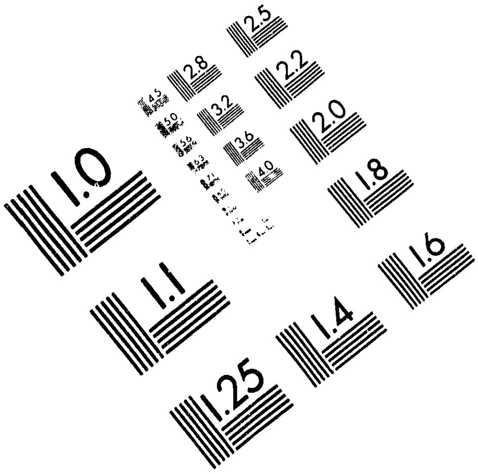

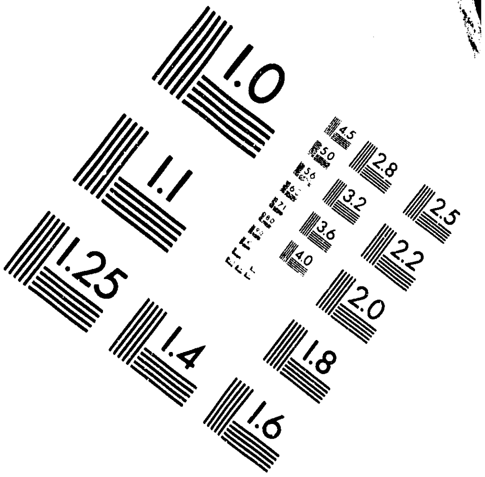

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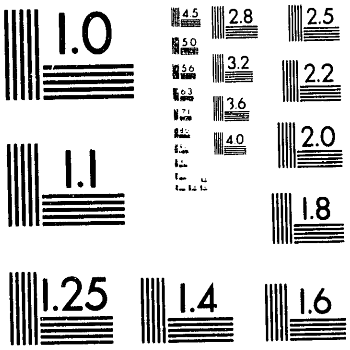

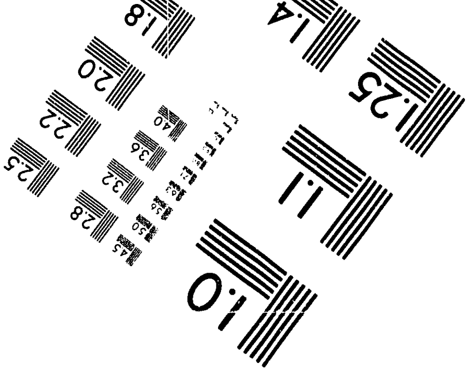

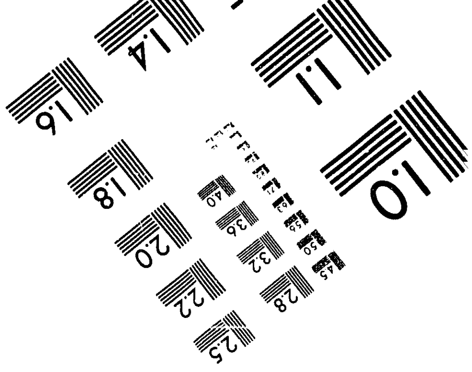

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ENTERPRISE INTEGRATION: A TOOL'S PERSPECTIVE

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ABSTRACT. The advent of sophisticated automation equipment and computer hardware and software is changing the way manufacturing is carried out. To compete in the global marketplace, manufacturing companies must integrate these new technologies into their factories. In addition, they must integrate the planning, control, and data management methodologies needed to make effective use of these technologies. This paper provides an overview of recent approaches to achieving this enterprise integration. It then describes, using simulation as a particular example, a new tool's perspective of enterprise integration.

1. Introduction

A revolution has taken place in manufacturing plants over the past two decades. This revolution has been fueled by the introduction of new computer and production technologies on the factory floor and in the front office. From FAX machines to computer-controlled, high-precision machine tools and from Computer Aided Design systems to Automated Data Collection systems, these technologies promised to increase quality, productivity and profits. Utilizing these new technologies, many companies have succeeded in substantially upgrading/automating individual production and office functions. They have been less successful when it comes to integrating all of these functions together within a single enterprise. The integration of multiple enterprises has progressed at an even slower pace.

In (Jones et al 1989) the authors expressed a commonly held view at the time, that the foundation for achieving this integration was a system architecture. This system architecture consists of four separate but related architectures: business management, production management, data management, and communications management. Business management includes all of those functions normally associated with running the business aspects of the company. Production management includes all of the functions related to the design, fabrication, and inspection of parts. Data management includes all functions related to the delivery of accurate and timely information to the production management processes. Communication management includes those functions required for the reliable transmission of messages between computer programs.

Each of these architectures has been the subject of intense world-wide research, at universities, individual companies, research institutes, and government laboratories. Numerous papers have been published which report the results of these efforts, but the fact is that only very low levels of integration have been achieved in real manufacturing companies. This paper provides some insight into 1) issues related to the design and implementation of each of these individual architectures and 2) reasons for the inability of enterprises to integrate these individual solutions into an overall system architecture. It then proposes a new focus for enterprise integration - a concentration on integrating key manufacturing software tools. This paper does this by way of a specific example, simulation.

The two most renown public efforts in this area have been undertaken by the National Institute of Standards and Technology (NIST) and The European Strategic Programme for Research and Development (ESPRIT). The NIST effort is centered in its Automated Manufacturing Research Facility (AMRF). The ESPRIT effort is centered in Project 688 - Computer Integrated Manufacturing Open System Architecture (CIM-OSA). This paper will touch on some of the work done at NIST. Those interested in finding out more about CIM-OSA are referred to two excellent sources: "The Proceedings of the First International Conference on Enterprise Integration Modeling (Petrie 1992) and a book titled "Open System Architecture for CIM" (ESPRIT 1989).

2. Issues in business and production management

Taken together, business and production management includes all functions needed to run a manufacturing enterprise. Many companies have invested a large amount of time and money to develop their own proprietary architectures. While these are typically separated in the real world, most government and university architecture-related research efforts have lump them together into a single factory control architecture. In the following sections we summarize the state of the art in this effort. Much of what follows is excerpted from (Jones et al 1989).

2.1 CURRENT APPROACHES TO DESIGNING FACTORY CONTROL ARCHITECTURES

Hierarchical organizational structures have been used to provide the coordination necessary to manage production activities in traditional human-based factories. The number of levels and the responsibilities of the individuals at each level can vary dramatically from one company to another. In many small companies, all decisions are made at the top, and subordinates simply implement various decisions at their own level. In most larger companies, people at every level are expected to make certain decisions, based on input from a superior, and exert the control necessary to have subordinates execute their decisions.

Early attempts to design and implement factory architectures for modern manufacturing enterprises have used the same hierarchical approach (Jones and Whitt 1985). Their designs are based on three principles (Albus, Barbera and Nagel 1981). First, levels are used to reduce the size and complexity of the problem and to limit the scope of responsibility and authority. Each "level" consists of a combination of people and computers which decompose commands from a supervisor at the next higher level into procedures to be executed by other entities at that same level and subcommands to be issued to one or more subordinate levels. Second, decision making and control always resides at the lowest possible level. That is where the most complete, up-to-date, and deterministic information is available. Third, planning horizons decrease as you go down the hierarchy. At the higher levels, the horizon can be months or years. At the lowest level, the horizon can be less than a second.

There are, however, three attributes that distinguish one hierarchy from one another. First, there is the number of levels and the assignment of functions to levels. In most designs, this "decomposition" depends on both the complexity of a given function and the actual physical configuration of the system. The Advanced Factory Management System (Liu 1985), which is based on the approach of grouping similar machines close together, has four levels. The Automated Manufacturing Research Facility model (Jones and

McLean 1986) is based on a group technology approach to shop floor layout and has five levels. The Factory Automation Moaei (Ottawa 1986), which attempts to accommodate both, has six. The second characteristic involves the identification and direction of control paths. Control relationships can be assigned once and remain static or they can be assigned dynamically as the situation dictates. The question of direction is independent of assignment. Most hierarchical architectures allow only vertical control flow. This means that each control module can have only one supervisor who issues commands. This supervisor always resides at the next higher level.

The last distinguishing characteristic is the method of handling data. In early hierarchical architectures data handling was viewed as one of the control functions at each level and is included in the existing control hierarchy. This means that the data needed to carry out a given command is either part of the command itself or tightly coupled to the control path. The consequence of this was that the only exchange of information, regardless of the content was between a supervisor and its' subordinates. Modern communication technologies have obviated the need for this restriction. In fact, there is a totally separate data management architecture which serves the control hierarchy. In this case, control modules must access the data needed to execute a command from the data management system.

During the last several years, many researchers have turned their attention to the heterarchical control strategies first advocated in (Hatvany 1985, Duffie and Piper 1986). In this approach, there are no supervisors per se. All entities are treated as co-operating equals in an ongoing process to plan, schedule, and control the manufacturing system. Decision are reached through a complicated series of broadcasts, bids, and negotiations.

2.2 WHERE ARE WE NOW

Although numerous designs (Jones and Whitt 1985, Jones 1990) have been proposed, major problems have arisen in the implementation of each design in real manufacturing enterprises. There have been and continues to be problems developing automated decision-making methodologies which adequately duplicate the way human beings conduct the negotiations needed to make complex decisions. Even if we could automate these decisions, we do not know how to integrate the results into the distributed computing environments that result from either a hierarchical or heterarchical architecture. Another major implementation problem arises because factory control architectures are typically imbedded as part of an existing factory. No suitable migration strategies have been developed which will allow the required modular implementation. In addition, there is no way to determine whether a given design is appropriate for a particular application before, during, or after initial implementation. No performance metrics or software tools are available which are designed to test a given factory architecture. We agree with (Nof 1988) that a combination of quantitative/qualitative performance measures and analysis tools must be developed which can be used to compare different designs and select the "best".

3. Issues in data management

The main purpose of a data management system in a manufacturing enterprise is to support functions in the business and production management architectures with timely access to all required data. There are, however, many characteristics of a manufacturing enterprise which makes this a difficult task. We now present a brief discussion of three of these characteristics.

The computer and data systems used in modern manufacturing enterprises are purchased from a variety of vendors over a long period of time. This implies that data is likely to be physically distributed across a network of local heterogeneous computer systems. These local systems will have a wide range of capabilities and restrictions for access, storage, and sharing. In addition, many of these systems were developed in-house or purchased from vendors that no longer support those particular products. These so-called legacy systems cause enormous integration problems. In many cases, the integration of these systems is performed manually. That is, the output from one system is manually re-entered in to another, because electronic integration is impossible. Finally, manufacturing data comes in all shapes and sizes ranging from gigabytes of CAD data down to bits of sensor data.

A second major characteristic is the fact that control computers for shop-floor equipment make real-time decisions. If the data is not present when it is needed, erroneous decisions or no decisions may be made, resulting in processing delays and reduced plant throughput. To complicate matters, some of that data may be shared by several users with different "real-time" access requirements. But, it is important to realize that data delivery, like material delivery, takes time and must be included in the planning of each job. This means that data is quickly becoming a critical resource which must be scheduled. Poor "data scheduling" will lead to delays, bottlenecks, and idle equipment. Therefore, the scheduling decisions made by the data manager have a direct impact on the scheduling decisions made by the production scheduler. This implies the need for coordination between the data scheduling function in the data management architecture and its counterpart in the production management architecture.

The third major characteristic is that many functions use parts of the same data package. This means that providing a uniform structure for these data packages will be a key to successful integration of these functions. Two of the most important of these data packages are product data and process plans. Electronic product data includes all of the raw data needed to design, fabricate, test, inspect, and maintain a product during its entire life cycle. A draft international standard (STEP) now exist for this product data (ISO10303 1992) . STEP is critical to external relationships with both customers and suppliers and the internal integration of many production management functions. Externally, it allows for the reliable, and unambiguous transfer of product information. That transfer can take place between customer and producer, or between two or more facilities involved in the manufacture of a single complex product. Internally, it is the main input to the process planning function which provides the integration of many downstream production functions. Major changes will be required in existing process planning systems to fulfill this role. All of the data (resources, timings, routings and alternatives) required to transport, fabricate, inspect, and ship a part must be included in the total process plan for that part. The total plan should be decomposed into subplans having the same generic structure. One or more subplans will be used by each production function to make decisions about each "job" it executes. Efforts are currently underway in ISO TC 184 SC 4 WG 3 to develop a standard process plan model.

3.1 WHAT CONSTITUTES AN ARCHITECTURE

A data management architecture must address three major concerns: data modeling, database design, and data administration.

Developing a "conceptual data model" of all the information involved in the enterprise is critical to the success of any integrated data management system. Because the amount of information is so large, a "divide-and-conquer" approach to performing the analysis must be taken. Experts on individual business and production functions will perform the analysis and develop a conceptual information model for each functional area. Then the resulting "component" models must be integrated into a single "enterprise model". The enterprise model is the conceptual representation of the global information base. To be successful, this integration must be based on the identification of common real-world objects and concepts, rather than trying to identify the "common data". A "conceptual model", therefore, must represent the relationships between information units as they apply to the real world, rather than the structured and limited relationships between these units as they are stored in a data system. Several powerful modelling techniques now available allow representation of the real-world objects themselves, as well as the information units which describe and distinguish them (Nijsen 1989, Peckman 1988, and Ullman 1988).

Once the global enterprise model has been constructed, we have the problem of mapping this model onto live databases. We must now choose systems, organizations and representations for the information units in the model. This process is called database design, and it is a difficult process to automate, particularly for manufacturing applications. It must result in databases which are consistent with the model and tuned to the timing and access requirements of the functions that use them. Since much of that data must be shared, two problems result: partitioning and replication. Partitioning means that some production functions must simultaneously access information stored in two or more databases. Replication means that some data must be stored simultaneously in two or more different databases, and maintained consistently. The available options for the placement of databases in the CIM computer system complex, and for the selection of specific data management systems to support them, are dictated to a large extent by the architecture of the "global" data administration system.

There are three control architectures for data administration systems which have been used with varying degrees of success in various business applications: centralized data and control, distributed data and control, and hybrid systems. The totally centralized approach is the traditional design, the simplest, and the most workable. There are currently available high-speed, internally redundant, fault-tolerant, integrated centralized systems. But even if such systems can keep pace with the growing demands and time constraints of automated production systems, the centralized architecture is not workable from the point-of-view of subsystem autonomy. The canonical architecture for the totally distributed approach consists of local data management systems which process locally originated and locally satisfiable requests and negotiate with each other to process all other requests. In this case, difficult problems of concurrency control, distributed transaction sequencing and deadlock avoidance occur and must be resolved by committee. While there has been considerable research in these areas, satisfactory solutions have not been found. The hybrid architecture attempts to combine the best features of both centralized and distributed architectures. Subsystem autonomy and high throughput are achieved by allowing local data systems to process locally originated operations on local data. Operations which transcend the scope of a local system are sent to a centralized "global query processor" for distribution to the appropriate sites. The global query processor acts as a central arbiter for resolving the characteristic problems of distributed transactions and for handling configuration changes in the data administration system itself. There are a number of ways of implementing such an architecture, but they are all characterized by standardized interfaces between the local data systems and the global query processor.

3.2 WHERE ARE WE NOW

There are many new commercial data systems available which are of this hybrid variety. But, in general, they have not yet resolved the control problems associated with distributed transaction management to the extent necessary to provide robust support for manufacturing applications (Thomas 1988). Unless the local system is aware of potentially global consequences of local changes, and can propagate those correctly, the integrity of the global information bases is always in doubt.

In the last decade, several object oriented database management systems have been commercialized (Morris et al 1992). These new systems provide many enhanced features like more advanced data modeling techniques and a more sophisticated transaction management. But, they have not yet reached the level of maturity seen in relational database systems.

Several standards are emerging which will have an impact on the development of data systems for manufacturing enterprises. These standards fall into two categories: those designed to make access and integration easier, and those for data representation. Some examples of standards falling into the first category include Structured Query Language (ISO/IEC 9075 1992), Remote Data Access (ISO/IEC 9579 1991), and Information Resource Dictionary System (ANSI -IRDS 1988). Some examples of standards falling into the second category include DFX (Autodesk 1992), Initial Graphics Exchange Specification (IGES5.1 1991) and Standard for the Exchange of Product Model Data (ISO10303, 1992).

In summary, while there have been numerous advances in data management and numerous standards adopted, there are still no commercially-available, distributed data systems that allow arbitrary data repositories. This means that we are still a long way from a commercially-available solution to the legacy problem for manufacturing companies. However, there have been prototypes developed in the research lab. One of the earliest and, perhaps best known, is the Integrated Manufacturing Data Administration System (IMDAS) developed at NIST (Libes and Barkmeyer 1988). IMDAS implements a hybrid four-level hierarchical planning and control architecture for information which provides a common interface to user programs and a common interface to the underlying data repositories. The interfaces transparency from the actual data repositories. That is, the actual location of data and the work done to satisfy a user request is completely transparent to the user. Conceptually, the user simply sees a single logical database managed by the IMDAS. This single database can contain several different physical data repositories ranging from commercial databases and file systems to "home-grown", application-specific data systems. The major unresolved problem with IMDAS and all other similar types of distributed systems is distributed transaction management (Thomas 1988).

4. Issues in communications

Communications can be divided into two classes: those WITHIN computer systems, and those ACROSS computer systems. The first type is often referred to as "interprocess communication" while the second is often called "network communication". Interprocess communication is dependent on features of the operating system. Many systems provide no such facility at all, or provide only for communication between a "parent" process and "child" subprocesses which are created by the parent. On such systems the coordination of multiple business, production, and data management activities is extremely difficult. On the other hand, properly implemented "network communication" software should provide for the case in which the selected correspondent process is resident on the same computer system as the process originating the connection. That is, the proper solution for the future is to make local interprocess communication a special case handled by the network software.

The accepted paradigm for network communication is the Open Systems Interconnection Reference Model (OSI) which separates the concerns of communication into 7 layers (Day and Zimmerman 1983). Traditionally, "network communication" has meant concentration on the lower four layers and "exposure" of the Transport layer to production management programs. The important aspect of this model is that it formalizes and separates the logical process-to-process link (in layers 5-7) from the physical network service considerations (in layers 1-4). By exposing only the Application layer service, we insulate them from the networking concerns. Consequently, we believe that it is meaningful and proper to build an Application layer interface which is common to ALL program-to-program communications, both "local" and "networked".

4.1 CIM network architecture

A great deal of flexibility is created by implementing the OSI model. On one hand, a single physical medium can multiplex many separate process-to-process communications. On the other hand, a given process-to-process connection can use several separate physical connections with relays between them. Ideally, all stations on the network implement common OSI protocol suites in the intermediate layers (3-5) and some globally common protocols for moving data sets in layers 6 and 7. In addition, other standard application layer protocols will be shared among systems performing related functions. The choices of protocol suites in the Physical and DataLink layers and the connectivity of individual stations will vary. They will depend on the physical arrangement and capabilities of the individual stations, and their functional assignments and performance requirements. There may be one physical network, or many. All of these separate physical networks, however, must be linked together by "bridges" that implement the proper Network layer protocols. This results in a SINGLE LOGICAL NETWORK on which any given production management or data management process can connect to other processors regardless of location. We note, that because this architecture is layered, multiple subnetworks become transparent.

4.2 Where are we now

There are now many standard protocol suites for the DataLink and Physical layers, and there will soon be more. They all provide frame delivery and integrity checking; some provide for reliability and recovery, others defer those considerations to the transport layer. The real distinguishing characteristics among these standards are the signalling technologies and the sharing algorithms. Loosely speaking, the signalling technology determines the raw transmission speed, the relative immunity to electronic noise, and the cost. The sharing algorithm determines the nature of network service seen by the station. There are generally three choices:

a) connection to one other station or one other station at a time, with fixed dedicated bandwidth (point-to-point, time- and frequency-division);

b) connection to multiple stations simultaneously, with variable bandwidth with fixed lower and upper bounds depending on the number of stations connected to the medium (token bus and ring);

c) connection to multiple station simultaneously, with variable bandwidth from zero to the bandwidth of the medium depending on the traffic generated by all stations connected to the medium (CSMA/CD).

In general, engineering and administrative activities, which have infrequent and variable communications requirements, can tolerate and use the type (c) services more effectively. The production control activities, which have frequent and regular messaging requirements, however, prefer type (a) or (b) services.

There are also several "standard" protocol suites for the intermediate layers as well. But in this area, the differences are historical rather than functional. It is clear that the existing intermediate layer protocols will be THE standard in the near future. In the upper layers, standards are still evolving. Here the only problem will be to determine the suite of protocols necessary to a given production management or data management function.

The Manufacturing Automation Protocols (MAP) concept of one physical bus connecting all factory-floor stations may be appropriate for some manufacturing facilities. It is not, however, general enough to meet all communications requirements of the factories of tomorrow. However, the "enterprise networking" concept, connecting MAP control networks with Technical Office Protocols (TOP) engineering networks, demonstrates that a more generalized manufacturing network architecture is, in fact, currently practical. We believe that this will lead customers to demand, and vendors to produce, products consistent with that architecture (MAP and TOP 1988).

It is likely that emerging physical networking technologies will, in time, make the physical layer standards selected by MAP/TOP obsolete. This will lead to the addition or substitution of subnetworks with new physical and datalink protocols to current manufacturing networks. Nevertheless, the transparent, multiple, subnetwork architecture can result in little or no impact on networks already in place and on process-to-process communication. At the same time, adherence to at least the layering, but preferably also the intermediate layer protocol suites, in various types of "gateway" machines, provides for the transparent interconnection of subnetworks based on proprietary, or nonstandard protocol suites in the lower layers.

5. Remarks

The key benefit of enterprise integration lies in the potential for consistently delivering the right information to the right people at the right time, regardless of the physical location of the information or those who need it. To achieve this benefit requires the solution to all of the problems described in the sections on information and communications management. But, for this benefit to have maximum impact, this concept of "just in time" information delivery must be coupled with the ability to perform “just in time” information processing and analysis. This requires the solution to all of the problems described in the section on business and production management. Remember, that these problems are divided into two classes: choosing the right architectures, and advancing the various technologies needed to implement those architectures.

The fact is that much more progress has been made on individual technologies than on the integration of those technologies. This is particularly true for business and production management. New and better software tools appear in the marketplace everyday. But, the integration of tools has been hampered because there are no standard architectures for vendors to build to. Consequently, each individual manufacturing enterprise must pay large sums of money to develop its own architectures to use as the basis for integration. And, unless something is done to decouple integration from architectures, enterprise integration will continue to be a costly, if not elusive, undertaking.

We believe that significant progress can be made in enterprise integration, in the short term, by shifting the focus away from this top-down approach. The time has come for to begin a bottom-up “integrated tools” approach. In other words, we should begin to answer the question “What does it take to integrate the software modeling/analysis tools needed to perform key business and production functions?” Examples of these key functions include manufacturing engineering, production planning and control, systems design, and cost estimating. Each of these has three important characteristics: each can be decomposed into several well defined subfunctions; modeling/analysis tools exist to perform these subfunctions; and these tools cannot be integrated together electronically today. How do we address the third of these characteristics?

In the remainder of this paper, we concentrate on one of the most important of these modeling/analysis tools - simulation. (Much of what is covered in the remainder of this paper applies to all such tools.) In section 6, we discuss 1) why simulation is important as an enabling technology for enterprise integration, 2) why simulation is not currently fulfilling that role, and 3) what new technological advances are needed before simulation can fulfill that role in the future. In section 7, we turn our attention to other barriers to the successful integration of simulation technology into the enterprise.

6. Simulation as an Enabling Technology for Enterprise Integration

6.1 WHO NEEDS SIMULATION MODELS?

There are three principle groups within the enterprise who must have access to models of products and production: 1) Product and Process Design Teams, 2) Production System Designers, and 3) Production Managers. Each of these groups will use these models in different ways and for different purposes, but they all share a need for easy access and inexpensive analysis.

6.1.1 *Product and Process Design Teams.* Product and process design teams are responsible for developing new products and their associated manufacturing processes. They need models that evaluate performance of the product versus product specifications, and, to an increasing degree, they require models that assess manufacturability and cost. The simulations performed by these teams often represent the dynamic behavior of the product or of a production process; they often represent the physical and chemical interactions of the production processes, and frequently the models are highly detailed. Such models are needed at three levels of detail: system, subsystem/assembly, and unit process.

System level models relate design characteristics to performance. For example, a systems level model of an automobile will relate "crashworthiness" to structural design characteristics. Such a simulation might be a complex, computationally intensive finite element model. Another example would be a model of radio frequency emissions from a computer's motherboard. These simulations are used to negotiate product requirements and cost trade-offs with customers, to perform virtual prototyping, and to reduce the number and variety of actual prototypes required.

Subsystem/assembly models focus on the cost, performance, and manufacturability implications of individual design decisions. These models are used to evaluate the ability of existing manufacturing processes to produce the product at acceptable quality and yield and to allocate design space, tolerance, and error budgets to avoid costly, technology-limiting configurations. These simulations may be statistical models that use process capability knowledge, heuristic/knowledge-based models of manufacturability, or they may involve computationally intensive process modelling of the interactions between product features and process characteristics. Examples include 1) tolerance analysis of total indicated runout for multi-axis mechanical assemblies and 2) prediction of functional yield for printed wiring boards from combined knowledge of statistical process capability and cross-trace electromagnetic interference.

Unit process models optimize the parameters of production processes to produce the required product characteristics, to prevent damage to the product from the process, and to reduce cost or environmental impact. Examples include finite element analysis of the solidification of encapsulants and glass-to-metal seals to reduce residual stresses and cracking, optimization of electro-plating control strategies to reduce environmentally damaging heavy metal wastes, and computer-aided casting design to produce good cast parts the first time.

6.1.2 *Production Systems Designers* . Production System Designers are responsible for developing production capability to manufacture products. They need simulations and models to plan capacity, develop control algorithms, and insure quality and flexibility. The simulations performed by this group generally represent the flow of materials to and from processing machines and the operations the machines perform. The critical issues that are assessed include throughput, location of bottlenecks, impact of machine unreliability, and cost. In addition, the flexibility of the production facility is often a key design consideration. It is rare for a production cell, shop, or plant to manufacture only a single product. The ability of the facility to handle a mix of products is often a key design concern. In fact, today, plants are being designed to economically produce a large mix of products each of which is made in small lots.

Production systems inherently include a large number of static and dynamic policy opportunities. Static, or one-time, decisions are usually the responsibility of the designer and include the answer to such questions as: which is better,

> 1) a single, high capacity machine with low operating costs but which completely interrupts production when it is off line, or
>
> 2) several smaller, lower capacity machines with greater total operating costs.

The performance of production systems hinges critically on these policy decisions, and intuition is frequently a poor guide to making optimal selections because of the complexity and stochastic nature of the interactions among subsystems. Furthermore, the performance objectives are highly correlated - sometimes positively and sometimes negatively. Minimizing cost and maximizing flexibility are two such negatively correlated objectives, because flexible, highly reliable equipment is expensive. As a result, analysis tools such as simulation are critical to capturing the trade-offs and helping the decision-maker select the best among the many alternatives available when configuring and running a production system.

6.1.3 *Production Managers* . Dynamic decisions, which include real-time operating policies and control algorithms for routing of automated guided vehicles, scheduling and sequencing procedures for production, queuing disciplines for work in process, tool management policies, and inventory control are made by production managers. They are the people who are responsible for day-to-day operation of production facilities. They can use simulations and models to perform master scheduling, production scheduling and sequencing, control of production equipment, factory reconfiguration, and troubleshooting. They are primarily concerned with the day-to-day dynamic policy decisions related to real time scheduling and sequencing of production to satisfy immediate delivery requirements. This is a challenging job because the shop floor environment is never static. Production machines become unavailable, processes go out of control, discrepant source materials must be accommodated, materials do not arrive on time, due dates change, scrap rates fluctuate, and the product mix changes wildly. Under these conditions, sequencing of production and the allocation of resources within the plant become challenging tasks. The level of detail that the Production Manager must deal with is usually significantly greater than the Production System Designer. Furthermore, the time horizon is usually much shorter. Production Management focuses on policy horizons of a single day or a fraction of a day whereas Production System Designers typically develop optimal designs for weeks or months of operation.

6.2 COMMON OPERATIONAL NEEDS FOR MODELS AND SIMULATIONS

Each of the three groups of simulation users has different application needs, and they use a variety of modeling methodologies. Nevertheless, in creating, using, and maintaining their models, these groups perform many similar activities, and they must all deal with the shortcomings of today's modeling technologies. These shortcomings arise because of several factors: inadequate descriptive methodology, poor interoperability among models, little or no information integration, clumsy user interfaces, and few intelligent decision-making aids. All of these factors contribute to the difficulty involved in the entire process from model building to output analysis process. Listed below are problem areas that exist with current simulation methods and enterprise technology.

Modelers should not have to translate system definition data that exists in one form into a special descriptive language that is unique to the simulation program. Simulation programs should work directly with the system definition information available to the user and modeler. A typical case is that of the product designers for whom this information is frequently a CAD representation. Examples of this type of technology are automated meshing programs for finite element analysis that operate directly on 3-D CAD models of the parts to be analyzed. Little is being done to address the problem on a broad scale, however. For example, in the case of factory modeling, shop floor layouts must still be translated into simulation software- specific descriptive formats, and data entry is still mostly manual (albeit interactive).

Users should not have to reenter information that is or should be in computer readable form. Most factories have information systems which contain or could contain process plans, equipment characteristics, order information, lead time data, shop floor status, inventory status, and resource availability. In the case of performance and process simulations, data such as material characteristics, electrical properties, component data, and other performance information is readily available in parts data bases and other sources which could be electronically accessible. This low level (if any) of integration between enterprise information bases and simulation continues to be a major reason for the high cost of developing, validating, using and maintaining models.

Users should not have to be experts in the design of statistical experiments and the subsequent analysis and interpretation of results from those experiments in order to safely and effectively use simulations. The design of experiments to yield valid results and the interpretation of outputs are largely procedural activities. Intelligent processing modules could relieve much of the burden of performing these chores, and they could bring simulation analysis within the reach of many potential users who are not experts in these arcane topics.

Users should not have to manually assure the accuracy and currency of all of the data and configuration information embedded in a model each time it is used. Models should be reusable without extensive checking and reentry of data which is readily available electronically. This issue is particularly acute in the case of Production Management where shop floor data and machine status may change daily.

Expert modelers should not be required to perform maintenance on the model each time a slightly different scenario is to be analyzed or a different performance parameter is to be examined. With today's simulation methods and architectures, it is difficult to separate the model from the analysis. It is also difficult to expand or contract the modeling viewpoint in order to change the focus of the analysis. Models are too frequently constructed (and chartered!) with only a single use in mind. This leads to an inseparable relationship between representation and data collection elements. In other words, the level of detail in the model is tailored specifically and narrowly to yield the performance data in question. To some, this may appear to be an admirable and even necessary economy to satisfy the customer's immediate needs at minimum cost. But, simulations, like most other software, are seldom used only once. Moreover, subsequent uses almost always require enhancement to the original mode. Today, experts are often needed (sometimes at high cost) to build models that a user or manager would consider to be minor extensions of an existing model. For example, a production model of a work center that contains several cooperating work cells cannot be modified easily to focus on only one of the cells. Nor can it be focused on a group of machines within a single cell. The reason is that today's modeling methodologies are not conducive to building different levels of aggregation within a single model. In other words, the monolithic architecture of today's simulation methods does not facilitate multiple views without reconfiguration of the model by experts.

6.3 A TECHNOLOGY RESEARCH AGENDA FOR THE NEXT GENERATION SIMULATION TOOLS

If simulation modeling/analysis methodologies were structured properly, then simulation could be as pervasive tomorrow as MRPII and CAD are today. Both MRPII and CAD are complex software systems that perform mathematical operations which are completely hidden from the users. Few users understand the details of the functions performed by these programs. Yet they are able to use MRPII and CAD effectively and routinely in their daily work. There are three main reasons. First, these applications have automated the labor intensive chores associated with manipulating data. Second, they have hidden the theoretical aspects of their functions from the users. Third, and perhaps most important, they can be utilized in a manner which is completely within the domain expertise of the users. Modeling and simulation must take a similar approach if it is to be an institutionalized and operationally useful tool. Several capabilities need to be developed before that will happen.

6.3.1 *Interfacing.* Simulations will need to interface seamlessly and automatically with other enterprise information systems. Manual gathering, analysis, formatting, and entry of data for simulations is an enormous barrier to the use of simulation. It is so burdensome that even users who have a nonrecurring need for analysis may decline to build the model because the data collection is so expensive. In the real time environment of a production plant, simulation as a management tool is out of the question unless direct links to shop floor status information are imported automatically.

6.3.2 *Simpler Construction and Maintenance.* Descriptive methods are needed which simplify the construction and maintenance of most simulation models. Once configured, the information that is contained in and manipulated by MRPII and CAD systems is maintained by users. A similar condition must be achieved for simulation. This implies that the system definition language must be contained in the domain expertise of the user. Today's simulation definition languages were developed to facilitate programming; indeed, these languages are equivalent to programming languages. Even those systems that use pictorial, interactive model building schemes have their roots in making the translation to a working program easy. They do not focus on capturing a dynamic representation of the user's design intent. Today's system definition languages fall into two categories. The first group tends to be static and descriptive in nature like NIAM (Nijsen and Halpen 1989) and IDEF$_0$ (Mayer 1979). These languages show relationships among functions, but capture none of the rich dynamics of interaction. The second class includes most of the simulation "languages." These tend to be programming language oriented and are structured around and constrained by artifacts of the underlying simulation engine. The contrast between the world views of Systems Dynamics (PughIII 1973) and GPSS (Schriber 1973) illustrates this clearly. The way in which a system is described by these two languages is determined by the computational scheme that will be used in the simulation. A fresh approach is needed which combines the best features of both categories. This new representation technique must have three important characteristics:

1) a tailorable external view that is simple enough to be learned by users of simulation who work in a diverse set of domains,

2) a hidden abstraction layer which maps the representation elements of the external view to a finite set of enterprise concepts, and

3) a dynamic modeling layer which can link operational models of the enterprise concepts into a coherent simulation of the user's intent.

6.3.3 *Distributed simulation architectures* . Distributed simulation architectures are needed which will enable multiple views and which will allow local construction and maintenance of models. A distributed architecture means that submodels interact through a well defined protocol with other submodels to achieve a combined simulation. Several benefits are achieved with this approach. First, the smaller submodels can be understood, built, and maintained at less expense and risk than a monolithic model. Second, the owner of a subsystem, such as a work cell, can be the owner of its submodel. Distributed ownership will mitigate against monolithic, single purpose models. The submodels will be designed to represent actual operations (at some defined level of detail) rather than be tailored to provide a specific performance parameter. Finally, a "plug and play" capability is conceptually possible in which the view of a simulation will change depending upon which submodels are included. It will be possible to focus a model on several machines within a cell as easily as performing an analysis that involves multiple cells.

6.3.4 *Statistical Design and Analysis*. Functions are needed for data reduction, experimental design, and output interpretation which are architecturally separate from the models. Users must be shielded as much as possible from the theoretical issues associated with the quality and meaning of the data that is input to and generated by the simulation. This separation also mitigates against embedding artifacts within the model to address specific data collection needs and therefore limiting the model's scope.

6.3.5 *Verification and Validation*. In a distributed environment, capability will be required to automatically verify the integrity of the simulation model. With distributed ownership of models, an automatic agent will be needed to verify that the correct versions of models are present, that the data sets are current, that the models selected to be a part of the simulation are coherent and compatible. In addition, real time manufacturing management applications will require that the latency of information is monitored and updated as required to create a coherent data set.

7. Simulation as Part of an Integrated Enterprise

We have argued that enterprise integration provides a common environment for data, information, and decision making. This common environment makes it possible to realize the goal of having all aspects of the manufacturing corporation managed consistently and effectively. We argued further that simulation tools have the potential to play an important role in the decision-making part of this goal. In the preceding section, we discussed several technology-related barriers to simulation realizing this potential. In this section, we will describe several other issues which must be resolved before simulation can be really integrated into the enterprise. These issues are quite complex, involving considerations of technology, culture, and corporate structure. In order for simulation to be effective in the integration of enterprise functions, it must be used at all levels in the enterprise. We begin with a description of the enterprise integration process, with special emphasis on those steps where simulation can make the process more effective. We will then describe a basic taxonomy for research in simulation and identify several important research topics to support the use of simulation in enterprise integration. Much of this can be generalized to include all tools that support enterprise integration

7.1 THE ENTERPRISE INTEGRATION PROCESS

The use of simulation in enterprise integration is based on the premise that simulation models of all aspects of the corporation can be constructed. These simulation models can provide the means to capture decision processes, data and knowledge about how an enterprise is designed to operate. The models can also be used to increase knowledge and understanding about an enterprise. They provide a vehicle for understanding and managing the continuous change and improvement of manufacturing operations. The need for this process is described in detail in (Hayes et al 1988). Pritsker (Pritsker 1991) also addresses the need to provide simulation-based modeling tools to help in managing the "capacity" of a manufacturing enterprise.

To understand how simulation can be used to enhance enterprise integration, we must have a firm grasp of the enterprise integration process. The following summarizes the major steps in enterprise integration, which occur continuously throughout the life of an enterprise, and discusses the role of simulation in each of these steps.

7.1.1 *Define the Enterprise Structure.* The first step in Enterprise Integration is to completely define the components of the enterprise and the relationship of each component to the others. This is a dynamic, or changing, representation but should reflect the current status of the organization. It would include a specification of the objectives of each component, their information requirements, and the flow of information from one component to another. Typical components in enterprises include executive management, research and development, product and process design, production or factory floor control, finance, and marketing.

Simulation models of these components and their relationships can be constructed. These models can be detailed or general, depending upon the specific analysis objectives. These models should at some level of detail, span enterprise components. For example, the models might include data flow representations between marketing and the factory floor, to investigate information system requirements to support the policies to be implemented. Other models might be focused in great detail, to represent, say, the scheduling and control of the manufacturing facility.

Along with the identification of the role of simulation in each of these components of the enterprise, the characteristics of the model users should also be specified. The model users should be involved intimately in the model development process and will flesh out the representation of the structure of the Enterprise.

7.1.2 *Identify Current and Future Enterprise Characteristics.* Enterprises change and evolve in a variety of ways. The strategic plan of a corporation may change in response to certain market conditions or opportunities. The enterprise may change in response to internal forces or characteristics. Key personnel can leave to explore other interests, new and dramatically different equipment can be purchased, or the location of the company can be changed. In planning for a successful, integrated enterprise, it is important to have the capability to represent all possible feasible “states” and to analyze their impact. The state of the enterprise includes not only the resources and information in the enterprise, but also the management procedures and decision processes which comprise it. These can all be effectively represented and analyzed using simulation models.

7.1.3 *Develop the Roadmap for Enterprise Change.* To reach a desired future state, an enterprise must often evolve through a variety of intermediate states before reaching it. A migration plan, or roadmap, is typically developed to support this evolution. The roadmap describes how each component will change over time. For example, if a new product line is to be introduced, manufacturing must have both capacity and capability to support it. This may happen over several months, perhaps including out sourcing as a interim measure until manufacturing develops the capabilities to support it. Other examples might include the development of new marketing capabilities for existing products, or changes to the information system of the company to allow important decision making information to be available.

Simulation can be used iteratively to represent the various interim states of the enterprise, and predict their performance. This might require several sets of models, each reflecting a step in the evolution of the enterprise. These models would need to interact as well, to communicate objectives and performance outputs.

7.1.4 *Manage the Enterprise.* As enterprises operate, changing or remaining static, they must be managed. This requires management tools to schedule and control the enterprise. This is needed on a variety of levels, from the Board Room to the Factory Floor. The models which were built to describe, and perhaps design, the enterprise can also be used to manage it. To be effective, these models must be linked into sources of data and information about the enterprise in real time.

One of the best examples of the use of simulation for enterprise management is factory floor scheduling. Tools have been developed which are effective in bringing simulation to the factory floor for use in day to day production management (Grant 1988) But other parts of the enterprise could benefit from this technology as well. Finance might use information flow and personnel models to schedule various accounting system updates. Marketing might use simulation tools to manage the schedule for the introduction of a new product in conditions of reduced resources.

7.2 A TAXONOMY FOR SIMULATION RESEARCH IN ENTERPRISE INTEGRATION

Simulation research in support of enterprise integration is broad and involves many parts of the enterprise. The development of a taxonomy for simulation research will be helpful in organizing the research and describing the relationships of various components of the research and where they should be focused. This section provides a basic taxonomy of research areas in which simulation research should be expanded to support enterprise integration.

7.2.1 *Enterprise Modeling.* Simulation tools in this area of the taxonomy are concerned with broad enterprise management issues and are typically, but not always, less detailed and more subjective in nature. They address problems concerned with strategic planning, and broad enterprise design issues. They also include issues of technology management, and management of the corporate culture. These high level modeling tools would tend to drive models developed in other sectors of the taxonomy.

7.2.2 *Process and Product Design.* Simulation modeling in this area is concerned with the development and introduction of new products as well as the development and refinement of production processes. A typical example of an application in this area would be the evaluation of the impact of a new product on existing production facilities. Other topics include production resource planning, process/product design integration, and detailed process simulation. Design alternatives can also be evaluated, regarding their impact on production.

7.2.3 *Factory Floor/Production.* The simulation and modeling tools in this sector of the taxonomy are concerned with managing and controlling the factory floor. Scheduling and dispatching is the most important example. Hierarchical simulation is also important, where varying levels of detail are included in the models, from factory wide representations, to detailed cell models. These hierarchical models would communicate between layers to develop local schedules, or reschedule broader areas as the performance of the enterprise demands.

7.2.4 *Information Infrastructure.* This sector of the taxonomy is concerned with the underlying information systems which are needed to support the various models described above. Real time databases would be needed to store up to the minute information on the factory status as it evolves. These databases may be distributed, logically or physically, as the characteristics of the enterprise demands. Network and hardware technology would also be needed to integrate the various models in the enterprise. Both the database and the network technology should be extended specifically for simulation applications.

7.2.5 *Simulation and Modeling Support.* The final sector of the taxonomy is concerned with the development of support tools to make the application of simulation technology easier and more cost effective. It would include tools for statistical analysis of simulation output, visualization of output data in new and varying forms. It would also include research in special purpose simulation languages, which perhaps could be developed by the application engineer, for his specific enterprise. Finally, user interface technology is needed to support the user's interaction with the large variety of models present in any enterprise.

7.3 RESEARCH PRESCRIPTION FOR SIMULATION IN ENTERPRISE INTEGRATION

The taxonomy described above broadly describes the major area of research required for the effective application of simulation in enterprise integration. The following is a list of specific research topics which should be addressed.

1. Research in the development of tools which support the integration of models with daily management tools and technology to better support the daily use of models.

2. Research in the interfacing of models to information systems so that this is easy and flexible for users to incorporate and modify.

3. Develop tools and technology which will support the integration of simulation with other management tools.

4. Develop output analysis tools which are more easily applied and imbedded in simulation models so that users can generate statistical analyses with confidence.

5. Research simulation tools and methodologies to build enterprise wide evaluation models to support strategic planning functions.

6. Research the development of tools which can integrate multiple views into enterprises including financial/accounting, sales, marketing, management, information, and manufacturing.

7. Research in the development of simulation and modeling tools which can effectively and automatically model change in dynamic systems, at various levels of complexity and detail.

8. Summary and Conclusions

In this paper we have concentrated on enterprise integration. We looked at two different approaches: a top-down architecture-based approach, and a bottom-up integrated-tools approach. Most of the research into enterprise integration has focused on the former. We reviewed the basic strategies and outlined some of the outstanding problems associated with designing and implementing these architectures. We concluded that enterprise integration can be achieved this way but, because there are no standard architectures, it tends to be company specific, thus, very costly. We then argued that a new integrated-tools approach should be undertaken. We used simulation as an example of one such tool. We described both the technological and the integration issues which must be resolved before simulation can become integrated into the manufacturing enterprise of the future.

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