PRODUCTION MANAGEMENT STANDARDS: INDUSTRIAL NEED

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PREFACE

The High Performance Computing and Communication (HPCC) program was formally established by the High Performance Computing Act of 1991 (Public Law 102-194). The goal of this program is to accelerate the development of future generations of high performance computers and networks and the use of these resources in the government and throughout the U.S. economy. NIST's Systems Integration of Manufacturing Applications (SIMA) Program coordinates many of the agency's HPCC activities. SIMA is addressing the information interface needs of the U.S. manufacturing community. Specifically, the SIMA program works with U.S. industry to:

* Develop information exchange and interface protocols to address manufacturing integration problems,
* Establish test mechanisms for validating protocols and implementations, and
* Transfer information technology solutions to manufacturing enterprises.

The primary output of the SIMA Program will be a collection of specifications called Initial Manufacturing Exchange Specifications (IMES). IMESs provide the means to improve the SIMA Program's ability to meet the needs of the U.S. industry in the area of standards and testing methods by providing a structured approach to the SIMA Program's activities in this arena. They will fill an important void in the manufacturing systems integration process as it exists today. Each IMES will be developed through an industry review and consensus process. It is expected that the manufacturing community will accept them as an authoritative specification.

Three types of IMESs have been identified: an interface specification between a human being and a software application; an interface specification between two or more software applications; and a reference information repository specification. Each IMES involves several components that define the integration aspect, specify a definitive solution to the integration problem, and demonstrate the validity of the proposed solution. It must contain a clear description of WHAT information the interface or repository MUST convey, and possibly HOW it is conveyed. The content is usually specified by an information model of all the objects and related information attributes which are covered by the specification.

To support the scope and domain specifications, the IMES shall address a particular "example scenario," identifying an actual interface/information requirement derived from a real industrial problem. The proof of the value of the IMES to industry will be the ability to build a prototype to the IMES, using the software applications actually used by the industrial practitioners, and solving the cited problem. To support the development of an IMES, SIMA projects will have seven phases: identify/define the industry need, conduct requirements analysis, develop proposed solution, validate proposed solution, build consensus, transfer technology, initiate standardization. Each of these phases has a well-defined set of deliverables.

This document describes the results of Phase I of the Production Management component of the Production and Production Data Management (PDM) project within SIMA. It identifies and documents the industry need, a manufacturing scenario, the interface specifications to be developed, potential collaborators, and the proposed technical approach for this project. It also describes the relationships between the proposed project and 1) the SIMA Reference Architecture, 2) other related projects, and 3) existing standards activities.

Work described in this paper was sponsored by the NIST Systems Integration of Manufacturing Applications (SIMA) program and US Navy Manufacturing Technology program. Certain commercial software and hardware products are identified in this paper. This does not imply approval or endorsement by NIST, nor does it imply that the identified products are necessarily the best available for the purpose.

1. Goals, Objectives, and Benefits

Production Management is one of the focus areas within the Systems Integration of Manufacturing Applications (SIMA) Production and Product Data Management project. The goal of this focus area is the development and demonstration of generic interface specifications for the integration of production management software applications. Work toward this goal will proceed in three stages. In stage one, specifications will be developed which enable the integration of scheduling and shop floor data collection applications. In stage two, specifications will be developed which enable the integration of scheduling with production planning, process planning, and shop floor control. In the last stage, specifications will be developed between shop floor scheduling, Manufacturing Execution Systems (MES), and Enterprise Resource Planning (ERP) systems.

During each stage, we will:

- Develop formal models of these interface specifications using modeling techniques such as Object Modeling Technique [1] and EXPRESS [2];

- Propose database schema and file formats to house physical instantiations of these models;

- Suggest communication protocols for exchanging data between production management software applications;

- Use these specifications, files, databases, and protocols to integrate commercial software applications into prototype tool kit environments;

- Test these tool kits using both laboratory and real-world environments; and,

- Recommend a collection of interface standards for the integration of production management software.

The benefits from this focus area will be applicable to a broad sector of manufacturing industry. The interface specifications will help manufacturers rapidly integrate commercial off-the-shelf production management software applications. Tool kit technology will help shop floor managers become more productive, increase shop throughput, and decrease work-in-process inventories. Integrated tool kits will also help them make better production planning and scheduling decisions, track the execution of those decisions on the shop floor, and recover from problems in a more timely manner. By improving the links to simulation, a number of what-if scenarios can be evaluated before decisions are actually implemented on the floor. This will result in better utilization of production resources, lower work-in-process inventory, and increased throughput. Finally, the seamless integration will reduce significantly the amount of time spent reentering the same data into multiple production management software applications.

2. Background

In the United States today, there are more than 40,000 factories producing metal-fabricated parts. These parts end up in a wide variety of products sold here and abroad. These factories employ roughly 2 million people and produce hundreds of billions of dollars worth of products every year. The vast majority of these factories are what we call "job shops", meaning that the flow of raw and unfinished goods through them is completely random.

During the last 10 years, many manufacturing companies have invested heavily in advanced technologies which have changed the "look" of the modern shop floor. These technologies include computer-controlled robots, machine tools, automated transportation systems and automated storage and retrieval systems. In addition, commercial software is available to perform all of the production management, information management, and communications functions. Today, it is possible to gather data about the events on the shop floor literally as they are happening and make that data available to the production management software.

There are a number of projects underway in the U.S., which are attempting to develop standards for that data. They include the CIM framework project at SEMATECH [3], the MES integration project within the NIIIP SMART program [4], and several projects funded by the ATP TIMA program [5]. There are no formal standards activities in the international arena related to production management integration, although the work within ISO TC 184/SC4 WG8 [6] may become relevant during the course of the project.

2.1 The Importance of Production Management

This integrated production management system has the potential to dramatically decrease costs and increase throughput and, thereby, profits. According to a recent DOD study, Shop Floor Labor and Manufacturing Support account for roughly 50% of total company cost. Production management directly affects all Shop Floor Labor costs and includes about 45% of all Manufacturing Support functions. The report also states that manufacturing support is estimated to cost DOD $24.7 billion annually. Even a 10% reduction in this cost would be dramatic. To reduce this cost, the report recommends increased investment in 1) integration methodologies, 2) simulation and modeling, and 3) engineering support tools. Each of these recommendations is related directly to the SIMA Program.

During recent discussions, several vendors estimated that throughput could be increased by as much as 30% by using real-time, reactive planning and scheduling. This has a direct impact on operator and machine idle time. When you consider that jobs can sit idle more than 85% of the time, such an impact can be truly dramatic. There are several major impediments to achieving this potential. The one most closely aligned to the SIMA Program is that current production management applications either run in a stand-alone mode or are tightly integrated with specific applications supplied by another vendor.

Over the years, the design and analysis of job shops have been the focus of considerable attention in the Operations Research (OR) literature. Research papers on topics such as factory layout, inventory control, process control, and production management can be found in almost every issue of every OR journal on the market today. The most popular of these topics is production management, which includes all functions required to plan, schedule, and control activities on the shop floor [7-11]. A large number of approaches to the modeling and solution of these job shop scheduling problems have been reported in the OR literature, with varying degrees of success. These approaches revolve around a series of technological advances that have occurred over that last 30 years. These include mathematical programming, dispatching rules, expert systems, neural networks, genetic algorithms, and inductive learning.

2.2 Current Software Environments

There are a large number of software tools on the market today which implement all of these technologies. Most of these tools were designed to be 1) stand-alone turnkey systems, and 2) run as off-line, open loop systems. The end result is that integration of these software tools continues to be a significant problem in today's factories, large and small. In addition, even though there is a general understanding about which tools need to share information, there is no agreement on the content or format for that information. Consequently, even though the communications technologies exist, these software tools cannot exchange information. Consider two kinds of data: process plans and shop floor data. The process plan provides the critical data about each new job that needs to be scheduled. Today, these plans are stored either as ASCII files or printed on a piece of paper. None of the available scheduling software packages can accept a process plan in these formats. As a result, a time-consuming, costly, and manual reformatting is required. There is also no capability in these tools for accessing, analyzing, and using real-time shop floor data. Until recently, the main reason for this was that the data was collected and stored on paper. Now there are numerous automatic data collection systems on the market. But, little use is made of the outputs from these systems by existing tools. In general, they cannot automatically access and examine that data to detect any information that is relevant to them. If this is done at all, it is done by hand and long after the data was originally collected. In addition, they cannot easily update their input files and system models every time this information indicates that an unexpected event of importance to them has occurred. Again, this is usually done by hand long after the fact.

Consequently, users are forced to pay for custom integration of production and Product Data Management (PDM) applications. The cost of this integration has been estimated by our partners to be around $100M per year for the mechanical parts industry. This cost could be reduced dramatically if generic interfaces existed between production management applications. These interfaces are the focus of this project.

2.3 Partners

As stated above, the first stage of this project will concentrate on the integration of scheduling and shop floor data collection applications. It will be a collaborative effort between vendors, users, academia, and NIST. Vendors of the major simulation-based scheduling software tools (Pritsker Corporation and AutoSimulation, Inc.) have agreed to participate in this initial project. They will participate in the development of the specifications and make changes to their products to conform to those specifications. Cooperative agreements are already in place with these companies. Two vendors of shop floor data collection systems, DLOG REMEX and Wonderware, Inc., will provide their software as part of the demonstrations. They will work with the scheduling vendors to implement the interface specifications. Negotiations with two users, AMP Incorporated and B.F. Goodrich are underway. These users will participate in the development of the specifications and provide the shop floor data and resource models needed for the demonstrations. A number of universities, including Ohio University, Purdue University, and Pennsylvania State University, will provide scheduling techniques to be used in the demonstrations.

3. TECHNICAL FOCUS

The project will focus on developing methods for integrating production management applications under the Production and PDM project within the SIMA Program. The project will focus on providing the models, integrated framework, operating environment, common databases, and interface specifications for a wide variety of emerging tools and techniques for managing shop floor operations. In collaboration with industry, the project will assess industry requirements for production system engineering tools and tool integration. Collaborators will also help define generic information models for production management data, specify interfaces for integrating tools, develop prototype integrated environments and shared databases, and implement test case production management projects. Prototype integrated production management tool kits will be constructed from commercial products using proposed interface specifications. Solutions will be validated at NIST laboratories and at industry sites.

The principal elements of the technical approach are:

- Identify and address critical industrial needs through collaboration,
- Develop solutions to engineering tool integration problems,
- Construct prototype environments using commercial products,
- Validate results through industrial testing of system implementations,
- Specify and promote needed industry standards, and
- Facilitate the rapid commercialization of new technology.

Initially, the primary integration mechanism will be file exchange. Information models for data to be exchanged will be modeled using the EXPRESS modeling language [2]. EXPRESS models are either obtained from the existing ISO 10303 - Product data representation and exchange (commonly called STEP, STandard for the Exchange of

Product model data), STEP parts currently under development, or NIST Initial Manufacturing Exchange Specifications (IMESs) [12]. From the EXPRESS models, STEP Part 21 will be used to define the format of data exchange files [13]. Existing STEP tools will be used to develop extensions to applications modules and/or independent translators to generate and parse exchange files. Typically exchange files will be maintained in the PDM system. Manufacturing software applications would access, check in, and check out all exchange files using the PDM system interface.

The SIMA Reference Architecture [14] will be used to identify the functions involved in production management and the data required to integrate corresponding software applications. This architecture is a process model that defines the functions that tools must perform in order to engineer a production system. It also defines inputs, outputs, controls, and mechanisms for carrying out the functions. This project focuses on the Produce Products node (A4) from the SIMA Manufacturing Activity Model: Develop Production Plan, Define Production Jobs, Schedule Jobs, and Control Production (see Figure 1). The first two of these functions are usually performed by some combination of Material Requirements Planning (MRP) and Manufacturing Resource Planning (MRPII) software. Schedule Jobs is usually performed by a separate scheduling application which can be based on a number of technologies including mathematical programming, simulation, dispatching rules, neural nets, genetic algorithms, fuzzy logic, and various hybrids. The Control Production function is typically split between a shop floor control systems application and a shop floor data collection application. With the recent introduction of Manufacturing Execution Systems (MES) applications, these distinctions have become blurred. Different combinations of these functions are contained in each MES product offering. The initial technical approach for this project is based on the assumption that a separate scheduling application is used. MES applications will be addressed at a later stage.

The first two stages of this project will focus on the integration of commercial scheduling software with commercial shop floor data collection, production planning, shop floor control, and process planning. Achieving integration will require the development of new interface and information exchange specifications. Interface specifications will specify the feedback information that is needed to update the simulation models used by the scheduling software. Information exchange specifications will specify how this feedback is actually stored and retrieved. These specifications will be defined in a collection of IMESs. NIST will work with industry, vendors and users to develop these IMESs. At the conclusion of the project, NIST will work with the national and international bodies to develop a set of standards based on these IMESs.

We have identified five IMESs to be developed (we anticipate that others will be identified as the project evolves). They are work orders, routings, schedules, dispatch lists, and shop floor status.

Work Order - This term is commonly used in industry and corresponds to the information flow called "Released Jobs" in the SIMA Manufacturing Activity Model. It is one of the primary inputs into the Schedule Jobs function. Orders (jobs) are provided (released) to this function either one at a time or as a list. Each such job is a request for the production of a specific quantity of parts, usually of the same type. Attributes of each such job will include quantity, part ID, due date, earliest release date, a pointer to an operations sheet, and a pointer to a routing. Typically, the operations sheet is not used by the Schedule Jobs function, but the routing is. Note, the operations sheet would be used in a hierarchical control system in which distributed schedulers existed at both the shop and the machine levels.

Routing - The routing is the other primary input to the Schedule Jobs function. It combines aspects of two information flows from the SIMA Manufacturing Activity Model: Job Routing and Routing & Operations Plan. It is a list of the machines, and associated activities, requirements, and timings for that machine, that must be visited in order to complete the production of the order. The list may be a completely ordered sequence or an arbitrary graph structure. [Today, the list is almost always an ordered sequence. It is likely that this will change in the near future to allow alternatives and precedence constraints that lead to arbitrary graph structures. Our specification will allow for both.] The machines could refer to a specific machine tool, robot, transporter, inspection machine, or artisan’s workbench; or it could refer to a group of identical machines, robots, etc. The activities may refer to specific tasks to be done or pointers to tasks in the corresponding operation sheets. The requirements could refer to skills or other special resources - like fixtures, tools, or measuring instruments - that are needed to carry out the tasks. The timings provide estimates of task durations at each of the machines.

Schedule - The schedule is the primary output of the Schedule Jobs function. It corresponds to the information flow "Scheduling Package" in SIMA Manufacturing Activity Model. The schedule provides a mapping of jobs to equipment stations - conceptually, it is a Gantt chart - and start and finish times. The jobs can be a single entity or a collection of entities. These collections are sometimes called a batch, a lot, or a load. As before, the equipment station can refer to a specific station or to a type of station. There is implied ordering for jobs and stations. The schedule may refer specifically to requirements, or it may simply point to the operations sheet. For each job, one can determine the list of stations it will visit, the order it will visit them, arrival time, departure time, and duration. For each station, one can determine the list of jobs it has been assigned, the order it will process them, and how long each will take.

Dispatch List - This corresponds to the information flow "Job Schedule" in SIMA Manufacturing Activity Model. It is a decomposition of the schedule by equipment stations. That is , for each equipment station identified in the schedule, the dispatch list specifies the list of the current jobs, and associated requirements, and start and finish times. Currently, it also specifies the exact sequence in which those jobs are to be performed. In a hierarchical control setting, this sequence would be replaced with a "list" as defined above.

Status - This is the major output from the "Control Production" function and a critical input to many upstream functions in the SIMA Manufacturing Activity Model. It corresponds to several information flows that have been defined in that model including work-in-Process, Resource Status, Production Order Status, Job Status, and Operations Status.

As noted above, NIST will work with all project participants to develop EXPRESS models for the interface specifications described above. We will start with **Status**. The major assumption will be that all status information needed by the scheduling application is generated by the shop floor data collection application. Using this IMES, we will demonstrate that the feedback from the shop floor data collection systems can be used to update the models of the shop floor, which are used internally by the scheduling applications. This demonstration will use the SIMA virtual production facility as the shop.

The integration of scheduling with shop floor data collection provides the impetus for improving the capabilities of the current generation scheduling software. Providing those improved capabilities requires new techniques to solve job shop scheduling problems. Such techniques have been under development for the past several years by NIST, Ohio University, and Purdue University. We have shown that these techniques can address some of the shortcomings of existing commercial scheduling packages and that we can get near optimal solutions to large problems very quickly. This project will integrate these techniques into the two simulation-based schedulers provided by the vendor participants, and demonstrate that they can generate schedules and respond to problems in real-time. This demonstration will be based on shop floor models, orders, and routings provided by actual manufacturers who are participating in the project. Once the effectiveness of these techniques has been demonstrated, NIST will work with vendors to incorporate these techniques into their next generation products. This commercialization task is, however, beyond the scope of this project.

4. Manufacturing Scenario

There are typically three major phases to the product realization process: design, engineering, and production. In the design phase, customer order requirements are used to generate a product design. This design provides the product data for all of the individual parts, components, sub-assemblies, and assemblies that must be produced. It includes product models and a detailed bill of materials. In the engineering phase, a process plan is created. This plan provides a recipe for how to produce everything that will go into the final product. It includes a list of required processes, the machines on which these processes will be implemented, the routing, and all other required materials and resources. Many different processes can be used including machining, heat-treating, painting, welding and inspection.

Customer orders, projected loads on the facility, and projected unused capacity are used to create work orders for the shop over the next planning horizon. These work orders, together with their corresponding routings and the current shop status are used to create a schedule. Each work order contains a list of jobs that must be performed at the machines listed in the routing. Each routing contains a partially ordered list of machines, together with other resources, and the tasks to be done at that machine. The shop status contains information about the current state of all the resources in the factory.

Initially, there will be two commercial schedulers, two commercial shop floor data collectors, and one commercial shop floor simulator. A dispatcher and data manager will be developed at NIST in cooperation with our university collaborators. These software applications will run on Personal Computers, SUN Microsystems, and Silicon Graphics platforms, which reside in both Advanced Manufacturing Systems And Networking Testbed (AMSANT) lab and the National Advanced Manufacturing Testbed (NAMT) lab. During the first demonstration of the project, integration will be achieved using file transfer. During the second demonstration, a message-passing integration scheme will be developed based on the Common Object Request Broker Architecture, CORBA [15].

For the initial demonstrations, work orders and routings will be manually keyed into the schedulers. Each scheduler will group the various jobs into scheduled units called loads. The actual output will be a schedule, which can be thought of as a Gantt chart [7]. This Gantt chart shows all of the loads, the resources to which they are assigned, and the order in which they will be done. It provides a single, comprehensive view of what is supposed to happen on the shop floor during the next planning period. While this may be appropriate for shop floor management, it is not sufficient for shop floor execution. For execution, the schedule must be decomposed into a collection of ordered lists, one for each machine on the floor. Each such list contains only those loads assigned to that machine, and, in the order in which they are to be executed. This decomposition operation is done in the dispatcher. The dispatcher creates individual files for each machine, which are commonly called dispatch lists. It also creates a load file, which tells when loads are released to the shop. The dispatch file, the load file, and the routing file are passed to the shop floor simulator for execution. We expect to build shop floor simulation models from real data provided by our collaborators.

The simulator will process these files until all of the loads have been completed. It will also send periodic status information to the data collectors. Several changes must be made to the shop floor simulator, before it can operate in this environment. First, the normal load arrival mechanism must be modified so that loads can arrive at predetermined, rather then at random, times. Second, the normal queue selection mechanism must be modified so that the next load to be selected comes from the external dispatch file, not some internal set of queuing rules. Third, routing must be done according to the external routing file, not some internally generated routing table. Fourth, the simulator must generate messages each time an event happens. These messages, which will be defined in the first phase of the project, must be collected into a status file and sent to the data collector.

Each time the data collector receives a status file, it must update its internal model of the shop floor. Modifications must be made to the data collection tools to accommodate this requirement. Currently, they are set up to accept manual inputs and not file inputs. Software must be written to parse the message file and update the status model. We expect that this model, which will be defined in the first phase of the project, will be stored in a relational database. In addition, when requested, it must transfer information from that database to the scheduler. Again, modifications will be made to parse the request and furnish the data.

Whenever a problem is detected, such as a machine breakdown, the scheduler will be able to generate a new schedule. This new schedule will be based on the up-to-date status information. This will conclude the first demonstration. For the second demonstration, integration will be based on client-server, message-passing paradigm of CORBA. Modifications will be made to the dispatcher, shop floor simulator, and data collector to use this paradigm. Once these modifications have been implemented, it will be possible to generate schedules at any time.

5. CONCLUSION

If the manufacturing industry is to remain competitive, it must strive continuously to improve the operation of its production systems. Seamless interoperation of production management software applications could become a reality, thereby reducing software integration costs. There are major needs in this area that could be served by better utilization of emerging information technologies. This Initial Manufacturing Exchange Specification (IMES) Phase I document has identified those needs and interfaces to address those needs. Subsequent IMES documents will discuss requirements analysis and specifications of individual interfaces and models, which were initially identified in this document.

6. GLOSSARY OF TERMS

Application protocol (AP) - A part of the ISO 10303 Standard for the Exchange of Product Model Data (STEP) specification.

Assembly process specification - A document which specifies the operations, sequences, and resources necessary to assemble a manufactured product.

EXPRESS - An standard information modeling language developed as a part of the ISO 10303 - Standard for the Exchange of Product Model Data (STEP), see ISO 10303-11 (1994).

High Performance Computing and Communication (HPCC) Program - A program established by the High Performance Computing Act of 1991 (Public Law 102-194). to accelerate the development of future generations of high performance computers and networks and the use of these resources in the government and throughout the U.S. economy.

Initial Manufacturing Exchange Specification (IMES) - An interface specification developed by the SIMA Program, i.e., an interface specification between a human being and a software application; an interface specification between two or more software applications, and a reference information repository specification.

Systems Integration for Manufacturing Applications (SIMA) - A NIST program to develop information exchange and interface protocols to address manufacturing integration problems, establish test mechanisms for validating protocols and implementations, and transfer information technology solutions to manufacturing enterprises

System architecture - A technical specification for a system that identifies its major modules, functions of the modules, types of data used by the modules, and interfaces between the modules.

Tool Kit - A set of software packages that provide an integrated set of functions and share data to serve a common business purpose, e.g., manufacturing engineering.

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APPENDIX I - LETTERS

APPENDIX II - COOPERATIVE AGREEMENTS