Manufacturing Enterprise Systems

A White Paper

by the Object Management Group's

Manufacturing Special Interest Group

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Acknowledgments

The Object-Oriented Manufacturing Systems White Paper is the collective work of the Manufacturing Special Interest Group (Mfg SIG) of the Object Management Group (OMG)—now the Manufacturing Domain Task Force (Mfg DTF). The members of the Mfg SIG who have contributed to this white paper are:

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PREFACE

Intended Audience

The intended audience of this paper consists of Object Management Group (OMG) members, representing the majority of object technology suppliers. The purpose of targeting this group is to obtain information about feasible application architectures and system designs that meet the manufacturing requirements as outlined in this white paper. Technical and managerial staff within the industry who are interested in learning more about Manufacturing Special Interest Group activities have also been targeted.

What Is an OMG Special Interest Group?

A Special Interest Group (SIG) is composed of OMG members with a general interest beyond the immediate goals of the Technical Committees (TCs). Typically, a SIG is formed to explore specific technology areas and generate OMG discussion documents for public review. A SIG is not an "OMG standards" body. By OMG charter, a SIG cannot issue Requests for Proposals (RFPs) nor can it develop specifications. It can, however, issue white papers (such as this one), conduct surveys to gather requirements, and make technical recommendations to OMG Task Forces. A SIG can also petition the Domain Technology Committee (DTC) to be recognized or transition to Task Force status.

What Was the Manufacturing Special Interest Group?

The OMG Manufacturing SIG was chartered as a forum for ensuring the consideration of manufacturing vertical market (industry specific) requirements in the evolution of OMG technologies. At the OMG Technical Committee meeting in January, 1996, the Mfg SIG became the Manufacturing Domain Task Force (DTF).

Charter and Goals of the Manufacturing Domain Task Force

The mission of the Manufacturing Domain Task Force, adopted in January 1996, is to "foster the emergence of cost-effective, timely, commercially available and interoperable manufacturing domain software components through CORBA technology."

The goals of the Task Force are:

- Recommend technology for adoption that enables the interoperability and modularity of CORBA-based manufacturing domain software components.

- Encourage the development and use of CORBA-based manufacturing domain software components, thereby growing the object technology (OT) market.
- Leverage existing OMG specifications.
- Recommend liaison with other appropriate organizations in support of the previous goals.

Scope of the Manufacturing Domain Task Force

"Manufacturing" entails an extensive range of subject areas related to the entire lifecycle of products, from development through production and beyond to product support and re-manufacturing or recycling. The activities of the Manufacturing DTF will attempt to address all of those aspects of manufacturing.

Problems the Manufacturing Domain Task Force is Addressing

Historically, manufacturing systems architectures were characterized as inflexible, centralized, monolithic and (at least partly) proprietary systems. Their design rendered them incapable of rapidly responding to changes in enterprise aspects such as process definitions, customer orders, inventory or product design. Thus, manufacturing systems have often become an impediment within a production facility to make changes quickly in response to some demand, be it customer or market driven.

The set of problems that the Manufacturing DTF is addressing are those which prohibit manufacturing system architecture design from overcoming this impediment. The problems occur from inefficient or deficient design and implementation of systems which cannot fully meet customer requirements.

In addition to a need for quicker response, manufacturing has other unique requirements. For example, performance requirements. The flow of information in some aspects of a manufacturing system (those dealing specifically with product manufacture) must occur in real time. This issue of timeliness surfaces at even a higher level as the business climate requires that all aspects of manufacturing systems become more agile (timely reconfiguration to meet new production demands).

Another problem in designing manufacturing systems is supporting shorter product cycles despite more complex manufacturing processes, more specialized product processes, leaner production strategies and the need for more information throughout the enterprise.

Manufacturing systems also present their own set of integration problems. For instance, ensuring that manufacturing systems "couple" factory equipment with the human part of the factory as well as the business systems.

Manufacturing DTF Plans for Solving These Problems

The OMG's goal is to promote the development of object-oriented technologies that will support distributed, interoperable applications. The Manufacturing DTF, as representative of industry manufacturing system groups, recognizes that the OMG technologies will play a key role in the design of future manufacturing systems. It is the DTF's goal, therefore, to assist in the development of OMG technologies through ensuring that industry requirements are addressed in all relevant OMG technology specifications.

The Manufacturing DTF can also serve as a channel back to the industry in recommending and providing educational material that helps the industry migrate to object technology.

This white paper is the fulfillment of the Manufacturing SIG's (the predecessor to the Domain Task Force) near-term plan to provide a mechanism for identifying industry issues and requirements. Requests for Information (RFI) and Requests for Proposals (RFP) will be derived from responses to this white paper, leading to the adoption of relevant technology specifications.

The Manufacturing DTF's plans will be further defined in a Manufacturing DTF Roadmap document. These plans are likely to include:

- Issuance of other white papers to explore manufacturing requirements in greater detail.
- Issuance of RFIs or RFPs covering specific areas, such as Product Data Management, or soliciting information on frameworks used to construct manufacturing systems.
- The development of an Object Model for manufacturing.

Participation in the Manufacturing DTF

Your participation is needed. For more information on the Manufacturing DTF, send a message to <request@omg.org>. In addition, there are several ways to obtain information on how to become a member of the OMG.

- You can send an e-mail message to <membership@omg.org>
- You can contact the OMG via the world-wide web (WWW) at <http://www.omg.org>
- You can contact the OMG by mail, telephone or facsimile at:

  Object Management Group
492 Old Connecticut Path
Framingham, MA 01701, USA
Phone: +1 (508) 820-4300
FAX: +1 (508) 820-4303
- You can enroll in the Manufacturing DTF's electronic mailing list by sending a message requesting this to <request@omg.org>. Once this is done, you can reach all other members of the list by sending messages to <mfg@omg.org>.

1. PAPER OVERVIEW

The goal of this white paper is threefold:

- Provide the OMG community with a *high-level* description of manufacturing systems, so that they can discuss the use of object technology with the developers and users of manufacturing and enterprise systems in a more informed manner.
- Preview special requirements from the manufacturing applications domain that the OMA infrastructure architects may find useful as they consider further developments, including the selection of additional CORBAservices and CORBAfacilities.
- Identify areas in which manufacturing applications may not be adequately or sufficiently supported by the current OMG specifications.

To achieve the above goals, the paper begins by defining a base model of a generic manufacturing enterprise. Although each industry has its own particular concerns, the base model is common at a sufficiently high level of abstraction. The base model includes a description of the product manufacturing process itself and of the organizational structures that support it.

From this generic manufacturing model, a list of *functional system requirements* is extracted that covers the various manufacturing applications and their interaction with the rest of the enterprise systems. The paper then focuses on the *system requirements* relevant to the implementation of these applications within a computing infrastructure. This establishes a context that allows us to discuss the concepts and several examples of application architectures. Finally, a high-level architecture for manufacturing systems will be presented with the intent of providing a common reference for all further Manufacturing DTF activity.

The white paper will have achieved its purpose if it fosters discussions of object technology requirements between three communities: object technology suppliers, manufacturing application developers, and manufacturing application users. However, the white paper does not include enough detail to lead directly to the generation of new specifications. To achieve this goal, additional work will be required. The OMG Manufacturing DTF envisions Requests for Information (RFIs) to acquire more information about potential directions.

2. HIGH LEVEL REQUIREMENTS

This chapter will discuss, at four successive levels of detail, the requirements that apply to a manufacturing enterprise:

- In Section 2.1, we discuss the high-level *challenges* that place pressure on enterprises, and how companies focus on some specific business strategies to respond to these pressures.
- In Section 2.2, we present a high-level manufacturing enterprise model, which provides a framework for a number of enterprise *processes*.
- In Section 2.3, we move to the "solution space" by giving examples of *manufacturing solutions* commonly used to package and deliver support for the enterprise process.
- In Section 2.4, we move beyond the part of the architecture that is visible to the end user, and address the information system *infrastructure* requirements which information systems personnel must meet to provide viable solutions.

2.1. The Overall Manufacturing Environment

2.1.1. Current Environment

Successful businesses understand customer needs, they develop product to meet customer needs, and they bring product to the market quickly, *priced for value*. These successful businesses are able to convince users that their product will improve their productivity, quality and profitability.

These successful businesses manage to do this at a time when global competition is more ruthless and unforgiving than ever before. In fact, they sometimes achieve success by cooperating with these competitors through the formation of Virtual Enterprises.

Businesses not only need to be ready for change, they must be adaptable and flexible, striving for continuous improvements. It is uncomfortable but necessary.

2.1.2. Business Challenges

A major business challenge for large enterprises is to achieve the proper level of decentralization; that is, to assign responsibility and decision-making to the appropriate level, so that decisions can be made quickly and accurately. In a large corporation, the corporate level and the divisional level play a peer role to assist the business units when and where they need it:

- The re-engineering required to achieve dramatic results (e.g., the introduction of concurrent engineering) requires cooperation and teamwork across organizational boundaries. Therefore, the commitment to these changes must be made at an executive level.

- It should be possible to apply change at individual business units, eventually adding up to the entire company, but it may take longer and be more expensive to achieve a continually improved business in that manner.

Another business challenge is to integrate the manufacturing processes and information with the other business processes. Many manufacturing environments consist of a suite of disparate applications that manage different business functions. These application services are usually created in a vertical fashion, and coexist side by side without horizontal integration between services. This means that similar information may be managed redundantly and incompatibly by several applications written for different purposes (e.g., shop floor control versus order entry). In order to run a business well, information must be shared and flow smoothly between business processes.

Time-to-market, global competition, continuous improvement, decentralization and the integration of business processes and information lead to one common underlying business initiative: the management of change. Companies must continually transform themselves to meet and address these challenges and initiatives. Change must be applied to the resources or areas of impact at the companies' disposal.

Successful businesses must understand how to respond to the tough questions posed by the following five focus areas. Each of these focus areas can be looked at as interdependent components of an overall business strategy. Although this white paper focuses on the requirements for technology, it is important to understand the challenges contained in each of these focus areas before going into the detailed requirements.

- **Time Management**
  - Introduce new products (and improvements to existing products) into the market more quickly, i.e., reduce the product cycle time.
  - Attain useful cycle time measurements to apply towards cycle time reduction.
- **Resources**
  - Effectively allocate materials, equipment and people to the right processes and tasks.
  - Attract and retain people with the right skills and qualities, then apply them to interesting and challenging problems (applying good people to invalid activities does not improve product development). Establish long term goals for employees, so that they are in line with the company's vision and work as a team to attain the business unit's goal. Provide continued education and training to maintain the quality of the work force.
- **Business Activities or Processes**
  - Effectively coordinate and manage the company's activities.
  - Use process automation, if applicable, to make increasingly complex activities more manageable in spite of that complexity.
  - Look for and implement continuous process improvement.
  - Develop and conduct the process measurements to understand each activity's cost. Continuously monitor whether every activity add value to the product.

- **Technology**
  - Determine the right level of automation that should be applied to business processes.
  - Define the best technologies to use or develop.
  - Support standard interfaces that allow access to all required applications, data, and operating environments. Determine the level of compatibility and integration required.
  - Apply a long-range vision to technology and tool usage.
- **Regulations**
  - Manage and track compliance with a variety of environmental, health, safety and consumer information statutes. Manufacturing companies in particular are faced in many countries with strict requirements that include hazardous material ("hazmat") tracking, chemical industry regulations, government and local regulations concerning the control and monitoring of emissions and exposure to various products.

2.1.3. Business Strategies

As a way to respond to these challenges, businesses develop strategies to guide the introduction and application of specific solutions. Six such strategies are listed below. These strategies are not exclusive of one another, and most businesses implement several of them simultaneously. Conversely, a given business may not implement all these strategies, some of which are quite dependent on particular business or social cultures.

- **Concurrent Engineering (CE)** primarily involves the use of a cross-functional team (including representatives from key suppliers and customers) to work jointly on product and process design. Concurrent engineering is necessary to achieve the kind of customer focus, high quality, low cost, and quick time to market that constitute world class performance today.

  The traditional approach to the product lifecycle was defined, in theory, as a sequential development methodology. Upon completion of each step, the product is often "thrown over the wall" to the next group. This serial process is time consuming, and defects are often introduced at the boundaries between successive processes.

  Instead, in the concurrent engineering approach, work is processed by a multi-disciplinary team which shares a common, high-level goal to achieve a defined result with respect to the product. Concurrent engineering implies not only that activities overlap in time – it also implies that organizational boundaries are blurred. Product change requests are handled simultaneously by the various members of the team from the viewpoints of marketability, cost, engineering feasibility and manufacturability. By involving key people earlier in the cycle, the overall cycle can be shortened and the time to market can be reduced.

- **Virtual enterprises** constitute another strategic response to the requirement for greater global competitiveness. A virtual enterprise is a temporary consortium of companies that come together quickly to explore fast-changing opportunities. Within the virtual enterprise, companies share costs, skills, and access global markets with each participant contributing its core competence. In many ways, this is an extension of the concurrent engineering strategy.

A virtual enterprise can only function (and manufacture products in particular) if it provides all personnel with ready access to the information they need, without having to duplicate this information every time it crosses a company boundary. Furthermore, this needs to be accomplished in a heterogeneous hardware and software environment.

- **Just-in-time (JIT)** is the elimination of waste in all business activities. JIT is a key to fast-cycle manufacturing, customer responsiveness, high productivity, and high return on investments. JIT production is typically implemented using a “kanban” system. A kanban is a sign (which may be as simple as a colored box, a metal tag on a parts container, or a computer-printed bar code or ticket) used to indicate the readiness of a part for processing.
- **Cost management** involves the use of activity-based costing (ABC) principles to more accurately determine the cost of products and services. ABC systems are based on two key assumptions: activities cause costs by consuming resources, and products (and services) create demand for activities. The first stage of ABC systems assigns the expenses of support resources to the activities performed by these resources. In the second stage, activity costs are assigned to products based on the individual products’ use of each activity. For example, the expenses of issuing engineering change notices are first assigned to the activity “Product Specification Change.” Then the expenses of this activity are assigned to products based on the number of change notices issued for that product. In this way, a product which undergoes more engineering changes would have more expenses assigned to it.
- **Total Quality Management (TQM),** formerly Total Quality Control (TQC), is first an attitude about quality, in addition to the application of proven quality initiatives to the design of products, processes and services. TQM includes the use if quality tools such as quality function deployment, Taguchi methods, and statistical quality control (SQC), among others. TQM is necessary to achieve today's world class quality standards of less than 50 defective parts per million.
- **Business Process Reengineering** consists of extensive modeling efforts that are focused on the sequence of events that lead to the development and delivery of a company’s products and services. Many companies are involved in such an effort today. The above sequence of events or tasks are often given the term “business processes,” hence the term “Business Process Reengineering.” Focusing on the sequencing and timing of these events allow a company to eliminate unnecessary dependencies between tasks and therefore shorten their time to market.

2.2. High-Level Manufacturing Enterprise Model

An Enterprise Model can define an enterprise in terms of its functions, resources, processes, products, data requirements and constraints. In the manufacturing enterprise, this model defines a unique set of business processes that are performed to design, plan, produce and market the enterprise’s products.

The Manufacturing Enterprise Model is a general description. There may be many unique variations to the model. Some enterprises may not require all functions, while others may require more functions than those described in the generic model. Figure 1 depicts how a Manufacturing Enterprise Model can be presented in a way that is independent of the type of product being manufactured:

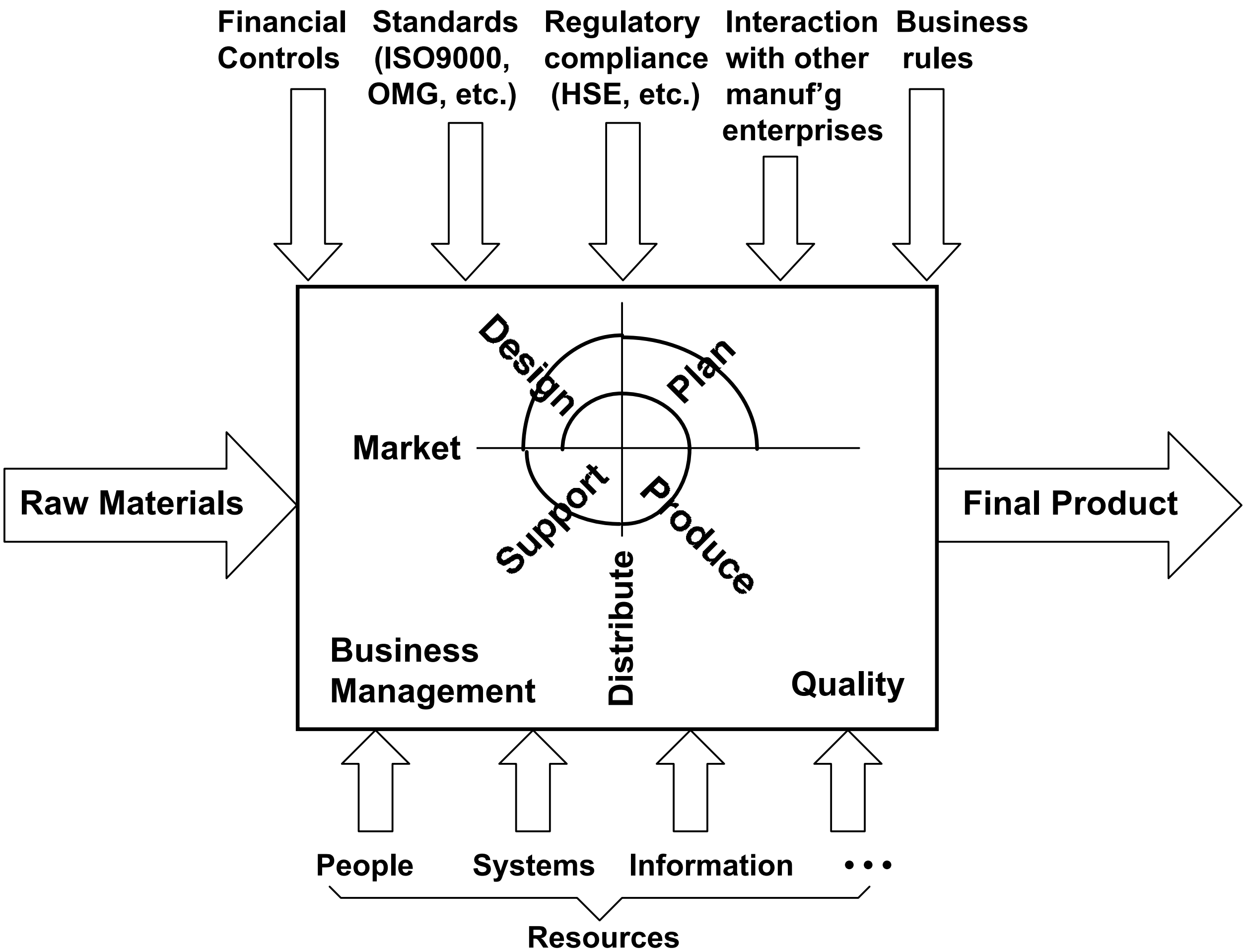

Figure 1. Manufacturing Enterprise Model

The formalism used is that of the SADT or IDEF methodologies: inputs come from the left (in this case, raw materials); outputs (finished products) exit from the right; resources are shown as coming from below the box that represents the manufacturing activity; and "controls" (rules, constraints, decisions, etc.) come from above.

To emphasize the broad scope given to the word "manufacturing," a spiral model of product development was drawn in the Manufacturing box. The spiral indicates typical processes, from Market to Support, which are included within the product lifecycle, as well as process that take place throughout the lifecycle. Such business processes can be identified for several major functional areas of a manufacturing enterprise. Six process areas are delineated below, roughly corresponding to the examples shown around the spiral, as well as two underlying processes.

2.2.1. Marketing Support

Marketing acts as the enterprise's primary contact with it customers. To help meet the key objective of increasing product sales, marketing personnel perform several tasks: market research; forecasting demand and sales; analyzing sales; tracking the performance of products, marketing segments, sales personnel and advertising campaigns; developing and managing market channels; controlling profits and revenues; managing sales personnel, sales plans and promotions.

2.2.2. Product Design

The ***Product Design*** areas of an enterprise can be further broken down into more distinct areas of activities such as research, product development (further broken down into hardware and software if applicable), process development, facilities engineering, engineering release control, and engineering management. These six activity areas are addressed in turn below.

- *Research* activities include investigating and developing new materials, products and process technologies.
- *Product Development* uses (in the hardware area) new materials and production technologies to design, model, simulate and analyze new products. The availability of laboratory analysis tools, Computer-Aided Design and Computer-Aided Engineering (CAD/CAE) tools help reduce product development time, increase productivity and improve product quality.
- *Process Development* creates process control specifications, manufacturing routings, quality tests and statistical quality control specifications, and numerical control (NC) programming.
- *Facilities Engineering* has as its chief responsibility plant automation.
- *Engineering Release Control* (also known as New Product Introduction, or NPI) involves the coordination of the release of new products, processes, tools and engineering change orders to planning and manufacturing.

2.2.3. Production Planning

Production Planning consists of several related business processes. These processes consolidate and conform demand, orders, forecasts and resource constraints to production plans, developing detailed schedules. These plans or schedules are then made available to the participating and appropriate functional areas. Some of these functional areas may include Finance, Marketing, Engineering and Plant Operations.

The processes are as follows:

- *Master Production Planning* consolidates information from customer order forecasts, distribution centers and multiple plants, in order to anticipate and satisfy demand for the enterprise's products.
- *Material Planning* and *Resource Planning* keep planning up to date with product demands.

- *Procurement* selects suppliers and handles purchase requisitions and purchase orders for parts and materials.
- The *Plan Release* function produces schedules, recipes to optimize the use of capacity, specifications and process routings. It can prepare electronic (or paperless) shop documents.

2.2.4. Production Operations

Production Operations can be described in terms of nine functions:

- *Production Management* provides dynamic scheduling functions for the plant floor by assigning priorities, personnel and machines.
- *Material Receiving* functions include accepting and tracking goods, materials, supplies and equipment from outside suppliers or other locations within the enterprise.
- *Storage* manages the enterprise's inventory, where materials are stored and accessible to the proper production locations.
- *Production Process* functions include managing the production process, processing materials, fabricating parts, grading or reworking components, assembling final products, and packing for distribution.
- *Quality Test and Inspection* is focused on testing items and products to make sure they conform to specifications.
- *Material Transfer* involves the movement of materials, tools, parts and products among the functional areas of the plant.
- *Product Shipping* supports the movement of products to customers, distributors, warehouses or other plants.
- *Plant Maintenance* includes those functions that ensure the availability of production equipment and facilities.
- *Plant Site Services* cover such functions as energy supply and utilities management, security, environmental control, grounds maintenance and computer and communications installations.

2.2.5. Product Distribution and Logistics

Product Distribution and Logistics activities usually fall into two major functional areas:

- *Physical Distribution Planning* involves the planning and control of the external flow of parts and products to warehouses, distribution center, other manufacturing locations and points of sale.
- *Physical Distribution Operations* include receiving, storing and shipping finished goods at the distribution center or warehouse.

2.2.6. Product Support

After the product has been delivered to the customer, ***Product Support*** activities such as field support, warranty and claims management, and product installation must be performed. *Customer Order Servicing*, a facet of Product Support, involves entering, tracking and shipping customer orders for standard or custom-designed products. Other activities include providing product quotes, checking customer credits, pricing products, allocating order quantities and selecting shipments from distribution centers.

2.2.7. Business Management

Within an enterprise model, the ***Business Management*** function may comprise seven areas:

- *Financial Planning and Management*, where financial resource plans are developed and enterprise goals are established.
- *Accounts Payable* primarily involves paying suppliers.
- *Billing and Accounts Receivable* prepares invoices to customers and manages customer account collections.
- *Cost Accounting* activity supports product pricing and financial planning by establishing product costs.
- *Payroll* computes the payments, taxes and other deductions for employees.
- *Enterprise Planning and Business Management* include establishing goals and strategies for Marketing, Finance, Engineering and Plant Operations, Plant Automation and Information Systems.
- *Enterprise Services* consists of office personnel, management information services, personnel resources and public relations.

2.2.8. Quality Management and Improvement

Quality efforts are used by enterprises to measure consistency of production or other output. The quality process varies across different industries and target markets. There are several efforts to define quality measurement and solutions, including Total Quality Management (TQM), Quality Function Deployment (QFD), Baldridge Award certification, and ISO 9000. Quality is closely tied to metrics as a method of defining and measuring performance.

ISO 9000

ISO 9000 is a widely adopted series of documented standards prescribing quality assurance management (see [ISO 94]). It presents a basic model for quality assurance. When requirements of the Standard are met, customers can be confident of the quality of products and services they purchase. In its most basic form, the standard requires that an organization document its procedures, carry out work according to them, record what is done, and compare results to plans in order to improve.

Metrics

Metrics define an objective measurement system to assess the capability of an organization, the quality of its people and systems, and the degree of success of its continuous process improvement efforts. The business goals of the enterprise help define metrics related to the desired functionality of the manufacturing applications and systems. When a measurement made against these metrics is too low, it can be for system-related reasons, but it can also come from other organizational reasons.

2.3. Current Approaches to Manufacturing Solutions

The existence of the above processes in this paper's definition of manufacturing drives the requirements for systems that support them. For instance, each of the seven processes listed above can be supported by appropriate computer-based systems:

- **Market and product support systems** help manage customer satisfaction by allowing electronic order entry from customers. They provide faster response to customer inquiries and changes, and more accurate sales projections.
- **Product design systems** allow quicker design, development, process simulation and testing; faster access to current and historical product information; and support for the paperless release of products, processes and engineering changes to manufacturing.
- **Production planning systems** allow more accurate, realistic production scheduling, a means to manage and control the expediting, canceling and rescheduling of production capacity and purchase orders.
- **Production operations systems** provide the means to assist the plant operations in controlling processes, optimizing inventory, improving yields, managing changes to products and processes, and reducing scrap and rework.
- **Distribution and logistics systems** help plan requirements; manage the flow of products; improve the efficiency of shipping, vehicle and service scheduling, and the allocation of supply to distribution centers; and expedite the processing of returned goods.
- **Business Management systems** include services for managing the company's finance and accounting systems, developing enterprise directives and financial plans, better cost tracking and more accurate financial projections.
- **Quality Management systems** include services for collecting and analyzing data, detecting and reporting trends, etc.

The following sections represent some of the specific ways in which computer-based solutions to manufacturing enterprise needs have been packaged, architected or standardized. Some of these "packaged solutions" map directly to one of the processes discussed earlier, while others meet several needs. Table 1 indicates this mapping (two crosses indicate the primary focus of a system):

	Marketing and Product Support	Product Design	Production Planning	Production Operations	Distribution and Logistics	Business Mgmt	Quality Mgmt
CIM			**X**	**XX**			**X**
Product Data & Workflow Management		**X**	**X**	**X**	**X**		**X**
CAD		**XX**					**X**
STEP		**XX**		**X**			**X**
Financial Interfaces	**X**					**XX**	
Real Time Applications				**XX**	**X**		

Table 1. Mapping Functional Systems to Enterprise Processes

2.3.1. Computer-Integrated Manufacturing (CIM)

CIM represents the integration, through the use of computational resources, of the manufacturing and assembly functions and resources within an industrial environment. At its broadest level, CIM interacts with all of the other functions of the factory enterprise from equipment on the floor to information systems in the main office. As such, integration occurs with all aspects of the manufacturing business enterprise. These aspects include such functions as product engineering, Computer Aided Engineering (CAE); process control; quality management; Computer Aided Design (CAD); sales; marketing; finance; environment safety and health; and labor management.

2.3.2. Product Design and Product Data

The design of a product is a key activity within the manufacturing lifecycle, especially when the design activity becomes part of a concurrent engineering approach (as opposed to a discrete activity that strictly precedes manufacturing). This approach typically requires two-way exchanges of product information between groups as varied as marketing, sales, development, engineering, production, distribution, after-sales service. The principal software support tools used in this area are:

- Product Design Automation (PDA) Systems
- Product Data Management (PDM) Systems

Product Design Automation (PDA)

Within new product introduction (PI) business processes, product design automation (PDA) software has evolved dramatically over recent years. The monolithic systems of the past have developed into systems which demonstrate greater modularity, where solutions which are more appropriate to the user can be delivered. This approach is being developed, typically through the CAD Framework Initiative (CFI), to enable a range of vendor products to be configured to provide more advanced CAD solutions.

Consideration of the design activity in the development of a manufacturing object model is crucial since, although in a concurrent engineering environment the design activity has many interfaces to essentially non-manufacturing disciplines, the "design object" should encapsulate the whole spectrum of information required to realize (manufacture) the product and in the abstract information- oriented world of a manufacturing object model, "the product" is essentially represented by its design content.

Product Data Management (PDM)

The role of PDM systems (including workflow management) is centered on controlling design information and processes resulting from or supporting engineering, and enabling logistical and manufacturing processes to gain access to it. The PDM system covers the management of many functional activities within the engineering of the product, including:

- Technical documentation;
- Informal workflows, formal workgroup processes, and enterprise processes;
- Bills of materials, product configuration, and part/process classification;
- Program or project management.

Many PDM systems also offer integration with other functions of the enterprise, or additional productivity tools. These include integration capabilities with CAD/CAM/CAE, Manufacturing Resource Planning (MRP), manufacturing execution, sales process automation, and order configuration.

2.3.3. Computer-Aided Design (CAD)

CAD is a design tool that has replaced the drafting board for the engineer. It includes not only two- and three-dimensional drawing capabilities, but also mathematical calculations for simulation or manufacturing purposes, and outputs such as numerical control programs for machines, masks for printed or integrated circuits, etc. Many CAD systems today allow the complete and realistic modeling of a the final product, including characteristics such as heat transfer and mechanical resistance. In many cases, this removes the need to create physical models or "breadboards."

As they grew through the accretion of new features, CAD systems have often become monolithic. Drafting, 3D visualization, modeling, simulation, and machine control program output have been lumped together in large packages with few standardized formats and interfaces if any. The data created by CAD systems embodies the product design knowledge of the organization, yet this information is hard to manage and access in the proprietary repository format imposed by the CAD system vendor. This is in stark contradiction with the trend toward concurrent engineering, which implies that many different enterprise systems may need to share the information that describes a product still in the design stage.

A decomposition of CAD systems into object classes with well-defined access methods would improve this situation by allowing better cooperation between separate design applications or modules. Drafting and visualization would become two such applications, among others that would have access to the same information.

2.3.4. STEP

STEP (STandard for the Exchange of Product model data) was developed by the International Standards Organization (ISO). STEP, or ISO 10303, supports the definition of a product and all the relationships it includes. STEP specifies how various applications, which support various aspects of the product development process, can exchange information about that product.

STEP allows product data to be defined in a way that is independent of software and hardware system characteristics. Accordingly, design specifications can be exchanged between a company and its subcontractors or suppliers, regardless of the specific systems they use to manage this information internally. This clearly represents a huge improvement over the incompatible, proprietary systems that used to exist. Incompatibilities between those systems either forced the exchange of information to occur on paper, or they imposed a massive and error-prone manual re-entry of information, or they forced suppliers to create expensive translation applications so that they could accept the specifications sent to them by their customers.

STEP has advantages in three main areas where the ability to exchange data in a reliable manner is critical:

- **within work groups**, it enables the sharing of data between designers who, for historical reasons, use systems from different suppliers;
- **across the product life cycle**, it smoothes the task of moving from design engineering to manufacturing engineering, and from prototype manufacturing to volume production, where different applications may be employed;
- **between enterprises**, it makes the sharing of data between customers, suppliers and other business partners (including different divisions of the same corporation) possible.

STEP includes a modeling language, EXPRESS, used to describe product models. EXPRESS uses an object-oriented approach. The product description covers generic aspects such as product data and configuration management, but also domain-specific aspects such as drafting, printed circuit boards, mechanical design, automotive design, numerical control, etc..

Another thrust of STEP is not only the static description of a product, but also the exchange of information across systems. Within STEP, the standard defines a data access language, the STEP Data Access Interface (SDAI). Furthermore, the STEP standard defines an IDL interface for this data access language. Thus STEP provides a standard, object-oriented interface for the access of EXPRESS-modeled manufacturing information.

2.3.5. Real Time Applications

Real time applications generally exist within the manufacturing execution systems area, whether one considers a process industry (chemical, petroleum, etc.) or a discrete manufacturing environment (automobiles, televisions or semiconductor chips). Real-time systems cover a variety of functions in the factory:

- Closest to the equipment, and easiest to understand in terms of real time requirements, are the **supervisory control** functions such as robot control, sensors and actuators to control the dispensing of materials or the processing steps (e.g., baking in an oven), automated material handling systems (AMHS), in-situ statistical process control, alarm detection and reporting, etc.
- With a lesser degree of time dependency, but still in real time because they are triggered by the preceding group of functions, one finds **scheduling** and **specification management** applications (process specification downloading, equipment parameter configuration, on-demand paperless documentation, etc.).
- Finally, **plant management** functions can usually be performed with some delay, but they still need to absorb the flow of information collected in real time from the lower levels of the system. These functions include reporting, labor management, material management (WIP and material tracking), equipment performance tracking and reliability analysis, preventative maintenance scheduling, quality metrics, certification, laboratory information management, etc.

In these areas, the ability of the manufacturing system to reliably gather information from manual or automated sources and to provide immediate, accurate alarms, is key to the ability of the company to operate safely for the personnel involved and for the surrounding community. In the longer term, the ability to store this information securely (often for very long times) and to analyze trends impacts the ability of the enterprise to meet the applicable regulations and therefore to stay in business.

2.3.6. Interfaces to External Systems

Manufacturing organizations often include functions typically considered in other vertical markets such as distribution, sales, customer service and financial services (such as leasing). All of these systems need to have interfaces for the data they share.

A well-integrated manufacturing system requires interfaces to standard accounting functions such as general ledger, accounts payable, accounts receivable, order entry systems and purchasing systems. Material costs, direct service costs as well as overhead allocations need to be available throughout the organization. Cost and pricing information must be available to the appropriate parties such as designers and product planners. Otherwise, cost-effective products may not be designed, quality may suffer and service problems may not be optimized.

Beside financial systems, interfaces may be required with other systems, including:

- Human resource management
- Product distribution

- Time and attendance
- Customer service
- Environment tracking.

2.4. Infrastructure Requirements

This section addresses requirements imposed by manufacturing applications on computing infrastructure. These requirements can be organized according to their performance (consumption of computing resources), system access and integration issues. There may be more dimensions to the infrastructure issue; however, within this context, the above are of particular importance.

2.4.1. Computing Performance Requirements

Performance includes not only response time but also the degree to which an application consumes computing resources such as memory, disk utilization, archival facilities, or network bandwidth. The emergence of new, more complex, distributed manufacturing applications, which are made possible by the use of object technology, imposes greater computing resource requirements due to the following two major reasons:

- co-location of computing facilities with the business processes they support (increasing the requirements for the communications infrastructure in particular);
- the increase in the number and kind of data types used, and the complexity of their physical representation.

A more thorough understanding of these performance requirements can be used by an organization for several purposes: to set objective criteria for the selection of manufacturing objects and services from commercial product offerings; to define requirements for systems or objects that are developed internally; and to make rational and timely decisions about system upgrades required to keep up with expanding workloads.

2.4.2. Semantic Integration Requirements

Existing applications often have different representations of the same business concept. For example, a Product Data Management (PDM) system might represent parts in terms of design and assembly characteristics while a Manufacturing Resource Management (MRM) system may represent the same part in different terms.

Semantic Integration means allowing a client system to access information in terms of common business concepts rather than in terms of its representation in the different systems. Continuing the example, client applications would access parts in terms of the integrated business concept rather than in terms of the PDM or MRM representation. While the benefits usually outweigh the costs, Semantic Integration increases system resource load because it introduces an additional layer of indirection in inter-application communication.

2.4.3. Access to System Information and Functionality

There is often a requirement to access, from newly-developed applications, data and functionality that are encapsulated in existing applications. Reusability of code is difficult and expensive if programmatic interfaces are not already provided to that functionality and data. (Furthermore, access to legacy systems may require maintaining obsolescent hardware platforms, operating systems, databases and networking facilities that would otherwise not be required).

2.4.4. Example Requirement Sources from New and Legacy Manufacturing Applications

Both the new and legacy applications present challenging infrastructure requirements. In the case of legacy systems, semantic integration as well as simplified access to existing system functionality are central issues. To give an example from leading edge application development, virtual enterprise systems provide a platform for interesting discussion.

Virtual enterprise systems work by combining two different models: a potentially distributed organizational model, and an enterprise process model. "Combining" takes the form of brokering *human resources* that are part of the organizational model to *tasks* that are part of the enterprise model. In general, the organizational entities from which these human resources come are not co-located with the process tasks they are being enlisted to perform. As a result, maintaining a coherent application state is difficult, and consumes substantial network resources (e.g., to constantly mirror information between databases located within different companies).

2.4.5. Other Potential Requirements

As stated in the introduction to Section 2.4, there may be more dimensions to the infrastructure issue than are addressed above. The following list, although itself not exhaustive, represents other potential requirements imposed by manufacturing applications on the computing infrastructure. The items on this list may fall under the dimensions listed above (performance, semantic integration, access to legacy systems), or they may dictate the definition of new dimensions.

- Open, distributed architectures (typically adhering to the client/server paradigm) conforming to international standards.
- Open communications between heterogeneous hardware platforms in a distributed network.
- Open communications between software applications, operating systems and database technologies.
- Ability to support loosely federated network schemes, databases and presentation mechanisms.
- Improved closed-loop control of manufacturing processes.
- Increased utilization of feed-forward/feed-backward data.
- Increased utilization of real-time information flow.
- Paperless manufacturing, in particular the direct downloading of drawings/design data to operating equipment on the factory floor.

- Improved configuration management of specifications, process recipes, software and hardware.
- Improved in-situ sensor access through cableless communications.
- Increased integration of external data bases with the factory information flow.
- Improved implementation and utilization of business rules in factory processes.
- Availability of high-volume data acquisition, analysis and presentation tools to factory personnel.
- Model-based production control validated through simulation of static system elements and optimized output.
- Support for business processes and workflows.
- Ability to incorporate heterogeneous commercial, off-the-shelf (COTS) components.
- Scalability to many interconnected sites.
- Extensibility to new functionality and application objects (without interrupting the system) as requirements change.
- Ability to dynamically migrate objects between computer systems while the system is running.
- Ease of learning and use.
- Built-in performance diagnosis and tuning capability.

Another potential category of factors that influence infrastructure requirements is the notion of metrics. Metrics define an objective measurement system to assess the capability of an organization, the quality of its people and systems, and the degree of success of its continuous process improvement efforts. Metrics certainly influence the two requirement categories already defined and may influence others.

3. ARCHITECTURE

This chapter defines and describes a proposed architecture for object-oriented manufacturing systems. This definition is intended to serve as the common reference point for discussing object-oriented manufacturing systems. This chapter defines the term "architecture," describes the Manufacturing SIG's current view of a proposed architecture for object-oriented manufacturing systems, presents each dimension of the architecture, and finally relates this proposed architecture to three examples of existing manufacturing system architectures.

3.1. Definitions

In order to understand the phrase "architecture of object-oriented manufacturing systems", it is necessary to define the term "architecture". The term architecture, as defined in several dictionaries such as Webster's or the American Collegiate Dictionary, includes the notions of a *structure*, a *unifying or coherent form*, or an *orderly arrangement*. For the purposes of this white paper, an architecture is simply a statement of the important concepts, and the important interconnections between those concepts, that define the unifying or coherent form of an integrated manufacturing computing system.

An object-oriented architecture is simply one that is described in terms of objects, classes, attributes, services, etc. A manufacturing system is a computing system whose purpose is to support a manufacturing enterprise.

3.2. The Architecture

Figure 2 depicts the top-level model of the proposed architecture for object-oriented manufacturing systems:

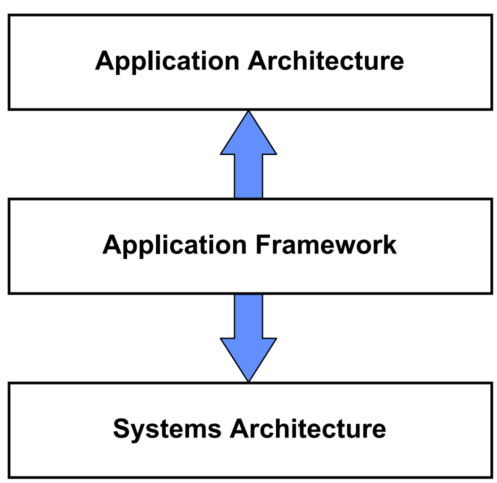

Figure 2. Proposed Top-Level Architecture for Object-Oriented Manufacturing Systems

Be aware that this particular model is at a very abstract, high level. No specific manufacturing requirements can be extracted from it. In fact, this model is applicable to a majority of computing systems, not just object-oriented manufacturing systems. However, even in this form, it establishes the context for discussing object-oriented manufacturing systems and identifies work areas for the Manufacturing DTF.

The following sections elaborate on the components of this architecture and describe the important interconnections between these components. The following sections also relate these components to topics that have already been discussed elsewhere, and identify issues that must be addressed for successful completion of an architecture for object-oriented manufacturing systems.

3.2.1. The Application Architecture

An application architecture, in general, is a model of the business policy and business process that a system is intended to carry out. An application architecture should be stated without regard to the mechanism that will be used to carry out that business policy or process. In fact, there is no mandate that the application architecture even be implemented in a computing system. The application architecture could be implemented as a set of operating policies and procedures which are carried out by humans.

In terms of manufacturing systems, the application architecture is a complete, consistent, concise, and coherent model of a manufacturing enterprise. This architecture must address the business process areas already identified in section 2.2 (High-level Manufacturing Enterprise Model). These business process areas are listed below as a reminder:

- Market and product support
- Product design
- Production planning
- Production operations
- Distribution and logistics
- Business management
- Quality management

The specifications of these processes must be much more detailed to provide a complete, consistent, concise, and coherent model of a manufacturing enterprise. The application architecture should also be described in terms of objects, classes, attributes, services, etc.

The Manufacturing DTF must eventually either obtain from submitters, or construct itself, a fully elaborated Manufacturing Enterprise Model to serve as the definition of manufacturing business policy and business process. The Manufacturing DTF has already identified the following issues related to this section of the architecture.

- No such fully elaborated model is currently available at any price. Furthermore, constructing such a model from scratch (and getting it adopted by the diverse community it is aimed at) is clearly a daunting task. The Manufacturing DTF may therefore be forced to build most, if not all, of the model itself, or in collaboration with other OMG groups, but it may be able to borrow significant portions of it from other organizations with which it could establish a liaison relationship. Candidate organizations, such as SEMATECH or NIIIP, are listed in Appendix A (Relevant Consortia and Standards Groups). On the positive side, such a model-building effort, if successful, may trigger a fundamental change in the practice of manufacturing system development.
- Every manufacturing concern's actual business policy or process may be different. This causes the dilemma that the application architecture must be abstract enough to be broadly applicable, but specific enough to provide a firm basis for defining the application framework.
- Neither the Manufacturing DTF nor the OMG as a whole may be able to motivate the proper players to participate in the construction of a fully elaborated Manufacturing Enterprise Model.
- Some application architecture concepts are specific to a particular subject areas. For example, a class representing a customer trouble report would be specific to the Market and Product Support subject area, while a class representing a stress vector in a finite-element structural analysis would be specific to the Engineering and Technical Computing subject area. More importantly, however, some of the concepts are shared across multiple subject areas. Clearly, the concepts Part, Bill of Material, and Work Station span multiple subject areas. This imposes the need to be extremely careful in integrating the specifications of these subject areas.
- The application architecture may impose requirements on the Analysis and Design Task Force to provide sufficiently robust analysis methods to capture the significant characteristics of manufacturing systems business policy and processes.

3.2.2. The Systems Architecture

The systems architecture is a model of an automation mechanism. It should be stated without regard to the many potential application architectures that it may support. Although there are many alternate useful systems architectures, the preferred model of the Manufacturing DTF is the OMG Object Management Architecture (OMA).

Components of the OMA

At a high level, the OMA contains the subject areas described in the OMG Object Management Architecture Guide [OMG 95d] and includes the following components:

- CORBA, the Common Object Request Broker Architecture,
- CORBAservices, previously known as Object Services,
- CORBAfacilities, previously Common Facilities,
- Application Objects.

Since the intended audience of this white paper is primarily composed of OMG members already familiar with these concepts, details about the OMA are not presented here.

In order to be useful for defining, describing, and constructing complete (manufacturing) computing systems, the system architecture must be specified down to the level of actual computing mechanisms. In OMA terms, these computing mechanisms are the IDL interfaces provided by objects defined in the adopted OMG technology specifications. The OMA is already described in terms of objects, classes, attributes, services, etc.

Potential Extensions for Manufacturing

The Manufacturing DTF intends to use the IDL interfaces already adopted by OMG as its systems architecture model. The Manufacturing DTF has already identified the following issues related to this OMG specifications:

- The existing OMG technology specifications may not offer sufficient services to enable efficient and economical automation of the Manufacturing Enterprise Model (see below).
- Some of the proven, robust technologies capable of supporting manufacturing requirements (e.g., database services) do not have object interfaces and even violate the basic principles of the object-oriented approach by separating data from the operations that affect it. Relational data base management systems (RDBMS) are a case in point. However, object databases may not yet have the robustness of an RDBMS, and definitely do not yet come with the rich suite of query and reporting tools that are characteristics of the RDBMS market. Such tools are required to avoid redundant implementation by application vendors and end users.

A preliminary review of the existing CORBAservices and CORBAfacilities specifications, and of some additional ones already on the OMG's roadmaps, already reveals the need to study these specifications for compatibility with the needs of manufacturing. In other cases, one can already discern a need to expand these specifications in order to meet these needs. A more detailed study will clearly be needed, but here is an initial list:

- The **externalization service** specification should be reviewed to validate how object state is provided within manufacturing systems.
- The **naming service** specification should be reviewed to make sure that it supports the way manufacturing entities are identified.
- The future **logging service** should be reviewed in conjunction with the forthcoming CORBAfacility for System Management or History Management to make sure that it supports the types of audit trails needed in manufacturing.
- The future **rule management** facility should be steered or reviewed so that it can support the needs of regulatory management. And it should also be examined in conjunction with the **compound document management** facility, in order to determine if they support, together or individually, the notion of process recipe which exists in many manufacturing domains. A process recipe is a kind of rule, but it is contained and managed within a document.

- The applicability of the **transaction service** to the very long-term transactions encountered in manufacturing should be studied.
- The ability of the **security service** to support the authentication of multiple, serialized users of the same object or facility should be reviewed. An example of this requirement is the sharing of a workstation by multiple plant operators who “re-login on the fly” on a transaction basis.
- A **synchronization service** between redundant data may be required for performance reasons, especially within the context of a virtual enterprise (where non-redundant storage of information would be unacceptable from a performance or reliability viewpoint).
- A **heartbeat service** may be required in order to be able to monitor the active status of critical components of the system.
- The **X/Open System Management** proposal should be reviewed with the intent of assessing its support of History Management and Policy Variable Management. The Properties Service, when available, should provide support for the latter.
- The existing **Event Notification Service** specification and the Event Management proposal contained in X/Open System Management should be evaluated to ensure that the publish/subscribe paradigm promoted by the OMG satisfy manufacturing requirements.
- The future **Collections Management Service** and **Query Service** should be studied to ensure that operations performed on collections, and the querying of members of collections (e.g., collections of factory resources) satisfy manufacturing requirements.
- **Rule Management and Workflow Management** within the X/Open System Management proposal should be studied to determine how the notion of job can be supported within a manufacturing enterprise.
- Other future CORBAservices that bear close scrutiny include the **Archive Service** (in support of persistent object storage); **Configuration Management**, which includes versioning; **Life Cycle Services**, in support of object state; and **Startup and Recovery Services** for initiating and “undoing” object state.

Quality of Service

In the Object Services domain of the Object Management Architecture, the phrase “quality of service” has adopted a specific meaning. Quality of service consists of various properties that a service may provide to a different degree, and which become discriminating factors in the selection of a specification or of an implementation.

In order to support the needs of manufacturing, object services, object facilities and application objects need to be measured and selected according to at least the following qualities of service:

- Performance—number of transactions or messages per second, ability to respond in real-time (e.g., predictability of the response time), etc.;
- Reliability—mean time to failure, mean time to repair, etc.;
- Scalability—number of systems, objects, instances, etc., that can be manipulated by the system before the performance specifications of the system stop being met;

- Resource consumption—amount of memory and disk space required to support a service of facility (e.g., percentage of overhead for the persistent storage of objects).

These qualities of service are also related to the system performance metrics of Section 2.4.5.

3.2.3. The Application Framework

Simply stated, a framework is a reusable, domain-specific design and the implementation of that design. A framework may be considered a skeletal, very general design of a particular application domain (e.g., user interfaces). An object-oriented framework is a collection of reusable, collaborating object abstractions (e.g., machine, operator), services (e.g., move a machine through its life cycle) and protocols (e.g., transfer of material between two machines). Relationships (associative, hierarchical) are defined between these abstractions to provide an overall design.

A framework provides the software infrastructure that permits the composition of existing framework classes (and possible extension of their behavior) to customize or enhance the domain knowledge. Customization occurs when a class is created as a sub-class of a framework class. For instance, a framework may provide the class *Machine,* which exhibits behavior common to all machines: it starts up, shuts down, processes material, requires maintenance, etc. A sub-class called *MillingMachine* would build upon that generic design and add specific machine tooling behavior.

A framework provides a common environment for the integration of applications and the sharing of information in a given problem domain. Framework protocols are platform independent, and should be language independent to the extent possible, thus promoting their interoperability and portability across distributed, heterogeneous systems. Ideally, only a portion of the framework implementation is platform dependent.

In mathematical terms, the Application Framework is a projection from the concepts in the Application Architecture onto the concepts in the System Architecture. For example, the Manufacturing Enterprise Model may define the concepts "Part," "Part Number," and "Release Part Design" as business concepts. The application framework could possibly project these business concepts onto the system concepts of "Persistent CORBA Object," "read-only attribute," and "COSS1 Event Notification Service" respectively. The source code for class "Part" could project, in an executable form, all of the application architecture concepts pertinent to "Part" on to mechanisms defined by OMG adopted technologies.

One of the principal goals of the Manufacturing DTF is to maintain a Manufacturing Application Framework definition (in OMG IDL), which will serve as the group's recommended technology specification for integrated automated manufacturing systems.

The Manufacturing DTF has already identified the following issues related to this section of the architecture:

- The sharing of application architecture concepts across multiple subject areas would probably impose the same kind of sharing on the application framework. If the source code were to be obtained from multiple vendors, a number of issues related to ownership, copyright, and development and maintenance responsibilities on resulting executable source code would emerge.

- There is not necessarily a one-to-one correspondence between the Manufacturing Enterprise Model concepts and application subject areas, and the ultimate partitioning of the Application Framework. This absence of direct mapping may be required for efficient and economical automation of the Manufacturing Enterprise Model, but it may also lead to confusion and possibly increased maintenance costs.
- The huge investment required for a supplier to recast an existing (legacy) manufacturing application into the form defined by an Application Framework introduces a significant barrier to commercial availability—at least in the near term.
- The Application Framework may impose requirements on the Analysis and Design Task Force to provide design methods that are sufficiently robust to capture its significant characteristics.
- In order to promote the adoption of a framework-based architecture among the manufacturing system supplier and user community, the Manufacturing DTF may need to undertake the development of a significant body of educational material tailored for this specific audience.

3.3. Relating the Architecture to Existing Examples

In this section we relate existing architectures to the architecture proposed above.

3.3.1. The SEMATECH Manufacturing Model

SEMATECH (SEmiconductor MAnufacturing TECHnology) is a consortium of U.S. semiconductor manufacturers that is chartered with improving semiconductor manufacturing processes and equipment. One of the key thrusts of SEMATECH's activity is the development of better manufacturing systems. To this effect, SEMATECH has constructed an application framework that aims at providing the minimum set of manufacturing object abstractions (and attendant services) needed to build compatible, pluggable applications for semiconductor manufacturing facilities. The building blocks of SEMATECH's CIM Framework are components, which comprise patterns of class behavior that perform indivisible units of work in the factory.

Although the SEMATECH CIM Application Framework constitutes a promising contribution to the Manufacturing SIG's effort, the following issues exist with respect to this architecture:

- The application architecture (business policy/business process) behind the SEMATECH application framework is not formally specified in a complete, consistent, concise, and coherent manner.
- In particular, the applications can only "hang together" if the semantics of the various components are compatible. Since IDL describes only the syntax of an interface but not its semantics, the framework definition is lacking a behavioral semantics component to ensure that a conformant system will work properly or that conformant component implementations can truly be substituted for one another. SEMATECH is working on this problem.

- It is hard to determine where the abstraction "line" is drawn between generalization (what behavior is "in" a framework) and specialization (what behavior is "in" an application). It should be noted, however, that this problem is generic to the definition of a framework, and is not specific to SEMATECH's.
- Although SEMATECH has defined its framework in OMA and IDL terms, it has stated that implementation of the framework's services is not necessarily object-oriented. This architectural consideration was required in order to embrace the significant investment represented by legacy systems. Yet there is a risk that this flexibility may compromise the architectural consistency of the framework.

3.3.2. CIMOSA

The Computer-Integrated Manufacturing Open Systems Architecture (CIMOSA, see [AMICE 93]) is the result of a consortium effort that took place under the auspices of the European Strategic Programme for Information Technology (ESPRIT)**.**

The major goal for CIMOSA is to enable enterprise integration in view of perpetual change and evolution in enterprise operation due to external and internal forces. CIMOSA meets this goal by providing an Open System Architecture to describe the real world of the manufacturing enterprise. These descriptive models allow an end user to plan, design, control, monitor, optimize and update enterprise systems without needing specialist knowledge of information technology.

CIMOSA provides a descriptive rather than prescriptive methodology supporting the enterprise and product life cycle covering requirements definition, design specification, implementation description and model maintenance. CIMOSA provides following three interrelated concepts to achieve its goals:

CIMOSA Modeling Framework

- Provides a Reference Architecture (not a standard architecture) to model all industrial environments from which architectures for specific manufacturing industries can be derived. The Reference Architecture defines a set of constructs (building blocks) to describe enterprise processes, their functionality and dynamic behavior, available and used information, available and used resources, and inter-relationships of resources and information.
- It provides definitions of enterprise model constructs and their graphical representations. Constructs are defined in a user oriented modeling language to enable common representation and understanding of enterprise models.
- Enables user to work with a subset of the model through model views by hiding the complexity and by only showing the selected aspects.

CIMOSA Environments

- To maintain a clear separation between the tasks associated with product life cycles (e.g. product design, product planning, production, etc.) and the tasks associated with enterprise system life cycle (facility design, facility operation, etc.), CIMOSA provides two mutually independent execution environments: the Enterprise Operations Environment, and the Enterprise Engineering Environment. Execution of product life cycle tasks takes place in the former and the execution of enterprise related tasks takes place in the latter.

CIMOSA Integrating Infrastructure

- It provides the mechanisms to integrate heterogeneous components (resources) and also provides the means to control the product and enterprise life cycle processes.
- Provides a set of services (Business Services, Presentation Services, Information Services and Systems Management Services) aimed at executing models conforming to the CIMOSA modeling concepts.
- CIMOSA structures the enterprise operations into a set of inter-operating domain processes exchanging requests and results.

3.3.3. The Manufacturing Virtual Enterprise (MVE) Architecture

The MVE architecture was defined by the NIIIP consortium (see Appendix A) as a mechanism to provide a manufacturing collaboration environment which allows customers, suppliers and even competitors to rapidly compose a virtual company to build a specific product. NIIIP is defining protocols for an MVE architecture which will facilitate the rapid composition, and ultimately the decomposition, of a Virtual Enterprise.

MVE is built on top of the OMG's CORBAservices and CORBAfacilities. It consists of a number of vertical market facilities that provide Computer-Integrated Manufacturing (CIM) services, a collection of services that support the sharing of product data using the STEP standard, and a number of services that can build upon the CIM and STEP services to enable the virtual enterprise.

STEP Services

MVE contains three levels of STEP-related services (STEP was defined in Section 2.3.4):

- Level 1 provides location transparency for STEP exchange files, and works in conjunction with the OMG's Persistent Object Service and Life Cycle Service.
- Level 2 supports the design of high-level, active product data objects. The data contents of these objects are defined in the EXPRESS language, and the operations are described in OMG's IDL.
- Level 3 encapsulates the Standard Data Access Interface (SDAI) of the STEP standard within an IDL interface.

Other MVE Services and Facilities

Other services included within the MVE architecture include the following.

- MVE Data Configuration Management Services — these services support the configuration and "warehousing" of product data.
- Agents (personal assistants, group collaboration agents, and information-specific agents).

- MVE Transport Services, an extension of the Persistent Object Services across a wide span of distribution.
- MVE Internet Services, a layer of services that enable the MVE to use Internet services, and conversely provides access to MVE services from other locations on the Internet.
- The MVE Session Service, a service that manages the user's working environment during and between connections to the MVE services. This service is based on the CAD Framework Initiative's (CFI) Task and Session Model, extended to accommodate the virtual enterprise.
- MVE Application Manager, a service that manages the registration and invocation of tools and applications.
- The MVE Monitor, a service that enforces the global consistency and correctness of MVE operations by applying global rules and constraints.
- The MVE Knowledge Base Management System (KBMS), a repository of the global MVE "knowledge" that is needed to control the operation of the MVE, including management and query facilities for the knowledge base.

3.4. Manufacturing Systems Development

The architecture, as described above, applies to the applications that are executed for the benefit of the end user, not to the development methods and tools used by the developers of those applications. By contrast, this section investigates industry-specific issues surrounding the software lifecycle of manufacturing systems and applications (what it sometimes called the *Development Architecture* in opposition to the *Execution Architecture*).

Some of these issues include:

- The need for interfaces that can be used to specialize software development objects to create manufacturing systems software.
- The weakness, or at least the lack of track record of many analysis and design methods, when it comes to modeling the real-time requirements that are typical of computer-integrated manufacturing applications, or other quantitative properties such as performance and reliability.
- The possibility that additional analysis or design artifacts are needed to represent other aspects of a manufacturing system.
- Manufacturing often deals with complex pieces of equipment which are truly "objects": they hold some information that is not visible from the outside, and they react to specific messages sent to them. Most suppliers of the equipment do not (and would be unable to) supply an object-oriented model of the equipment, which would make it considerably easier to design an application that communicates with that equipment.
- Most methods are good at analyzing and designing new systems of moderate complexity and may not scale up to very large or complex systems.

- Most methods are not aimed at modeling an existing legacy application for the purpose of interfacing it to a new system.
- While there are many test methods and tools supporting the procedural paradigm, those in support of the object paradigm are still emerging. The reliability of manufacturing systems is of paramount economic importance, and in some cases physical harm and property loss can result from a malfunctioning manufacturing application. Therefore, the lack of testing methods and tools for object-oriented systems is a crucial issue.
- The manufacturing requirement for uninterrupted operations makes the migration from a manual business process to a computer-based one, or from an existing system to a new one, particularly difficult to accomplish. When a transition occurs, existing business rules and data, created under the previous system, constitute important company assets that need to be maintained through the lifecycle of the new system. Thus migration strategies must be considered as part of the development of a new system.

Appendix A. RELEVANT CONSORTIA AND STANDARDS GROUPS

There are many activities in the intersection of manufacturing and information technology. So many in fact that it would be impossible to catalog them all. The purpose of identifying related activities is that they are sources of information that can contribute to the program of the Manufacturing DTF (e.g., assist in the evolution of the Manufacturing Enterprise Model). This section comprises a cross-section of such activities as of 1995. In general, individual vendors and specific projects of only a single vendor have been excluded. Associations, consortia, standards-related organizations, and multiple-organization research and development projects are included. The material in this section could be the basis for a continuing catalog of such activities to help the DTF track related work in other organizations. Where practical, this material is taken from the activity's own description in on-line documentation. Please see the cited Internet sites for more information.

A.1. Agile Forum

The Agile Forum evolved from the Agile Manufacturing Enterprise Forum (AMEF) in the Iacocca Institute at Lehigh University. It comprises a variety of research and outreach activities, including the Next Generation Manufacturing (NGM) Project and the Agile Manufacturing Initiative, jointly sponsored by Advanced Research Projects Agency (ARPA) and National Science Foundation (NSF) programs. Its purpose is to develop, demonstrate, and evaluate the advanced design, manufacturing, and business transaction processes described in the 21st Century Manufacturing Enterprise Strategy report, an industry vision statement developed with sponsorship from the U.S. Department of Defense's Manufacturing Technology program (DoD ManTech).

See http://absu.amef.lehigh.edu/

A.2. CAD Framework Initiative (CFI)

This consortium is devoted to standards for electronic computer-aided design (CAD). One of their standards is the design representation (DR). They are also active in the developing testing and certification procedures for their standards (see http://www.cfi.org).

One of the manufacturing-oriented CFI standards effort is on Semiconductor Process Representation (SPR), currently in working group development (see http://www-mtl.mit.edu/CFI/SPR.html).

A.3. CIMOSA Association

An association involved in promotion of the Computer-Integrated Manufacturing Open System Architecture (CIMOSA, originally CIM-OSA), developed by ESPRIT project AMICE. ESPRIT is the European Strategic Programme for Information Technology, and AMICE is a reverse acronym for European Computer-Integrated Manufacturing Architecture.

The CIMOSA Association actively supports national, European and international standardization in consolidation of the evolution of its technical specification—the CIMOSA Technical Baseline. The CIMOSA Association acts as a focal point for all parties involved in applying CIMOSA in industrial and research environments. Members of the CIMOSA Association are industrial and research organizations involved in exploitation of CIMOSA or interested in the subject of enterprise integration (EI). Membership is open to any organization interested in supporting EI and CIMOSA.

For more information about CIMOSA, see http://iaipc80.kfk.de/mccim/conews/, the CIMOSA Association News page, or http://iaipc80.kfk.de/mccim/cimosa.htm.

A.4. Computer-Aided Acquisition Logistic Support (CALS)

CALS was originally a U.S. Department of Defense (DoD) program to improve their acquisition process through information technology standards. There is also a CALS International within the NATO community. In the U.S., there is a CALS Industry Steering Group, and its executive board, separate from DoD although with DoD representation. Be aware that this program is best known as CALS because the abbreviation has stayed the same while there have been several different versions of what it stood for, including Continuous Acquisition and Lifecycle Support.

There are a number of sites with CALS information; see http://navysgml.dt.navy.mil/cals.html as a starting point.

A.5. Computer and Automated Systems Association (CASA)

CASA is part of the Society of Manufacturing Engineers (SME). It has published a model called the "New Manufacturing Enterprise Wheel." The model shows six fundamental elements for competitive manufacturing, graphically represented as concentric circles: the customer, the role of people and teamwork in the organization, shared knowledge and systems, key processes, resources and responsibilities, and the manufacturing infrastructure.

A.6. Concurrent Engineering Research Center (CERC)

The Concurrent Engineering Research Center is an independent, inter-disciplinary research laboratory at West Virginia University (WVU) in Morgantown, West Virginia. CERC's primary mission is the advancement of enabling technologies for the collaborative enterprise—an organization that emphasizes collaboration among its many components as the key to its success. CERC was established in 1988 as part of the ARPA, at that time DARPA, Initiative in Concurrent Engineering (DICE).

See http://www.cerc.wvu.edu/

A.7. Consortium for Advanced Manufacturing*International (CAM*I)

One of the oldest consortia for manufacturing. The Institute for Manufacturing and Automation Research (IMAR) is the research arm for this organization.

A.8. Electronic Industries Association (EIA)

EIA is primarily a trade association representing the U.S. high technology community. EIA has many activities such as technical standards development, market analysis, government relations, trade shows and seminar programs. It is an ANSI accredited standards development organization responsible for many standards important to manufacturing and shop floor communication. For example, ANSI/EIA-274 (also known as RS274) is a standard for numerically controlled machine tools.

See http://www.eia.org/

A.9. Institute of Electrical and Electronics Engineers Standards Coordinating Committee 20 (IEEE SCC-20)

IEEE SCC-20 is responsible for the creation of standards associated with automatic test. The ABBET (A Broad Based Environment for Test) 1226 subcommittee is developing an architecture for test through a comprehensive Test Foundation Framework (TFF) using OMG IDL technology to define the interfaces. This effort spans from product design through field usage, and from design tools and information through test equipment and buses. The object interface definitions can be used even if a distributed object system is not. The ATLAS 716 subcommittee is working on a signal-oriented framework which is a part of the TFF. These efforts are joined by several other subcommittees with the purpose of increasing test understanding and information usage, portability, and reuse.

A.10. Intelligent Integration of Information (I^3)

I^3 is an ARPA-sponsored program "to provide easy access to information — in the form needed by end-users and high-level applications — by extracting, integrating, and abstracting information from the growing morass of available data. I^3 will enable the development of large-scale, intelligent applications by providing the technology to transform disperse collections of heterogeneous data sources into virtual knowledge-bases which integrate the semantic content of disparate sources and provide integrated information, at the right level of abstraction, to end-user applications."

See http://haifa.isx.com:80/pub/I3/

A.11. Intelligent Manufacturing Systems (IMS)

IMS is an international initiative for collaborative R&D in advanced manufacturing technologies. Industry leads the effort, with university and government participation from member regions. Major research themes include: product lifecycle design and manufacturing, clean manufacturing, global concurrent engineering, enterprise integration, rapid product development, biological manufacturing systems, agile manufacturing, the virtual enterprise, and agent-based enterprises. New IMS projects will be proposed by consortia such as the Consortium for Advanced Manufacturing-International (CAM*I).

IMS started in 1989 when Japan's Ministry of International Trade and Industry (MITI) invited U.S. and European companies to participate in a proposed international cooperative R&D program in intelligent manufacturing systems.

See http://fuji.stanford.edu/Center/Research/IMS/ims.html

A.12. ISA, the International Society for Measurement and Control

ISA (originally the Instrument Society of America, hence its abbreviation) is a non-profit engineering society with nearly 50,000 members around the world. It is involved in measurement and control in the process and discrete manufacturing industries. ISA is an ANSI accredited development organization with responsibility for developing many of the measurement and control standards used in manufacturing. It is also active in the IEC.

See http://www.nando.net/isa/

A.13. International Federation for Information Processing / International Federation for Automatic Control (IFIP/IFAC)

IFIP is an organization of professional information processing societies. It fosters cooperation and exchange among its members. IFAC is an organization of engineering and scientific societies of individual countries promoting the science and technology of automatic control in its broadest sense.

A Generic Enterprise Reference Architecture (GERAM) is being developed by the IFIP/IFAC Task Force on Architectures for Enterprise Integration, formed in 1990. The Task Force's mission is to study the field of enterprise reference architectures for the purpose of picking the best one for future use, and/or develop a better one. Extensive analysis led to the identification of three candidate architectures in 1993: CIMOSA, GRAI-GIM and PERA (Purdue Enterprise Reference Architecture). GERAM is an attempt at combining the best features of each into a more complete architecture.

A.14. The International Organization for Standardization (ISO) / International Electrotechnical Commission (IEC) Joint Technical Committee 1 (ISO/IEC JTC1)

ISO (see http://www.iso.ch/) and IEC (see http://www.hike.te.chiba-u.ac.jp/ikeda/IEC/iec.html) are two major international formal standardization organizations. Together they have formed JTC1 (see http://www.iso.ch/meme/JTC1.html), which includes Subcommittee 21 (SC21) on open systems interconnect (OSI), data management, and open distributed processing (ODP); and Subcommittee 22 (SC22) on programming languages.

IEC Technical Committee 93 (TC93) on electronic design covers standards and testing technology for electronic manufacturing.

Another ISO technical committee worth noting is TC184, Manufacturing automation systems and integration (see http://www.iso.ch/meme/TC184.html). TC184 contains the following subcommittees and working groups:

- SC4, Industrial data and global manufacturing languages (see http://elib.cme.nist.gov/sc4/ and separate entry for STEP)
- SC5, Architecture and communications (see http://www.iso.ch/meme/TC184SC5.html)

- WG1, Modeling and architecture. Scope: to develop a standard framework that coordinates existing, emerging, and future standards for the modeling of enterprises to facilitate computer-integrated manufacturing.
- WG4, Programming language environment. This working group is currently working on the standard for MAPLE (Manufacturing Automation Programming Language Environment), a common, vendor-independent, neutral support facility for the programming of multiple manufacturing devices and controls.

OMG has a liaison with JTC1/SC21/WG7 (Open Distributed Processing).

A.15. International Product Data Management Users Group (IPDMUG)

The International Product Data Management User Group "represents, and is exclusively for, the users of PDM systems — regardless of vendor solutions used." It facilitates communication within the user community on issues of mutual interest. It is a relatively new group that has focused thus far on integration and interoperability of PDM systems as well as some of the cultural and technical issues surrounding any PDM implementation.

See http://www.ideal.com/pdmic/wpipdmug.html for their white paper.

A.16. Manufacturing Automation and Design Engineering (MADE)

Manufacturing Automation and Design Engineering is an ARPA program that supports research, development and demonstration of enabling technologies, tools, and infrastructure for the next generation of design environments for complex electromechanical systems. The MADE program is concerned with the comprehensive information modeling and the design tools needed to support rapid design of electromechanical systems. This program emphasizes the notion of "tag team" design in which each designer performs the functions he or she is most expert at, while leaving behind enough information for other designers to pick up wherever they left off.

Two relevant URLs are http://elib.cme.nist.gov/made/made.html and
http://www.arpa.mil/sisto/symp/Overview/MADE.html

A.17. National Center for Manufacturing Sciences (NCMS)

The National Center for Manufacturing Sciences is a consortium of over 200 U.S. and Canadian corporations committed to making North American manufacturing more globally competitive through development and implementation of next-generation manufacturing technologies. Its membership is a diverse cross-section of North American industries including some of the largest manufacturers in the aerospace, automotive, electronics, and machine tool sectors. There are presently seven Strategic Interest Groups, or SIGs, at NCMS: Computer Integrated Operations; Electronics Manufacturing; Environmentally Conscious Manufacturing; Management Practices; Manufacturing Processes and Materials; Production Equipment and Systems; and Technology Access. Of these, the Computer Integrated Operations SIG is most closely aligned with the OMG mission and may, in fact, be a mechanism to accelerate the progress of the OMG Manufacturing DTF. (See http://www.ncms.org/)

A.18. National Industrial Information Infrastructure Protocols (NIIIP)

NIIIP is a consortium of companies led by IBM to develop virtual enterprise technology based on STEP, OMG, workflow management, and the Internet. An initial program for two years with funding shared by the Advanced Research Projects Agency (ARPA). They are creating a reference architecture, scenarios for potential virtual enterprises, and pilot projects.

See http://www.niiip.org.

A.19. Open Application Group (OAG)

A new consortium of client/server software suppliers organized to develop application interfaces. The consortium comprises SAP AG, American Software, Inc., The Coda Group PLC, Dun & Bradstreet Software, J. D. Edwards & Co., Marcam Corp., Oracle Corp., PeopleSoft, Inc., and Software 2000, Inc. While their interests appear more generally management oriented than manufacturing specific, there are many interfaces in common.

A.20. SEMATECH

A consortium of major U.S. semiconductor manufacturers (see http://www.sematech.org). Its CIM Application Framework project is developing a specification for semiconductor manufacturing software based on OMG's CORBA (Common Object Request Broker Architecture) technology (see [SEMATECH 96] and http://www.sematech.org/public/cim-framework/home.htm). The Framework is object-oriented and uses CORBA/ IDL, English narrative, Rumbaugh diagrams, and Harel statecharts in the specification. Much of this specification is quite general to manufacturing beyond semiconductors. Although it is much more specialized, there are many similarities between the CIM Application Framework and the NIIIP Reference Architecture, including their commitments to CORBA technology. SEMATECH is a corporate member of OMG and an active member of SEMI.

A.21. Semiconductor Equipment and Manufacturing International (SEMI)

An international trade organization with membership from companies that supply equipment, materials and services used in the semiconductor manufacturing industry. SEMI publishes industry-related standards, examples of which are their SECS-I, SECS-II and GEM standards. GEM is an equipment model that is used as a reference model for any type of semiconductor equipment. The GEM standard contains generalized functionality that applies to most semiconductor equipment. It does not address unique requirements of specific equipment. SECS-I is a standard that specifies a method for a message transfer protocol with electrical signal levels based upon EIA RS232-C. SECS-II is a standard that specifies a group of messages and the respective syntax and semantics for those messages relating to semiconductor manufacturing equipment control.

SEMI has recently chartered a task force to study the feasibility of developing an object-based equipment model influenced by its GEM standard and by SEMATECH's CIM Application Framework specification (see above).

See http://www.semi.org/

A.22. Standard for Exchange of Product Model Data (STEP)

This is an international standard, ISO 10303, for representing product data. Several "Parts" (major independent components of the standard) have already been formally adopted. There are additional Parts in various stages of development. The idea of dividing a standard into Parts, which are balloted separately, provides a way to develop a very complex standard over a period of years. There are many groups in North America, Europe, and the Pacific involved in supporting this standard. Two examples are PDES, Inc. and USPro. NIST provides the secretariat for TC184/SC4, the ISO committee responsible for STEP.

See http://www.hike.te.chiba-u.ac.jp/ikeda/documentation/STEP.html, the STEP Home Page.

A.23. Systems Integration for Manufacturing Applications (SIMA)

A NIST laboratory program with about 20 projects devoted to manufacturing. This is an internal program in that it does not fund work outside NIST, but many of the projects work jointly with other projects such as TEAM (see below) and STEP (see above).

See http://elib.cme.nist.gov/msid/projs/sima-pm/sima.htm

A.24. Technology to Enable Agile Manufacturing (TEAM)

A Department of Energy (DoE) sponsored manufacturing initiative with a number of projects in the DoE laboratories in partnerships with U.S. industry.

See http://cewww.eng.ornl.gov:443/team/

A.25. Windows for Science, Engineering, and Manufacturing (WinSEM) and OLE for Design and Modeling

Two of several groups working on interface standards based on Microsoft's Windows series of operating systems. These two groups cover areas of interest to manufacturing.

See http://www.labtech.com/winsem.html

A.26. Workflow Management Coalition (WfMC)

"The Workflow Management Coalition, founded in August 1993, is a non-profit, international organization of workflow vendors, users and analysts. The Coalition's mission is to promote the use of workflow through the establishment of standards for software terminology, interoperability and connectivity between workflow products." Workflow is an important generalization of a broad class of processes that are vital to businesses of all types. Both NIIIP (see above) and OMG have established contacts with WfMC. They have papers and draft specifications that are available electronically.

See http://www.aiai.ed.ac.uk/WfMC/

A.27. X/Open

X/Open is a not-for-profit, vendor-independent, international consortium which is dedicated to the advancement of open systems throughout the world. It has become the integrator of standards within the industry, bringing together users, vendors and standards bodies working towards the proliferation of open systems. (Quoted from their overview in http://www.xopen.co.uk/).

Appendix B. REFERENCES

The following bibliographic references concern the definition or needs of manufacturing, or specifications and standards mentioned in the rest of this White Paper as having relevance to object-oriented manufacturing systems. General literature about object-oriented systems, including object-oriented analysis and design methods, is omitted for brevity.

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