Virtual Manufacturing: An Emerging Technology

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Abstract

In this paper, Virtual Manufacturing (VM), an emerging technology, that provides the capability to *"Manufacture in the Computer"*, and the modeling approaches necessary to realize VM are presented and discussed. VM has the ability to interchange models between their use in simulation and control environments. The use of VM concepts improves decision-making and quickly achieves products with high performance and quality at a low cost. VM can provide accurate and realistic means to predict schedule, cost, and quality; address affordability as an iterative solution; and bridge the gap between engineering (design) and manufacturing in an interactive fashion. The benefits, costs, limitations, and risks associated with adopting VM are highlighted and discussed.

1. Introduction

It is known that acquisition strategies require the capability to prove the manufacturability and affordability of new products/systems prior to the commitment of large production resources and/or to shelving the system for restart in the future. Loosing the manufacturing capability and experience in production is a major risk in the current manufacturing environment [6, 8]. Maintaining the state-of-the art manufacturing proficiency without actually building/ manufacturing the products is a major challenge. Virtual Manufacturing meets the above challenges by providing the capability, in essence, to continue manufacturing in the virtual world of the computer. Through the use of distributed manufacturing modeling and simulation, VM enables the enterprises to evaluate the producibility and affordability of new product and/or process concepts with respect to risks, their impacts on manufacturing capabilities, production capacity, and cost.

Virtual Manufacturing is one of the key technologies that allow going beyond the assumptions driving the old acquisition strategies. It provides the following fundamental changes: VM can be used to *"prove out"* the production processes, resulting in *"pre-production hardened systems"* - i.e., the systems which are developed and verified but never actually undergo actual production runs; VM can significantly improve production flexibility, and hence, reduce the fixed costs; and VM can substantially improve the decision making process of acquisition managers by reliably predicting schedule, risks, and costs.

2. Background

According to the Air Force Man Tech *"Virtual Manufacturing is an integrated, synthetic manufacturing environment exercised to enhance all levels of decision and control"* in a manufacturing enterprise[6, 10]. Here, *"synthetic"* refers to a mixture of real and simulated objects, activities, and processes; *"environment"* supports the construction and use of distributed manufacturing simulations by synergistically providing a collection of tools (simulation, analysis, implementation, and control), models (product, process, and resource), equipment, methodologies and organizational principles; *"exercising"* refers to the construction and execution of specific manufacturing simulations using the environment; *"enhance"* refers to increasing the value, accuracy and validity of decisions; *"levels"* indicate from product concept to disposal, from the shop floor to the executive suite, from factory equipment to the enterprise and beyond, and from material transformation to knowledge transformation; *"decision"* reflects how one can visualize, organize, and identify changes in the alternatives; *"control"* corresponds to predictions that effect actuality.

However, it is clear from the results of the Virtual Manufacturing Workshops organized by Air Force Man Tech[11, 12] that a single definition of VM is inappropriate. A definition of VM is proposed to capture design, production, and control aspects of manufacturing: The Design-Centered VM adds manufacturing information to the Integrated Product and Process Design (IPPD) process with the intent of allowing simulation of many manufacturing alternatives and the creation of many *"soft"* prototypes by *"Manufacturing in the Computer"*. The Production-Centered VM adds simulation capability to manufacturing process models with the purpose of allowing inexpensive, fast evaluation of many processing alternatives. The Control-Centered VM uses machine control models in simulations, the goal of which is process optimization during actual production. Production-centered VM may or may not use actual control models for the simulation. Using them is desirable, however, this may not be possible because the models were not designed for simulation purposes or because they may simply be code without the knowledge/information necessary for simulation. In one sense, production-centered VM will *"control"* the factory because the factory will "*operate*" according to the plan created with the assistance of VM.

Vision of VM: The vision of Virtual Manufacturing is to provide a capability to *Manufacture in the Computer*. VM will ultimately provide a modeling and simulation environment so powerful that the design, fabrication/assembly of any product including the associated manufacturing processes, can be simulated in the computer. A comparison between the physical and virtual manufacturing is shown in Figure 1.

VM Concepts: VM supports implementation of lean/agile manufacturing to achieve improvements in enterprise flexibility and economy. The use of simulation results in manufacturing systems those are less risky to change. Computer assisted model-based planning and control systems require less coordinating communications. The models provide a basis for sharing knowledge between organizations. VM based systems are expected to enhance operations by providing timely answers to the questions:

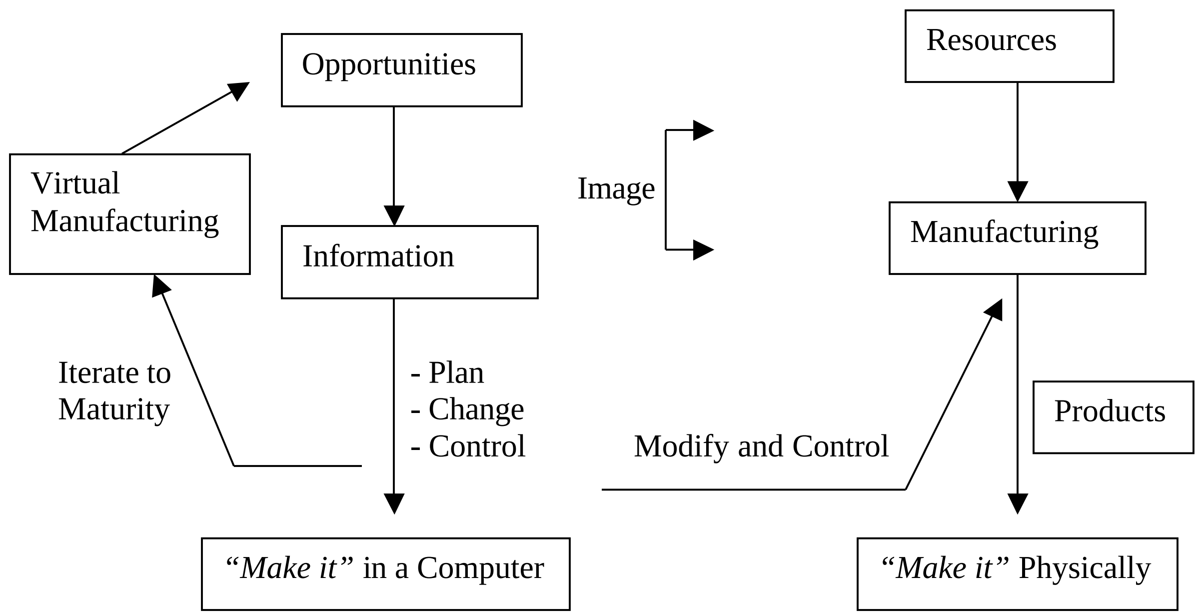

Figure 1: Comparison between physical and virtual manufacturing.

- Can we make the product?
- What are the alternatives?
- What is the best way to produce the product?
- When can we deliver the product?
- How much will it cost?

The relation between the existing enterprise and the market force in creating a new product, the needed changes, the bottlenecks, and the requirements for the new product development are highlighted in Figure 2.

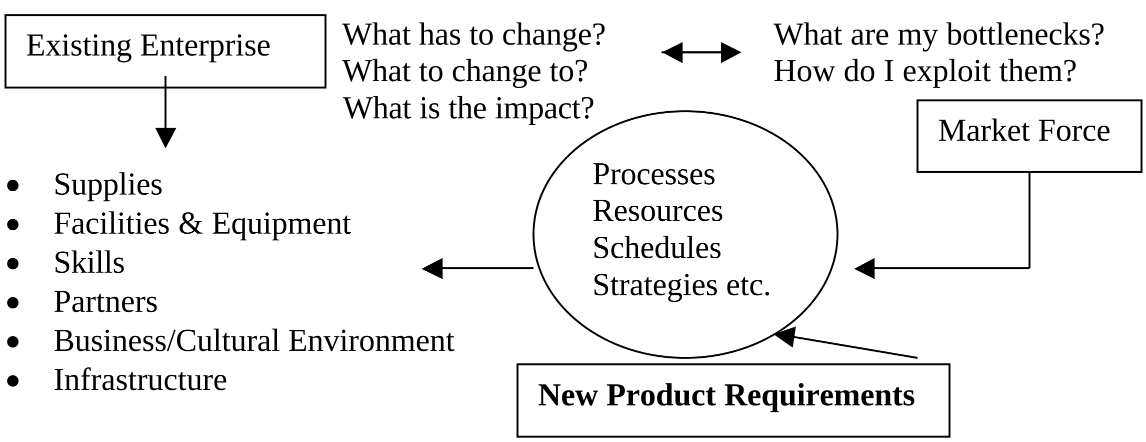

Figure 2: Requirements for new product development.

VM relies on modeling and simulation technology to simulate the production process and to enable us *"make it virtually."* It is an application of modeling and simulation, but extends that discipline beyond the conventional use. VM supplements the IPPD process since it provides a pathway for the manufacturing knowledge to be migrated to the early phases in the life cycle. VM also adds simulation to the Virtual Enterprise (VE) concept and Virtual Prototyping. VM must be integrated with all the relevant enterprise functional areas via a trade-off mechanism (IPPD process) as shown in Figure 3.

PRODUCT DEVELOPMENT PROCESS

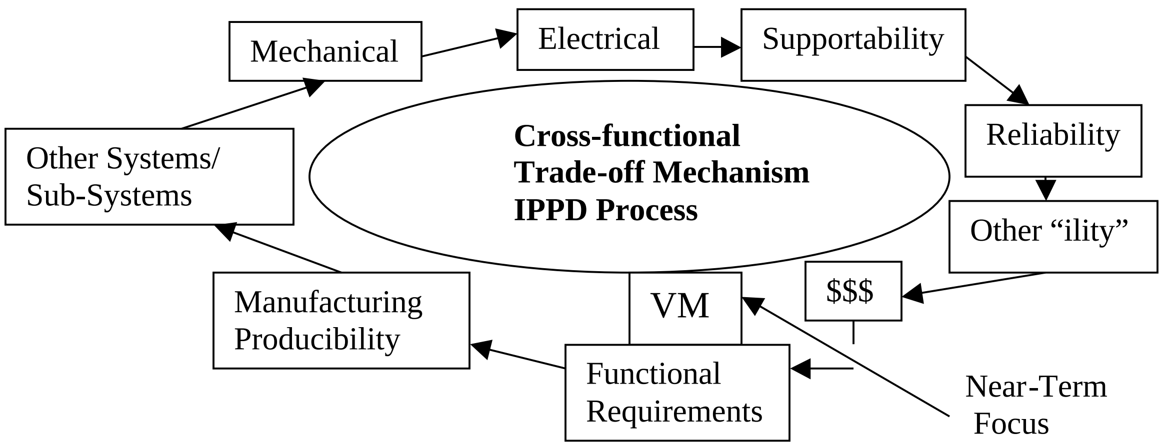

Figure 3: The integration of VM with enterprise functions.

VM Benefits: The expected benefits of VM are summarized below: preparedness for market trend, affordability, shorter cycle times, producible prototypes, flexibility, quality, responsiveness, and customer. Virtual Manufacturing as an emerging technology looks for the development of appropriate new tools and techniques for its successful implementation and realization.

Existing Tools: Some of the existing design and production engineering tools that can be effectively incorporated for realizing VM are[9]:

- *Design Tools* - Computer Aided Engineering (CAE), 3-Dimensional Computer Aided Design (CAD) Models, and Design for Manufacturability & Assembly (DFMA).
- *Production Tools* **-** Computer Integrated Manufacturing (CIM), Advanced Modeling and Simulation, Distributed Interactive Simulation (DIS), Integrated Product/Process Development (IPPD), Just in Time (JIT), Materials Requirement Planning (MRP), Manufacturing Resources Planning (MRP II), Kanban, Virtual Reality, Visualization/ Animation Tools, Hybrid System Theory, Complexity Theory, Distributed Computing, and Self-Directed Control.
- *Quality Tools* **-** Total Quality Management (TQM), Quality Function Deployment (QFD), Quality Standards (ISO/QS 9000), and Robust Design.

- *Artificial Intelligence (AI) Tools* **-** Expert Systems, Neural Networks, Fuzzy Logic, Object Oriented Technologies, and Autonomous Agents.
- *Computer Science Tools* - Programming, National Information Highway, and Modern Telecommunications.
- *Management Tools* - Quality Philosophies in Manufacturing, Manufacturing Strategies, and Management Information Systems (MIS).
- *Mathematical Tools* **-** Advanced Mathematics, Advanced Statistics, Optimization, and Stochastic Models.

Technical Areas: The Technical Workshop results indicated that the technologies critical to VM could be organized into the following major categories[12]:

- Visualization;
- Environment construction technologies;
- Modeling technologies;
- Representation;
- Meta-modeling;
- Integrating infrastructure and architecture;
- Simulation;
- Methodology;
- Integration of legacy data;
- Manufacturing characterization;
- Verification, validation, and measurement;
- Workflow; and
- Cross-functional trades.

VM Applications: VM environment enables a shortening and simplification of the life cycle, by improving the reliability of analyses and accelerating decisions through the use of modeling and simulation. VM helps to evaluate product making using simulation and supports operations to provide timely response to the Integrated Product and Process Design (IPPD) functions in the development of new products and/or processes. Collections of objects in a VM environment may also simulate the entire manufacturing enterprise to provide rapid response to customer requirements. Customers with multiple VM-based supplier organizations can use models of their suppliers' enterprises to provide knowledge to an Enterprise Capabilities Expert. Vertical partners can contribute to capabilities models for use in the knowledge-based computer programs that will evaluate customer requirements and supplier capabilities to establish the organizations desirous of responding to specific customer needs. VM also will support rapid technology transfer by enabling the sharing of the advanced manufacturing capabilities between cooperating organizations. VM applications and tools of one organization may be shared by means of the National Information Highway to the operations of manufacturing partners. VM may also be used in the design of systems and provide the tools necessary to continually and rapidly improve manufacturing system's capability. Using an evolutionary development approach the operation of individual components and the interactions between components are simulated. Some of the specific areas of applications are: corporate memory, capital investment, supplier management, product design, cost estimation, risk management, customer interface, functional interface, and shop floor. The components of VM architecture are shown in Figure 4.

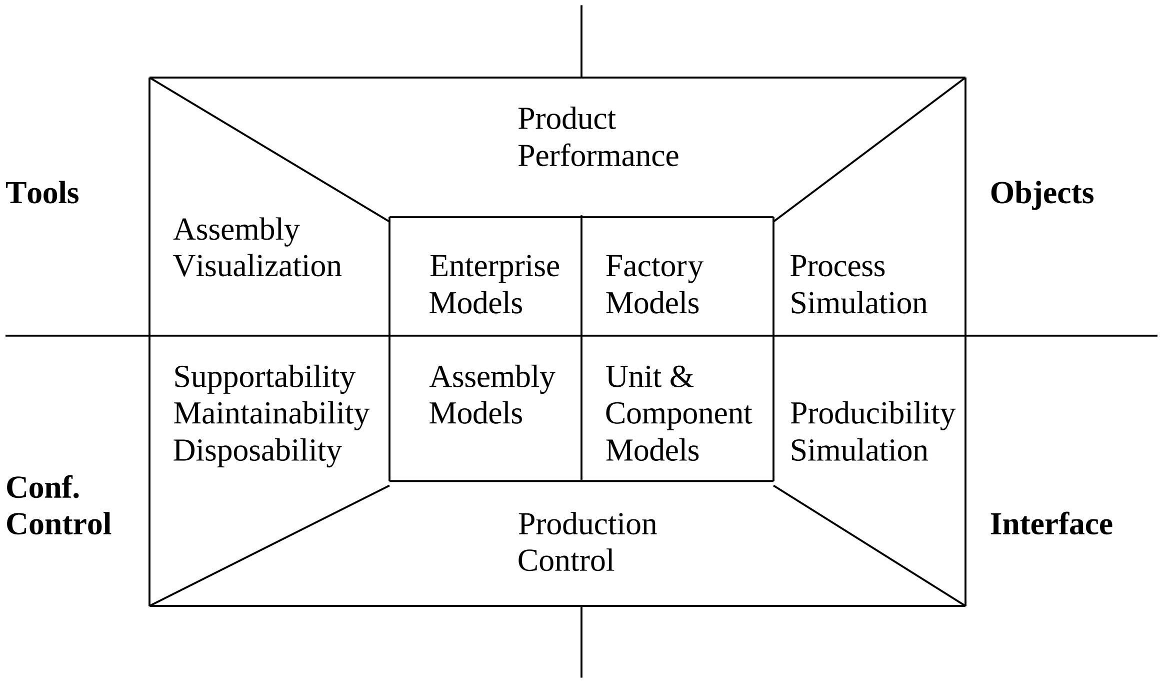

Figure 4: Architecture of virtual manufacturing technology.

3. Key Issues for Realizing VM

Some of the key issues for realizing VM are:

- To what extent are simulations being used to organize and run factories?
- Can (is) VM be used to improve scheduling, provide more effective dynamic scheduling, and support line leveling (produce using varying processes depending on load)?
- Can VM be used to support production planning decisions?
- Can VM be used to support more accurate costing of production processes, incorporate labor/facilities availability in cost estimates at the time of production?
- Can VM support a cultural change in manufacturing cost accounting?
- To what extend can simulations be integrated with analytical methods to solve complex production planning and scheduling problems?
- Will VM enable a stronger movement toward distributed manufacturing?
- What advantages accrue from distributed manufacturing?
- Is it any different from current supplier relations?
- Does the availability of an *"information highway"* offer opportunities to significantly change the way manufacturing is accomplished?
- Does VM have a role in facilitating a distributed design?

- To what extent can distributed manufacturing models be integrated and used in a fashion similar to DIS? Essentially, DIS demands low bandwidth, high frequency communication among nodes, while VM will generally demand high bandwidth, low frequency, with the frequency being high when analyzing processes much faster than real time.
- Do these extreme difference preclude VM from taking advantage of DIS accomplishments in networking and standards?
- What are the differences in requirements between integrating distributed information systems and integrating distributed manufacturing models?

4. Results and Discussions

Based on the literature search to identify the key issues for realizing VM, it can be summarized that new integration technologies and philosophies are emerging. Visualization hardware and software is becoming more affordable and widespread. New modeling and model abstraction techniques are appearing. The most important set of technologies center on modeling and simulation. Some of the key areas that require attention in modeling and simulation are: model object selection (what to model); degree of abstraction; level of depth; flexibility and maintenance of models; integration of different models; and model validation. The results are discussed under the following headings:

Flexible Manufacturing: The discussion with a National Research Group from Oak Ridge National Laboratory, Sandia National Laboratories, and Los Alamos National Laboratories indicated that the research in telerobotics and flexible manufacturing systems though showed progress, it would be practically impossible to totally replace human with robots. Maturity in existing and emerging technologies (both hardware and software) is needed to see potential success in this area.

Lean Manufacturing: Womack et al.[13] in their book on *"The Machine that Changed the World"* addressed the future of the automobile and extensively discussed the importance of lean production. A team spent five years exploring the differences between mass production and lean production in one enormous industry. They have been both insiders with access to vast amounts of proprietary information and daily contact with industry leaders, and outsiders with a broad perspective, often very critical, on existing practices. In this process they have become convinced that the principles of lean production can be applied equally in every industry across the globe and that the conversion to lean production will have profound effect on human society - it will truly change the world.

The Lean Aircraft Initiative research conducted by Massachusetts Institute of Technology resulted in addressing the principles of lean manufacturing, lean supply, lean design and development, lean production organization, and lean production; The research group also indicated the evidence of lean production.

The major goals of the lean aircraft initiative were: perfect first time quality; waste minimization; and continuous improvement. The desired outcome of this study were: lower product cost;

improved product quality; high productivity; efficiency at lower scale of production; rapid product development cycle; and product mix diversity.

Virtual Prototyping: The discussion with a rapid prototyping user group revealed that the customers have difficulty is accepting *"Virtual Prototyping"* as one of the means of acquisition for the following reasons: There exists a significant difference in the prototype they see *"virtually in the computer"* and the real product they receive; One can show a colorful, attractive, and high quality products *"virtually in the computer"*; however, the real product may differ in various aspects - including functional and aesthetic aspects - of what was seen in the computer. Virtual Prototyping is still in the experimental stage and it will take a few more years to mature in terms of technology (visualization, representation, abstraction, and appropriate hardware and software) and be used by vendors and consumers.

Virtual Quality: The discussion with the users of TQM, and ISO/QS 9000 showed that virtual manufacturing concepts will aid significantly the way business will be done in the future for the following reasons: Once the VM technologies mature, the concept of building quality in the product is much easier even before the product is made and hence the concept of *"Right First Time"* will have much more meaning in term of Quality Standards. Quality is defined as *"Fitness for Purpose"*, and the VM technologies will make it happen since the customers can make *"changes virtually"* in the product and make it fit for the intended purpose even before the product is made. In terms of quality, VM can go beyond the customer satisfaction and help in achieving Quality Function Deployment (QFD).

Virtual Reality: Despite the enthusiasm surrounding virtual reality (VR), there is a substantial gap between current technology and that needed to bring virtual environments closer to reality. That is the conclusion of a National Research Council committee report on 3D computer-generated worlds with which people can interact. According to the committee, certain areas hold the most promise for practical uses of VR: training, hazardous operations, medicine and health care, design, manufacturing, and marketing. Using VR and telerobotics, one can or will be able to explore the ocean floor and outer space, dig up a 10-ton container of hazardous waste, take a submarine trip through the human circulatory system, and try out products not yet manufactured, for example. It is not yet clear how to select the most appropriate tasks for VR, the committee reported. Also, much research is needed to understand how people will interact with VR systems, how the systems will affect work performance, and what problems might arise from their extensive use. The entertainment industry is currently serving as a massive informal test-bed and major economic driving force for the technology. Improving VR technology will require better computer hardware and software to generate virtual environments, the equipment worn to interact with them, and the telerobotics that extend the ability to sense and work in remote and hazardous environments. On equipment concern is the discomfort and poor image quality of currently available headgear. The NRC says users suffer frequently from chronic fatigue, lack of initiative, drowsiness, and irritability or nausea when interacting with a virtual environment for a long time. In telerobotics, reductions in time delays between the human operator and the telerobot as well as hardware improvements are needed.

Virtual Reality in Education: The objective is to redesign the introductory mechanical engineering course in an effort to incorporate the learner as designer strategy, and positively impact the students' conceptual understanding. To achieve these objectives, the courses were designed to use virtual reality as a tool that integrates the fundamental concepts of design, analysis, and manufacturing. Further, virtual reality is used to create an arena for constructivism, interactive learning and experimentation with design[7]. Dessouky et al[2] proposed a Virtual Factory Teaching System (VFTS) in support of manufacturing education – i.e., a multimedia collaborative learning network that illustrates the concepts of factory management and design in a realistic setting. To assess the viability of a VFTS for manufacturing education, a prototype was developed that aids the students in learning a specific manufacturing topic, factory scheduling.

Virtual Organization and Agile Manufacturing: In the search for agility, companies will rely increasingly on virtual enterprises, virtual manufacturing, and virtual reality. Goals of virtual manufacturing include analyzing design, product, and process alternatives for viability, cost and risk; integrating product and process development; improving customer response time and cost estimates; and retaining corporate knowledge.

The Society of Manufacturing Engineering developed a videotape on *"Agile Manufacturing: Moving to the Next Level"* [1]. The video addressed *"agility"* as the new survival concept for global manufacturing competitiveness and indicated that the emerging concept of agility is based on the factors: markets of all nations are combining into a single global economy; rapid change in the global market place is inevitable; the explosion of technology makes every country a potential competitor; customers are demanding customized products with short lead times.

One can learn from the video the logic behind Agile Manufacturing and how it can be implemented through virtual enterprise. It discussed agility issues, principles and benefits under the following topics: what is behind the move to agile manufacturing; why agility is essential to survival in the 21st Century; how lean manufacturing and the virtual enterprise support agility; the pros and cons of partnering (virtual enterprises); creating a new transportation infrastructure; developing a network of global communication; how to assess your company identify obstacles, find solutions and create Agile Manufacturing goals; how to identify Agile Manufacturing project candidates; how to measure Agile Manufacturing project success etc.

Goldman et al.[3] in their book on *"Agile Competitors and Virtual Organization: Strategies for Enriching the Customer"* addressed how to confront and thrive on change and uncertainty. They presented in their book: What is agility? How does it work? How to create agile competitors? How to measure agility? They addressed the importance of virtual organizations for strategic benefits. They presented several case studies from Lehigh University's Iacocca Institute, Agility Forum (is a consortium of over one hundred manufacturing companies working with government and academia to bring the concept of agility to American Manufacturing) and discussed agility issues, principles and benefits.

Realization of VM: The STEP standard[5] is intended for long-term development and uses a widely available language called Express to describe the complexities of solid geometry. STEP, also referred to as ISO-10303, is an international standard for the exchange of product model data. Designers and engineers should be aware of its capabilities, how it might be used, and what developers have planned for it. The super-model database, in progress, will be Web compatible and it can be accessed by the entire supply chain. The Web based languages such as SGML (Standard Generalized Markup Language), HTML (Hyper Text Markup Language), and XML (eXtensible Markup Language) are helpful in implementing VM. SMMS software[4] developed by RTSe (USA), Inc., is an ideal product for creating, managing, and publishing metadata to improve overall management of large data archives. SMMS can also be used in the realization of VM.

Research Relevant to VM: The Virtual Manufacturing Technical Workshop[12] identified technologies that are critical to virtual manufacturing. The technologies were classified under Core Technology, Enabling Technology, Show Stopper Technology, and Common Technology. The Core Technologies identified and reported are: VM methodology for process characterization; technologies to simulate assembly operations; declarative representation of product and processes; natural language for VM meta-model; cost database and integration; VM user interface (communication between VM knowledge base and user); VM verification & validation methods, algorithms & tools; process model and simulation validation; methodology for using a VM system; VM framework (guidelines, integration standards, etc.); methodology for design abstraction; tools to relate conceptual design with possible manufacturing methods and processes and cost estimates based on manufacturing features; manufacturing engineering automation (knowledge-based computer applications to perform manufacturing engineering decision making); and simulation architecture.

It is seen that some of the technologies listed above and other related technologies are being studied by government agencies, academia, and industry in the U.S. and other nations. It is necessary to coordinate and bridge the gaps in randomly emerging technologies related to VM and mature them. The gaps in research and technologies need to be addressed to *"sell"* VM to the industry leaders. Some of the technologies that need immediate attention are: selective addition to animation, shop floor based generic models, metrics, representation, and integration.

5. Conclusions

The potential scope of VM is very large. What is important is that a time phased, realizable scope for VM be defined. VM should be implemented incrementally starting at unit product/process level, then at subsystem level, and finally at system level. The manufacturing process and the scope of VM products should be improved in the *"big M"* manufacturing domain: concept through production including marketing, sales, and service. Disagreement remains on what VM is and the key issues for realizing VM - there is a need to define VM more precisely. VM is a powerful tool to reduce the risk involved with new products development/ acquisition. VM is a valuable tool for changing the way to do business. There is a need for mechanism to integrate related programs.

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