Industrial Need: Production System Engineering Integration Standards

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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 System Integration of Manufacturing Applications (SIMA) program is the agency's coordinating focus for its HPCC activities, see Barkmeyer (1995). 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, see Kemmerer (1997). 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, specifies a definitive solution to the integration problem, and demonstrates 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 Systems Engineering component of the Production and PDM Project within SIMA. It identifies and documents the industry need, technical specifications to be developed, potential collaborators, a proposed technical approach, and a manufacturing scenario for this project. It also describes the relationships between the proposed project, the SIMA Reference Architecture, other related projects, and current standards activities.

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1. GOALS, OBJECTIVES AND BENEFITS

Production systems engineering (PSE) is one of the focus areas within the SIMA Production and Product Data Management (PDM) project. Its goal is to develop solutions for integrating engineering software applications which are used to design, plan, and implement production systems for discrete parts manufacturing. The initial focus for the project is on the engineering of small assembly lines for electromechanical product production. Objectives of the project include:

- Develop architectures, information models, database structures, interfaces, and techniques for integrating production system engineering tools, e.g., process specification, plant layout, and manufacturing simulation systems,

- Develop new database structures and exchange file formats, or as appropriate identify suitable existing formats for maintaining and sharing production system engineering data,

- Integrate commercial software applications into prototype tool kit environments using those database and exchange files to evaluate architectures and interface solutions,

- Test and validate interfaces in the prototype integrated system using real world data,

- Recommend potential standards based upon project results, i.e., information models for the relevant data, database structures for common databases, functionality of software tools, interfaces between tools and other system elements.

The benefits realized from the ability to implement integrated tool kits for production system engineering will be applicable to a broad sector of manufacturing industry. Architectures and interface solutions will help manufacturer's to rapidly integrate commercial off-the-shelf software applications. Tool kit technology will help engineers become more productive and reduce the cycle required to develop new production systems. Integrated tool kits will also help engineers identify design errors, make better decisions and more quickly evaluate the effects of those decisions. By improving process specification and simulation capabilities, a much greater percentage of products will be produced correctly the first time. Better utilization of production resources may be expected. The best resources for the job will be selected more often and less time will be consumed by non-productive work, e.g., producing scrap and performing rework. Furthermore, the overall time to perform the engineering function will also be reduced if fewer changes to plans and programs are required once a product goes into production. These improvements will result in fewer scrapped parts and less re-work. The integration of software packages and common databases will ensure that less time is wasted re-entering the same data into multiple engineering tools.

2. BACKGROUND

Just as computer-aided design and engineering tools have revolutionized product design during the past decade, computer-based tools for production system engineering could revolutionize manufacturing. One of the major problems today is the lack of software integration--engineers need to move data between tools in a common computing environment. An unpublished NIST study of manufacturing and production engineering tools has identified more than 400 software products marketed today, all of which are largely incompatible with one another. Unfortunately, the interface and database standards do not currently exist that would enable the construction of integrated tool kits from these independently developed software packages. This document discusses industrial needs and suggests standards that could be established to facilitate the integration of engineering software applications.

A report from the DOD Manufacturing Systems Committee, i.e., "Manufacturing Systems Strategic Plan," suggests ways that the U.S. Department of Defense and industry can obtain major economic benefits. It recommends increased investment in 1) integration methodologies, 2) simulation and modeling, and 3) manufacturing-industrial engineering support tools. Engineering tools are used to increase productivity of engineers in virtually all aspects of design, analysis, process planning, manufacturing cost estimating, quality control, and maintenance. These tools are particularly useful in performing extremely complex tasks such as multi-variant design tradeoff studies.

The report also states that manufacturing support is estimated to cost DOD $24.7 billion annually. Manufacturing engineering functions represent an estimated $3.2 billion of these support costs. If manufacturing engineering costs could be reduced by only 10% annually, this would represent a $320 million/year saving to DOD. Additional savings could also be expected within the private sector. This project will focus specifically on improving the productivity of the manufacturing engineers through the development of prototype tool kits. As the results of this project are widely implemented, it is reasonable to expect that manufacturing engineering cost savings could easily exceed the 10% figure.

Tool kit environments are needed which integrate clusters of functions that manufacturing engineers use to perform related sets of tasks. Integrated production system engineering environments would provide functions to specify, design, engineer, simulate, analyze, and evaluate a production system. Some examples of the functions that might be included in an integrated production system engineering environment are:

- Identification of product specifications and production system requirements,
- Producibility analysis for individual products,
- Modeling and specification of manufacturing processes,
- Measurement and analysis of process capabilities,
- Modification of product designs to address manufacturability issues,
- Plant layout and facilities planning,
- Simulation and analysis of system behavior and performance,

- Consideration of various economic/cost tradeoffs of different manufacturing processes, systems, tools, and materials,
- Analysis supporting the selection of systems/vendors,
- Specification and procurement of manufacturing equipment and support systems,
- Specification of interfaces and the integration of information systems,
- Task and work place design,
- Handling of various organizational and personnel concerns, e.g. labor issues, human factors, health, safety,
- Compliance with various regulations, specifications, and standards,
- Planning for control of hazardous materials, and
- Management, scheduling and tracking of projects.

Examples of production systems which may eventually be engineered using this type of environment include transfer lines, group technology cells, automated or manually-operated workstations, customized multi-purpose equipment, and entire plants. The initial focus and test cases selected for this project are on small production lines used to assemble power tools.

The interoperability of the commercial engineering tools that are available today is extremely limited. As such, users must re-enter data as they move back and forth between different software applications carrying out the engineering process. Examples of the types of shared data under consideration by the collaborators for the common database includes:

- Production system requirements,
- Product specifications,
- Process specifications (diagrams, flowcharts, plans, routings, operation sheets, programs),
- Equipment specifications,
- Cost estimates,
- Budget spreadsheets,
- Project plans,
- Simulation models and model elements,
- Setup illustrations,
- Tooling,
- Plant layouts,
- Information models,
- Interface specifications,
- System descriptions,
- Estimated yield data,
- Process capabilities, and
- Quality data.

A long-term objective of the project is to improve the productivity of users by specifying interfaces that enable the creation of integrated environment where changes to data and decisions automatically flow seamlessly through the various software applications.

Collaborators on this project include users and vendors of production system engineering applications, as well as university researcher teams. Industrial collaborators include Black and Decker, Boeing, McDonnell-Douglas, Raytheon, and Litton Amecom. Data from the miter saw production line at Black and Decker Power Tools Plant in Fayetteville, NC is being used to define test cases and information requirements for integrating production system engineering software. Participating software vendors include Deneb Robotics, CimTechnologies, Promodel Corporation, Adra Systems, and Framework Technologies. Academic partners include: Ohio University, California Polytechnic University, Virginia Polytechnic Institute, Michigan Technological University, University of Maryland, Northeastern University, and Wichita State University. Government partners include U.S. Navy Manufacturing Technology Program, DOD Joint Strike Fighter (JSF) Program, and the Defense Systems Management College.

Other organizations and related efforts that the project is collaborating with, and/or is drawing technical information from, include:

- JSF Simulation Assessment Validation Environment (SAVE) Program,
- Lockheed Martin Corporation,
- ISO 10303 STEP product data standardization efforts (in particular STEP Application Protocol 227- Plant Spatial Configuration),
- NIST Advanced Technology Program Rapid Response Manufacturing Project (manufacturing resource data), and the
- NIST Design Engineering Program.

3. TECHNICAL APPROACH

The NIST focus for production system engineering is under the Production and PDM project within the SIMA Program. Other SIMA Program efforts are described in Barkmeyer (1995). The project will focus on providing the models, integrated framework, operating environment, common databases, and interface standards for a wide variety of emerging tools and techniques for designing manufacturing processes, equipment, and enterprises. 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 system engineering data, specify interfaces for integrating tools, develop prototype integrated environments and shared databases, and implement test case production system engineering projects. Prototype integrated production system engineering tool kits will be constructed from commercial products using proposed interface specifications. Solutions will be validated 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 implementation of new standards by industry.

The primary mechanism used to integrate software applications in the near term is file exchange. Information models for data to be exchanged will be developed using the EXPRESS modeling language, see ISO 10303-11 (1994). EXPRESS models are either obtained from the existing STEP standard, STEP parts currently under development, or NIST Initial Manufacturing Exchange Specifications (IMESs). From the EXPRESS models, STEP Part 21 will be used to define the format of data exchange files, see ISO 10303-21 (1996). 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 product data management (PDM) system according to an individual manufacturing user's business model. Manufacturing software applications would access, check in, and check out all exchange files using the PDM system interface.

A process model will be used to identify the functions involved in production system engineering and the data required to integrated engineering software applications. The process model defines the functions that tools must perform in order to engineer a production system. The model also defines inputs, outputs, controls, and mechanisms for carrying out the functions. The process model is a key reference for defining the data flows and interfaces.

The process model for PSE has been developed using Integrated Definition Method (IDEF0) modeling techniques and the Meta Software Design/IDEF ™ tool, see Meta (1994). The model defines the tool kit functions and data inputs/outputs for each function. Detailed information models are under being developed that further specify each data input and output identified in the process model. The information models are being used to implement shared-databases, exchange files, messages, and subroutine calls for passing information between the commercial software tools.

The top level of the model identifies the production system engineering function, its inputs, and its outputs. The next level of the model decomposes the engineering process into five major functions or activities:

1) Define the PSE problem,
2) Specify production processes required to produce the product,
3) Design the production system,
4) Model the system using simulation and evaluate its performance under expected operating conditions, and
5) Prepare plans and budgets.

Inputs to the production system engineering function include:

- Production requirements,
- Product specifications,
- Quality, time, and cost constraints, and
- Manufacturing resources.

Outputs of the function include:

- Process specifications,
- Simulation models,
- Performance analyses,
- System specifications,
- Implementation plans, and
- Budget spreadsheets.

Figures 1 and 2 illustrate the first two levels of the IDEF0 model. Further decomposition is beyond the scope of this document.

An initial, minimal set of specifications is envisioned which would enable the integration of functions contained within the PSE reference model. Some of the specifications will be developed as part of the production system engineering IMES efforts. Other specifications are being developed as standards or as a part of other SIMA program activities. The required specifications are:

- *production system requirements*,
- *product design*,
- *assembly process specification*,
- *plant layout*,

- *production resource models,*
- *production system evaluation,*
- *engineering management data, and*
- *PSE problem solving language.*

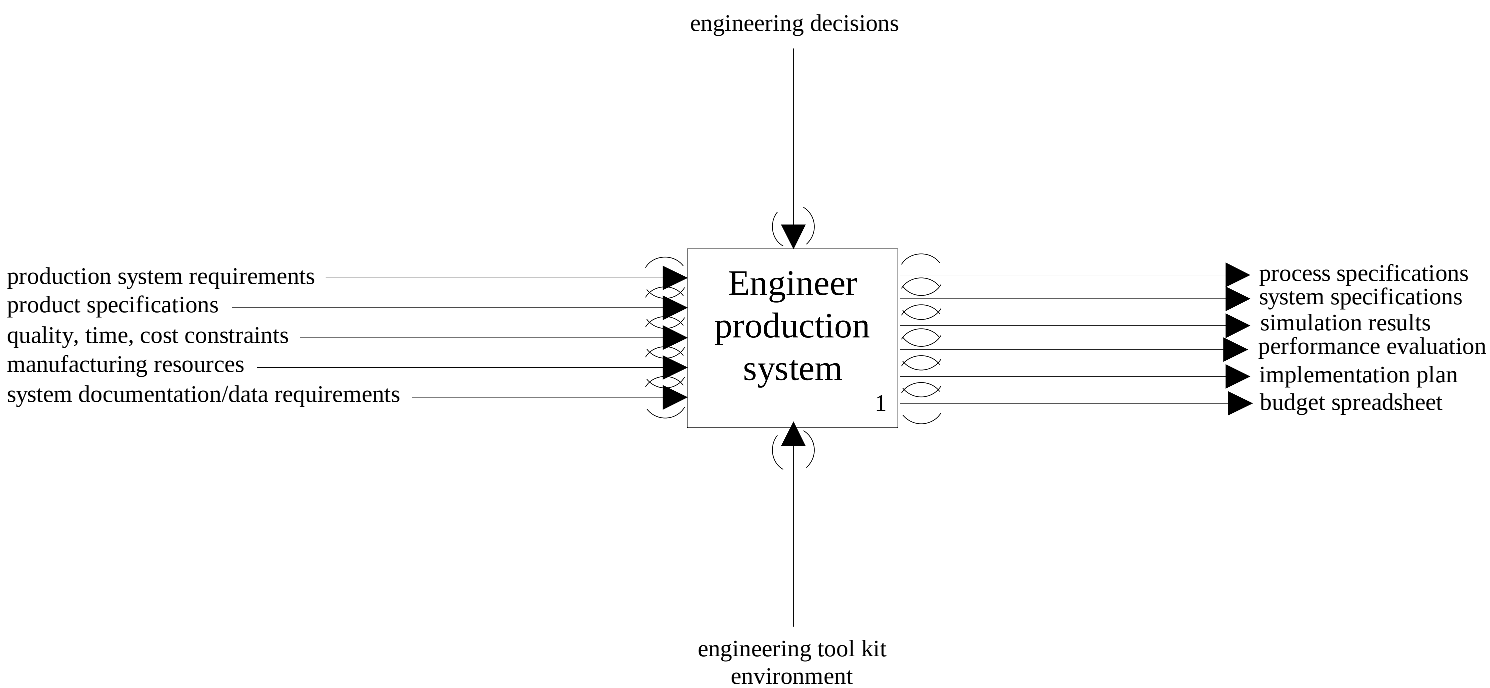

Figure 1 - Top level of the production system engineering IDEF model

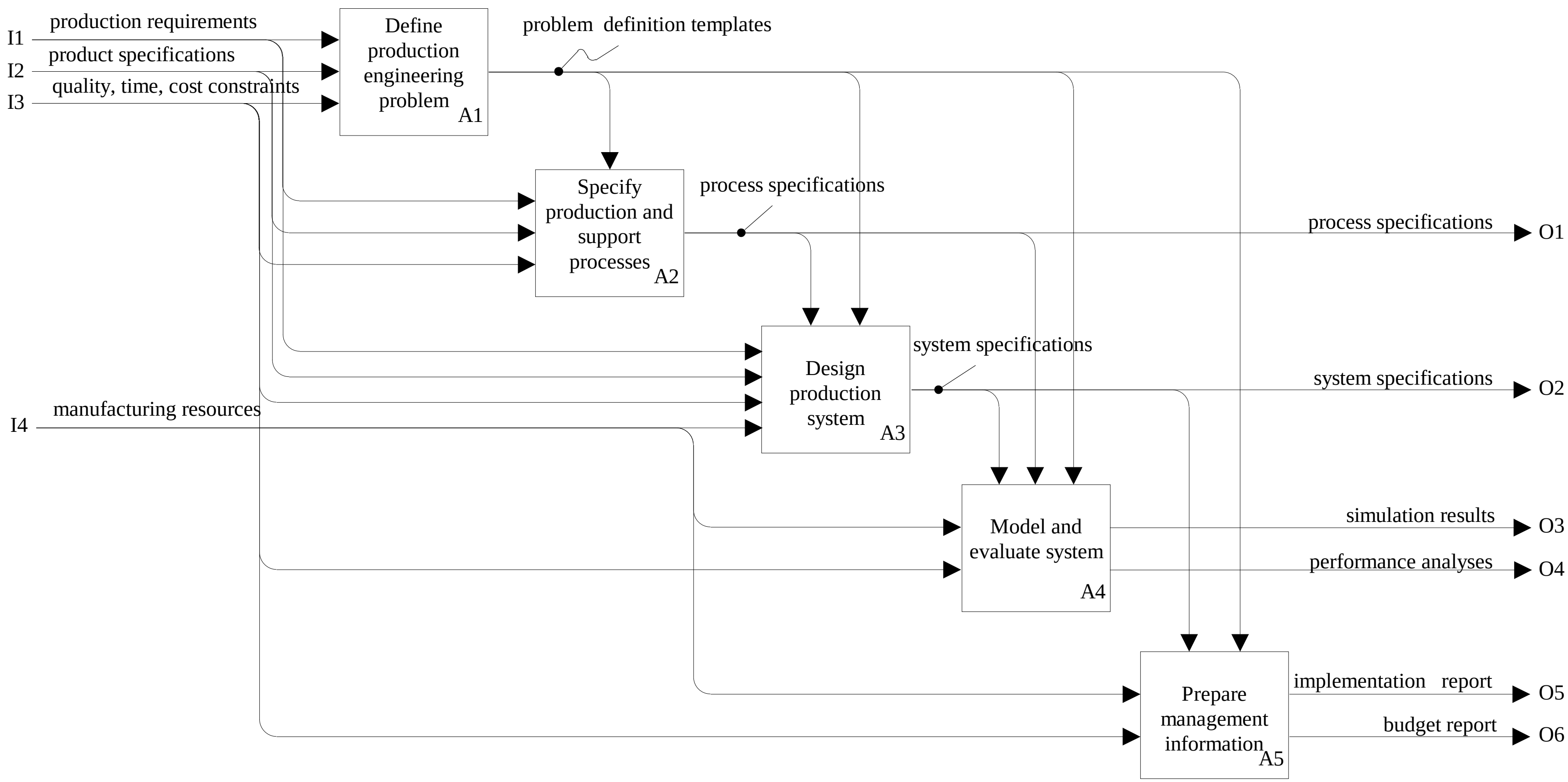

Figure 2 - First level of decomposition of the PSE model

brief description of each existing or proposed specification required to integrate PSE applications follows.

Production system requirements - This specification will describe a model for the information that is required to fully describe a production system engineering problem. It will define the constraints that characterize the production system that is to be designed. A standard model for production system requirement data will ultimately enable application developers to access common or shared databases that describe the intended system. Examples of required data includes:

- *Product data and key product attributes* - (also see Product Design below) product name, part number, model number, description, functionality, product structure (bill of materials), material composition, dimensions, weight, reference drawings, part geometry models, part family or group technology classification codes, technical specifications, reference documents,
- *Production system and engineering project type* - new production system (e.g., plant, line, cell), modification to existing system (i.e., product or process changes), relocation of system to new site, phasing out of a production system,
- *Manufacturing constraints and issues* - market forecast and production rates required (minimum, normal and peak production rates in units/hour, units/shift, units/day, units/year), production capacity, level of automation versus manual operation expected, information and control system requirements, target production site(s), floor space limitations, quality and yield requirements, safety stock requirements, storage availability, known environmental or safety hazards, production plant calendar,
- *Critical milestone dates and schedules* - (also see Engineering Management Data below) production ramp up plan, target dates for: system requirements specified, system design completed, requests-for-proposals issued, systems installed, testing completed, training completed, system operational, post production support, system phase out,
- *Expected or estimated costs* - product price, manufacturing cost, system implementation, operating costs,
- *Manufacturing data for related products* - production engineering data for this or previously manufactured products (in some cases all outputs from previous engineering projects), competitor products and sites, possible benchmarking sites.

Product design - These specifications are used to describe the product to be manufactured, components, production resources, and other physical objects within the production system itself. Product designs contain various types of data including: product structure or bill of materials, geometry, topology, tolerances, configuration management data. The specifications must provide neutral, common structures and information models for describing and accessing product data, e.g., ISO 10303 Standard for the Exchange of Product Model Data, commonly referred to as STEP. In developing solutions to integrate production system engineering applications, STEP is the preferred specification for representing product data. Initial Graphics Exchange Specification (IGES) and the file formats associated with specific CAD applications may also be used.

Assembly process specification - This specification will provide an interface for defining the product assembly process. Information contained within the process specification includes:

- *Process identification* - process step identifier, process name, process type (operation, storage, inspection, delay, transportation, information, or combined activity), process parameters,
- *Process resources* - input product components, output product (subassembly or part identifier), tooling and fixtures, staff and job skill requirements, process by-products and hazards,

- *Process time and costs* - process duration, estimated process cost, product value-added,
- *Process relationships* - sequence, precedence, and other relationships among processes.

Other process data that may be part of this specification includes:

- Activity relationship matrices are defined which describe how different processes relate to each other, e.g., required proximity or location.
- Specification of requirements for processes, tooling, job skills, timing and line balancing, quality control, process audits, production yield,
- Development of process and inspection plans, process description sheets,
- Development of time standards for operations,
- Ergonomic analyses of manual tasks,
- Value engineering analysis (i.e., determination of job activities/steps which can be eliminated).

Plant layout - This specification will define an interface for conveying manufacturing layout information between design and simulation software applications. Examples of information contained within layouts includes:

- Site or facility identification data,
- Drawing annotations,
- Dimensions and tolerances,
- Reference points,
- Location and orientation of process machinery (both two dimensional footprints and solid models),
- Material handling systems,
- Tooling,
- Fixture devices,
- Safety systems,
- Human ergonomic models,
- Work areas,
- Storage areas,
- Aisles,
- Building structural elements,
- Utilities and services, and
- Layer naming conventions within drawings and models.

The work done under ISO 10303 STEP AP 227 Process Plant Spatial Configuration will provide a basis for developing an application protocol specification for manufacturing plant layout, see ISO (1995).
Production resource models - This specification will define information models for representing production resources. It will identify the types of production resources and attributes required to support assembly. Production resources nominally include machinery, test systems, material handling devices and carriers, tooling, work holding devices, materials, and staff. These models must not only characterize the attributes of production resources, but also enable encapsulation of their geometry and behaviors to support simulation.

Specifications initiated under the NIST Advanced Technology Program Rapid Response Manufacturing Project in the area of manufacturing resource models will provide a foundation for the specifications needed in this area, see Jurrens (1995). The specifications developed under RRM will need to be extended to support additional data required to support assembly operations and construct manufacturing simulations.

Production system evaluation - This specification will define information models for representing the data applicable to the evaluation of the design of a production system. Examples of evaluation data include cost, performance measures, system reliability, safety, ergonomics, and timing data that is either associated with a particular production system or industry benchmark data used for reference and comparison purposes. Cost data may include: system design, engineering and construction costs, training costs, material costs, consumable costs, utility costs, unit production cost, touch labor cost per unit, estimated system maintenance costs. Performance measures include process yield, throughput, machine utilization, cycle time, work-in-process, and inventory turnover rates. Reliability data include machine downtime, mean-time-between-failures, and mean-time-to-repair systems. Safety data may include identification of processes and chemicals that are hazardous to employees, systems, or products. Ergonomic data identifies the level of physical effort and/or special physical abilities are needed to perform the production tasks.

Engineering management data - This specification will define the project management and cost data required to support the engineering of production systems. Project planning data includes: project phases, tasks, resources, and timing data (early/late start and end dates, estimated task durations, slack and float, and lead times.) Budget and cost data may include: project phase, planning, labor, tooling, capital equipment, projected maintenance, information and control system, operational, training, licensing and inspection, construction, installation, material (components, consumables), overhead (utilities, labor multipliers, area usage), and rental costs. Engineering management data will also reference and/or be associated with production system engineering data outlined in the models and interfaces that were previously described.

Production system engineering problem solving language - This interface would provide an application programmer interface by which different production system engineering applications could be made to inter-operate. The language would enable the representation of manufacturing/industrial engineering problems, definition of sub-problem initial and goal states, constraints on problem solutions, enable communication and interaction between different engineering domains, and the management/control of problem solving activities. The application programmer interface would define remote procedure calls to invoke functions within specific software applications. Integrating applications or expert systems could invoke the functionality within specialized applications to solve larger, multi-disciplinary problems.

4. INTEGRATION SCENARIO

This section provides a scenario describing the activities that would be performed in an integrated PSE environment. The scenario closely follows the IDEF model previously introduced. Each step in the process would normally be initiated by following the business model contained in a product data management system (PDM). Electronics documents would be checked in or out of the PDM system. The PDM system provides configuration control as well as data management functions. As each electronic document in the engineering process is completed, the data would be reviewed by the appropriate authority, and promoted to the appropriate release level to indicate that it is ready to be used in planning the assembly line. Notifications would be sent to the appropriate users. To simplify this scenario, discussion of the repetitive PDM-related operations have been omitted. The scenario is described in five steps.

a) *Define production-engineering problem* - The first step in engineering the production system is to clearly identify the problem that is to be solved. Problem definition data will influence how all of the other PSE functions are carried out. This activity is primarily one in which an engineer, or team of engineers, gather and organize data from a number of different sources. Typical sources for this data will include the product manager, other managers, the design team, sales and marketing, and manufacturing or production engineers who have worked on related products. Ultimately data gathered as a part of this activity would be recorded in the computer either using templates (data entry forms), imported from other software applications or databases, and maintained in a shared database, i.e., one that is accessible by all production system engineering software applications. Critical data (detailed in the previous section) which must be identified to initiate the engineering process includes: product data and key product attributes, production system and engineering project type, manufacturing constraints and issues, critical milestone dates and schedules, expected or estimated costs, manufacturing data for related products. With the exception of critical milestone dates, most of the information outlined above may be used in the next step in the scenario, i.e., the specification of production and support processes.

b) Specify production and support processes - The second major step is to develop a process specification for the production and support operations required to manufacture the product, see Tanner (1985), Salvendy (1992), and Sule (1994). An assembly process specification for the assembly line is developed using a process specification tool, e.g. flowcharting or process modeling system. Process work elements, their relationships to each other, operator skill types, work locations, processing/delay times, and tools are identified in the assembly process specification. Data developed during this step will ultimately take the form of process flowcharts that show the sequential relationships between process operations. Nodes in the flowcharts will contain attributes that identify processes to be performed as part of production and their parameters. Attributes may also refer to product specification and problem definition data.

Design data and prototype product models are analyzed to develop assembly process specifications. An assembly precedence structure chart is developed from the product geometry data and bill of materials. From the precedence structure, processes and processing precedence constraints may be derived. The derivation process may be based on human experience and intelligence, or implemented as a rule-based expert system. Data developed during this step in the process (and detailed in the previous section) includes process identification, process resources, process time and costs, process relationships.

This process is recursive--high level processes are decomposed into sub-processes until all basic or primitive operations are specified. Constraints on groups of processes and operations are identified and precedence relationships are specified. Process specifications may be represented as diagrams and/or tables. Graphical editing functions and human interaction are normally required to layout diagrams in an understandable form. Large diagrams may be unwieldy and should be decomposed into multiple levels of sub-diagrams.

Alternate processing scenarios may also be defined which describe how production will be carried out before, during, and after the new production system is implemented. Process specifications next must be reviewed and revised to correct errors, inconsistencies, etc. As the system design is developed in the next step of the scenario, feedback may be provided indicating required changes in process specifications or the problem definition.

c) Design production system - The next step is to design the production system, e.g., assembly line that will manufacture the product. This activity may include equipment design and/or selection, layout of systems. Systems include the physical processing systems, material storage and delivery systems, and information management/control systems. Computer-aided design, modeling, or plant layout software is typically used to perform this step. The production system design problem is addressed in Sule (1994). The mechanical assembly system and flexible manufacturing system problems are described, respectively in Nevins (1989) and Draper (1984). Facility layout is presented Apple (1977) and Francis (1992). Manufacturing system architecture, design, and specification development processes are defined in Rechtin (1991), Bertain (1987), Rembold (1993), Compton (1988), and Purdy (1991).

A generic decomposition of production system design is:

1) Identify system (e.g., equipment) requirements for each process,
2) Assign requirements to system modules,
3) Develop system operating scenarios for the modules,
4) Identify candidate systems, machines, and tooling for each module,
5) Evaluate alternative technologies and candidate offerings,
6) Determine number of systems required based on processing cycle time and required throughput,
7) Conduct system build or buy analyses,
8) Select systems for acquisition, and
9) Develop detailed design for overall system based upon build and buy decisions.

The design process can also be viewed in terms of the specific types of systems involved, i.e., process, logistics support, and information. The remainder of this scenario step briefly summarizes considerations associated with the design of each of these elements in an overall production system. The design of the processing system involves: the selection of a hierarchy of processing systems to implement the modules (including plants, centers, lines, cells, stations, equipment, devices, and tooling), assignment of processes to the systems, estimation of resource utilization levels, and balancing of production systems.

The design of the logistics systems can be divided into two related problems: production material logistics and plant logistics. Production material logistics includes: packaging design, determination of production material requirements (raw materials, components, packaging, carriers), estimation of consumption rates, replenishment rules, frequency of deliveries, determination of source selection strategies (make-or-buy analyses and supplier selection), lead times, and shipping (air/land/sea) methods for source materials.

Plant logistics concerns the systems that move and store materials within the facility. Plant logistics involves:

- Determination of floor space and volumetric requirements for each process/machine/system,
- Identification of production and tooling material storage requirements (i.e., loading docks, staging areas, centralized storage areas, line side storage), selection of storage systems (i.e., automated storage and retrieval systems, manual storage systems, production line buffers and feeders),
- Specification of material flow through the facility (i.e., raw materials, components, work-in-process, and finished goods from the dock to lines through lines and back to dock),
- Selection of material handling systems (e.g., hand truck, fork lift, conveyor, AGV),
- Determination of stock replenishment strategies, design of safety and environmental systems,

- Development of physical plant layout in two and three dimensions, and
- Evaluation of logistic system for production capacity growth capabilities.

Production information systems may include:

- Monitor and control systems,
- Communications,
- Display and user interface systems,
- Database management systems and their databases,
- Data collection systems,
- Production information systems,
- Peripheral devices (e.g., printers, magnetic scanners, monitors, bar code readers, RF scanners and readers, infrared tracking systems),
- Production accounting and reporting,
- SPC/SQC systems,
- Time and attendance recording,
- Payroll and financial systems,
- Inventory control,
- Energy management,
- Tool management,
- MRP/ERP systems,
- Shop floor control, and
- Preventive/corrective maintenance support systems.

The information systems design activity includes: requirements specification, architecture development, process and information modeling, detailed design, interface specification, integration and test planning, and user documentation development.

The outputs of the production system design are detailed system specification documents. The data resulting from the design process will ultimately be captured in the form of layouts which define the logical and physical location of systems, their orientation, and the paths by which material and information flows between them. The next step in the scenario is the modeling and evaluation of the system design.

d) Model and evaluate system - Once a design, or partial design, for the production system is specified, it can be modeled and evaluated using simulation technology. The purpose of this step is to better understand the dynamics of the proposed system and help ensure that it satisfies the constraints outlined in the problem definition. Pegden (1990), Askin (1993), and Carrie (1988) describe the simulation modeling process. Knepell (1993) describes the evaluation and validation of models.

The first step in developing a simulation model for the system is to define a problem statement and simulation objectives, i.e., what will be learned from the simulation model. The types of alternative models to be considered and constructed need to be identified, e.g., discrete event simulation, material flow, system mechanics and kinematics, ergonomic, and/or manufacturing process. Appropriate simulation tools must be selected based on the types of models to be constructed. Next, system performance measures must be identified.

System simulation model elements and their behaviors must be specified. Model elements used will depend on the types of simulations to be constructed. Elements of these models may include the attributes associated with: manufacturing resources, servers, queues and selection criteria, work pieces/loads/objects, arrival distributions, processes, system movements and material flows, timing distributions, failure and repair rates, etc. The information needed to derive the model elements will be drawn from problem definition, process specification, and system design data. The actual simulation models may then be constructed using the selected simulation tools.

Another critical activity in modeling and evaluation is the development of test data for simulation runs. This activity includes: identification of data sources, gathering of test data, formatting and loading the data, and determining the number of simulation runs required to produce significant results. Once the simulation has been constructed and the test data has been loaded, the models can be run and evaluated.

The simulations must be validated, i.e., it is necessary to determine whether results are believable based on experience, other data, etc. There are two aspects to this problem: 1) does the simulation program behave as expected and 2) does the outcome reflect reality? If the results are not correct or creditable, either the simulation must be fixed, models modified, or the test data may need to be changed. Some examples of evaluations that may be performed on the results include: verification of the accuracy of model, analysis of errors and failures, bottlenecks, throughput, flow time, expected yields and quality, interference problems, collisions, etc.

After the results of the simulation are reviewed, it may be necessary to revise design specifications and the system models, process specifications, or even basic assumptions spelled out in the problem definition.

e) Prepare management information - Another step in the production system engineering scenario, which may go on concurrently with the other steps, is the development of engineering management data. Activities within this step include development of project plans and schedules, preparation of budgets, establishment of configuration management controls, and generation of reports. Project management and budgeting is described in Kerzner (1984).

Project planning involves defining the PSE project in terms of: phases, tasks, resources, and timing data. Possible phases may include: feasibility study, planning, needs and requirements analysis, detailed design, acquisition and installation, testing, training, pilot and full production operation, and phase out. Critical milestones are identified as part of the phase definition activity.

Each major project phase is specified in terms of tasks and sub-tasks. Task precedence constraints and overlap options are identified. Required resources associated with each task are identified. Staff responsibilities are specified on each task. Resource balancing may be required. Timing information is also estimated for each task, including expected or required start, end dates, estimated task durations and lead times. From this data, schedules may be generated and critical paths determined.

Cost factors and their analysis is an extremely important part of the system design and implementation process. Malstrom (1984) provides detailed guidance on manufacturing cost engineering processes that can be used to develop cost estimates and budgets. The budgeting process includes: gathering of cost data, entering data into spreadsheets or databases by budget categories, projecting estimates where data is unavailable, generating summaries by categories, and producing budget reports. Budgeting data is reviewed for significant deviations from targets and opportunities for savings are identified. Budget data is then used to generate feedback, if required, to reconsider the problem definition and/or the production system design.

Another critical activity included in this step is the configuration management of engineering data and project documents. Product data management systems provide many of the functions necessary to carry out this activity. Principles of configuration management are outlined in Daniels (1985). This activity includes: identification of key documents, definition of revision control-review-promotion policies and procedures, identification of organizational responsibilities, establishment of notification procedures for project staff, establishment of security policies and access control mechanisms, and the placement of documents and data under configuration management.

The final activity in the management area is generation and publication of reports that summarize the results of each of the other steps. Reporting functions include: outline development, document editing and assembly, layout and formatting, and printing.

Once plans, budgets, configuration management policies, and reports are completed they need to be reviewed to ensure that they are realistic and meet the requirements established in the problem definition step. If not, either the plans need to be changed or information must be fed back to problem definition and/or system design to re-scope the system.

5. Conclusion

If manufacturing industry is to remain competitive, it must not only continue to improve its products and offer new ones. It must also strive to continuously improve its engineering processes and production systems. There are major opportunities to better utilize information technology in the design and implementation of manufacturing systems. This document has identified industrial needs and identified interfaces to address those needs.

The development of interface specifications and standards enabling the integration of production system engineering applications could have a major impact on reducing the time and costs involved in bringing new products to market. Standard interfaces would help to formalize the production system engineering process and turn what is now more often an art, into a science. Seamless interoperation of plug-compatible software applications developed by different vendors could become a reality, thereby reducing software integration costs. Reduced integration costs would open the market for these products to a greater number of small and medium-sized manufacturers.

Standardization of several major types of information will be necessary to achieve this goal, namely:

- *production system requirements,*
- *product design,*
- *assembly process specification,*
- *plant layout,*
- *production resource models,*
- *production system evaluations,*
- *engineering management data, and*
- *PSE problem-solving language.*

These standards can only be achieved through the cooperation of software vendors, industrial users, researchers, and standards organizations. The Initial Manufacturing Exchange Specifications (IMES) documents developed by the Systems Integration for Manufacturing Applications (SIMA) Program at NIST will establish baseline interfaces and help fast track the development of these standards. Subsequent IMES documents will document requirement analyses and specifications of individual interfaces and models which were initially identified in this document.

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 that 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.

Production System Engineering (PSE) – The process of design and engineering of system to produce discrete products.

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.

REFERENCES

Apple, J.M., (1977) *Plant Layout and Material Handling*, John Wiley and Sons, New York, NY.

Askin, R.G., Standridge, C.R. (1993) *Modeling and Analysis of Manufacturing Systems*, John Wiley and Sons, New York, NY.

Barkmeyer, E.J.,[ed.] (1996),: “SIMA Reference Architecture, Part 1: Activity Models,” NISTIR 5939, National Institute of Standards and Technology, Gaithersburg, MD, 1996.

Barkmeyer, E.J., Hopp, T.H., Pratt, M.J., Rinaudot, G.R., editors (1995) *Background Study: Requisite Elements, Rationale, and Technology Overview for the Systems Integration for Manufacturing Applications Program*, NISTIR 5662 National Institute of Standards and Technology, Gaithersburg, MD.

Bertain, L., Hales, L. (1987) *A Program Guide for CIM Implementation*, Society of Manufacturing Engineers, Dearborn, MI.

Carrie, A. (1988) *Simulation of Manufacturing Systems*, John Wiley and Sons, Chichester, Great Britain.

Compton, W.D., editor (1988) *Design and Analysis of Integrated Manufacturing Systems*, National Academy Press, Washington, DC.

Daniels, M.A. (1985) *Principles of Configuration Management*, Advanced Applications Consultants, Rockville, MD.

Draper Laboratory Staff (1984) *Flexible Manufacturing Systems Handbook*, Noyes Publications, Park Ridge, NJ.

Francis, R.L., McGinnis, Jr., L.F., White, J.A. (1992) *Facility Layout and Location: An Analytical Approach*, Prentice-Hall, Englewood Cliffs, NJ.

ISO 10303-11 (1994). *Industrial automation systems and integration - Product data representation and exchange - Part 11: Descriptive methods: EXPRESS reference language manual*, ISO, Geneva, Switzerland.

ISO 10303-21 (1996). *Industrial automation systems and integration - Product data representation and exchange - Part 21: Implementation Methods: Clear text encoding of exchange structure*, ISO, Geneva, Switzerland.

ISO/CD 10303-227 (1995). *Industrial automation systems and integration - Product data representation and exchange - Part 227: Application Protocol: Plant Spatial Configuration*, ISO, Geneva, Switzerland.

Jurrens, K.K., Fowler, J.E., Algeo, M.E.A. (1995), “Modeling of Manufacturing Resource Information: Requirements Specification,” NISTIR 5707, National Institute of Standards and Technology, Gaithersburg, MD.

Kemmerer, S. (1997), “Initial Manufacturing Exchange Specification (IMES): IMES Concept Document For Manufacturing Systems Integration,” Draft NISTIR, National Institute of Standards and Technology, Gaithersburg, MD (in review).

Kerzner, H. (1984) *Project Management: A Systems Approach to Planning, Scheduling, and Controlling*, Van Nostrand Rheinhold, New York, NY.

Knepell, P.L. and Arangno,D.C. (1993) *Simulation Validation: A Confidence Assessment Methodology*, IEEE Computer Society Press.

Leong, S.and Smith, M. (1996): "Computer - Aided Manufacturing Engineering Forum 2nd Technical Meeting Proceedings," NISTIR 5846, National Institute of Standards and Technology, Gaithersburg, MD.

Malstrom, E.M. (1984) *Manufacturing Cost Engineering Handbook*, Marcel Dekker, NY.

McLean, C.R. (1993) "Computer-Aided Manufacturing Systems Engineering" in *IFIP Transactions B-13 Advances in Production Management Systems*, North-Holland, Amsterdam, Netherlands.

McLean, C.R. and Leong, S. (1995): "A Process Model for Product System Engineering," Proceedings of the IFIP WG 5.7 on Production Management Systems, Seattle, WA.

Meta Software Corp. (1994), *Design/IDEF User's Manual and Tutorial For Microsoft Windows*, Meta Software Corp., Cambridge, MA.

Nevins, J.L., Whitney, D.E., (1989) *Concurrent Design of Products and Processes: A Strategy for the Next Generation in Manufacturing*, McGraw-Hill, New York, NY.

Pegden, C.D., Shannon,R.E., Sadowski,R.P. (1990) *Introduction to Simulation Using SIMAN*, McGraw-Hill, New York.

Purdy, D.C. (1991) *A Guide to Writing Successful Engineering Specifications*, McGraw-Hill, New York, NY.

Rechtin, E., (1991) *Systems Architecting: Creating and Building Complex Systems*, Prentice-Hall, Englewood Cliffs, NJ.

Rembold,U., Nnaji, B.O., Storr, A. (1993) *Computer Integrated Manufacturing and Engineering*, Addison-Wesley, Wokingham, England.

Salvendy, G., editor (1992) *Handbook of Industrial Engineering*, John Wiley and Sons, New York, NY.

Smith, M. and Leong, S. (1995): "Computer-Aided Manufacturing Engineering," NISTIR 5699, National Institute of Standards and Technology, Gaithersburg, MD.

Sule, D.R., (1994) *Manufacturing Facilities: Location, Planning, and Desig*n, PWS Publishing Company, Boston, MA.

Tanner, J.P. (1985) *Manufacturing Engineering: An Introduction to Basic Functions*, Marcel Dekker, New York, NY.