practices is ability to (1) rapidly convert standard-based product specifications into process plans and machine operations and (2) quickly integrate process plans for new orders into the existing production schedule to best accommodate the current load of the facility, the status and allocation of machines,

fixtures and tool and the availability of raw materials. In contrast to traditional manufacturing practice, where process planning and production scheduling are treated as two independent processes, we are developing an Integrated Process Planning/Production Scheduling (IP3S) shell capable of supporting concurrent process planning/production scheduling solution development and revision. Our IP3S Shell is designed around an innovative *blackboard architecture* that emphasizes (1) *concurrent* development and dynamic revision of integrated process planning/production scheduling solutions, (2) the use of a *common representation* for exchanging process planning and production scheduling information, (3) *coordination* with outside information sources such as customer and supplier sites, and (4) *mixed initiative decision support*, enabling the user to interactively explore a number of tradeoffs. The shell is expected to significantly boost the ability of companies to adapt to rapidly changing conditions, both external and internal, and yield significant improvements in manufacturing performance (due date performance, lead-times, inventories, resource utilization, engineering costs, etc.). The system is scheduled for demonstration and evaluation in a complex, highly dynamic machine shop at Raytheon's Andover manufacturing facility.

## 5 ACKNOWLEDGMENTS

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