Integrated Manufacturing Technology Roadmapping Project

Modeling & Simulation

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and the IMTR Roadmapping Project Team

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Integrated Manufacturing Technology Roadmapping Project:
Roadmap for Modeling & Simulation

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FOREWORD

This document, the IMTI *Roadmap for Modeling & Simulation*, is a "living plan" being distributed to a wide audience of industry, government, and academic reviewers. Your comments and suggestions for improvements are welcome and strongly encouraged.

The IMTI roadmaps represent an important first step in the initiation of a broad-based effort by government and industry to identify, develop, and deliver advances technologies that will enable manufacturers to operate with unprecedented speed, quality, precision, efficiency, responsiveness, and cost-effectiveness.

We appreciate your involvement and support in IMTI's initiatives, and look forward to working with all members of the manufacturing community to help make our vision for future manufacturing excellence come alive.

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CONTENTS

CONTENTS
(continued)

APPENDICES

EXECUTIVE SUMMARY

The Challenge of 21st Century Manufacturing

Manufacturers today face greater challenges than ever. Globalization has greatly expanded the availability of new markets, while simultaneously spurring intense competition in all manufacturing sectors. New technologies enable us to design, build, distribute, and support new and improved products with speed and quality not to be believed just a few years ago.

Clearly, innovations in processes, equipment, and systems are driving a major transformation of the U.S. manufacturing base over the next few decades. Although this transformation is well underway, it is far from complete, and even greater changes can be expected in the future.

Manufacturers, technology suppliers, researchers, and government agencies have a unique opportunity to lead and accelerate the transformation of the U.S. manufacturing infrastructure and enhance the economic well-being of the nation. While a tremendous volume of resources is being expended on developing new manufacturing technologies, it is clear that 1) there is much redundant effort being focused in a few key areas; 2) many manufacturing infrastructure issues that affect all of industry are receiving insufficient attention; and 3) huge investments in proprietary solutions are either not delivering on their promises or are being rendered moot by new technologies or unpredicted changes in the business environment.

Many manufacturing sectors have developed roadmaps to define a path to the future for their industry, and identify technology advances that will help them reduce costs, increase profitability, improve quality, shorten time-to-market, respond to regulatory drivers, and better serve their customers and other stakeholders. Roadmapping has proven to be a valuable strategy to assure that investments are well placed. Many of these roadmaps identify infrastructure issues as major barriers to progress, but there has been little concerted attempt to attack these barriers with the intensity required for success.

IMTR: Building a Strong National Manufacturing Infrastructure

Recognizing these challenges, the National Institute of Standards and Technology (NIST), U.S. Department of Energy (DOE), National Science Foundation (NSF), and Defense Advanced Research Projects Agency (DARPA), launched the Integrated Manufacturing Technology Roadmapping (IMTR) Initiative in 1998 to develop a research and development agenda that:

- Defines key technology goals that cut across all manufacturing sectors
- Provides focus for concentrated effort to achieve the goals
- Promotes collaborative R&D in support of critical requirements.

Leveraging work done by the Next-Generation Manufacturing (NGM) project, which published its final report in early 1997, IMTR is defining future manufacturing technology requirements and outlining solution paths to meet these requirements in four interrelated areas:

- Information Systems for Manufacturing Enterprises (IS)
- Modeling & Simulation for Manufacturing (M&S)
- Manufacturing Processes & Equipment (MPE)
- Technologies for Enterprise Integration (TEI).

Using a series of workshops and reviews involving more than 400 individuals representing a broad cross-section of the nation's manufacturing community, the IMTR team has completed its baseline roadmaps for IS, M&S, and MPE, and is now developing the roadmap for TEI. The first three roadmaps are available on the IMTR web site (http://www.IMTI21.org) for downloading by interested reviewers.

Each IMTR roadmap provides an assessment of the current state of art and practice in the technology area, a vision of the future state, and a series of goals, requirements, and tasks to achieve that vision. Each document includes a series of milestone schedules that lay out a time-phased plan for accomplishing the defined scopes of effort.

The sponsor agencies – and other technology users and developers – will use the roadmaps as an input to their planning processes, with a goal of focusing more resources on high-payoff needs, reducing redundant parallel efforts, and maximizing returns on their R&D investments.

The IMTR Vision

In developing the IMTR roadmaps, there has emerged a common vision of several attributes of future manufacturing enterprises and how they will function internally and interact with their customers, partners, suppliers, workforce, and other stakeholders.

Some key aspects of this vision include:

- **Total Connectedness** – All enterprise processes, equipment and systems will be linked via a robust communications infrastructure that delivers the right information at the right time, wherever it is needed.
- **Integrated Enterprise Management** – Hierarchical, interconnected, simulation-based engineering, manufacturing, and business systems will ensure that decisions will be made in real-time and on the basis of enterprise-wide impact.
- **Fully Integrated Product Realization** – Intelligent design systems linked to a rich base of science- and experience-based knowledge will enable products and manufacturing processes to be conceived and optimized for performance, cost-effectiveness, and quality with no iterative physical prototyping – right the first time, every time.
- **Plug & Play Interoperability** – All technical, manufacturing and business systems will be seamlessly plug-compatible and self-integrating, such that a new software module or new piece of equipment can be inserted into the manufacturing enterprise and be operational immediately, with zero integration cost.
- **Seamless, Flexible Distributed Operation** – Self-integrating systems, shared knowledge bases, and a robust communications infrastructure will enable widely distributed operations to interoperate in real time, regardless of geographic separation. This will help companies to establish "virtual enterprise" teaming relationships on the fly to pursue emerging opportunities.
- **Intelligent, Efficient Processes** – The ability to measure, analyze, and control processes in uncertain conditions will mature to the point that all processes will operate intelligently in closed-loop environments with 100% assurance of quality, in-process. Improved processing technology, optimized product and process design, and life-cycle responsibility will enable zero net waste in every aspect of the manufacturing enterprise.
- **Science-Based Manufacturing** – Improved understanding and shared knowledge of the scientific foundations for material and process interactions will support optimized process design and total understanding of complex transformations and interactions at the micro and macro levels.

Modeling & Simulation: the Engine and Control Systems for Lean, Agile, Responsive Manufacturing

Modeling and simulation are emerging as key technologies to support manufacturing in the 21st century, and no other technology offers more potential than M&S for improving products, perfecting processes, reducing design-to-manufacturing cycle time, and reducing product realization costs. Although specialists currently use M&S tools on a case-specific basis to help design complex products and processes, use of M&S tools other than basic computer-aided design/engineering (CAD/CAE) applications is largely limited to solving specialized design and production problems.

The real value of M&S tools is their ability to capture and represent knowledge to make confident predictions – predictions to drive product design, process design and execution, and management of the enterprise. Product and process development has historically been accomplished through testing designs to see how well they work, then modifying the design and testing it again. This test/evaluate/modify phase consumes a vastly disproportionate share of the time and cost required to move a product from concept to delivery.

These costs can be significantly reduced by investing more in the initial design, using M&S tools to optimize products and processes in the virtual realm before committing resources to physical production.

Beyond design, simulation tools can greatly help improve the efficiency of manufacturing processes. For example, being able to accurately simulate the performance of a device over a range of temperatures can eliminates the need for lengthy temperature testing and expensive test facilities. In the electronics industry, accurate models of the process of epitaxial growth help maximize production yields for microchip wafer fabrication

The Boeing 777 and Dodge Viper are outstanding examples of how M&S tools can greatly reduce the cost and time of bringing products to market. The 777, the first jetliner to be designed entirely with 3-D modeling technology, used digital preassembly and concurrent collaborative engineering to eliminate the need for full-scale mockups, improve quality, and reduce changes and errors – all of which contributed to significant reductions in cost and time compared to conventional techniques.

The savings provided by M&S are significant. In the automotive industry, M&S tools have helped reduce the time required to move a new car design from the concept stage to the production line from 3 years to about 14 months. The U.S. Air Force's Joint Strike Fighter (JSF) program expects to apply advanced M&S technologies to reduce aircraft development costs by 50%.

In the IMTR vision, M&S tools will couple evolutionary knowledge bases (that continuously learn and grow using genetic principles) with validated, science-based first principles models. This deep understanding will enable "continuum modeling" of products and processes down as far as the molecular level, enabling prediction of macro behavior that takes into account the cumulative effects of all factors at the micro level.

Product and process models will be smart, self-correcting, learning systems that adapt in real time based on changing conditions and past experience. M&S systems will provide the knowledge and rules (constraints) to enable individuals to perform their functions within the enterprise to the best of their ability, with no specialized training.

As described in the IMTR *Roadmap for Information Systems*, the M&S systems of the future will be interconnected and supported by a robust and seamless information infrastructure that interfaces these systems to internal and external sources of accurate, real-time data. This will enable products, processes, and facilities to be designed, optimized and validated entirely in the virtual realm.

Supporting analytical tools will be invoked automatically and run near-instantaneously in the background, and computer-based advisors will be available at the touch of a button or a spoken command to aid designers and managers in evaluating options, understanding issues, and making the best decisions.

This robust M&S infrastructure will enable creation and operation of totally integrated enterprise control systems, where product models, process models, and resource models interconnected within an overarching master enterprise model interact to drive and control the living enterprise – fed by accurate, real-time data drawn from the lowest levels and farthest reaches of the enterprise. The desktop PCs and information reporting systems of today will be replaced by "virtual cockpits" where executives, managers, designers, and administrators interact with the living enterprise model at the appropriate level to:

- Have instant, clear, accurate visibility into the status and performance of their operations.
- Quickly evaluate issues and options to determine the best solutions.
- Instantly propagate changes to all parts of the enterprise, and automatically update the living enterprise model.

Other specific benefits of the next-generation M&S systems and tools inherent to the IMTR vision include:

- Rapid evaluation of alternatives, trends, and risks, based on accurate data, to confidently predict the results of contemplated actions.
- Greatly shortened product development time and cost, by eliminating the need for physical prototyping.
- Rapid optimization of new product designs, processes and equipment, and business operations, to maximize efficiency and profitability while reducing all forms of waste
- Automatic producibility, affordability, and other critical analyses, running in real or near-real time, and intelligent decision support to ensure both the products and the processes used to create them are the best they can be.
- Significant reduction of economical order quantities, enabling "mass customization" to better meet the needs of individual customers while enhancing profitability.
- Fast, accurate exploration of many more product and process design options, to increase value to the customer and reduce concept-to-production time and cost.
- Ubiquitous service throughout the enterprise, enabled by low-cost, interoperable tools. This will also enable rapid, seamless integration of new supply chain relationships to pursue new opportunities.
- Comprehensive, globally accessible knowledge bases of validated plug-and-play models, simulations, and supporting tools upon which all companies can draw, thus greatly reducing the cost of acquiring and implementing M&S capabilities.

Table 1 on the following page provides a summary-level view of where we are today, from the standpoint of the current state of art and practice, and where we want to go. The goals reflected in the "IMTR 2015 Vision" column encompass most of the goals identified in the IMTR *Roadmap for Modeling & Simulation*, and readers are encouraged to read the full document for a deeper understanding of these requirements.

It is important to note that there is a very wide range separating the current "state of practice" and "state of the art." Many of the systems and processes now being pioneered by leading-edge companies are closely attuned to the IMTR vision, and it is our expectation that these capabilities will evolve to widespread use over the next 5 to 10 years.

The "Nuggets" of Modeling & Simulation for Manufacturing

The IMTR *Roadmap for Modeling & Simulation* identifies some 40 top-level goals and more than 170 supporting requirements and tasks to meet the needs of future manufacturing enterprises. However, out of these goals and requirements there are 10 "nuggets" – critical capabilities or attributes – that underpin the IMTR vision and which offer the greatest return on investment by virtue of their broad applicability to industry:

- **Nugget #1: Micro to Macro Continuum Modeling** – A major drawback of current product and process models and simulations is that they are generally valid only for the exact parameters around which they were built, and are not valid at larger scales. Future models will be infinitely scaleable, assuring the ability to create models on a manageable scale that are valid when extrapolated to the real world.
- **Nugget #2: Science-Based Models Integrated with Living Knowledge/Experience Bases** – The models and simulations of the future will be built on a foundation of deep understand of first principles, providing perfect fidelity with the real world they are designed to emulate. They will be able to adapt and learn based on real-world experience, capturing the insights and lessons learned of their users.

Table 1.
Modeling & Simulation: Where Are We Now, and Where are We Going?

Manufacturing Function	Current State of Art/Practice	IMTR 2015 Vision
	Product Modeling & Simulation Functions	
Physical Representation	• Solid models of nominal shapes; limited ability to accurately model complex interfaces, many attributes represented by symbols & notes • Unable to capture design intent or product functionality; limited ability to translate design to actual product • Limited product data exchange or across different domains • Complex tools requiring high skill & long processing times	• Object-oriented and feature-based models scaleable from micro to macro levels and containing all product info • Complete interoperability between physical models • Direct linkage to prototyping systems • Collaborative modeling & simulation using integrated environments
Performance	• Modeling of electrical performance more advanced than mechanical performance • Highly specialized applications with tremendous & complex computational demands – high cost & complexity • Poor understanding of underlying physics	• Performance design advisors and fast automatic performance optimization • Performance modeling & assessment tools plug-compatible with design systems • Multivariate performance analysis
Cost/Affordability	• Bottoms-up cost modeling from component level; no linkage to actual, real-time data • Custom cost models or generic tools (e.g., spreadsheet apps or database-driven simulations); specialized tools tailorable to similar processes with many variables	• Cost data available on commodities & downstream life-cycle costs • Performance-based cost modeling • Enterprise-wide cost models
Producibility	• Limited to assessment based on parts count, number of part surfaces, or known chemistry; no tools for assessing non-physical factors • Lengthy simulation times limit number of alternatives	• Producibility alternatives automatically modeled during all development phases; autonomous agents to track producibility-related changes for products • Producibility models interoperate with other technical & business models
Life Cycle Considerations	• Little or no modeling & simulation of life cycle issues • Limited modeling of environmental attributes (e.g., product "greenness") • Some modeling of product support costs	• Environmental & support analytical modules included in or interfaced to product M&S applications • All life-cycle considerations included in product models, such as recycling, disassembly & disposal
	Process Modeling & Simulation Functions	
Material Processing	• Excellent analytical M&S capabilities in continuous processing industries (e.g., chemicals); some knowledge-based advisory systems in use • Good base of material models for simple & traditional materials; simplified models & assumptions; data from handbooks • Applications based on empirical data or past "art"; high costs & special skill needs limit use • Emerging base of material models for newer nontraditional processes (e.g., composites)	• Automated process model creation from design models & enterprise data • Validated, science-based models for all materials • Model repository for reuse • Open, universal framework for M&S standards & model interoperability • Collaborative distributed analysis & simulation systems supporting global distributed manufacturing enterprises
Assembly/Disassembly/ Reassembly	• Good electronics assembly modeling applications • Assembly line balancing (workflow optimization) • Tolerance & interference modeling in limited use • Few standards	• Immersive VR system for assembly modeling & simulation, with automated optimization • Integrated links to production systems for real-time troubleshooting, change response, & optimization across enterprise & supply chain

Table 1. (continued)
Modeling & Simulation: Where Are We Now, and Where are We Going?

Manufacturing Function	Current State of Art/Practice	IMTR 2015 Vision
Quality, Test & Evaluation	• Models from empirical data for statistical control • Limited modeling of dimensional metrology	• Virtual system for test & evaluation modeling coupled to test & evaluation knowledge bases • Automated model generation from specifications
Packaging	• Product flow models coupled with part tracking systems • Models for packaging design for some industries (e.g., defense, food, chemicals)	• On-line virtual system for modeling packaging, including environmental impacts
Remanufacture	• Limited, specialized applications for specific product types • Existing process modeling apps used to evaluate remanufacturability of designs (not tailored for remanufacturing)	• "Reverse engineering" modules to optimize life-cycle performance and re-use • Robust applications integrating all aspects of remanufacturing in initial product and process design stages
	Enterprise Modeling & Simulation Functions	
Strategic Positioning	• Little or no modeling & simulation • Limited use of simple, "homegrown" models	• Strategic decision models with real-time data links • Easy, transparent modeling & simulation
Market Assessment & Positioning	• Primarily use of spreadsheets • Some market share modeling & gaming simulations	• Domain specific models with links to external & internal information sources • Extensive market assessment models & tools
Risk Management	• Little or no automated modeling • Spreadsheet-based models based on individual expertise	• Domain & function specific risk models • Risk assessment & avoidance models
Financial/Cost Management	• Spreadsheet-based financial modeling • Deterministic cost models	• Predictive cost modeling • Integrated cost & profitability models
Resource Management	• Many tools for specific uses; expensive data collection • No common standards or integration frameworks	• Enterprise-wide resource models • Extended enterprise resource models
Quality Management	• Limited "cost of quality" modeling	• Quality impact assessment & tradeoff tools • Quality no longer a discriminator – all excellent
Enterprise Architecture Management	• Little or no modeling • Structured models (e.g., IDEF & GRAF)	• Generic enterprise architectures, metrics & modeling tools • Full enterprise architecture models
Extended Enterprise Management	• Little or no modeling • Supply chain modeling using proprietary or custom systems	• Techniques for modeling functions across the supply chain • Automated knowledge management across extended enterprise
Operations Resource Management	• Many tools available for specific functions or resources • Large, complex, hierarchical models	• Tools & standards for model building & integration • In-depth resource management models
Performance Management	• Cost & schedule performance models • Larger custom models	• Accurate data collection techniques for model building • Self-optimizing simulation models
Factory Operations	• Many domain-specific models • Expensive & time-consuming systems	• Data collection techniques, standards & frameworks • Virtual factory models using real-time data
Facility Infrastructure Management	• Domain-specific systems • Some ERP systems have infrastructure features	• Standard taxonomies & generic infrastructure models • Integrated physical control & performance models

- **Nugget #3: M&S Is Rule, Not Exception** – M&S technology will evolve from a specialized, application-specific troubleshooting tool to a ubiquitous capability that pervades and supports all functions of the manufacturing enterprise. Executives, managers, supervisors, and manufacturing staff will interact with the manufacturing enterprise through a user-friendly virtual interface on their desktop PC to a living enterprise model that links them to real-time information about all of the operations, activities, and processes relevant to their jobs. Proliferation of high-fidelity, generic product and process models, coupled with intelligent software for creation and tuning of models and simulations, will make M&S tools inexpensive and easy to use.
- **Nugget #4: Intelligent Design & Analysis Advisors** – Product and process developers will tremendously increase the productivity, speed, and quality of their work with aid of intelligent software-based advisors that assist in every step of the product realization cycle. These advisors will draw on an ever-expending knowledge base of scientific principles and captured experience (lessons learned) to help designers work around obstacles, avoid false starts, and optimize their work product at every stage of its evolution.
- **Nugget #5: M&S as Real-Time Enterprise Controller** – As modeling and simulation become pervasive, manufacturers will be able to build a real-time, accurate simulation model of the entire enterprise, including all of its products, processes, resources, assets, constraints, and requirements. In its ultimate form, the living enterprise model will be the control interface for all enterprise operations, monitoring real-time performance and status of every operation. Managers will interface with the enterprise model to evaluate performance, identify issues and concerns, and assess outcomes of contemplated actions, ensuring that enterprise performance is continuously optimized in response to changing requirements and conditions.
- **Nugget #6: Smart, Self-Learning Models** – Next-generation models and simulations will "understand" their own needs, goals, and requirements, and will interact with other models and simulations – and the enterprise knowledge bases – to continuously improve their depth, fidelity, and performance. Product models, for example, will be "smart" enough to optimize themselves for producibility, maintainability, and similar attributes based on real-time access to information on factors such as availability of components and raw materials, shop capacity, and individual process equipment and unit operation capabilities and workloads.
- **Nugget #7: Open, Shared Repositories & Validation Centers** – The creation of science-based models and simulations for widely used materials and processes will give rise to the establishment of national and international libraries of validated models and simulations that can be shared by many manufacturers across different sectors. This will drastically reduce a manufacturer's cost and time in developing models and simulations to support critical business requirements. Open access to common process and product models and M&S tools will also enable rapid integration of new partners and supply chain members to pursue new opportunities.
- **Nugget #8: Integrated, Robust Product & Process Models Supporting All Domains & Applications** – M&S will move from the product and process domains to support all facets of the manufacturing enterprise. Product models will be robust, high-fidelity representations that capture all relevant attributes of the product, from the molecular composition of its materials to the physics of its interactions in the manufacturing process and in its real-world use. Manufacturing and business process models will have similar high fidelity, and all models will be able to integrate to enable creation of "macro models" that accurately represent end-to-end processes, collections of processes, and the total enterprise. This will enable users to accurately predict how the effects of a change will ripple throughout the enterprise, and thus assure that all decisions are made based on a clear understanding of advantages, disadvantages, risks, and probable outcomes.

- **Nugget #9: Total, Seamless Model Interoperability** – Future models and simulations will be transparently compatible, able to plug-and-play via self-describing interfaces, and require no outlay of resources for integration or tuning. Every product and process model will understand its own behavior, its own input needs, and its own output capabilities, such that when a new element is added to the system (e.g., a process control sensor), it will negotiate with the models of all other elements of the system to "fit in" with no human assistance.
- **Nugget #10: Real-Time, Interactive, Performance-Based Models** – Future models and simulations will be linked via enterprise information systems to all data they need to remain current based on changing business considerations. Product models, for example, will be able to link to real-time material and labor cost databases so as to provide continuous visibility of actual product costs and be able to alert product managers when a changed parameter (e.g., increased price for a constituent material) requires attention (e.g., a change to a lower-cost material).

Achievement of these cross-cutting goals will have a major impact on manufacturing enterprises, enabling them to:

- Reduce the cost of developing and manufacturing products
- Enhance product quality and reliability
- Reduce the time required to move new products from concept to market
- Improve responsiveness to changes in customer needs
- Enhance ability to establish competitive position and increase market share
- More effectively manage capital investments (and therefore, increase return on investment).

Figure 1 illustrates how each of these attributes is supported by each of the M&S Nuggets.

M&S "Nuggets" / Areas of Beneficial Impact	Reduced Development & Mfg Costs	Improved Product Quality	Faster Time to Market	Greater Responsiveness to Cust. Needs	Increased Competitiveness & Mkt Share	Higher Return on Capital
1. Micro to Macro Continuum Modeling	●	●	○	○	●	○
2. Science-Based Models Integrated w/ Living Knowledge/Exp. Bases	●	●	●	●	●	●
3. M&S Is Rule, Not Exception	●	●	●	●	●	●
4. Intelligent Design & Analysis Advisors	●	●	●	●	●	●
5. M&S as Real-Time Enterprise Controller	●	●	●	●	●	●
6. Smart, Self-Learning Models	●	●	●	●	●	○
7. Open, Shared Repositories & Validation Centers	●	●	●	○	○	●
8. Integrated, Robust Product & Process Models for All Domains /Apps	●	●	●	●	●	●
9. Seamless Interoperability	●	●	●	●	●	●
10. Real-Time, Interactive, Performance-Based Models	●	●	●	●	●	○

● = Major Impact ○ = Moderate Impact

Figure 1. Benefits of the IMTR M&S "Nuggets" on Future Manufacturing Enterprises

Next Steps: The Call to Action

Now that the IMTR project is delivering its roadmaps, what next? How do we make the IMTR vision come alive? How do we move from plan to implementation?

If you are a CEO or senior executive of a manufacturing firm or a manufacturing technology organization, we want you to GET BEHIND THE PLAN. Read it. Have your senior staff members read it. Identify those goals and requirements that you think offer the greatest benefit to your organization, and join with other IMTR implementation partners to MAKE IT HAPPEN.

If you are a manufacturing technologist, we want you to help MAKE IT WORK. Read the plan. Have your associates read it. It's full of great ideas, and even a few far-fetched ones. Have we missed something? If so, let us know. But most importantly, identify those challenges that you can help meet, and work with your sponsors to develop programs that deliver the critical technologies. Many of the capabilities identified in the roadmaps are already in the pipeline; our challenge to you is to BRING THOSE CAPABILITIES HOME and launch new programs to FILL THE GAPS. Seek opportunities to start or join the teams that will deliver the right solutions.

1.0 INTRODUCTION

1.1 The IMTR Challenge

Manufacturing is changing rapidly in the U.S. and around the world. The processes, equipment, and systems used to design and produce everything from automobiles to computer chips are undergoing dramatic changes in response to new customer needs, competitive challenges, and emerging technologies. Recent advances in information systems, business practices, engineering techniques, and manufacturing science now enable companies to produce new and better products more quickly and at a much lower cost than ever before.

Clearly, these innovations are driving a major transformation of the U.S. manufacturing base. Although this transformation is well underway, it is far from complete, and even greater changes can be expected in the future.

Manufacturers, technology suppliers, and research institutions have a unique opportunity to lead and accelerate the transformation of the U.S. manufacturing infrastructure and enhance the economic well-being of the nation. While a tremendous volume of R&D resources is being expended on developing and implementing new manufacturing technologies, it is clear that 1) there is much redundant effort being focused in a few key areas; 2) many manufacturing infrastructure issues that affect all of industry are receiving very little attention; and 3) huge investments in proprietary solutions are either not delivering on their promises or are being rendered moot by new technologies or unpredicted changes in the business environment.

While many industries have developed technology roadmaps for their specific business sectors, there has been no concerted effort to address technology requirements and associated barriers that cut across multiple sectors. Many of the industry-specific plans mention cross-cutting infrastructure needs, but the challenges they present are beyond the ability of any one group of companies to solve.

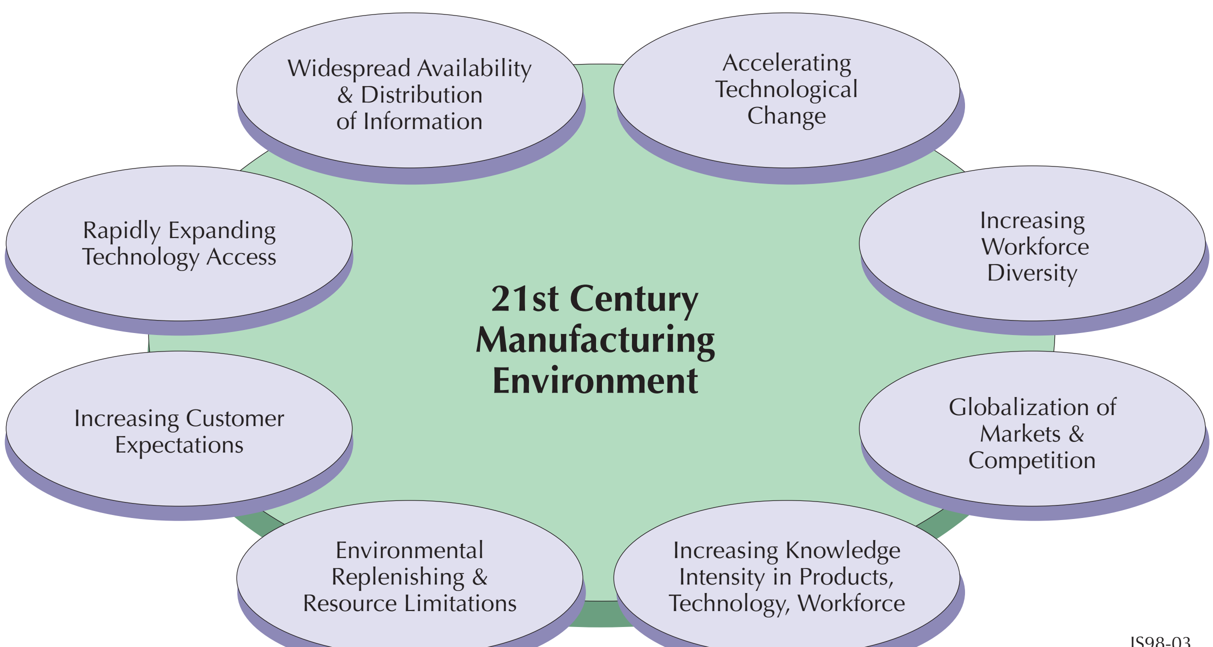


Figure 1.1-1. Forces Shaping the 21st Century Manufacturing Environment

Recent studies such as the Next-Generation Manufacturing (NGM) project (see Appendix A) have highlighted the need for R&D in several important areas that affect the entire manufacturing community. However, a comprehensive plan does not exist to:

- Define key technology goals that cut across all manufacturing sectors
- Provide focus for concentrated effort to achieve the goals
- Promote collaborative R&D in support of critical needs
- Move these developments from the laboratory to industrial use.

The IMTR initiative is providing that plan. IMTR is a focused effort, sponsored by the National Institute of Standards and Technology (NIST), U.S. Department of Energy (DOE), National Science Foundation (NSF), and Defense Advanced Research Projects Agency (DARPA), to develop a manufacturing R&D agenda that cross-cuts the diverse needs of government and industry across all major manufacturing sectors. Leveraging work done by NGM, which published its final report in early 1997, IMTR is conducting a structured process (see Appendix B) to define future manufacturing enterprise technology requirements and outline solution paths to meet these requirements in four interrelated areas:

- Information Systems for Manufacturing
- Modeling and Simulation
- Manufacturing Processes & Equipment
- Enterprise Integration.

Each IMTR study area correlates to one of the four technology-focused "Imperatives" for future manufacturers defined by the NGM project. Collectively, the four areas span all of the processes and enabling technologies that support the modern manufacturing enterprise. There is however, inherent overlap among all four areas. Enterprise integration, for example, relies heavily on information technologies to link widely distributed enterprise functions and operations. Modeling and simulation, which deal with the representation and manipulation of data, are inextricably linked with many aspects of information standards and processing. Manufacturing processes and equipment rely on modeling and simulation and on information systems to perform their functions, particularly within the context of the integrated enterprise.

Recognizing these relationships, the IMTR project team has developed each of the roadmaps as a plan that can stand alone to the maximum extent possible, without redundancy. In each document, however, we have included cross references to the other documents where supporting goals and requirements are addressed.

This report represents the key findings and recommendations in the area of Modeling & Simulation (M&S). The contents were developed by a core Roadmapping Project Team of eight individuals operating under the guidance of a 27-person Working Group representing a diverse set of industrial, governmental and academic organizations, with additional inputs from invited reviewers and subject matter experts. To date, more than 100 individuals have contributed to the contents of this volume.

1.2 Modeling & Simulation – Faster, Cheaper, Better

Modeling and simulation[1] (M&S) are emerging as key technologies to support manufacturing in the 21st century, and no other technology offers greater potential for improving products, perfecting processes, reducing design-to-manufacturing cycle time, and reducing the cost of moving product from concept to delivery. Although specialists currently use M&S tools on a case-specific basis to help design complex products and processes, use of M&S tools other than basic computer-aided design/engineering (CAD/CAE) applications is largely limited to solving specialized design problems.

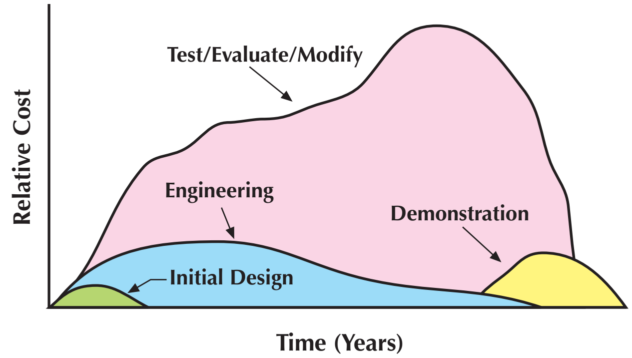


Figure 1.2-1. Iterative prototyping consumes billions of dollars and years of development for complex products. M&S can drastically reduce those costs.

The real value of M&S tools is their ability to capture and represent information to make confident predictions – to drive product design, process design and execution, and management of the enterprise. As indicated in Figure 1.2-1, product and process development has historically been accomplished by testing a design to see how well it works, then modifying the design and testing it again. This test/evaluate/modify phase consumes a vastly disproportionate share of the time and cost required to move a product from concept to delivery.

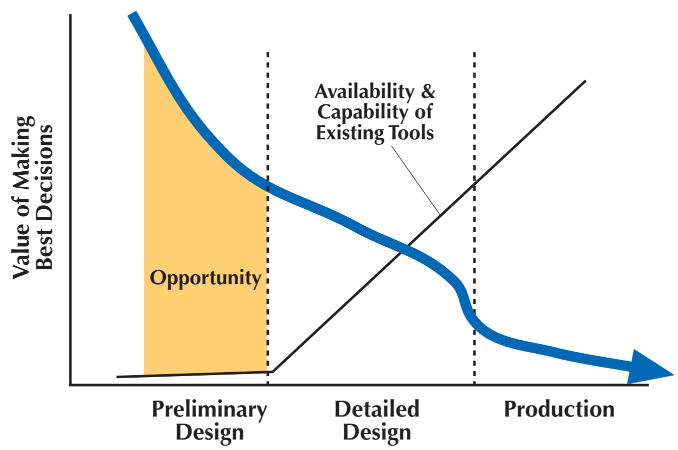


Figure 1.2-2. Few tools are available to help designers make best decisions early in the product realization cycle, where they provide the greatest benefit.

The cost-time profile can be significantly reduced by investing more in the initial design, by using M&S tools to optimize products and processes in the virtual realm before committing resources to physical production.

Figure 1.2-2 reinforces the point. As indicated in the figure, the impact of making good decisions early in the product life cycle is very high, and declines steeply as a product matures. Conversely, while there are many tools (including M&S tools) to help manufacturers make good decisions about a product late in the process, there are very few available early in the process – where they are needed the most.

Beyond design, simulation tools can greatly help in improving the efficiency of manufacturing processes. For example, being able to accurately simulate the performance of a device over a range of temperatures can eliminates the need for lengthy temperature testing and expensive

[1] "Model" and "Simulation" are often used interchangeably or in conjunction to describe representations of objects and processes. Definitions of these terms vary widely, even in the M&S community. For purposes of this document, a "**model**" is a mathematical representation of an object (a part, a product, a machine, a facility, an organization, etc.) or a process (e.g., a specific manufacturing process or a business process). A mathematical model characterizes the behavior of its subject through the form of the equation(s) chosen, the variables and parameters present, and the ranges or values of those terms for which the model is considered valid. "**Simulation**" is a process for exercising mathematical models through simulated time wherein one or more models can be run with varying values of input parameters to evaluate the effects of interaction among variables.

test facilities. In the electronics industry, accurate models of the process of epitaxial growth help maximize production yields for microchip wafer fabrication.[2]

The Boeing 777 and Dodge Viper (Figure 1.2-3) are outstanding examples of how modeling and simulation tools, when applied as part of an integrated computer-based design and manufacturing environment, can greatly reduce the cost and time of bringing products to market. The 777, the first jetliner to be designed entirely with 3-D modeling technology, used techniques such as digital preassembly and concurrent collaborative engineering to eliminate the need for full-scale mockups, improve quality, and reduce changes and errors – all of which contributed to significant reductions in cost and time compared to conventional techniques.

The savings provided by M&S technology are significant. In the automotive industry, M&S tools have helped reduce the time required to move a new car design from the concept stage to the production line from 3 years to about 14 months. In the defense industry, a key goal of the U.S. Air Force's Joint Strike Fighter (JSF) program is to apply advanced and emerging M&S technologies to reduce development costs by 50%.

M&S tools and techniques are rapidly expanding beyond the domain of product design to become increasingly valuable in all aspects of manufacturing enterprise operation – including tools in business decision making, sales and marketing, customer service, and total product life-cycle management.

The IMTR Vision: Modeling & Simulation as the Engine and Control Systems for Lean, Agile, Responsive Manufacturing Enterprises

In the IMTR vision, M&S tools will provide designers and managers the ability to trade off for best solutions, create accurate and complete models of the product, establish processes that best produce that product, link those processes for optimization and integration of the total process environment, establish enterprise models that control the factory operations and help manage the enterprise, and have the capability to adapt to change in real time – including intelligent control and assisted decision making

These M&S tools will couple evolutionary knowledge bases (that continuously learn using genetic principles) with science-based first principles models. This deep understanding will enable "continuum modeling" of products and processes from the micro to macro level, enabling prediction of macro behavior that takes into account the cumulative effects of all factors at the micro level. Product and process models will be smart, self-correcting, learning systems that adapt in real time based on changing conditions and past experience. M&S systems will provide the knowledge and rules (constraints) to enable individuals to perform their functions within the enterprise to the best of their ability, with no specialized training.

Figure 1.2-3. The Boeing 777 (left) and the Dodge Viper (above) both made extensive use of advanced modeling and simulation tools to create state-of-the art products faster, better, and more affordably.

[2] Photonics Manufacturing, NIST ATP 1998 Focused Program Paper for Simulation and Modeling; Philip Perconti, Program Manager.

As described in the IMTR *Roadmap for Information Systems,* the M&S systems of the future will be interconnected and supported by a robust and seamless information infrastructure that interfaces these systems to internal and external sources of real-time data. This will enable products, processes, and facilities to be designed, optimized and validated entirely in the virtual realm. Analytical tools that support the design process will be invoked automatically and run near-instantaneously in the background, and intelligent computer-based advisors will aid designers and managers in evaluating options, understanding issues, and making the best decisions.

This robust M&S infrastructure will enable creation and operation of totally integrated enterprise control systems, where product models, process models, and resource models interconnected within an overarching master enterprise model interact to drive and control the living enterprise. These systems will be fed by real-time data drawn from the lowest levels and farthest reaches of the enterprise, ensuring very high accuracy and fidelity of live operation simulations and what-if scenarios. The desktop PCs and information reporting systems of today will be replaced by “virtual cockpits” where executives, managers, designers, and administrators interface with the living enterprise model at the appropriate level to:

- Have instant, clear, accurate visibility into the status and performance of their operations and areas of responsibility.
- Quickly evaluate issues and options to determine the best solutions.
- Instantly propagate change actions to all affected parts of the real-world enterprise, and automatically update the living enterprise model.

Other specific benefits of the next-generation M&S systems and tools inherent to the IMTR vision include:

- Rapid evaluation of alternatives, trends, and risks, based on current and accurate data, to confidently predict the results of contemplated actions.
- Greatly shortened product development time and cost, by eliminating the need for physical prototyping.
- Rapid optimization of new product designs, production processes and equipment, and business operations, to maximize efficiency and profitability while reducing all forms of waste
- Automatic producibility, affordability, and other critical analyses, running in real or near-real time, and intelligent decision support to ensure both the products and the processes used to create them are the best they can be.
- Significant reduction of economical order quantities, enabling “mass customization” to better meet the needs of individual customers while enhancing profitability.
- Fast, accurate exploration of many more product and process design options, to increase value to the customer and reduce concept-to-production time and cost.
- Widely available service throughout the enterprise, enabled by low-cost, interoperable tools. This will also enable rapid, seamless integration of new partners and supply chain relationships to pursue new opportunities.
- Comprehensive, globally accessible knowledge bases of validated plug-and-play models, simulations, and supporting tools upon which all companies can draw, thus greatly reducing the cost of acquiring and implementing M&S capabilities.

1.3 Maximizing Return on R&D Investments: The "Nuggets" of M&S

This document sets forth a high-level R&D plan for M&S technologies to support the IMTR vision of lean, agile, seamlessly integrated manufacturing enterprises able to thrive in the competitive environment of the 21st century. The IMTR M&S plan identifies some 40 top-level goals and more than 170 supporting requirements and tasks to achieve the vision. However, out of these goals and requirements there are 10 "nuggets" – critical capabilities or attributes – that underpin the IMTR vision and which offer the greatest return on investment by virtue of their broad applicability to industry:

1. **Micro to Macro Continuum Modeling** – A major drawback of current product and process models and simulations is that they are generally valid only for the exact parameters around which they were built, and are not valid at larger scales. Future models will be infinitely scaleable, assuring the ability to create models on a manageable scale that are valid when extrapolated to the real world.
2. **Science-Based Models Integrated with Living Knowledge/Experience Bases** – The models and simulations of the future will be built on a foundation of deep understand of first principles, providing perfect fidelity with the real world they are designed to emulate. They will be able to adapt and learn based on real-world experience, capturing the insights and lessons learned of their users.
3. **M&S Is Rule, Not Exception** – M&S technology will evolve from a specialized, application-specific tool to a ubiquitous capability that pervades all functions of the manufacturing enterprise. Executives, managers, supervisors, and manufacturing staff will interact with the manufacturing enterprise through a user-friendly virtual interface on their desktop PC to a living enterprise model that links them to real-time information about all of the operations, activities, and processes relevant to their jobs. Proliferation of high-fidelity, generic product and process models, coupled with intelligent software for creation and tuning of models and simulations, will make M&S tools inexpensive and easy to use.
4. **Intelligent Design & Analysis Advisors** – Product and process developers will tremendously increase the productivity, speed, and quality of their work with aid of intelligent software-based advisors that assist in every step of the product realization cycle. These advisors will draw on an ever-expending knowledge base of scientific principles and captured experience (lessons learned) to help designers work around obstacles, avoid false starts, and optimize their work product at every stage of its evolution.

Rethinking the Benefits:

The New View of M&S Investments

Perhaps the biggest inhibitor to widespread modeling and simulation in manufacturing is the perception of its costs. Historically, M&S tools were expensive. Computing platforms had to be high-end Unix workstations because of the need for rapid computation and high-resolution graphic displays. Software was expensive because of the effort required to develop it, and the limited size of the market. Highly trained professionals were required to run the systems because the tools were not well integrated and because expert judgment was required to interpret the results. At the same time, companies perceived that the knowledge gained from M&S analyses was usually not critical to their operations and that the benefit-to-cost ratio was small compared to other manufacturing technology investments.

Several factors are changing this picture. The explosion of low-cost, high-performance desktop computing power, coupled with growth of easier-to-use, more capable applications, is greatly enhancing the cost-effectiveness and value of M&S systems. Although many problems remain to be solved to achieve seamless integration between CAD systems and analytical tools, interaction between CAD and M&S systems has improved considerably.

The cost of NOT performing relevant analyses is frequently ignored. New products and processes can be designed without using modeling and simulation; we have operated in that mode for years. However, if one considers the costs of reengineering a product and its manufacturing processes using traditional "trial and error" practices, the benefit-to-cost ratio of M&S tools that can optimize products and processes before production is potentially very large. M&S can also reduce the time it takes to get new products to market, which accelerates return on investment and growth of market share.

5. **M&S as Real-Time Enterprise Controller** – As modeling and simulation become pervasive, manufacturers will be able to build a real-time, accurate simulation model of the entire enterprise, including all of its products, processes, resources, assets, constraints, and requirements. In its ultimate form, the living enterprise model will be the control interface for all enterprise operations, monitoring real-time performance and status of every operation. Managers will interface with the enterprise model to evaluate performance, identify issues and concerns, and assess outcomes of contemplated actions, ensuring that enterprise performance is continuously optimized in response to changing requirements.
6. **Smart, Self-Learning Models** – Next-generation models and simulations will "understand" their own needs, goals, and requirements, and will interact with other models – and the enterprise knowledge bases – to continuously improve their depth, fidelity, and performance. Product models, for example, will be "smart" enough to optimize themselves for producibility, maintainability, and similar attributes based on real-time access to information on factors such as availability of components and raw materials, shop capacity, and individual equipment and unit operation capabilities and workloads.
7. **Open, Shared Repositories & Validation Centers** – The creation of science-based models and simulations for widely used materials and processes will give rise to the establishment of national and international libraries of validated models and simulations that can be shared by many manufacturers across different sectors. This will drastically reduce a manufacturer's cost and time in developing models and simulations to support critical business requirements. Open access to common process and product models and M&S tools will also enable rapid integration of new partners and supply chain members to pursue new business opportunities.
8. **Integrated, Robust Product & Process Models Supporting All Domains & Applications** – M&S will move from the product and process domains to support all facets of the manufacturing enterprise. Product models will be robust, high-fidelity representations that capture all relevant attributes of the product, from the molecular composition of its materials to the physics of its interactions in the manufacturing process and in its real-world use. Manufacturing and business process models will have similar high fidelity, and all models will be able to integrate to enable creation of "macro models" that accurately represent end-to-end processes, collections of processes, and the total enterprise. This will enable users to accurately predict how the effects of a change will ripple throughout the enterprise, and thus assure that all decisions are made based on a clear understanding of advantages, disadvantages, risks, and probable outcomes.
9. **Total, Seamless Model Interoperability** – Future models will be transparently compatible, able to plug-and-play via self-describing interfaces, and require no outlay of resources for integration or tuning. Every product and process model will understand its own behavior, its own input needs, and its own output capabilities, such that when a new element is added to the system (e.g., a process control sensor), it will negotiate with the models of all other elements of the system to "fit in" with no human assistance.
10. **Real-Time, Interactive, Performance-Based Models** – Future models and simulations will be linked via enterprise information systems to all data they need to remain current based on changing business considerations. Product models, for example, will be able to link to real-time material and labor cost databases so as to provide continuous visibility of actual product costs and be able to alert product managers when a changed parameter (e.g., increased price for a material) requires attention (e.g., a change to a lower-cost material).

Table 1.3-1 provides an overview of the M&S Nuggets and identifies supporting requirements addressed through this document. Achievement of the Nuggets and the cross-cutting goals, requirements, and tasks that support them will better enable manufacturing enterprises to:

Table 1.3-1.
IMTR Nuggets for Modeling & Simulation R&D

M&S Nugget	Benefits of Implementation	Supporting Requirements*	See Section
1. Micro to Macro Continuum Modeling	Robust, infinitely scaleable product, process, and business models able to predict macro-level behaviors from micro-level attributes, and to accurately and quickly propagate effects of changes at macro level down to affected micro levels	• Continuum Modeling Capability • Functional Specifications Derivation • Integrated Life-Cycle Material Behavior Modeling • Continuum Quality Modeling	3.3.1 3.3.3 3.3.4 4.3.1.6
2. Science-Based Models Integrated with Living Knowledge/Experience Bases	High-precision, high-fidelity models continuously incorporating accurate data and best knowledge for accurate simulation and confident prediction	• Information-Centric Product Model Objects • Integrated Life-Cycle Cost Modeling • Science-Based Material Modeling Knowledge Base • Analytical Systems Integration	2.3.1 2.3.3 3.3.1 3.3.1
3. M&S Is Rule, Not Exception	Widespread use of M&S tools to support all functions in all kinds of companies in all manufacturing industries will drastically reduce the cost of developing and using the tools, and enable seamless operation of distributed, extended manufacturing enterprises	• Virtual Product/Process Planning Structure • Integrated Packaging Modeling • Quality, Test & Evaluation Certification Models • Qualitative Forecasting Tools • Performance Data Integration & Assessment	3.3.2 3.3.4 3.3.3 4.3.1.2 4.3.2.2
4. Intelligent Design & Analysis Advisors	Automatic execution of analytical functions and design suggestions based on best captured knowledge and experience, shortens product/process development times and prevents false starts	• Intelligent Models • Automatic Performance Optimization • High-Fidelity, Multi-Model Analytical Applications • Contact Interface Management • Material Assessment Tools • Discontinuity Event Modeling	2.3.1 2.3.2 3.3.1 3.3.1 3.3.5 4.3.1.2
5. M&S as Real-Time Enterprise Controller	High-level enterprise model linked to all process, product, and business models provides instant visibility of all aspects of enterprise performance, enables fast, accurate simulation to evaluate impacts of change	• Direct Product Realization • Market Data Model Integration • Manufacturing Capacity/Capability Representation • Adaptive, Real-Time Process/Equipment Control Models • Enterprise Multi-Model Integration • Multi-View Factory Vision	2.3.1 2.3.3 2.3.4 3.3.2 4.3.1.8 4.3.2.3

* This is not an all-inclusive list of all IMTR requirements that support each “nugget” capability, but rather provides a representative sample of major R&D requirements. Many requirements and tasks also support multiple nuggets.

Table 1.3-1.
IMTR Nuggets for Modeling & Simulation R&D (continued)

M&S Nugget	Benefits of Implementation	Supporting Requirements*	See Section
6. Smart, Self-Learning Models	Continuously increasing accuracy and depth of underlying data and knowledge enables true continuous improvement in all model-driven applications and operations	• Control Program Autocreation • Intelligent Material Separation Modules • Plug & Play Resource Models • Change Requirements Identification • Embedded Process & Equipment Simulators • Self-Assessment & Learning Tools • Automated Reconfiguration Capability	3.3.2 3.3.5 4.3.1.5 4.3.1.5 4.3.2.1 4.3.2.2 4.3.2.2
7. Open, Shared Repositories & Validation Centers	Drastically reduces cost and time of developing accurate, robust models; all users contribute to and benefit from refinements	• Vendor-Supplied Models • Interactive Knowledge Base & Validation Methodology • Packaging Criteria • Materials Knowledge Base Interface • Process Knowledge Base Interface • Boundary Conditions Database Interface • Plug & Play Enterprise Process Model Library • Infrastructure Model Library	2.3.1 3.3.1 3.3.4 3.3.4 3.3.4 3.3.4 4.3.1.8 4.3.2.4
8. Integrated, Robust Product & Process Models Supporting All Domains & Applications	Enables all disciplines to realize benefits of M&S tools, supports real-time enterprise control through linking and integration of individual product/process/business models to create high-fidelity enterprise "metamodel"	• Model Federation • Single Product Model Representation • Plug & Play Cost Models • Strategic Decision Modeling • Real-Time Model Data Links	2.3.1 2.3.1 2.3.3 4.3.1.1 4.3.1.1
9. Total, Seamless Model Interoperability	Infinitely composable, transparent plug & play models enable instant integration of models at any level – product, process, facility/operation, enterprise, and extended enterprise	• Interoperability Methods • Hierarchical Models • Multi-Source Data Integration • Multi-Resource Optimization • Extended Factory Integration & Optimization	2.3.1 2.3.1 4.3.1.5 4.3.2.1 4.3.2.1
10. Real-Time, Interactive, Performance-Based Models	Supports real-time control of processes and operations and rapid, accurate evaluation of issues and options	• Interoperability Methods • Robust Product Modeling Standards • Intelligent Models • Generic Performance Attribute Representation • Distributed Enterprise Assembly Planning System	2.3.1 2.3.1 2.3.1 2.3.2 3.3.2

* This is not an all-inclusive list of all IMTR requirements that support each "nugget" capability, but rather provides a representative sample of major R&D requirements. Many requirements and tasks also support multiple nuggets.

- Evaluate alternatives, options trends, and risks, based on current and accurate data, to predict – with high confidence – the results of product, process, and enterprise decision actions.
- Reduce product development time and cost by eliminating the need for physical prototypes.
- Rapidly optimize new product designs, production processes, and business operations, to maximize efficiency and profitability while greatly reducing all forms of waste.
- Automatically run producibility, affordability, and other critical analyses in real or near-real time, aided by intelligent decision support to ensure both products and processes are the best they can be.
- Reduce the economical order quantity of production lot sizes, enabling "mass customization" to better meet the needs and wants of individual customers while enhancing enterprise profitability.
- Provide ubiquitous service throughout all enterprise operations, enabled by low-cost, completely interoperable tools. This will also enable easy, seamless integration of new business relationships to pursue new opportunities.

Figure 1.3-1 illustrates how each of these attributes is supported by each of the M&S Nuggets.

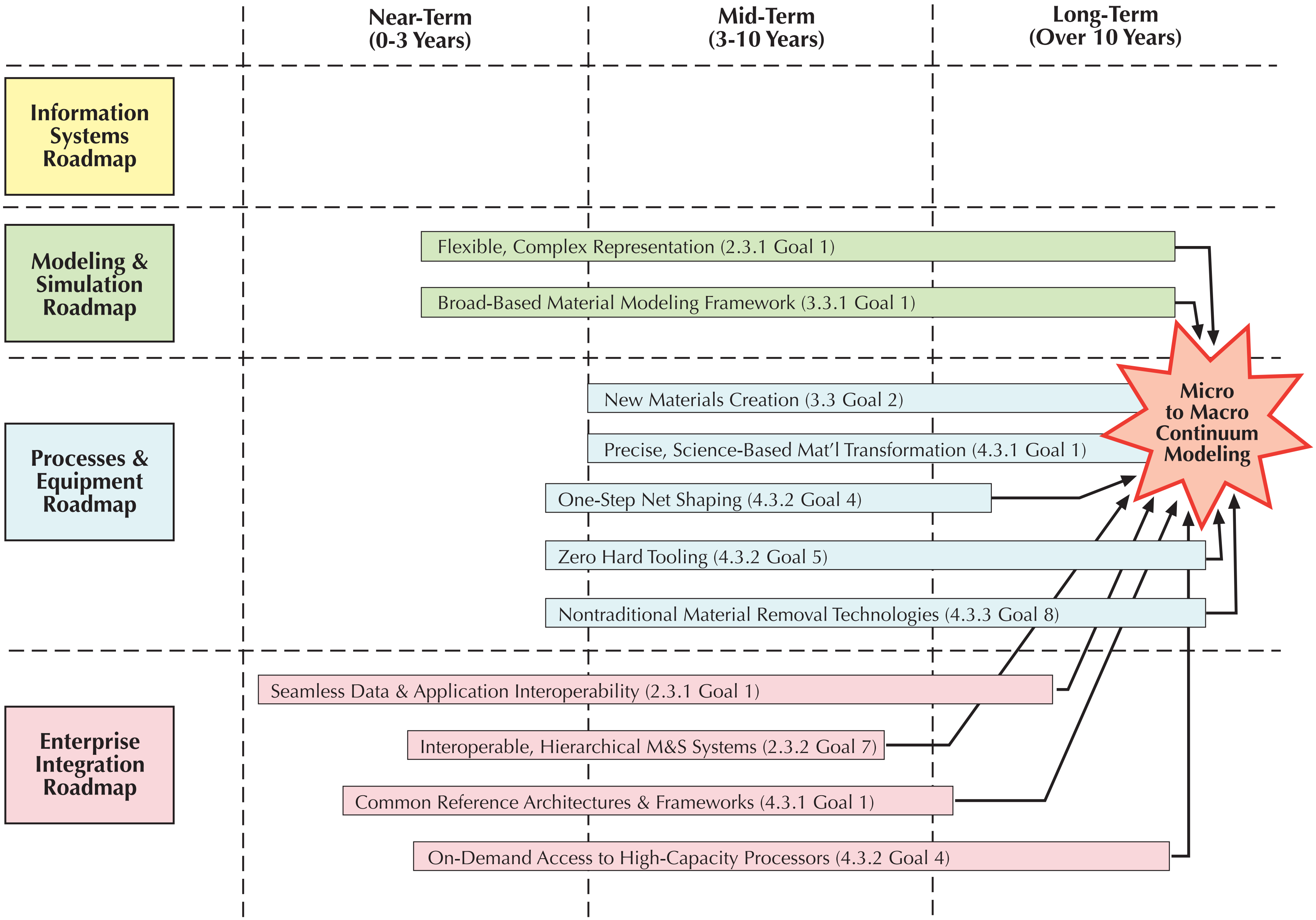
As a first step towards interrelating the key findings of the three IMTR Roadmaps, we have developed a series of "nugget roadmaps" that map the nuggets for each document against all of the goals across all three documents. Individual roadmaps for the Information Systems nuggets are presented on the following pages.

M&S "Nuggets" / Areas of Beneficial Impact	Reduced Development & Mfg Costs	Improved Product Quality	Faster Time to Market	Greater Responsiveness to Cust. Needs	Increased Competitiveness & Mkt Share	Higher Return on Capital
1. Micro to Macro Continuum Modeling	●	●	○	○	●	○
2. Science-Based Models Integrated w/ Living Knowledge/Exp. Bases	●	●	●	●	●	●
3. M&S Is Rule, Not Exception	●	●	●	●	●	●
4. Intelligent Design & Analysis Advisors	●	●	●	●	●	●
5. M&S as Real-Time Enterprise Controller	●	●	●	●	●	●
6. Smart, Self-Learning Models	●	●	●	●	●	○
7. Open, Shared Repositories & Validation Centers	●	●	●	○	○	●
8. Integrated, Robust Product & Process Models for All Domains /Apps	●	●	●	●	●	●
9. Seamless Interoperability	●	●	●	●	●	●
10. Real-Time, Interactive, Performance-Based Models	●	●	●	●	●	○

● = Major Impact ○ = Moderate Impact

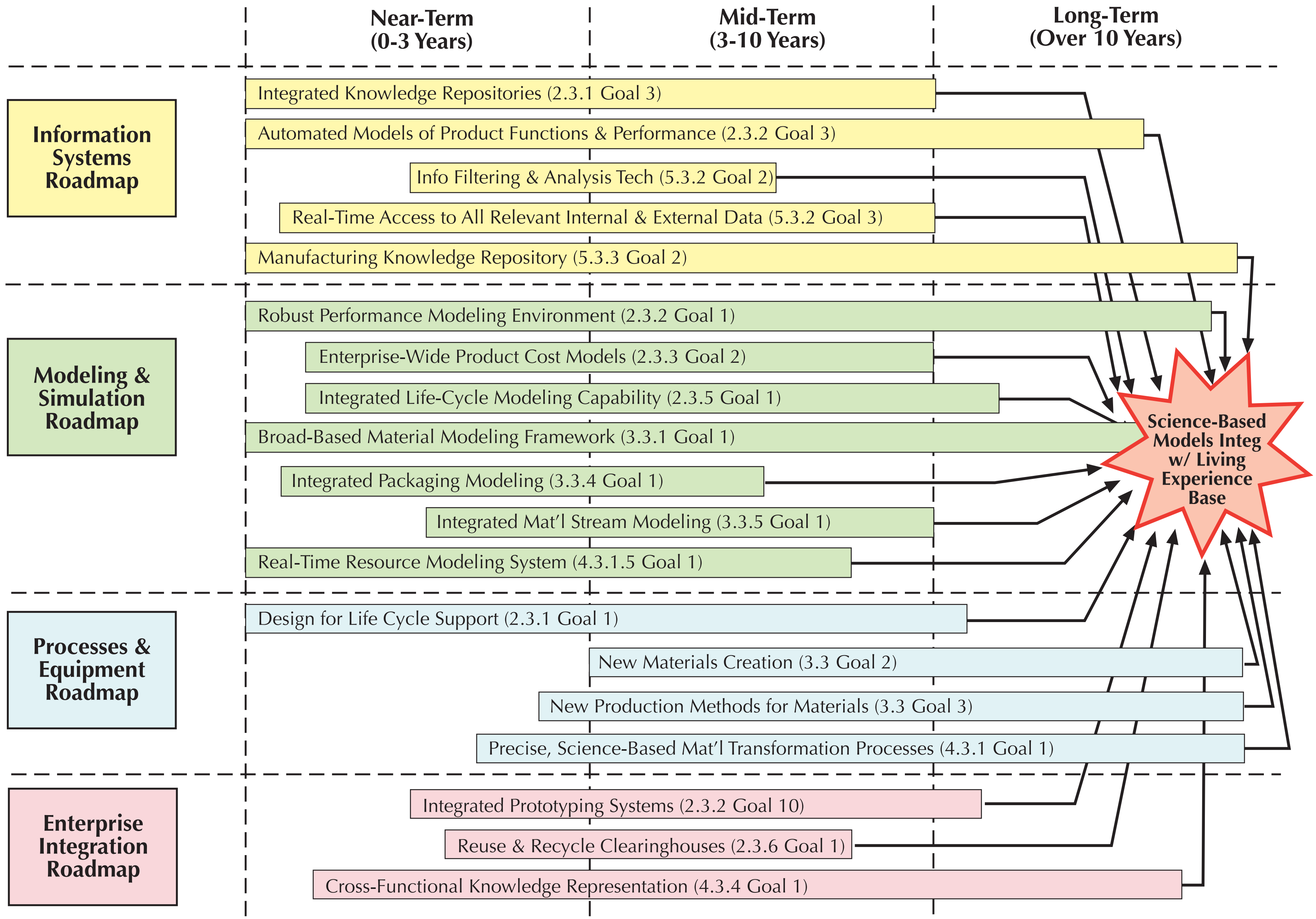
Figure 1.3-1. Each of the M&S Nuggets makes significant contributions to improved manufacturing enterprise performance.

Roadmap for Modeling & Simulation Nugget 1 – Micro to Macro Continuum Modeling



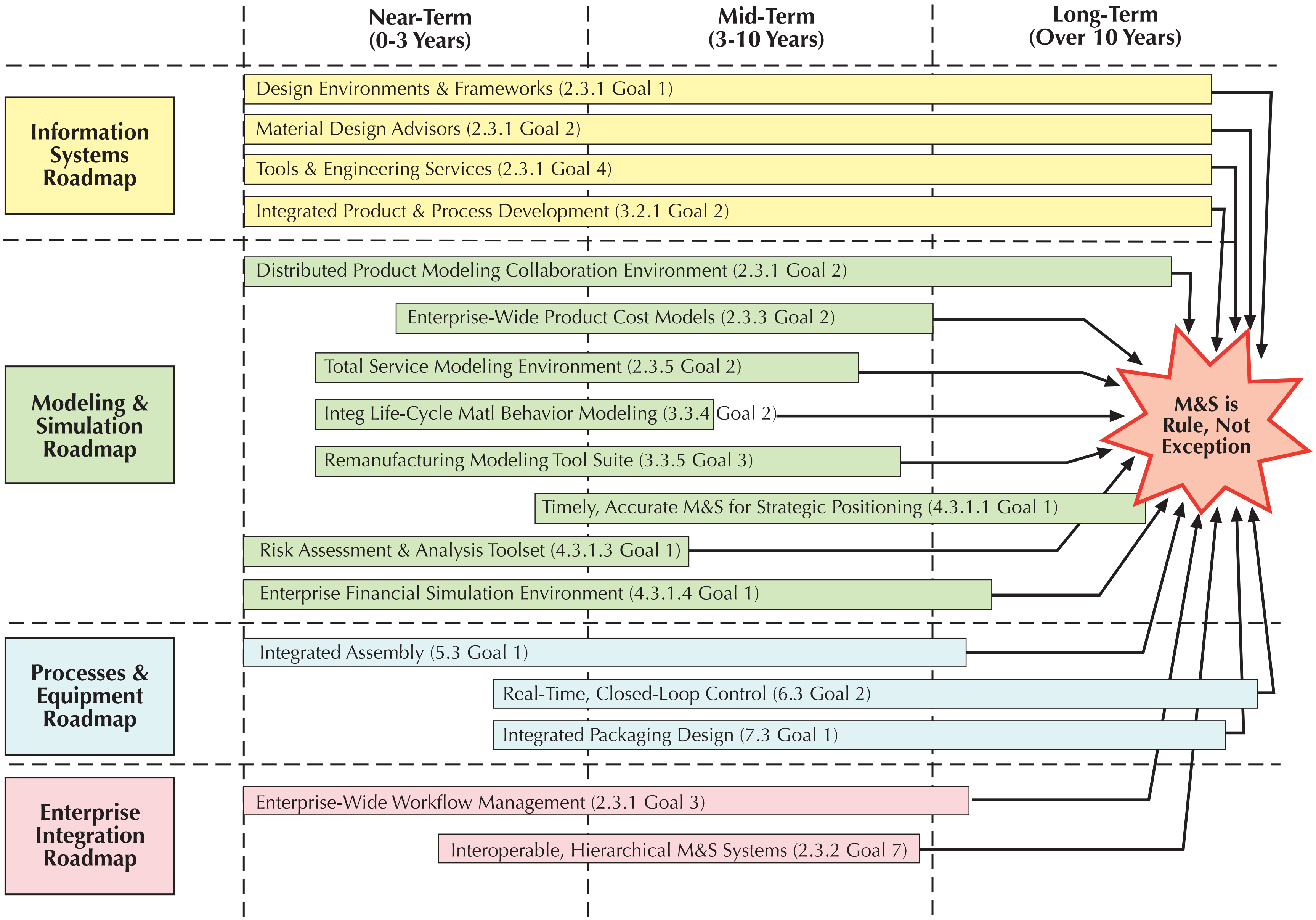
Note: Referenced Sections of the respective IMTR Roadmap documents are indicated in parentheses

Roadmap for M&S Nugget 2 – Science-Based Models Integrated w/ Living Knowledge/Experience Bases



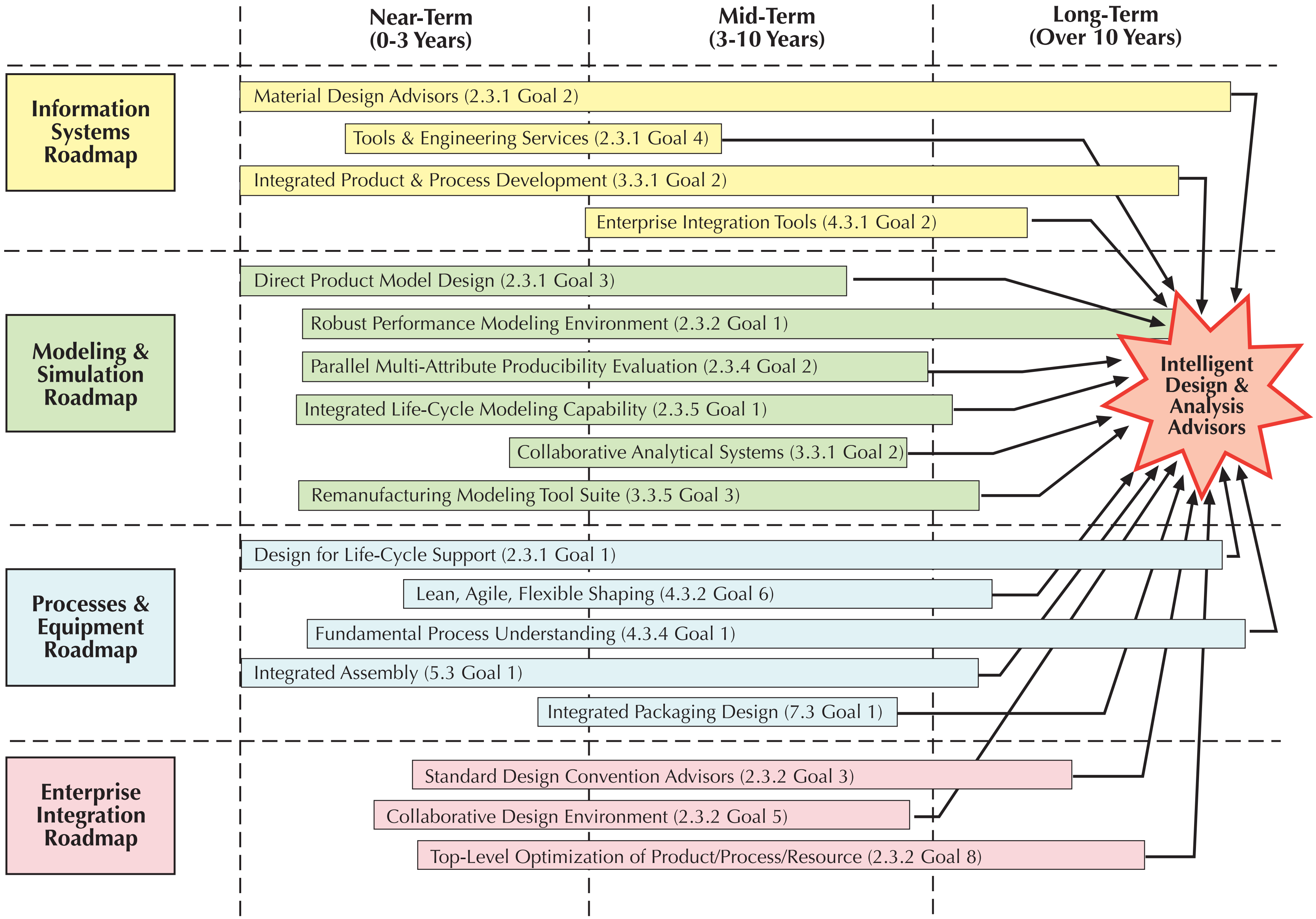
Note: Referenced Sections of the respective IMTR Roadmap documents are indicated in parentheses

Roadmap for Modeling & Simulation Nugget 3 – M&S is Rule, Not Exception



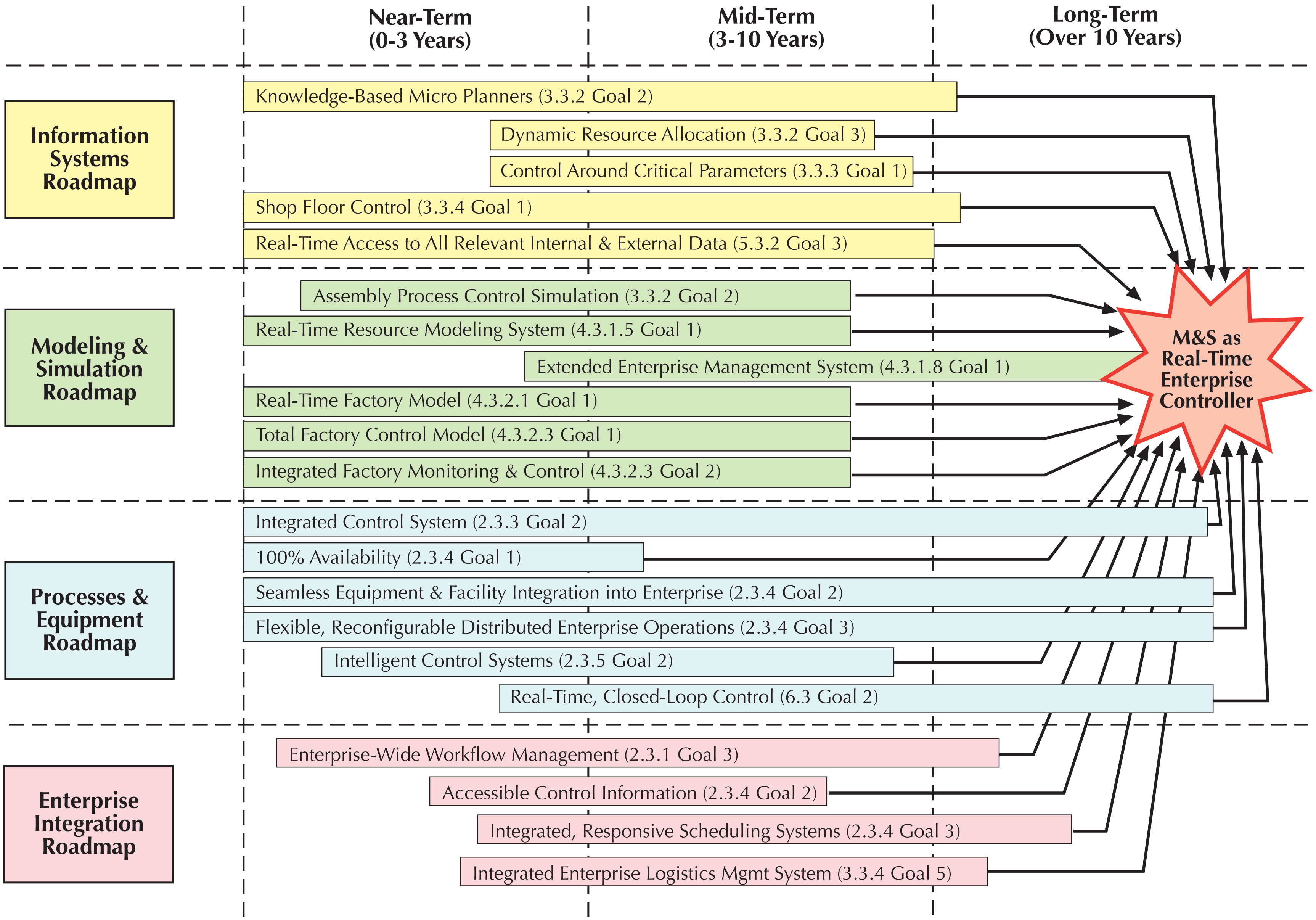
Note: Referenced Sections of the respective IMTR Roadmap documents are indicated in parentheses

Roadmap for Modeling & Simulation Nugget 4 – Intelligent Design & Analysis Advisors



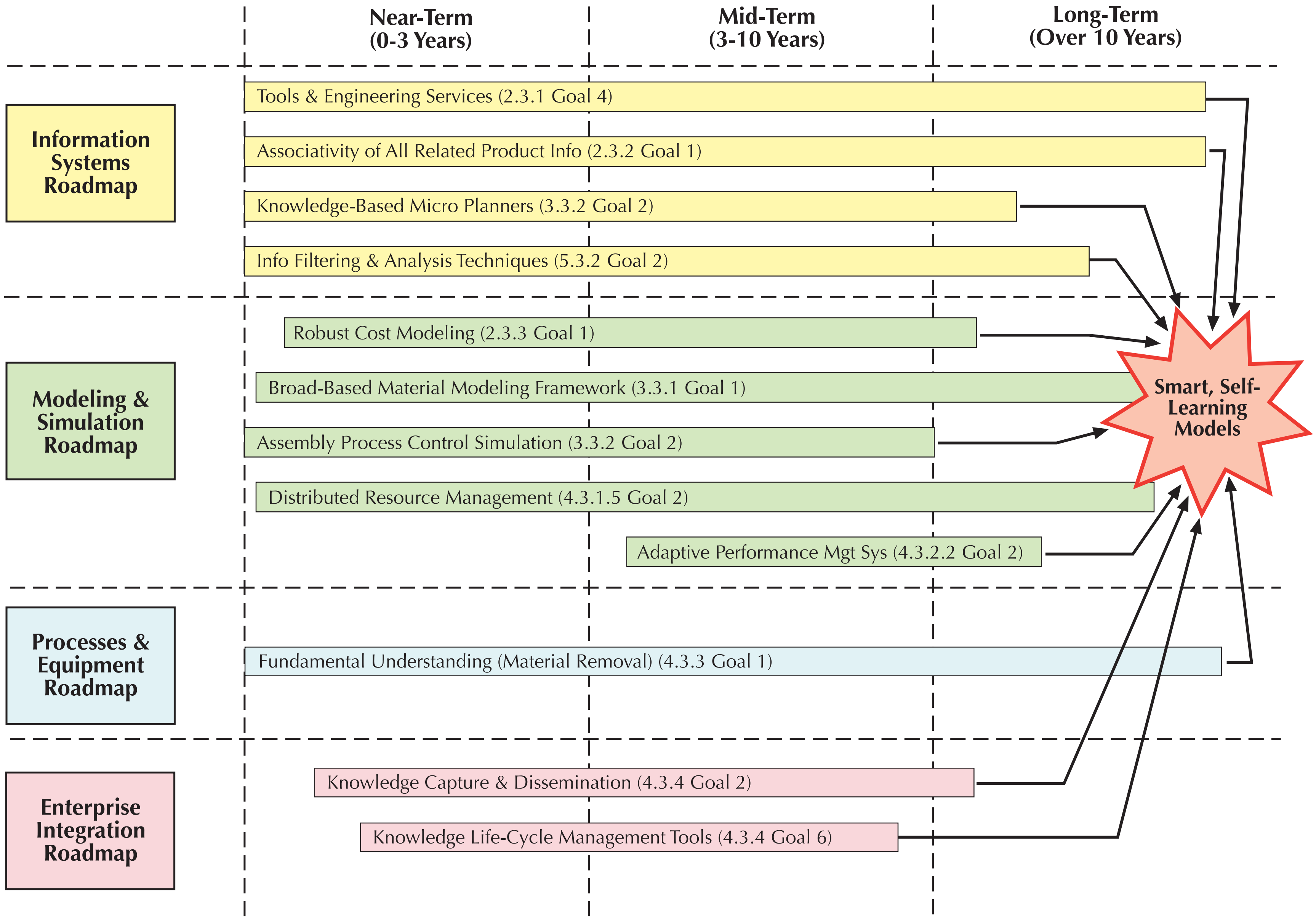
Note: Referenced Sections of the respective IMTR Roadmap documents are indicated in parentheses

Roadmap for Modeling & Simulation Nugget 5 – M&S as Real-Time Enterprise Controller



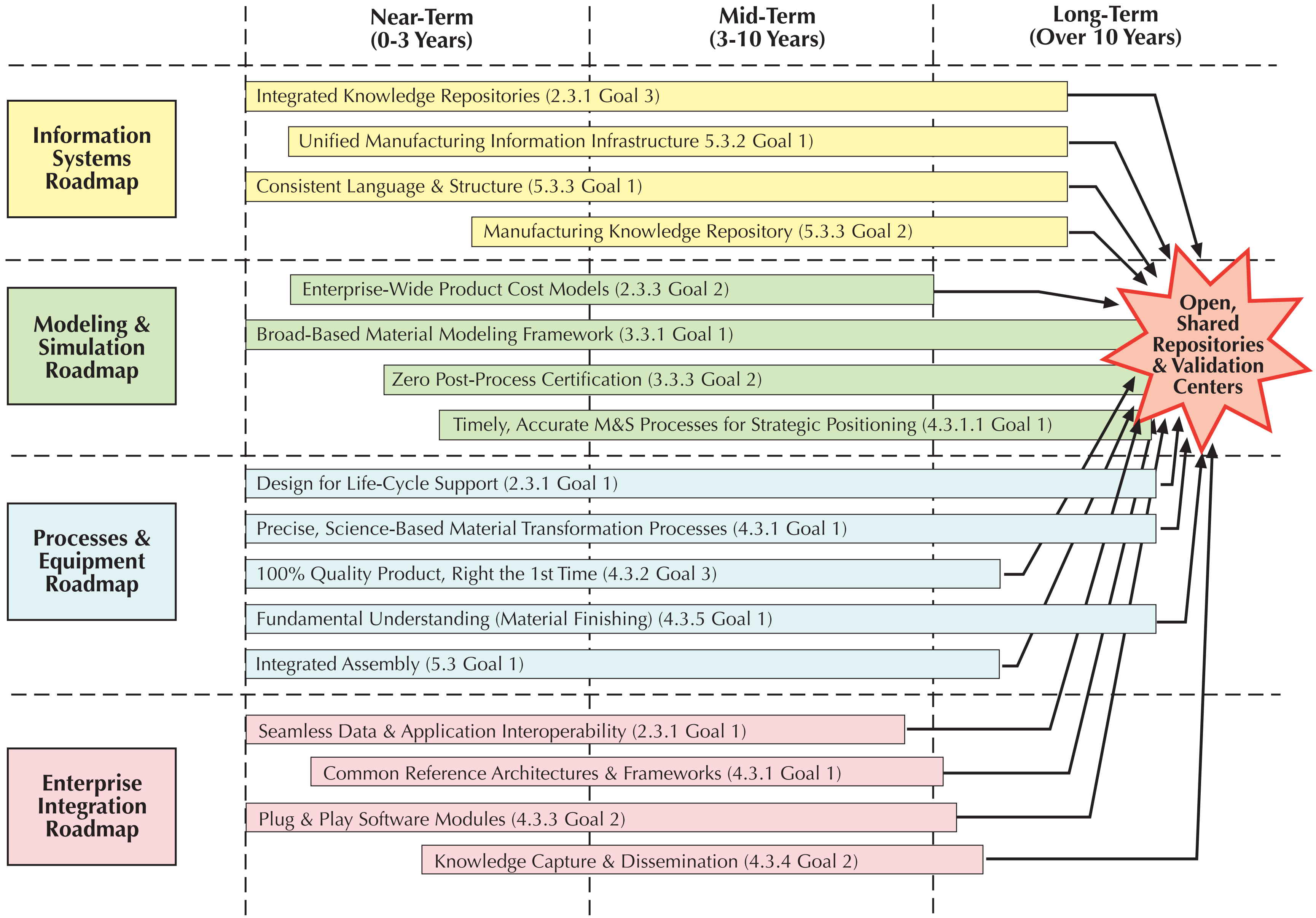
Note: Referenced Sections of the respective IMTR Roadmap documents are indicated in parentheses

Roadmap for Modeling & Simulation Nugget 6 – Smart, Self-Learning Models



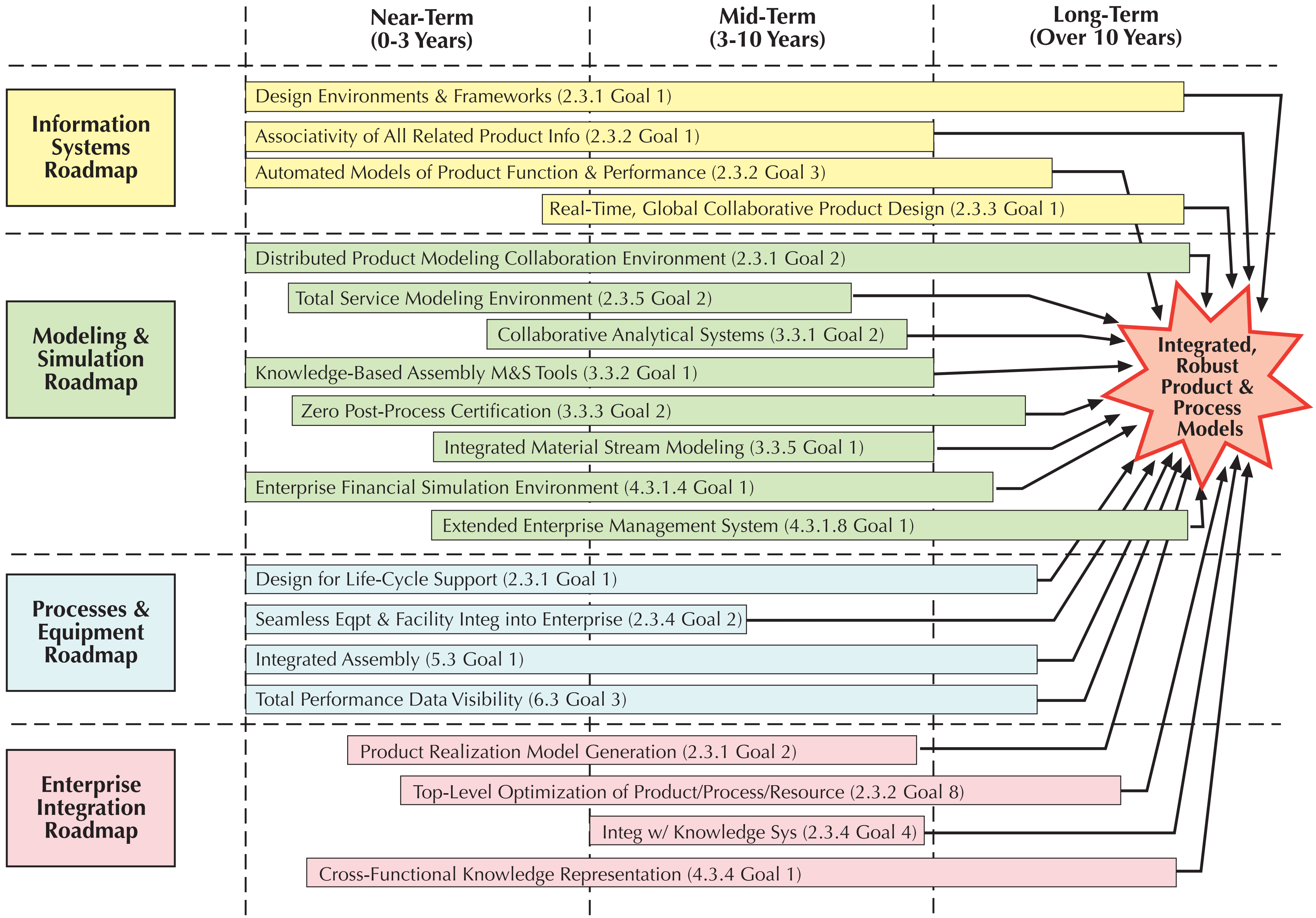
Note: Referenced Sections of the respective IMTR Roadmap documents are indicated in parentheses

Roadmap for Modeling & Simulation Nugget 7 – Open, Shared Repositories & Validation Centers



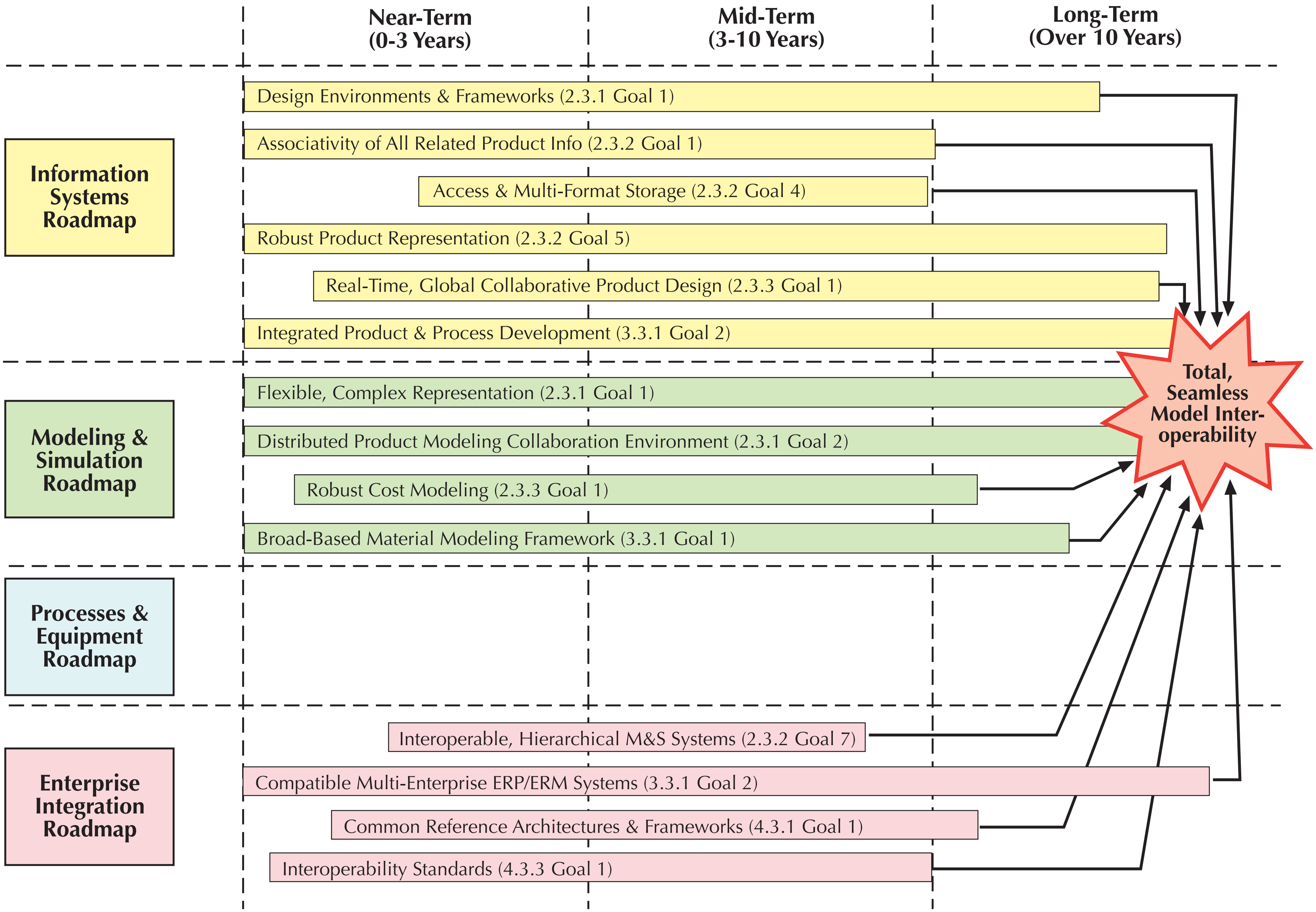
Note: Referenced Sections of the respective IMTR Roadmap documents are indicated in parentheses

Roadmap for M&S Nugget 8 – Integrated, Robust Product & Process Models Supporting All Domains & Apps



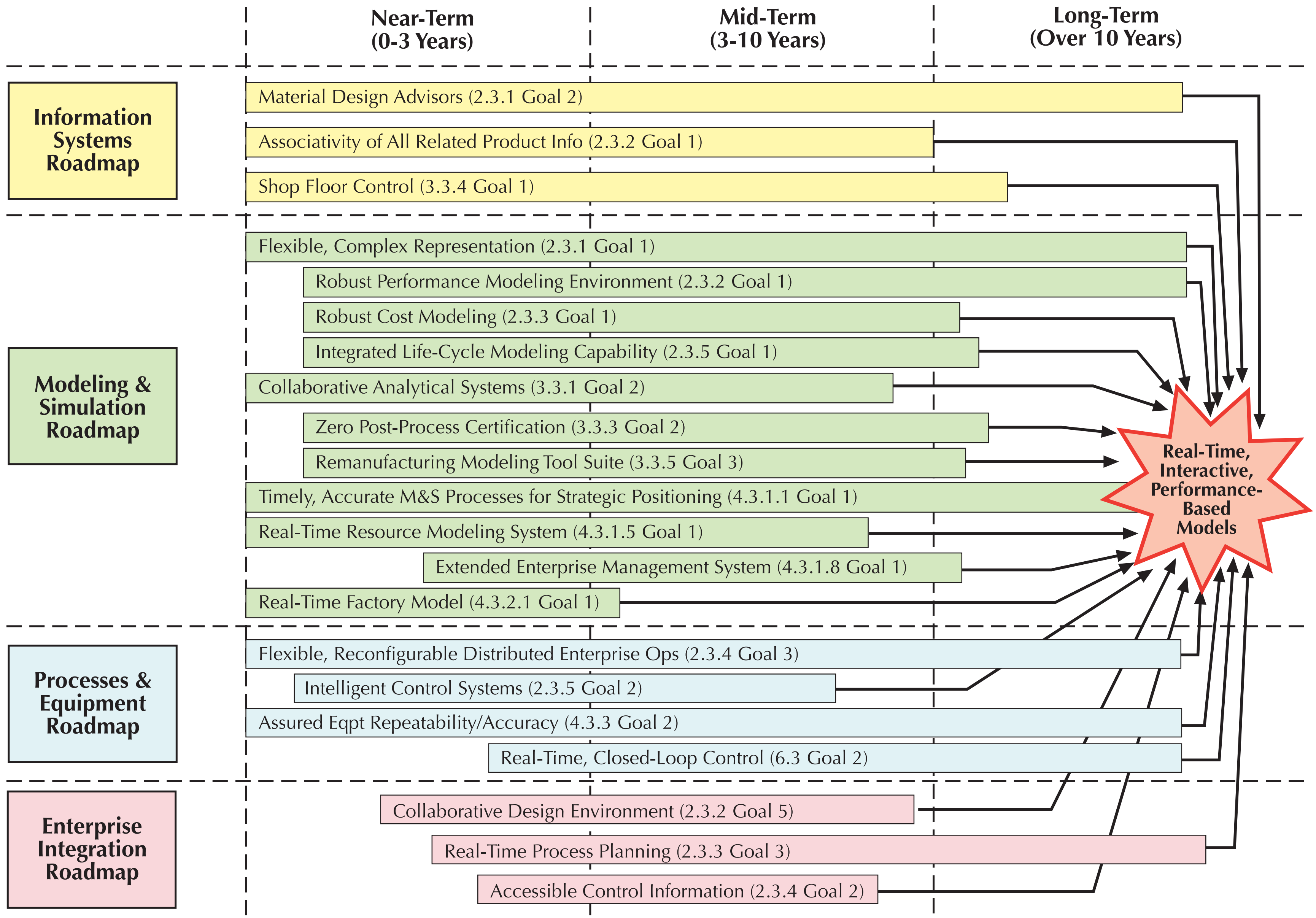
Note: Referenced Sections of the respective IMTR Roadmap documents are indicated in parentheses

Roadmap for Modeling & Simulation Nugget 9 – Total, Seamless Model Interoperability



Note: Referenced Sections of the respective IMTR Roadmap documents are indicated in parentheses

Roadmap for Modeling & Simulation Nugget 10 – Real-Time, Interactive, Performance-Based Models



Note: Referenced Sections of the respective IMTR Roadmap documents are indicated in parentheses

1.4 Roadmap Organization

This document is organized around the basic functions inherent to a typical manufacturing enterprise[3], in the context of modeling and simulation. These functional elements, and their respective sub-elements, are shown in Figure 1.4-1.

In the IMTR workshops, the participants used the "goals > requirements > tasks" methodology to develop the draft roadmaps in top-down fashion, first defining goals and then fleshing out the supporting detail to the lowest level possible.

For each functional element, this roadmap presents four basic sections:

1) **Functional Model Definition**: Descriptions of the different elements (i.e., the manufacturing enterprise processes) included in the functional model.
2) **Current State Assessment**: A brief overview of the current state of industry art and practice for each functional element, highlighting major deficiencies, barriers to advancement, identified needs, and some relevant ongoing R&D initiatives.

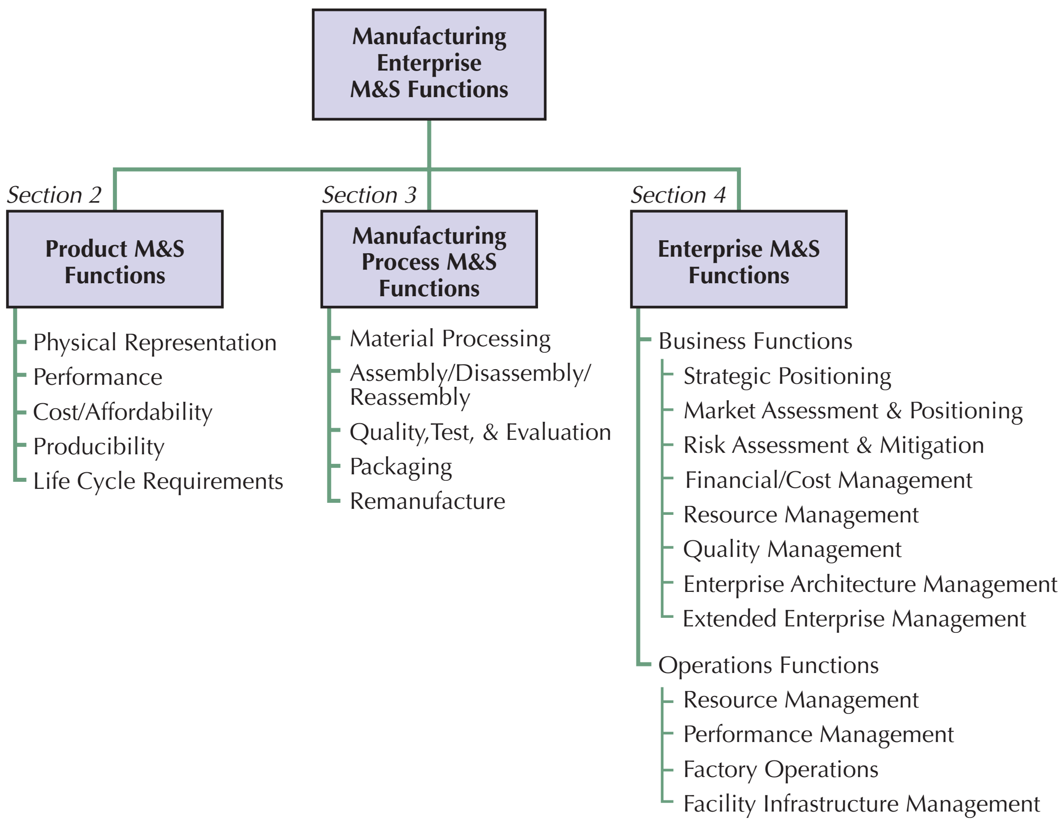


Figure 1.4-1. The functional model for Modeling & Simulation provides a framework for identifying R&D requirements according to specific areas of need.

[3] The term "manufacturing enterprise" has come into popular use to define a manufacturing firm as more than just a single factory location, and many variants of the term have appeared to describe different corporate relationships. In the IMTR context, the "enterprise" is the manufacturing firm without respect to its component parts. A "distributed enterprise" is the manufacturing firm including all of its operations, regardless of geographic separation. An "extended enterprise" is the firm plus all of its suppliers and partners, including partnerships of convenience that may be formed for specific purposes under formal or informal arrangements. The term "supply chain" is also used to specifically refer to the manufacturing firm and the tiers of subcontractors and suppliers who provide products, materials, services expertise, or other assets that enable the manufacturing firm to create, deliver, and support its products and services. The supply chain concept has also been modified with descriptors such as "value chain," to extend the concept beyond the traditional view of suppliers simply delivering parts and materials, and "value webs," which recognize that the supply chain is more than just a vertical relationship of multiple tiers of subcontractors and suppliers supporting one prime contractor.

3) **Future State Vision, Goals, & Requirements**: A conceptual view of the future state of the manufacturing enterprise relative to each functional element, and goals and requirements to achieve that vision (a framework for recommended R&D activities)

4) **Roadmap**: A high-level milestone plan that maps the future-state goals and requirements over time in a framework intended to support research, development, validation, and implementation plans.

The Future State Vision, Goals, and Requirements sections lay out a top-level "statement of work" to achieve their respective future visions. As indicated in Figure 1.4-2, the Goal statements describe the functionalities or capabilities that must be achieved to fulfill the vision, the Requirement statements define the work that must be done, and the Task statements provide a lower-level breakout of major activities that support their requirements. Significant input for these requirements was developed using Internet-based surveys of the manufacturing technology community. (See Appendix C.) In some areas, the work that needs to be done to fulfill the vision is defined only down to the Goal or requirement level. It is expected that organizations who seek to work toward specific goals will work together to establish the detailed R&D plans for their accomplishment.

It is important to note that the milestone plans are not intended to provide a definitive, stepwise project plan for every goal. Rather, they are to identify major R&D tasks that should be done, based on the recommendations of the IMTR workshop team and contributing reviewers. The timeframes in the plans represent a collective consensus on reasonable spans of effort. It is expected that projects organized around the IMTR objectives will define detailed statements of work and task plans consistent with sponsor requirements, and it is the IMTR team's intent to update the baseline roadmap to reflect progress of specific implementation efforts.

It is also important to note that much work is already underway in many of the technology areas identified in the IMTR Roadmaps. In some cases, the ongoing work may map very closely to the IMTR requirements, and may merely require extension or acceleration to implement the desired capability consistent with the IMTR vision of totally integrated, plug-and-play enterprises. In other areas, companies and research institutions are already developing or piloting point solutions that meet IMTR-relevant requirements within the context of their own needs. In these instances, our goal is to see these solutions adapted and enhanced as required to support the IMTR concept of seamless plug-and-play functionality.

In all cases, the R&D projects defined in the IMTR roadmaps culminate with a validated tool or capability either ready for widespread commercial implementation, or implemented to the point of significant use (standard practice) among multiple major manufacturers.

Goal: A basic capability to be developed to support the future vision

- **Goal 1: Broad-Based Material Modeling Framework** – Provide a broad-based framework to provide validated, interoperable material models that serve many process applications. This framework must consist of open, shared models for a wide range of materials and enable tailoring with proprietary extensions for specific applications.

Requirement: A specific R&D effort required to achieve the goal

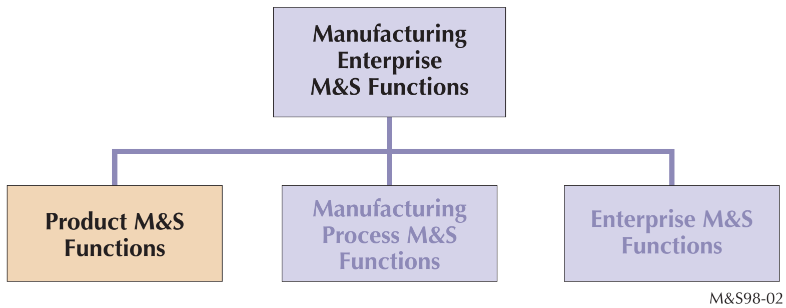
– **Science-Based Material Modeling Knowledge Base** – Establish a "body of knowledge" to provide a foundation for more accurate and cost-effective material modeling and simulation applications. (Specific knowledge bases needed to support this requirement are identified in the IMTR Roadmap for Information Systems, Section 2.3.1, Databases/Libraries, and Knowledge Repositories.)

Task: A specific action that must be taken to meet the requirement

* **Standard Information Representation Framework**– Establish a standard framework for representing material properties and characteristics data in plug & play models.

Figure 1.4-2. The roadmapping process identifies top-level goals to be achieved, requirements to support the goals, and tasks to accomplish the requirements.

2.0 PRODUCT MODELING & SIMULATION FUNCTIONS



2.1 Functional Model Definition for Product Modeling & Simulation

The product-related modeling and simulation activities of a manufacturing enterprise can be functionally divided into five elements for assessment and planning purposes:

Physical Representation ⇒ Includes the conceptualization, creation, capture, preservation, and depiction of the product and its associated features based on defined requirements, needs, desires, and goals.

Performance ⇒ Includes all performance attributes of the product, including size, weight, strength, material properties, operating environmental limits, reliability, availability, maintainability, supportability, interoperability, and similar features.

Cost/Affordability ⇒ Includes determination of product cost and associated affordability trade-offs with various price and performance factors.

Producibility ⇒ Includes determination and optimization of product manufacturability aspects such as material selection, part and feature complexity, tolerances, assembly interfaces, process options, and similar factors.

Life Cycle Considerations ⇒ Includes specific performance factors related to overall product life cycle attributes, including sparing, repairability, replaceability, and transportability, and environmental requirements such as recyclability, reusability, and disposability.

Each of these elements is intimately tied to the overall process of product design. Since product design is, at its heart, the creation, manipulation, and application of information to drive the physical processes of manufacturing, product design as a function is addressed in the IMTR *Roadmap for Information Systems* (specifically, Section 3 of that document). This roadmap, for Modeling & Simulation, addresses specific aspects of the product design process from a modeling and simulation perspective.

2.2 Current State Assessment for Product Modeling & Simulation

In progressive companies where concurrent engineering and integrated product/process development (IPPD) are rapidly becoming the way of doing business, the results have been impressive. Time to market is being reduced by orders of magnitude, costs of development and non-value-added activities are being slashed, and initial product (first article) quality is increasing dramatically. Despite these advances, however, IPPD is not yet supported by the rich toolset required to reach its full potential. Even the leading practitioners are limited by the capabilities of available tools, and the few integrated toolsets that are available, do not fully support emerging IPPD philosophies. Progress is being made: 2-D and 3-D CAD systems are continuing to evolve with increasingly better fidelity of design data, more robust abilities to output the data needed to drive manufacturing processes, and improved capabilities to evaluate more than just the physical configuration of the product.

Modeling techniques such as quality function deployment (QFD) are enabling cross-disciplinary teams to compare and contrast customer needs and wants in a structured way against design and manufacturing options – and business drivers – to help optimize the total product strategy very early in the process.[4] QFD is still largely a paper-based modeling tool that uses highly subjective measures, but it points the way for future tools that will bring greater rigor to these kinds of modeling applications.

Improvement and expanded use of product modeling and simulation tools is hampered by several issues that are true for all M&S domains:

- Models and simulations are expensive and time-consuming to build and validate, since they are typically created from scratch for a very specific purpose.
- Creation and use of models and simulations requires sophisticated technical skills and extensive application-specific training and practice.
- Models with any substantive value are not openly shared, but rather are protected as proprietary assets.
- Since most models and simulations are developed and applied exclusively for problem-solving, the majority of manufacturers do not have a good basis for making cost/benefits decisions about enterprise-wide use of M&S tools and techniques.
- Most models and simulations (and most M&S tools) are not interoperable.

Current tools for modeling and simulating physical products are limited in their ability to fully characterize all of the attributes of the product. The term "product model" is almost a misnomer, because even the most robust models today are little more than a geometric representation coupled with limited product definition and manufacturing information. Thorough modeling of a complex product today requires the creation of multiple models of different types, none of which work together.

Computational complexity and time constraints prevent simulation tools from providing adequate and timely decision-making support in the product design process. There is little knowledge of the underlying physics of most materials and transformation processes, very little ability to capture and reuse knowledge about a product, and few tools or methods (other than QFD) that enable product designers to take organizational, social, or other nonphysical factors into account. Modeling the physical representation, performance, cost/affordability, producibility, and life-cycle features of a product demands robust capabilities to capture, transform, translate, and exchange knowledge and data.

Lack of standards is a major concern in all M&S applications. Compatibility in product data exchange, standard representation of product and process, compatibility of M&S systems with process information systems, scaleability between micro and macro levels, all must be addressed as we move to the next level of cost-effective, accurate simulation. STEP is a major factor in this migration. Constraints and features are now represented in STEP standards, but incorporation in commercial tools is in its infancy. There is little incentive for technology suppliers to model assemblies because the multiplicity of incompatible systems limits the scope of utility and cost-effectiveness.

[4] For more about the Quality Function Deployment methodology, see the Harvard Business Review, May-June 1998, pages 63-73.

Many examples of M&S cost savings in product and process design do exist. The continuous processing industry – particularly large manufacturers such as Dow Chemical – has made modeling and simulation an integral part of its product and process design operations for many years, and has reaped the benefits of very high product quality and "right the first time" process facilitization. In the aerospace and automotive industries, high-profile products such as the Boeing 777 and the Dodge Viper (see page 1-3) have demonstrated the large cost and time savings achievable with all-digital, model-based design and manufacturing. The semiconductor industry is a good example of modeling and simulation as "the way" to move from concept to manufactured product. This sector has done a superb job of defining needs and developing tools and technologies that directly support those needs. The job is not complete, but a good benchmark does exist.

Neural networks[5] have also brought accurate and cost-effective solutions to bounded applications, and genetic algorithms[6] are showing revolutionary promise in a number of areas. A good example of a useful genetic algorithm-based tool is a transportation routing system developed by Westinghouse which models the management of perishable goods to assure their safe and spoil-free arrival. Knowledge-based systems are coming into their own and, coupled with good M&S capability, automated advisors are helping designers make better decisions. Fast computing on the desktop and automation of highly complex processing techniques (e.g., creation of finite element meshes) are revolutionizing the modeling and simulation world.

Federal facilities are likewise leveraging leading-edge technologies to design, develop, and test products entirely in the virtual realm. In November 1998, the DOE Kansas City Plant (KCP) cut the ribbon on its new "Heartland Supercomputer," a massively parallel processing system which will be the centerpiece of KCP's virtual design and manufacturing operations. With the new system, KCP engineers will be able to analyze product designs in collaboration with DOE's national laboratories; minimize variations that occur in processes such as welding, bonding, and encapsulation; and simulate complex interactions between electrical and mechanical components of an assembly.

2.2.1 Physical Representation

Modeling of physical objects is the most common and well-developed application of computer modeling technology. The emergence and growth of 3-D CAD and manufacturing engineering systems in the 1980s gave product developers powerful tools for creation, evaluation, and refinement of prototype designs, greatly reducing the time required to create specifications and drawings for handoff to manufacturing. In the aerospace and electronics industries, a number of specialized tools and systems have evolved to enable direct output of manufacturing data (e.g., numerical control programs) to drive actual manufacturing process equipment. The maturation of electron beam lithography systems, coupled with 3-D CAD systems, now enables creation of complex unitary physical shapes directly from a 3-D electronic model. These "rapid prototyping" systems provide very high fidelity of form and fit, and enable creation of physical prototypes that would otherwise require the services of an entire machining shop.

However, the ability of current M&S tools to physically represent a product in models or simulations is inadequate to support the integration and application of transformations from design features (physical and non-physical attributes) to manufacturing features, or to simplify or modify the models to meet the needs of users other than M&S experts. Solid models are primarily limited to display of nominal shape and capture of geometric specifications, and joining features are represented with only limited fidelity, if at all.

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[5] Neural nets: A method for analyzing large amounts of data to create "convergence" (define common trends and reach conclusions) faster than conventional methods. The methodology is based on the biological model of the neurons of the human brain.

[6] Genetic algorithms: A method for representing knowledge in decision support tools, based on the analogy of DNA and Darwinian "natural selection." In simple terms, a decision process involves "chains" of options from a limited set (as in the four basic compounds of DNA) and can decompose complex decisions into strings of selection of best options. Although the discussion seems complex, the methodology greatly reduces time and provides a systematic approach for automated decision support.

Many problems are caused by the ability of modeling systems to create mathematical shapes that can't be manufactured. Product model interfaces are also limited in dealing with non-geometric issues such as environmental considerations and materials of composition. Current modeling applications are unable to represent the different states of a product throughout its life cycle, such as "green" or preform, or to support creation of a synthesized component model based on a specific process. Multipurpose material models are available for some homogeneous materials, but not for complex or non-homogeneous materials (e.g., multilayer composite structures, liquid mixtures with multiple chemical constituents or entrained particulates).

Current-generation product models are not robust. That is, they are unable to capture knowledge about the product beyond much more than simple geometry and materials of construction. Today's solid modeling languages do not relate to product functionality, which limits their ability to capture design intent. The physical representation of the product is performed through symbology in many domains (e.g., gases or liquids are represented symbolically with an engineering note). Capture of product updates is based on product model version control. It is also true, particularly in the chemicals industry, that very detailed, high-fidelity models are created during the product design stage to help engineer the process chemistry, then left to collect dust in the lab when the process is implemented for production.

There is limited ability to use models in one domain that were created in a different domain, and product data exchange is still in its infancy in many industries. Most models are currently preserved only in hardcopy form. Some modeling is beginning to be archived electronically. Modeling in the current state requires multiple models for each domain, and linkages and associativity between the models are virtually nonexistent.

One of the most vexing barriers in this area is the complexity of simulation tools. Their very high computational demands, long turnaround times, and high operator skill needs dictate that their application is almost exclusively limited to troubleshooting of cost-critical problems.

2.2.2 Performance

Current modeling systems for physical components address size, weight, materials of construction, and similar factors, but product performance modeling is limited in most industries. Specialized applications (e.g., finite element analysis tools) are used to custom-build mathematical models to evaluate performance in different operational regimes of temperature, pressure, stress, and similar factors. Functional performance modeling of electrical circuitry, which relies on a large base of validated component models and a handful of popular simulation codes (SPICE, etc.), are very well developed compared to that for mechanical systems.

However, performance modeling systems in both domains are inadequate to support the transformations between design features and manufacturing features – i.e., how characteristics at the micro level relate to behavior at the macro level – in the context of how the product will behave in the real world.

Current-generation operational analysis simulations use Monte Carlo techniques to predict how a weapon system will perform with different attributes in different battlefield scenarios. However, these simulations do not use a complete and accurate model of the system, but rather a few defined performance parameters such as range, speed, accuracy, and lethality. Making non-financial "affordability" tradeoffs of multiple performance attributes (e.g., to balance the need for low weight against the need for long range, which dictates a large, heavy fuel load) is more art than science, and driven almost exclusively by a customer's "must" requirements.

Little capability exists to model and simulate complex interactions outside of highly specialized aerospace and defense applications. Simulation codes are used extensively for specialized needs such as aerodynamic (e.g., for airframes and aerostructures) and hydrodynamic (e.g., submarine hulls and control surfaces) performance evaluation, but these applications require expert operators and huge amounts of high-speed computing power, and certainly do not provide the confidence to do away with traditional engineering practices such as wind-tunnel testing of scaled physical prototypes.

Existing performance modeling applications are not adequate to support capture of the full range of knowledge about the product, the process of product design, or the processes required to produce the product. Such applications also have only limited capabilities to link and associate related models from different domains.

The fundamental physics of actual product and material characteristics are not understood in most domains. Product performance modeling offers only a few tools that can analyze a product in the context of its actual use, to help optimize designs for ease of use, maintenance, repair, or final disposition (e.g., recycling). Physical interface interactions such as braze joints are difficult to model and there is very little correlation between failures on a microscopic scale and a macroscopic scale. There is little capability to model the interaction of multiple dependencies for complex products, particularly chemicals (e.g., multiple drugs).

2.2.3 Cost/Affordability

Accurate cost models are difficult to create, due largely to poor traceability between estimated and actual costs – and due to limited understanding of the cost interdependencies of product constituents and the different processes used to create the product. Cost models are traditionally developed in "bottoms up" fashion by estimating design and manufacturing costs for individual components, materials, and their assembly, test, packaging, and handling (plus overhead), then "scrubbing" the results to arrive at a set of numbers that management feels are appropriate. Opportunities for reducing the costs of individual items or processes are generally pursued only for the most expensive elements, or where affordability or competitiveness problems are perceived.

There are no good M&S tools for estimating costs for conceptual designs or determining to what extent a given design is affordable, unless there are very close parallels with an existing product for which costs are well known. Complex products such as a new military aircraft, or the Space Station as a good example, typically end up costing two to three times their initial estimates, regardless of the level of detail and rigor in those initial estimates.

Other flaws in traditional cost modeling processes include:

- Few cost models take into account all possible cost factors, or enable the cost impacts of changes in any one area to be accurately reflected in other areas.
- Estimates are based largely on experience and intuition, and "top-down" estimating (establishing a target cost and then determining how to achieve it) is often the only way to bring a product to market with acceptable profit margins.
- Cost estimates from partners, suppliers, and vendors are problematic for all but simplest kinds of work, largely because the underlying assumptions are based on a limited set of specific conditions, which inevitably change.

Life-cycle costs are often given only passing consideration in the costing process, and in most cases are not well enough understood – especially for complex products – to create accurate life-cycle cost models with sufficient validity to enable confident predictions. For example, although reliability data about delivered products is often gathered to forecast maintenance and repair requirements, these data are rarely linked back to the product design to help enhance the product and refine the original cost model. Some companies use proprietary models – mostly spreadsheets – to create life-cycle cost estimates that incorporate the costs of spare parts, consumables, repairs, and maintenance, but these tools are limited in their accuracy and utility. Accurate modeling of product and process costs cannot be achieved without a valid modeling architecture and tools for consistent, accurate representation of costs and cost relationships in all enterprise functions and product life-cycle phases.

Other barriers to accurate life-cycle cost modeling include:

- Few models of manufacturing resources (i.e., factory models, machine models) exist.
- Engineering and business perspectives of cost are different and lead to an inconsistent view of product cost within the enterprise.
- Inability to adequately model customer requirements and satisfaction criteria hinders the enterprise's ability to make optimum decisions regarding product design tradeoffs.
- There is little understanding of the relationships between product features and manufacturing costs.
- Costing of components and assemblies is done largely in isolation, not from a "total systems" view, which can cause a small component to drive up life-cycle costs for the total product.
- Existing cost models are not optimized or integrated.
- No tools exist to create metamodels[7] that integrate multiple cost models across related products and processes.
- Little ability exists to adequately predict and define the costs impacts of post-manufacture support requirements and optimize designs based on an integrated set of cost and resource models.

2.2.4 Producibility

Producibility of a product has traditionally been a secondary consideration in product design, addressed only after basic product functionality and performance are tuned to the designer's satisfaction. An excellent example of this is the Value Engineering change proposal (VECP) process, where a government contractor may suggest producibility enhancements to a product that is already in production, and share in the resulting cost savings. This actually incentivizes contractors to get serious about producibility only after a design is frozen, when they can realize additional revenue that otherwise would not have been accrued had the product been properly optimized for manufacture in the first place.

Although increasing competition and cost-consciousness have made producibility an increasingly important factor early in the design phase, only recently have designers been able to apply M&S tools to this facet of the process. Increasingly sophisticated 3-D modeling tools are enabling designers – and manufacturing process engineers – to see how complex parts fit together and to modify problematic designs to make them easier to fabricate and assemble. Coupled with improved capabilities to manufacture complex shapes, exotic materials, and chemical formulations, designers are increasingly able to attack traditional producibility barriers such as parts count, fastener complexity, curing/annealing schemes, and ease of assembly.

Perhaps the greatest advances in producibility engineering have not been provided by new tools, but by new ways of doing work. Concurrent engineering and integrated product/process engineering (IPPD) disciplines bring product designers and process designers together as members of an integrated team, ensuring that a product benefits from the expertise of all do-

[7] In the "metamodel" concept, many detail-level or micro models of different types can be quickly and easily composed to create macro models that reflect the attributes and behaviors of the whole system as well as those of the constituent parts. As an example, detailed models of the individual processes and equipment that comprise a factory can be composed to create a macro factory model. Tuning of the factory model automatically propagates appropriate changes in individual micro models, thus keeping every process in continuous tune with every other process.

mains at each step of the product realization process. Still, outside of leading-edge applications by the most forward-looking practitioners, optimizing a product for producibility still depends largely on trial-and-error manufacturing: build one, decide what could be done better, change the design of the product or the process, and build another one to see how the new approach works.

Despite recent advances, there are no truly robust M&S tools for evaluating and optimizing producibility in a systematic fashion. There is little fundamental understanding of the physical phenomena related to producibility, and human experience and intuition – and a few rules of thumb – remain the most valuable tools for judging producibility concerns and making good decisions.

Although dynamic modeling of a part or an item of material in the production process can be done, such simulations have very low fidelity, other than for modeling the flow of material through the factory or the interaction of a specific part or material with a specific piece of process equipment. Existing product models do not relate geometric and non-geometric tolerances, or have sufficient depth, accuracy, or flexibility to be imported directly into process models for evaluation of interactions at the micro or macro levels.

2.2.5 Life Cycle Requirements

Many factors, including environmental regulations, product liability, and support (training, maintenance, repair, sparing, etc.) drive the design of a product and the processes for its manufacture. Unfortunately, there are few tools to provide feedback (especially automated feedback) from point of use to the product design function. This creates long timelines to pass information back to designers to influence subsequent designs. The detailed information designers need to model and evaluate attributes such as field supportability, effectiveness of training, and environmental suitability is rarely available. Even when such data exists, there are few or no decision-making M&S tools available to help designers use the data to guide the design of products and processes to optimize their life-cycle performance.

2.3 Future State Vision, Goals, & Requirements for Product Modeling & Simulation

Future manufacturing enterprises will have seamlessly interoperable, easy-to-use modeling and simulation capabilities that allow them to efficiently engineer totally optimized products that satisfy customers' needs and desires. Accurate, complete information about products and processes will be accessible throughout the enterprise, regardless of geographic separation. In turn, product models will be 'living" entities that understand what enterprise data influences their "existence," and will respond appropriately when changes in the enterprise dataspace affect them (such as a change in the price of a part or material used in the product). Product models will thus have perfect fidelity, and contain or transparently link to all data needed to drive manufacturing, support, and other downstream processes. Product models will be virtual building blocks, stored as objects and associated features, enabling high-speed automated integration of complex designs drawing on knowledge bases of validated material and component designs. Product models will thus be seamlessly sharable and exchangeable between and among different manufacturers and suppliers.

Product modeling and simulation applications will be easy to use with little formal training, and embedded advisor utilities will provide guidance and training tailored to each user's unique needs, knowledge, and skills. These advisors will have direct access to the enterprise's knowledge resources (including model repositories), both internal and external, and will be able to provide recommendations or actual model modules based on initial design parameters and the designer's plain-language requests or queries.

"Break-the-mold wins" for product M&S technology to achieve this vision include:

- Advancing object-based and feature-based data management technology to enable applications to manage product data "intelligently."
- Product models will contain all the data needed to support all required modeling and simulation of their performance attributes, at both the micro and macro levels.
- All product models will "know" their own product life cycle, performance characteristics, cost of realization, and other attributes, providing a "superset of behaviors" that enable the greatest possible optimization of their design.
- The product data objects and features used to compose models will all hook together in plug-and-play fashion, enabling creation of metamodels that extend from the total product representation down to the lowest level of the product definition – even down to the molecular constituent level.
- The systems that manage the product models will be intelligent. Required manipulation and analysis will be done in the background, transparent to the user, in real or near-real time, greatly reducing the time and cost of computation.

Table 2.3-1 provides a summary-level view of where we are today and where we expect to be in the next 15 years.

2.3.1 Physical Representation

Vision: ***Seamlessly integrated, infinitely scaleable building blocks for perfect products***

In the future state, product models will no longer be simple physical representations coupled to a database of dimensions and other physical attributes. The future product model will be a complete virtual product, containing and linking to all information related to its manufacture, performance, use, and life-cycle support. Reusable, scaleable (both spatially and temporally), self-populating models will be the standard tool of product engineering and manufacture. A model will itself determine what it needs to fulfill the designer's requests and automatically retrieve information and perform necessary data manipulation and analysis, enabling designers to focus purely on the product innovation and optimization process.

Future product models will be populated with or transparently linked to all relevant information describing the product, and have neutral design representation or robust application programming interfaces (APIs) that ensure their ability to interface with other models, applications, and data sources. Product models will also integrate macro- and micro-scale

Quest for the Supermodel:

Federation is Key to Quantum Leap

An important issue in modeling and simulation is how to link models developed for different purposes, or by different organizations, so that the combined models can be used to simulate larger applications. This combining of models is often referred to as "model federation."

A good example of model federation is in the area of battlefield simulation, in which terrain, weather, weapon systems, and tactical models are combined to evaluate the effect of interactions in each of the models on the outcome of the hypothetical battle or the performance of different weapons working together.

A similar need exists to combine various product, material, process, and operational models to simulate manufacturing enterprises. There is also a need to link models in a hierarchical manner so they provide consistent views of a product or manufacturing operation at differing levels of abstraction or life cycle stages – so that a manager or a product designer can quickly see the right view of the product or process that they need to make decisions. For example, product "supermodels" that integrate separate models of physical representation, constituent material, manufacturing process, and quality certification requirements would be extremely useful.

The ability to link or federate different models will dramatically reduce the cost of modeling and simulation by enabling reuse of existing models and by making it easy to create higher-level representations. However, achieve this model federation ability, research needs to be undertaken in model architectures, frameworks, and interface techniques.

Table 2.3-1.
State Map for Product Modeling & Simulation Functions

Function	Current State of Practice	Current State of Art	Expected 2005 State (Major Goals)	IMTR 2015 Vision (Major Goals)
Physical Representation (Section 2.3.1)	• Solid models of nominal shapes • Creation of models that are not physically realizable • Little ability to accurately model complex interfaces • Many attributes represented by symbols & notes • Limited ability to translate design to physical prototype or actual product	• Unable to capture design intent or product functionality • Limited product data exchange or linking of different domain models • Complex tools requiring high skill & long processing times • Multipurpose models for some homogeneous materials	• Models that incorporate macro- & micro-level info • Generic virtual "backplanes" for creation of plug-&-play models & simulations • Models that link process & enterprise features into product models	• Object-oriented models containing all product info • Complete interoperability between physical models • Direct linkage to virtual & physical prototyping systems • Collaborative modeling & simulation using integrated environments
Performance (Section 2.3.2)	• Modeling of electrical performance more advanced than mechanical performance • Very high cost & complexity	• Highly specialized applications with tremendous & complex computational demands • Unable to support or link multiple user perspectives • Poor understanding of underlying physics	• Performance design advisors • Fast background simulation • Performance modeling & assessment tools plug-compatible with design systems	• Multivariate performance analysis • Automatic performance optimization • Linkages to many user types
Cost/ Affordability (Section 2.3.3)	• Bottoms-up cost modeling from component level • Custom cost models or generic tools (e.g., spreadsheet apps or database-driven simulations) • No linkage to actual, real-time data	• Specialized tools tailorable to similar processes with many variables • Difficulty modeling true product or process costs due to low fidelity of life-cycle models and data	• Cost data available on commodities & downstream life-cycle costs	• Performance-based cost modeling • Enterprise-wide cost models
Producibility (Section 2.3.4)	• Limited capability to capture knowledge in this area • Limited to assessment based on parts count, number of part surfaces, or known chemistry • No tools or methods for assessing non-physical factors	• A few highly complex tools requiring skilled users • Lengthy simulation times limit number of alternatives • Lack fundamental understanding of physical phenomena of producibility	• Models of internal & external manufacturing capabilities • Autonomous agents to track producibility-related changes for products	• Producibility alternatives automatically modeled during all development phases • Producibility models interoperate with other technical & business models
Life Cycle Considerations (Section 2.3.5)	• Little or no modeling & simulation of life cycle issues	• Limited modeling of environmental attributes (e.g., product "greenness") • Some modeling of product support costs	• Environmental & support analytical modules included in or interfaced to product M&S applications	• All life-cycle considerations included in product models, such as recycling, disassembly & disposal

Note 1: There is a wide gap between "state of practice" and "state of art" for product M&S capabilities among different industries and companies. A number of the attributes of the "Expected 2005 State" and the "IMTR 2015 Vision" are already emerging among leading practitioners; however, from the IMTR perspective these capabilities will not be considered mature until they are in wide use among more than a handful of companies, and meet the test of total plug & play compatibility and robust functionality to serve any industry.

Note 2: The timeframes given for various capabilities reflect application of "reasonable" R&D resources toward their attainment. The timelines for most capabilities shown could be significantly shortened through creation of focused R&D efforts with adequate funding.

views, enabling designers to optimize product designs all the way down to the constituent material level.

Designers will be able to “run” candidate designs through virtual factories, virtual manufacturing processes, and virtual point-of-use environments to evaluate and optimize producibility and quality attributes, and exercise designs in a real-world simulation environ-ment to evaluate functionality and support requirements (reliability, maintainability, etc.). They will be able to run these simulations in the background at extremely high speed, to quickly arrive at optimum design solutions, and also will have the ability to visually “zoom in” to examine any detail from any aspect. More importantly, product and process models will be valid at any scale, retaining their integrity at both the micro and macro levels regardless of the transformations that naturally occur when a model is translated to real-world application.

Future product models will provide the exacting fidelity and depth to directly drive the manufacture of the actual product, enabling creation of “net products” (see the IMTR *Roadmap for Manufacturing Processes & Equipment*, Section 3.3.4) directly from the designer’s workstation. No physical prototyping will be required, because the product will be totally optimized and validated in the virtual design environment.

Goals & Requirements for Physical Representation

Section 2.3.1 of the IMTR *Roadmap for Information Systems* defines goals and requirements to develop unified design environments and frameworks that support the IMTR vision of truly integrated product/process development capabilities that support all manufacturing. Modeling and simulation capabilities are key to making these design environments a reality, and in this section we identify M&S-specific requirements to support the product design vision and goals defined in the Information Systems roadmap.

- **Goal 1: Flexible, Complex Representation** – Provide product model representation technologies that enable capture and representation of all product design attributes in a single model that enables multiple customizable views as desired by different types of users.

  - **Model Federation** – Develop procedures and standards that enable product models to be built by integrating physical representation models with material, process, and quality certification models to yield a complete, federated simulation model.
  - **Single Product Model Representation** – Develop technologies and standards enabling creation of a single mathematical product model that allows all modeling tools to work with the model through user interfaces.
    - **Design Intent Capture** – Develop modeling techniques that completely capture design intent in the product model and enable visual representation and clear understanding of design intent factors.
    - **Integrated Functional/Performance Modeling** – Extend modeling and representation systems to provide capability for creation of complete functional/performance models.
    - **Multi-Sensory Design Representation** – Develop standards and methods for model representation which incorporate tactile and other useful sensory perception attributes of the product.
  - **Interoperability Methods** – Develop methods for ensuring interoperability of product modeling systems through neutral design representation and seamless application programming interfaces (APIs), without translators.

  * **Seamless Model Access** – Develop modeling standards and interface protocols for enabling product design models to be seamlessly accessible to and useable by all users, including shop floor production functions.
  * **Reusable Generic Product Models** – Develop basic, tailorable models that are useable by anyone.
  * **Nongeometric Model Extensions** – Extend the generic models to include physical considerations and representations other than geometrical features.
  * **Multi-Scalar Model Scaling & Integration Framework** – Develop a framework that allows modeling from atomic to macro scale that integrates all necessary functions to create product.
- **Hierarchical Models** – Develop techniques for creating models that can be expanded or collapsed to increase or decrease the amount of detail and level of assembly as appropriate for a particular simulation need, while maintaining consistency of data between levels.

• **Goal 2: Distributed Product Modeling Collaboration Environment** – Provide a uniform standard modeling environment for integration of complex product models using components and designs from multiple companies, where any model is completely interoperable and plug-compatible with any other model.

- **Robust Product Modeling Standards** – Develop a modeling structure and definition to support a modeling approach that includes: a product performance requirements survey, a method to identify models necessary to fulfill requirements, a common reference language for different models, robust enterprise representation models, and methods to move data among the models.
- **Information-Centric Product Model Objects** – Develop capability to create product model "objects" populated with all relevant information describing the product.
  * **Continuous Static Representation** – Develop capability to create models which use STEP[8] continuous static representation.
  * **Composable Single Object Models** – Develop capability to create single object models that can be combined quickly and transparently, without manual adjustment, to build complex product designs up from the material and component levels.
  * **Interactive Product Model Objects** – Develop capability to create models that understand their own attributes and can interact with other model objects to understand the resulting superset of attributes and behaviors.
  * **Plug & Play Model Interface** – Develop an engineering "container" – the computer model equivalent of a plug & play backplane.
  * **Simulation Data Hooks** – Develop techniques for making simulation factors, elements, requirements and other data inputs readily available and seamlessly integrable into product models.
  * **Complex Object Representations** – Develop capability to create object representations for product, process and enterprise that interact in models.

[8] The Standard for Exchange of Product Model Data (STEP) is an ISO standards project to develop mechanisms for representation and exchange of product models in a neutral form. The goal is to enable a product representation to be exchanged without any loss of completeness or integrity. Individual applications are supported through Application Protocols (APs) which specify unique and unambiguous mappings of an application's information elements to the STEP information resources. APs constrain the use of the standardized representations to satisfy only the specific requirements of the application.

* **Cut & Paste Features** – Develop capability to cut, copy, and paste product model features from one environment or domain into another.

– **Vendor-Supplied Models** – Develop procedures and standards that enable vendors to supply plug-and-play models for purchased parts and components that can be integrated into larger product models.

• **Goal 3: Direct Product Model Design** – Provide the capability to create and manipulate product models by direct communication with the design workstation, enabling visualization and creation of virtual and real-time prototyped product.

– **Intelligent Models** – Develop intelligent modeling capabilities to automate and accelerate labor-intensive modeling tasks and reduce the need for human intervention in the design-build process, where modeling and simulation functions are automatically invoked at required stages as the product design is conceived and evolves toward release for production.

– **Direct Product Realization** – Develop capability to produce virtual and real-time prototypes – and end-item products – directly from design models interfaced to rapid prototyping and production systems. (This requirement is expanded on in the IMTR Manufacturing Processes & Equipment roadmap, Section 3.3.4.)

2.3.2 Performance

Vision: *Fast, Accurate, Total Performance Optimization*

In the future, product performance modeling and simulation applications will facilitate multivariate analysis to accurately predict how the product will behave in the manufacturing process and in its operating environment, and how it will react to external forces and changing conditions. Product performance models will be based on a robust knowledge base of first principles and experience, and self-aware[9] at the system level.

Advanced performance modeling and simulation systems will enable elimination of all but the most critical physical prototype testing, such as for weapons and other safety-critical products (see Sections 3.2.6 and 3.3.3), greatly reducing the time and cost of moving products from concept to production. These next-generation systems will enable optimization of all performance attributes, including reliability, maintainability, recyclability, and other life-cycle factors.

Goals & Requirements for Performance

• **Goal 1: Robust Performance Modeling Environment** – Provide modeling and simulation methods that allow input and understanding, in both concrete and abstract terms, by all participants to all aspects of product performance.

– **Customer Requirements Translation** – Create tools that convert customer needs and wants to product performance goals and requirements.

– **Generic Performance Attribute Representation** – Develop modeling semantics that characterize product performance in fuzzy, generic terms.

– **Automatic Performance Optimization** – Develop modeling and simulation tools providing automated design advice and automatic optimization of product performance attributes.

[9] In the IMTR vision, all models will have links to all information relevant to their purpose and "recognize" when changes in that information require a response. The response may take the form of an alert to a designer or a manager that a change is required to resolve a conflict or desired to optimize a result, or the model may autonomously update itself within allowed parameters.

– **Total Performance Modeling** – Develop capability to create a product model "object" (individual model or metamodel) that contains all product performance data.

– **Physics Modeling** – Develop capability to create models that demonstrate the physics of how products reacts to their environment.

- **Goal 2: Fast Background Performance Simulation** – Provide simulation techniques and supporting processing technologies that enable complex simulations of product performance to run orders of magnitude faster and more cost-effectively than today.

– **Auto Background Performance Analysis** – Develop methods enabling required analyses to run automatically in background (user-transparent), including ability to answer performance questions automatically in real or near-real time.

– **Functional Performance Simulation** – Develop M&S capability to quickly and accurately predict how a product's functionality reacts to changes in environment (both in its manufacture and its use).

2.3.3 Cost/Affordability

Vision: *Current, true cost visibility across the extended enterprise*

In the future, infinitely scaleable product models will accurately, efficiently, and instantaneously calculate the cost of materials, labor, equipment and other resources required for their realization, enabling designers to predict – with very high confidence – the true cost of any design feature. Linkages to real-time global and enterprise financial information will enable product cost models to fully account for commodity prices, subcontracting/sourcing costs, specification compliance impacts, exchange rate and interest rate fluctuations, overhead rates, net present value of assets, cost of money, and similar factors.

Goals & Requirements for Cost/Affordability

- **Goal 1: Robust Cost Modeling** – Create and extend product feasibility modeling techniques to include financial representations of the product as an integral part of the total product model.

– **Plug & Play Cost Models** – Develop techniques and standards for creating uniform cost models that are plug-compatible with product representation and performance models.

– **Integrated Product Family Cost Models** – Develop suites of generic, interoperable cost models for common product types at the material, component/part, subassembly, and final assembly levels.

– **Intelligent Cost Models** – Develop adaptive cost modeling techniques that automatically and accurately calculate and distribute the effects of a change in one cost parameter across the entire cost model, regardless of complexity, and automatically perform dynamic updates against enterprise data sources to ensure currency.

– **Affordability Optimization** – Develop tools and techniques for automatically linking affordability data to the product and process models.

– **Robust Feasibility Modeling** – Develop capability to create feasibility models where the financial representation of the product is modeled as part of the overall performance model.

- **Goal 2: Enterprise-Wide Product Cost Models** – Provide cost modeling systems and techniques that integrate all required data, from within and external to the enterprise, to support analysis of producibility, profitability, and other cost attributes of a product design.

  – **Market Data Model Integration** – Develop modeling standards and methods to access and integrate global market data (e.g., current commodity pricing and lead times) and time-to-market projections into product models for cost/affordability analysis. (Supporting requirements are addressed in further detail in Section 4.3 of the IMTR *Roadmap for Information Systems*.)

  – **Interchangeable Cost Models** – Develop and unify product modeling standards and techniques to enable seamless integration and interchange of cost models among partners and suppliers.

  – **Integrated Life-Cycle Cost Modeling** – Establish methods for integrating life cycle considerations such as maintenance, repair, spares, recycling, and disposal in cost/affordability models.

2.3.4 Producibility

Vision: *Total optimization for manufacturing efficiency*

Future modeling and simulation tools will enable simultaneous dynamic evaluation of internal and external production alternatives, seamlessly from concept through development, to determine feasibility of designs and optimize product producibility (ease of manufacture) attributes for speed, cost, quality, and ultimate product performance.

Producibility attributes of multiple product design alternatives, including materials of construction/composition, parts count, and geometric complexity will be evaluated in parallel to enable very fast tradeoffs and optimization of design characteristics for production. Real-time capacity and capability of all manufacturing assets available to the enterprise, including in-house and supplier/partner facilities, will be adequately represented and modeled to optimize the total production strategy. Autonomous software agents will track factors that affect producibility (e.g., material availability, and capacity and capabilities of production equipment) to keep product models continuously up to date.

Producibility models will be transparently integrated as an aspect of the total product model, which in turn will be transparently interoperable with manufacturing process and enterprise models.

Goals & Requirements for Producibility

- **Goal 1: Producibility Requirements Integration** – Provide modeling and simulation techniques to directly translate product goals to producibility requirements for application to product designs.

  – **Customer Requirements Translation** – Develop modeling and simulation techniques to directly translate customer needs to producibility goals and requirements for product designs.

  – **Manufacturing Capacity/Capability Representation** – Develop product model interface standards to enable real-time access to and incorporation of information that affects producibility, including material availability and manufacturing capability and capacity throughout the extended enterprise.

- **Goal 2: Parallel Multi-Attribute Producibility Evaluation** – Provide the capability to simulate and evaluate many design alternatives in parallel to perform fast tradeoff evaluations, including automated background tradeoffs based on enterprise knowledge (i.e., enterprise experience base).

  – **Producibility Engine** – Develop a generic producibility modeling system that integrates seamlessly with product design systems and supports multivariate producibility analysis and tradeoffs for major product families (e.g., mechanical and electrical parts and assemblies, composite structures, chemical product formulations).

  – **Producibility Attribute Modules** – Develop suites of producibility analysis modules, for generic product families, that are plug-compatible with the generic producibility engine.

2.3.5 Life-Cycle Requirements

Vision: ***Complete optimization for total life-cycle performance***

Future product modeling systems will provide the capability to optimize product designs – as a natural, integral step in the design process – for all aspects of life-cycle performance, including reliability, maintainability, repairability, reusability, recyclability, and disposability. Knowledge-based systems will automatically factor life-cycle requirements and considerations into product models to guide designers in making tradeoffs among life-cycle attributes in light of product functionality, cost, quality, producibility, and time-to-market drivers.

Life-cycle considerations will be built into product models to facilitate selling customers a long-term capability instead of just a product. Material reclamation models, including the cost of remanufacturing, recycling, disassembly, and disposal, will be part of front-end product design modeling. Models will incorporate functional specification tradeoffs and projected technology advancements to aid designers in making informed decisions about a product's entire lifespan.

Goals & Requirements for Life-Cycle Requirements

- **Goal 1: Integrated Life-Cycle Modeling Capability** – Provide integrated, plug & play toolset for modeling and simulation of all life-cycle factors for generic product types (e.g., mechanical, electrical, chemical).

  – **Reclamation Modeling Tools** – Develop M&S tools to incorporate the expected percentage of material reclamation into the product model, including the cost of remanufacturing, recycling, disassembly, and disposal. (Related manufacturing process and equipment requirements are discussed in the IMTR Manufacturing Processes & Equipment Roadmap, Section 2.3.1).

  – **End-of-Life Prediction** – Develop capability to incorporate accurate prediction of product conditions at end of life into product models, to support design decisions about refurbishment, recycling, and disposal.

  – **Integrated Life-Cycle Support Modules** – Develop plug-compatible modeling modules that enable modeling and simulation of all factors relevant to product support, including reliability, availability, maintainability, and supportability, to optimize the product design for performance, cost-effectiveness, and ultimate customer value.

  – **Technology Impact Forecasting** – Develop the means to link enterprise knowledge and projections about expected technology progressions (e.g., faster processors for computers, material recycling capabilities) to optimize the product design over its intended useful life.

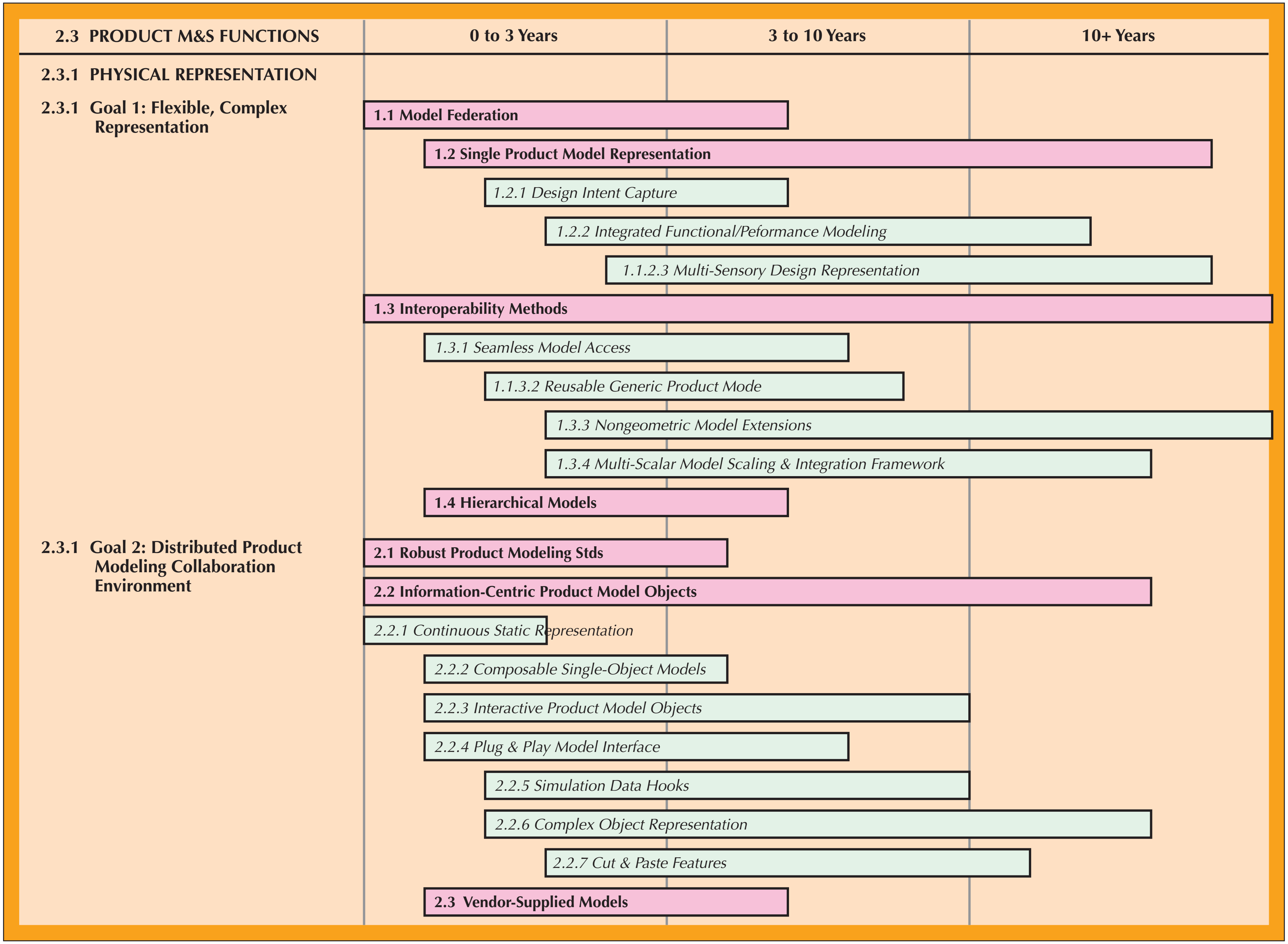
- **Goal 2: Total Service Modeling Environment** – Provide modeling and simulation techniques that facilitate selling customers not just a product, but a lifelong service.

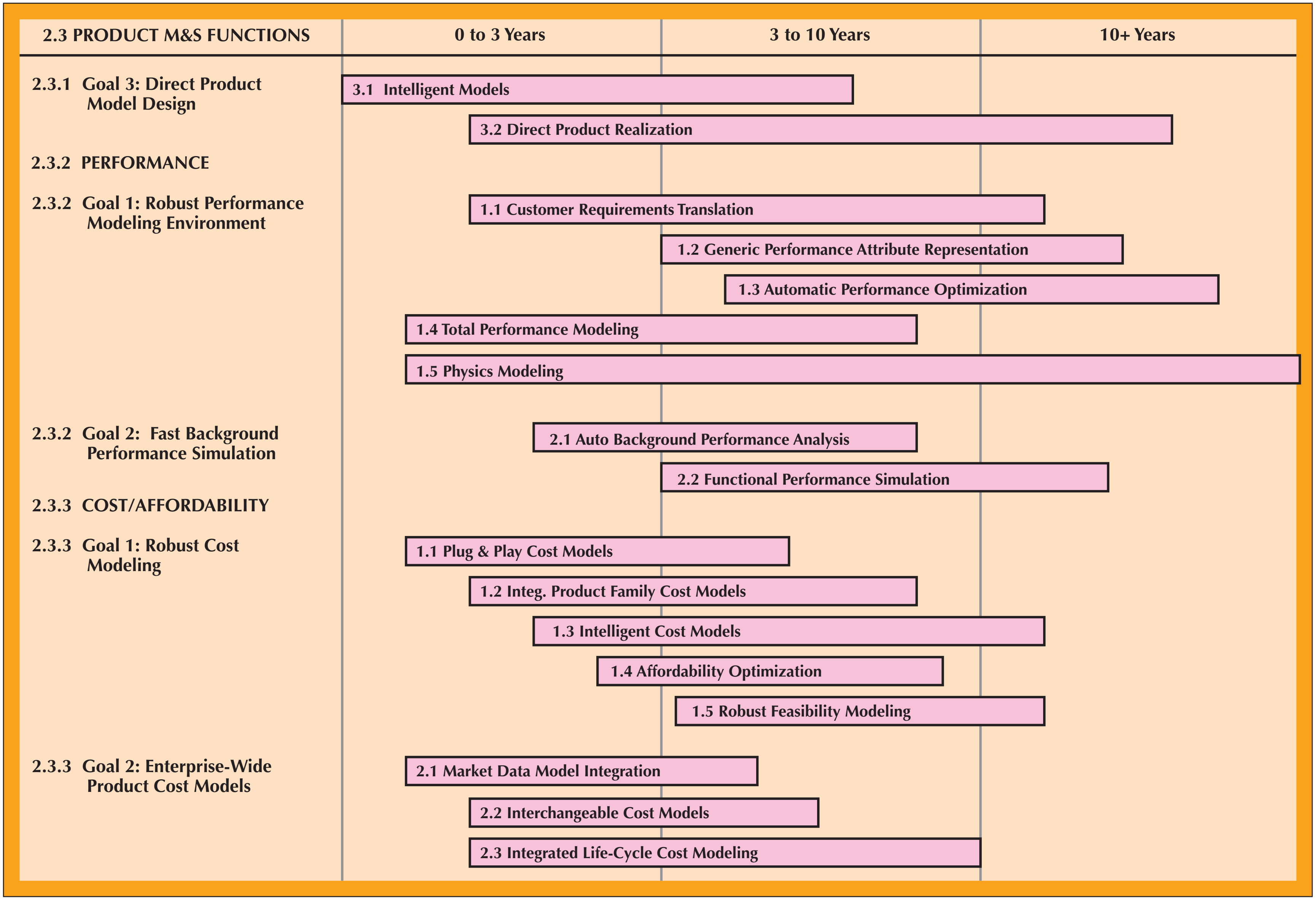
  – **Service Modeling Tools** – Develop service modeling tools that enable and support lifelong customer relationships – such that when a customer is done with a product, the manufacturer will replace it and take it back for recycling, reprocessing, or disposal.

  – **Robust Requirements Modeling Tools** – Develop M&S tools that incorporate functional specification tradeoffs including warranty data in the product model, and simulate the entire chain of a product's life-cycle events, including factors such as regulatory requirements for hazardous and recyclable constituents.

2.4 Roadmap for Product Modeling & Simulation

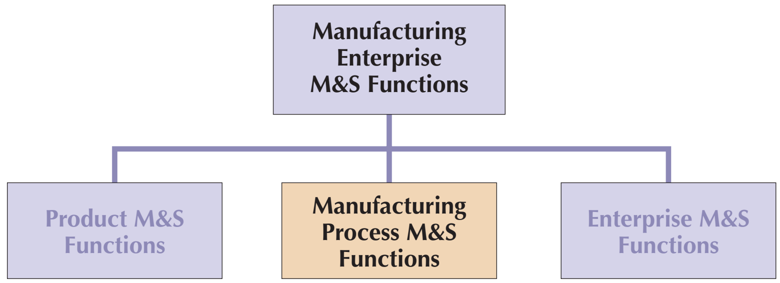
Using the goals outlined in Section 2.3 above, the workshop team mapped the associated requirements and R&D areas over near-, mid-, and long-term timeframes as presented on the following pages. The attached roadmap represents a "first cut" at defining a research, development, and implementation plan, and additional work is required to develop detailed task plans as well as to align dependencies among the various activities.


2.3 PRODUCT M&S FUNCTIONS
0 to 3 Years
3 to 10 Years
10+ Years
2.3.1 PHYSICAL REPRESENTATION
2.3.1 Goal 1: Flexible, Complex Representation
1.1 Model Federation
1.2 Single Product Model Representation
1.2.1 Design Intent Capture
1.2.2 Integrated Functional/Peformance Modeling
1.1.2.3 Multi-Sensory Design Representation
1.3 Interoperability Methods
1.3.1 Seamless Model Access
1.1.3.2 Reusable Generic Product Mode
1.3.3 Nongeometric Model Extensions
1.3.4 Multi-Scalar Model Scaling & Integration Framework
1.4 Hierarchical Models
2.3.1 Goal 2: Distributed Product Modeling Collaboration Environment
2.1 Robust Product Modeling Stds
2.2 Information-Centric Product Model Objects
2.2.1 Continuous Static Representation
2.2.2 Composable Single-Object Models
2.2.3 Interactive Product Model Objects
2.2.4 Plug & Play Model Interface
2.2.5 Simulation Data Hooks
2.2.6 Complex Object Representation
2.2.7 Cut & Paste Features
2.3 Vendor-Supplied Models


2.3 PRODUCT M&S FUNCTIONS
0 to 3 Years
3 to 10 Years
10+ Years
2.3.1 Goal 3: Direct Product Model Design
3.1 Intelligent Models
3.2 Direct Product Realization
2.3.2 PERFORMANCE
2.3.2 Goal 1: Robust Performance Modeling Environment
1.1 Customer Requirements Translation
1.2 Generic Performance Attribute Representation
1.3 Automatic Performance Optimization
1.4 Total Performance Modeling
1.5 Physics Modeling
2.3.2 Goal 2: Fast Background Performance Simulation
2.1 Auto Background Performance Analysis
2.2 Functional Performance Simulation
2.3.3 COST/AFFORDABILITY
2.3.3 Goal 1: Robust Cost Modeling
1.1 Plug & Play Cost Models
1.2 Integ. Product Family Cost Models
1.3 Intelligent Cost Models
1.4 Affordability Optimization
1.5 Robust Feasibility Modeling
2.3.3 Goal 2: Enterprise-Wide Product Cost Models
2.1 Market Data Model Integration
2.2 Interchangeable Cost Models
2.3 Integrated Life-Cycle Cost Modeling

2.3 PRODUCT M&S FUNCTIONS	0 to 3 Years	3 to 10 Years	10+ Years
2.3.4 PRODUCIBILITY			
2.3.4 Goal 1: Producibility Requirements Integration	1.1 Customer Requirements Translation		
	1.2 Manufacturing Capacity/Capability Representation		
2.3.4 Goal 2: Parallel Multi-Attribute Producibility Evaluation	2.1 Producibility Engine		
	2.2 Producibility Attribute Models		
2.3.5 LIFE-CYCLE REQUIREMENTS			
2.3.5 Goal 1: Integrated Life-Cycle Modeling Capability	1.1 Reclamation Modeling Tools		
	1.2 End-of-Life Prediction		
	1.3 Integrated Life-Cycle Support Modules		
	1.4 Technology Impact Forecasting		
2.3.5 Goal 2: Total Service Modeling Environment	2.1 Service Modeling Tools		
	2.2 Robust Requirements Modeling Tools		

3.0 MANUFACTURING PROCESS MODELING & SIMULATION FUNCTIONS



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3.1 Functional Model Definition for Manufacturing Process Modeling & Simulation

The manufacturing process-related modeling and simulation activities of a manufacturing enterprise can be divided into eight functional elements for assessment and planning purposes:

Material Processing ⇒ Material Processing involves all activities associated with the conversion of raw materials and stocks to either finished form or readiness for assembly. Material Processing includes four general categories of processes:

1) Material Preparation/creation processes such as material synthesis, crystal growing, mixing, alloying, distilling, casting, pressing, blending, reacting, and molding;
2) Material Treatment processes such as coating, plating, painting, thermal conditioning (heating/melting/chilling), chemical conditioning (pre-treating);
3) Material Forming processes for metals, plastics, composites, and other materials, including bending, extruding, folding, rolling, shearing, stamping, and similar processes;
4) Material Removal/Addition processes such as milling, drilling, routing, turning, cutting, and sanding, deburring and trimming, etching, sputtering, vapor deposition, solid freeform fabrication, ion implantation, and similar processes

Assembly/Disassembly/ Reassembly ⇒ Includes all assembly processes, including joining, fastening, soldering, integration of higher-level packages (e.g., electronic packages) as required to complete a deliverable product; also includes assembly sequencing, error correction & exception handling, disassembly & reassembly (maintenance & support issues).

Quality, Test & Evaluation ⇒ Includes design for quality, in-process quality, all inspection and certification processes, such as dimensional, environmental, and chemical and physical property evaluation vs. requirements and standards; diagnostics & troubleshooting.

Packaging ⇒ Includes all final packaging processes, such as wrapping, stamping & marking, palletizing, and packing.

Remanufacture ⇒ Includes all design, manufacture, & support processes that support return & reprocessing of products upon completion of original intended use.

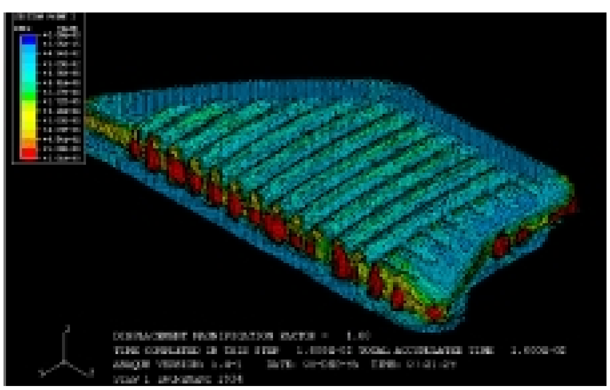
3.2 Current State Assessment for Manufacturing Process Modeling & Simulation

The current state of modeling and simulation in manufacturing process applications is best stated in one sentence: they are not "critical path" activities, but rather are used as troubleshooting tools. Models of products and factory equipment and simulations of manufacturing processes are often created to help diagnose a problem, but are rarely used as the method to create and optimize process and product designs. Modeling and simulation of processes is expensive and time-consuming, and use is thus limited to applications with a high return on investment.

While limited in scope, the successes have been significant. In 1997, a demonstration by Pratt & Whitney for the joint DOE/industry Technologies Enabling Agile Manufacturing (TEAM) program used simulation tools (Figure 3.2-1) to optimize the design of a forming process for jet engine nozzle panels. The simulation results enabled ensuing tests using a digital press controller to produce high-quality parts in a one-step operation – and demonstrating a 6:1 reduction in design-to-manufacturing cycle time.

However, the lack of awareness of and confidence in process M&S tools makes it difficult to secure support for application development efforts with potentially large payoffs in time, resources, and profitability. A good example of such impact is materials failure, where fatal flaws that might otherwise have been found by thorough process simulation are inevitably discovered long after tooling is in place and production lines are committed.

Integration and interoperability of M&S tools is sorely lacking in the process realm. Most M&S tools are single-function. They may deal with the stress and temperature profiles of products undergoing individual processes, but seldom do they deal with the total performance profiles of products and processes across multiple operations, and even more rarely do they deal with interactive, real-time optimization of multiple product and process parameters. Attempts at improving the interoperability of process M&S tools are frustrated by grossly incomplete data representations as well as incompatible data structures and representation formats. Rich standards do not exist or are not widely used for representing and manipulating product designs, and product and process parameters; and no good standards exists to ensure compatibility between process M&S tools and the rest of the systems that support any given manufacturer's product design and manufacturing environment. These are major barriers to realizing the full potential of the integrated product and process development (IPPD) concept that is fundamental to our vision of future manufacturing enterprises.



Nozzle Panel Simulation

Completed Part

Figure 3.2-1. Use of simulation tools to optimize a forming process for precision components helped Pratt & Whitney demonstrate a 6:1 reduction in design-to-manufacturing time.

Environmental issues must be considered in the manufacturing process model, and often are not. Different materials are hard to separate, and many chemical compounds used in manufacturing processes (and the products themselves), present a major environmental challenge. The ability to identify and simulate all material streams in a process model would reduce this concern. Process modeling that considers the environmental aspects of multiple processes and materials is also a prerequisite to "green manufacturing."

The final consideration in the current state assessment is technology foundation. In general, a good fundamental understanding of the scientific basis for most manufacturing processes does not exist. Physical and chemical interactions are not well enough understood to support the design of optimum material processing applications with accurate models and simulations. Macro and micro behaviors of materials may be quite different due to material phase transformations, and there is little understanding of how effects at the micro level impact macro-level attributes.

3.2.1 Material Processing

Material Preparation

M&S applications for material preparation processes are highly niche specific. The applications represent islands of knowledge and are well-bounded. Most of the applications are based on empirical data, and supporting scientific understanding is limited, particularly in the discrete manufacturing industries. Casting still depends on pattern masters, and heat treatment follows time-proven processes with limited understanding of the underlying metallurgical physics. The science for controlled volume and fundamental geometry (conservation of volume with "rules of thumb" for deviations and compensations) is understood, but not successfully applied on the smaller (micro) scale. The fundamental science of distortion, residual stress, phase transformations, and similar factors is not well understood.

On the upside, present models are the basis for much success, and we have excellent information on which to build. Consortium activities such as FASTCAST[10] are making great strides in addressing fundamental understanding and improved applications. Niche applications do exist, and, in some cases, the science and knowledge base is well-defined. Advanced analytical techniques are being successfully applied for many material preparation activities, particularly in continuous processing industries.

Material Treatment

Material treatment processes, as with material preparation, are considered by most manufacturers as more art than science, and thus modeling and simulation are used in only limited, well-defined applications. In most cases, material treatment models are based on empirical data, or, more often, "we have done it this way for years; it works, and we are not going to change it now." Several drivers are forcing change, however, such as the environmental effects of material treatments and the demand for reduced timelines and greater efficiency.

Environmental impact plays a strong role in the selection and execution of material treatment processes. Some curing techniques, for example, use chemical compounds or have byproducts that must be managed and controlled to avoid environmental and human health impacts. Although curing process selection and design is normally based largely on human experience and judgment, there are modeling systems that can assist in this process to optimize processes and assure safe, compliant operation. However, much better models of the total behavior of processes and their effects are needed.

[10] The FASTCAST project, conducted by an industrial consortium of U.S. producers and users of investment castings and rapid prototyping technologies, is aimed at developing and implementing computational simulation of investment casting; developing rapid prototyping technologies and practices specifically integrated for the investment casting process; and experimental validation of computational simulations with instrumented casting facilities.

Time compression drives the need to reduce curing times. Better tools for analyzing curing processes are needed to help increase process efficiency and shorten curing times. Models that clearly define the effects and underlying principles of processes such as heat-treating and annealing can make major contributions to shortening the manufacturing timeline.

Progress is being made. Empirical and analytical building blocks do exist, and models are being coupled with knowledge systems for optimized operations. One example is an advisory system for electroplating, electroforming, plasma spraying, and similar operations. This system, developed by Lockheed Martin at DOE's Oak Ridge Y-12 Plant, uses material deposition models and product geometry (both of the mandrel and the finished product) to automatically design the "cells" and shielding to be used in the process. Neutral networks are being used to synthesize process knowledge and ensure more accurate reliable results in conjunction with M&S systems.

Material Forming

Modeling and simulation for material forming has a long history, and many excellent tools and applications exist. Creation of finite element meshes constitutes perhaps the most popular application of simulation technology in this area. Meshing has gone from an intense, manual process to an automated and flexible function in the computer-aided engineering (CAE) environment. However, the advantages of forming simulation are not being fully realized:

- Lots of data is generated in forming simulations, but we often lack the ability to manage and present the data for maximum impact.
- Even the best forming models are subject to interpretation, and there is a "leap of faith" from the model predictions to the true part shape.
- Finite element modeling is still the domain of expert technologists, and use by designers and shop floor personnel is limited.
- The cost of forming simulation is still high, and return on investment is difficult to calculate.
- The ability to validate existing forming models and extend them to other applications, with confidence, is lacking.
- Many legacy modeling systems are more comfortably used and accurate in two dimensions. The transition to three dimensions to support forming is problematic.
- Benchmark information that clearly defines the ability of modeling codes to accurately predict forming process performance is lacking.

While modeling and simulation have been successfully applied for deformation of metallic parts, additional materials and processes have often not been included. Current technologies for modeling of fibrous structures and cellular solids, polymer paper laminates, and composites are very limited. Specifically, composite performance and composite design for performance are not well understood. Powder metallurgy, rolling, stamping, and forging are not nearly as well addressed as more traditional metalforming operations.

The lack of reliable, consistent feedstock is a major limitation in accurate projection of final part shape. For example, rolled material feedstock as called out in the specification rarely matches actual test data from the laboratory, especially for cold-rolled thin foils. The reason for this is, at least in part, that the ASTM, DIN, and ISO tests for mill certification were developed for generic test samples, not for thin-foil specimens. Many discrepancies can be explained by looking at the actual material data, but the ability to link test data to model calculations is immature.

The same situation is true in continuous processing industries, where inconsistencies (contamination or unacceptable variations in uniformity) in feedstocks are often not discovered until they cause problems in the end product. Rigorous process control is critical to feedstock and end product quality, but better M&S tools could certainly help process designers anticipate situations where minor problems in feedstock will cause major problems with end product, without incurring the expense and risk of production line failures.

Progress is being made. Knowledge-based systems coupled with modeling and simulation tools are creating successful design advisors that produce dies which "get it right the first time." Neural networks, trained through models and empirical data, are being extended as accurate predictors of forming performance.

Material Removal/Addition

Material removal is probably the best understood of all manufacturing processes. Universities and research institutions have done a good job for years in building the knowledge base, both at the operations level and the scientific level. There is probably better understanding of the interface between the tool and the workpiece than with other processes, with prismatic parts being the best understood. Traditional applications such as milling, drilling, turning, slitting, burning, and, to a lesser extent, electrical discharge machining (EDM), are well understood. Examples of material removal processes that are not well understood include micro processes, electrochemical machining, laser cutting, very high-speed machining, and water-jet cutting. Special materials such as ceramics and certain composites present challenges beyond our present realm of knowledge. The following general statements can be made regarding use of modeling and simulation for material removal.

- Modeling and simulation are readily applied to homogeneous materials; heterogeneous materials greatly increase model complexity.
- The state of technology for interactions at the tool/material interface is based on long-held assumptions, not on scientific understanding of the underlying physics.
- Models and simulations for material removal seldom account for variable machine tool behavior, and assume consistent and predictable performance.
- Rigidity of the machine tool and the part/cutting tool interface is commonly assumed, but is rarely the case.
- Shared knowledge is pervasive; e.g., the Metcut machining handbook is widely used but is not alone sufficient to practice the state of the art. Expert tools are emerging that select the best machining parameters and cutting tools based on simulations and captured knowledge.
- As is the case with most processes, M&S cannot provide reliable performance predictions for material removal and addition processes involving phase transformations.
- New tools and new materials are not well understood, although M&S tools can have impact. For example, nickel aluminides are desirable in high-temperature applications, but are difficult to machine at room temperature. M&S tools based on metallurgical principles have predicted optimum machining parameters for efficient cutting. As predicted by M&S and verified in practice, dry (coolant-less) machining heats the interface to about 1100 °F and makes machining much easier.

Material addition technologies are flourishing, aided by advanced modeling and simulation capabilities. A few years ago, stereolithography was a revolutionary technology. Today, new solid free-form fabrication techniques, driven by very precise 3-D models are producing real parts from real materials.

3.2.2 Assembly/Disassembly/Reassembly

Modeling and simulation are now used routinely to optimize product and process designs for efficient assembly of complex products. Using 3-D models, designers can study and refine assembly sequences for ease of execution, and identify problems that otherwise might not be detected until significant resources were already committed to production As-sembly modeling is well developed for rigid bodies, and tolerance stack-up (the cumulative buildup of the individual tolerances of different parts that fit and work together) is addressed well in limited applications. Assembly models that include deformable bodies (e.g., cables and wiring harnesses) are much less mature, as are applications that address fluid/structure interactions (e.g., pumps). Automated interference checking for assemblies exists today in leading-edge applications, but these tools are not widely used.

High-level models of assembly operations (e.g., blending, container sealing) are common in the continuous processing industries. However, the ability to accommodate both continuous and discrete processes together, at a good level of fidelity, is missing.

Material handling is a critical element of assembly modeling, but is often omitted because of its complexity. Models that do focus on material handling are usually very simple in their treatment. These models may identify sources of defects from errors in material flows, but not from excessive forces or strains on parts during assembly. The link between assembly modeling systems and enterprise-level models is often found in the material handling simulation.

> **Assembly Modeling:**
>
> ***Right the First Time***
>
> **Anyone who has worked on or around an assembly line knows there's two ways to do it. The way the engineers tell you to, and the way that actually works. Much attention has been focused on modeling of assembly processes over the years to help manufacture complicated products correctly and efficiently, without losing too much time in the startup process. The increasing complexity of modern products, particularly electronics and electromechanical systems, and the growth of manufacturing enterprises that span dozens of participating "supply web" members across the nation and overseas, demands that the trial-and-error assembly processes of the past be replaced with far better solutions.**
>
> **Rapidly maturing computer-aided design and manufacturing technologies, coupled with advanced modeling and simulation techniques, offer the potential to totally optimize assembly processes for speed, efficiency, and ease of human interaction.**
>
> **Imagine an intelligent assembly modeling system that takes lessons learned from problems encountered in one assembly operation and transfers this knowledge to subsequent operations automatically...and where assembly processes self-configure in real time to fix manufacturing issues as they arise.**
>
> **Next-generation assembly models will integrate seamlessly with master product models and factory operations models to provide all relevant data to drive and control each step of the design and manufacturing process, including tolerance stack-ups, assembly sequences, datums, ergonomics issues, tooling, fixturing, quality, and production rate to support art-to-part assembly, disassembly and reassembly.**
>
> **The product assembly model will be a dynamic, living model, adapting in response to changes in requirements and promulgating those changes to all effected elements of the assembly operation – including process control, equipment configuration, and product measurement requirements.**

It is also generally true that the designer does not think of assembly modeling as a tool for life-cycle engineering. Design of assemblies for disassembly, refurbishment, reuse, or recycling is seldom included in the modeling objectives or supported by M&S applications.

3.2.3 Quality, Test, & Evaluation

Many of the statements about current state of M&S for all processes also apply to Quality, Test, and Evaluation. In general, the first principles are well understood, but modeling tools that support the application of those principles are lacking.

Recent philosophy changes have benefited the disciplines of design for quality and in-process quality control. Modeling, simulation, and statistical methods are widely used to establish control models to which processes should conform. Characterization of processes leads to models that define the impact of different process parameters and their variations on product quality. These models are used as a baseline for establishing and maintaining in-control processes.

Design for quality is taking quantum leaps with the widely publicized all-digital design of the Boeing 777. Lesser known examples exist at companies such Caterpillar and in the DoD Joint Strike Fighter (JSF) and Affordable Multi-Missile Manufacturing (AM^3) programs.

Over the years, significant investment has been made in M&S for destructive and non-destructive testing – albeit with limited impact on the way products are made and certified as fit for use. In general, the physics behind these techniques (e.g., radiological testing, ultrasonic evaluation, tomography, tensile testing) are well understood. However, many of the interactions are treated probabilistically and, even though models of the fundamental interactions exist, in most cases empirical methods are used instead. In today's mindset, the best way to find out whether a part has a flaw is to test samples and analyze the test data. "Models" are used in setting up these experiments, but many times the models reside only in the brains of the experts who support the evaluations. As the migration to science- and knowledge-based manufacturing accelerates, the need for first principles understanding of the physical relationships applied to manufactured materials will increase. Combination of first-principles models with empirical techniques has been addressed in probabilistic mechanics methods, such as those employed by the Nuclear Regulatory Commission (NRC), and those developed and taught at Southwest Research Institute. However, these methods have not penetrated many industries. The modeler and the experimenter have not converged on computational techniques for test and evaluation.

Modeling and simulation for dimensional metrology has lagged behind material processing applications, but is now gaining speed. Until recently, programmed points for coordinate measuring machines (CMMs) were calculated and input manually. Tools such as Cimstation from Silma Corporation and Valysis from Technomatics, and the acceptance of DMIS as a standard for CMM programming, have had great impact. Simulation of toolpaths before inspections are performed is now common in many companies. Tools are emerging that enable programming of dimensional metrology equipment directly from the solid model and, in early applications, dimensional inspection information is being fed back directly to the product model to help refine the product design. Maturation of these tools will have great impact. The movement to Lean Manufacturing has brought great pressure to reduce and eliminate inspection for certification.

Other observations in this area include:

- Present quality goals are driving processes for better performance, but models of quality expectations are lacking.
- Test plans are created by applying statistical methods. Statistical models define the confidence in the quality output of the process.
- CAD models have tolerance information in textual notes. Some emerging releases include discrete part geometric dimensions and tolerances.
- An immature linkage exists between product quality and satisfying the needs of the customer, based on process capability models.
- Evaluation of a factory's ability to perform needs to be based on models that include process capability and capacity.
- Use of static and dynamic models of certification and testing equipment, processes, and analysis tools is not common practice.
- Process capability models for test and evaluation are mostly empirically developed and empirically maintained.

- Deformable parts are often tested and evaluated via industry "home brewed" methods. National and international standards are lacking for test and evaluation of many composites, fibrous materials, and cellular solids.

- Simulation is being used more frequently for operator training and certification.

3.2.4 Packaging

Packaging has undergone a major revolution in the last decade. From products in a box, to the package as part of the functional equation; from protecting products moving from source to destination, to the emergence of radio frequency and infrared tags that record product manufacturing and distribution history. Modeling and simulation are playing a major role in this transformation. Logistic models and part tracking systems help ensure the proper packaging and labeling for correct product disposition.

Modeling and simulation are critical in designing packaging to assure product protection. These applications range from the proper wrapping for chemical, food, and paper products to shipping containers that protect military hardware and munitions from accidental detonation. Some specific observations include:

- Modeling and simulation plays a strong role in the design and evaluation of multifunctional packages to replace the separate functions of packaging,

- Modeling of packaging for protection of product is viable today, but not widespread.

- Defense industries have led the way in packaging innovation, with techniques such as self-packaging (e.g., the Javelin antitank missile, which is delivered and deployed in a protective container that doubles as the launch tube); and packaging techniques that protect delicate electronic components from adverse environments and rough handling).

- Automated marking and labeling are part of a modeled flow environment. Differentiation of product (trade names, model and size determination, options included, etc.) is optimized through flexible manufacturing techniques.

- Lack of a rich and re-usable library of models and the lack of a strong experience base for M&S of packaging processes.

3.2.5 Remanufacture

The current state of remanufacture as a discipline covers the entire spectrum of material and part/component reuse. Over several decades there has evolved a large number of products that are returned to their original manufacturer or a third-party processor when the product is worn out, then reworked and re-sold. This practice was developed not because of environmental regulations but because it made sense economically. A number of automobile components (batteries, alternators, brake components, etc.) fall into this category. Other remanufactured products, such as recycled motor oil, paper, and plastics, were developed initially because of regulatory requirements. Subsequent development of remanufacturing techniques and markets has now made recovery and recycle a profitable industry. Recycle of materials (particularly metals) for use in new products has gained emphasis in the past couple of decades, but this practice was first employed to reduce the cost of the input material stream. Likewise, a wide range of process chemicals are recycled internally by manufacturers or reclaimed and recycled at the end of the product life cycle.

Remanufacturing has received little attention from the M&S community, although many M&S applications (such as assembly modelers) designed to support "original" manufacturing of products can be used to support remanufacturing. The same process models used to support production of car batteries can be used to support remanufacturing and refurbishment, taking into account additional requirements such as disassembly, cleaning, replacement of degraded components, and repackaging.

What is lacking in this domain are good M&S tools and robust process models that enable designers and manufacturing planners to evaluate remanufacturing considerations and options in the initial product and process design phase, and optimize manufacturing process designs to efficiently accommodate both original manufacture and remanufacture.

3.3 Future State Vision, Goals, & Requirements for Manufacturing Process Modeling & Simulation

In the future state, modeling and simulation will be *the way* of doing business to assure the best balance of all constraints in designing, developing, producing, and supporting products. Cost, time compression, customer demands, and life-cycle responsibility will all be part of an equation balanced by captured knowledge, on-line analyses, and human decision-making. Modeling and simulation tools will support best practice from concept creation through product retirement and disposal, and operations of the tools will be transparent to the user. Difficult-to-run codes will run transparently behind easy-to-use graphical user interfaces. Seamless integration will allow manufacturing to operate as a single process, not as separate processes connected by a material handling system. Modeling and simulation systems will be dynamic, with learning a part of every operation, and training of manufacturing personnel will be an integral part of the process.

Science-Based Process Modeling

Science-based process modeling is the representation of a process mathematically by application of material properties and physical laws governing geometry, dynamics, heat and fluid flow, etc. to predict its behavior.

For example, finite element analyses are used to represent the application of forces (mechanics, strength of materials) to a defined part (geometry and material properties) to model a metal forging operation. The result of the analyses is a time-based series of pictures, showing the distribution of stresses and strains, that depict the configuration and state of the part during and after forging. The behavior predicted by process models is compared the results of actual processes to ensure the models are correct.

As differences between theoretical and actual behavior are resolved, the basic understanding of the process improves and future process decisions are more informed. The analysis can be used to iterate tooling designs and make processing decisions without incurring the high costs of physical prototyping.

Table 3.3-1 provides a summary-level view of where we are today and where we expect to be in the next 15 years. To achieve this vision, there are some key goals that must be realized. Among these are:

- Establish a rich, integrated process M&S capability based on best science, best knowledge, and best practices for product and process development. Process M&S tools must incorporate the best of analytical and empirical methods.
- Establish life-cycle process modeling capabilities that integrate all processes within the enterprise model. This will allow manufacturing to be modeled as a single integrated process.
- Reverse the ratio of the time spent finding data and the time spent using it. Today's engineers and scientists spend 80% of their time finding the right information and 20% of their time using it.
- Compress the time from concept to distribution by optimizing the benefit from each design iteration and eliminating design detours through effective, accurate, reliable M&S.
- Establish a framework for compatible data representation within the M&S domain.
- Integrate product and process development through M&S.

Table 3.3-1.
State Map for Process Modeling & Simulation Functions

Function	Current State of Practice	Current State of Art	Expected 2005 State (Major Goals)	IMTR 2015 Vision (Major Goals)
Material Processing (Section 3.3.1)	• Niche applications based on empirical data • Excellent analytical M&S capabilities in continuous processing industries (e.g., chemicals) • Good base of material models for simple & traditional materials • Applications based on empirical data or past "art" • Finite element modeling of forming processes • High costs & special skill needs limit use • Simplified models & assumptions • Data from handbooks	• Rapidly advancing understanding of science for some processes • Emerging base of material models for newer nontraditional processes (e.g., composites • Some knowledge-based advisory systems in use • Automated finite element mesh generation • 3-D modeling • Traditional processes & materials relatively well understood	• Large base of robust models for nontraditional materials & processes, including engineered materials • Models include variations in materials, tooling & equipment • Modeling advisor systems • Automated process model creation from design models & enterprise data	• Validated, science-based models for all materials • Model repository for reuse • Include time & cost results • Open, universal framework for M&S standards & model interoperability • Collaborative distributed analysis & simulation systems supporting global distributed manufacturing enterprises
Assembly/ Disassembly/ Reassembly (Section 3.3.2)	• Good electronics assembly modeling applications • Assembly line balancing (workflow optimization)	• Tolerance & interference modeling in limited use • Lack of standards	• Model disassembly & reassembly	• Immersive VR system for assembly modeling & simulation, with automated optimization • Integrated links to production systems for real-time troubleshooting, change response, & optimization • Assembly modeling across enterprise & supply chain
Quality, Test & Evaluation (Section 3.3.3)	• Statistical control models • Models from empirical data • Electronic testing models	• Modeling of dimensional metrology • Process capability models	• Test & evaluation knowledge bases	• Virtual system for test & evaluation modeling • Automated model generation from specifications
Packaging (Section 3.3.4)	• Product flow models coupled with part tracking systems	• Models for packaging design for some industries (e.g., defense, food, chemicals)	• Model environmental impact of packaging	• Virtual system for modeling packaging
Remanufacture (Section 3.3.5)	• Limited, specialized applications for specific product types	• Existing process modeling apps used to evaluate remanufacturability of designs (not tailored for remanufacturing)	• "Reverse engineering" modules plug into product and process engineering tools to optimize life-cycle performance and re-use	• Robust applications integrating all aspects of remanufacturing in initial product and process design stages across all product families and industries

Note 1: There is a very wide gap between "state of practice" and "state of art" for process M&S capabilities among different industries and companies. A number of the attributes of the "Expected 2005 State" and "IMTR 2015 Vision" are already emerging among leading practitioners; however, from the IMTR perspective these capabilities will not be considered mature until they are in wide use among more than a handful of companies, and meet the test of total plug & play compatibility and robust functionality to serve any industry.

Note 2: The timeframes given for various capabilities reflect application of "reasonable" R&D resources toward their attainment. The timelines for most capabilities shown could be significantly shortened through creation of focused R&D efforts with adequate funding.

- Establish standards, protocols, and taxonomies to assure effective communication (the right information delivered at the right time to the right application in the right format).
- Provide an M&S capability to streamline new technology insertion into existing operations and thereby compress the technology insertion pipeline. The uncertainty and risk of new technology is mitigated through modeling and simulation.
- Establish a framework and infrastructure for a globally accessible, validated repository of best manufacturing process knowledge in a format to support its use in M&S.
- Develop computational modeling capability to a maturity level sufficient to eliminate the need for physical prototypes as product and process validation tools. Confidence in design, functional performance, life-cycle attributes, marketability, and affordability and profitability will be derived from computational models.

3.3.1 Material Processing

Vision: ***Best processes through applied understanding of fundamental principles***

Modeling and simulation for all material-related processes (material preparation, treatment, forming, removal, and addition) have several goals in common. To eliminate redundancy, the common processes are grouped here under "material processing" and the common goals are listed.

The future enterprise process M&S environment will provide the integrated functionality to assure the best material or material product is produced at the lowest cost. The models will treat new, reused, and recycled materials. An open, shared industrial knowledge base and model library will be created to provide:

- Ready access to material properties data using standard forms of information representation (i.e., scaleable plug & play models).
- Means for validating materials property models prior to use in specific product/process applications.
- A fundamental, science-based understanding – including validated mathematical models – of the response of material properties under the stimuli of a wide range of processes.
- Standard, validated time and cost models and supporting estimating tools for the full range of material processing processes.

Process design M&S tools will use the shared material properties database to greatly reduce the time and cost of designing and validating processes, and optimize decision-making. Analysis tools will use the properties data to model materials and processes at the "micro" level to predict "macro" behavior with extreme accuracy. Intelligent tools that draw on historical knowledge and understanding of first principles, and learn by process experience, will help resolve discrepancies between predicted and actual material responses. Knowledge-based tools will gather and assimilate new material knowledge and also give directed advice to support design of specific processes.

Goals & Requirements for Material Processing

- **Goal 1: Broad-Based Material Modeling Framework** – Provide a broad-based framework to provide validated, interoperable material models that serve many process applications. This framework must consist of open, shared models for a wide range of materials and enable tailoring with proprietary extensions for specific applications.

– **Science-Based Material Modeling Knowledge Base** – Establish a "body of knowledge" to provide a foundation for more accurate and cost-effective material modeling and simulation applications. (Specific knowledge bases needed to support this requirement are identified in the IMTR *Roadmap for Information Systems*, Section 2.3.1, Databases/Libraries, and Knowledge Repositories.)

  * **Standard Information Representation Framework**– Establish a standard framework for representing material properties and characteristics data in plug & play models.

  * **Material Knowledge Gap Analysis** – Assess gaps and validity of available material models, by process type, to identify voids in the initial knowledge base; identify high-priority voids and conduct R&D to fill them.

  * **Expanded/Sustained Knowledge Base** – Populate the material modeling framework via focused efforts by federal agencies, academic institutions, and industry consortia, and provide for continuous refreshment.

– **High-Fidelity, Multi-Model Analytical Applications** – Develop a suite of validated analytical applications that enable correct prediction of the results and attributes (including time and cost components, and environmental considerations) of widely used processes for all of the material models captured in the shared knowledge base developed under Goal 1 above. Specific process needs include:

  * **Material Preparation**: Anisotropy, adiabatic heating, hyperelasticity, strain hardening, and rate dependence.

  * **Material Treatment**: Surface chemistry, multi-phase materials, fibrous and cellular solids, fluid structure interactions, and turbulent fluid dynamics.

  * **Material Forming**: Working fluid interface, and transfer of momentum and heat to workpieces.

  * **Material Removal/Addition**: Tool paths, tooling and fixturing, feeds and speeds, coolants, deposition rates, curing rates, flow, fiber placement, entanglement, and bonding.

  * **Process-Specific Applications** – Develop analytical M&S applications specific to particular processes such as metal forming:

    — **Conditions Definition** – Develop capability to establish initial and boundary conditions.

    — **Multi-Code Integration** – Include multiple analytical applications to accommodate a broad range of materials e.g., metals, plastics, composites, polymers, textiles, liquids, and fibrous materials.

National Model Repository:

Making the Most of Our M&S Investments

Good models of products and manufacturing processes are expensive and time-consuming to develop, and closely held by companies seeking competitive advantage. This means that models for widely used processes and similar components are re-created over and over again by different companies. Common sense says this practice is ludicrous. Why waste all that money re-creating the wheel? Shouldn't we rather focus our collective resources on making better products, faster and cheaper?

The time has come for manufacturers to share their resources for the benefit of all. A central repository of validated models, designed in common formats and having the plug-compatibility to mix and match different models into seamless "supermodels," would save huge amounts of time and money for all manufacturers while promoting technical cross-pollination between different industrial sectors. The National Model Repository concept provides a means for companies to have their models rigorously validated at little or no cost, and companies contributing models to the repository would receive royalties whenever their models were used by other firms.

Companies looking for a particular model could quickly search the repository and download whatever they need – process models, standard part/component models, material properties models, or enterprise models. Users would help validate the models through use and could earn a share of royalties by developing enhancements and extensions to the master models. Adjustments and expansions of existing models could be made for new processes and applications, and thus the repository would continually grow.

— **Low-Cost Dynamic Contact Modeling**– Reduce the computational cost of dynamic contact modeling, enabling computational prediction the interaction of forming equipment, tools and dies, operational parameters, and materials interfaces.

– **Interactive Knowledge Base & Validation Methodology** – Establish an interactive knowledge base for material processing technologies and a validation methodology for testing results. Goal 1 above establishes a science-based data and information repository from which modeling and simulation systems can acquire fundamental information e.g., validated materials models. This goal takes that basic information to the next level – application in validated process models that can assure optimized operations.

* **Knowledge Capture Methodology** – Use the Material Modeling Framework developed under Goal 1 to establish a methodology for capturing and updating new knowledge, in real or near-real time, in the shared material processing repository.

– **Continuum Modeling Capability** – Develop continuum modeling capabilities to reveal and predict macro process behaviors resulting from microstructure attributes and address requirements on microstructure to attain macro behavior.

* **Model Validation** – Validate micro-to-macro continuity of process models throughout the ranges of interest; e.g., include phase transformation due to strain and temperature, and provide the capability to identify parameters for disconnects between micro and macro behavior and incorporate these disconnects in the models.

* **Parameter Identification** – Identify parameters for disconnects between micro and macro behavior and incorporate these disconnects in the models.

* **Flagging Capability** – Develop "flagging" ability to assure that deviations and discontinuities are identified and communicated throughout the system.

* **Genetic Inheritance/Engineering of Microstructures** – Develop genetic engineering M&S capabilities for microstructure to achieve macro requirements.

• **Goal 2: Collaborative Analytical Systems** – Provide collaborative analytical systems using modeling and simulation tools and decision support tools for resolving material processing conflicts among any and all enterprise members (partners, suppliers, etc.).

– **Analytical Systems Integration** – Integrate available analysis systems to provide a robust, science-based environment for optimization of material processing designs. Features to be included are optimization criteria and weighting factors, constraints and trade-off rules, a methodology for invention (theory of inventive problem solving), and an open framework of best practices such as neural nets, genetic algorithms, advisors, knowledge-based systems, visualization technologies, and computer-based imaging analysis driving audio-visual interfaces.

– **Automated Parameter Abstraction** – Provide framework with the capability for automated abstraction of modeling and simulation parameters from the detailed material processing design model.

– **Contact Interface Management** – Develop and incorporate schemes for dynamically managing surfaces, particularly contact surfaces, during operations such as forming, assembly, and blending. Include the capability to dynamically identify & re-calculate mid-surface locations for thin shells.

3.3.2 Assembly/Disassembly/Reassembly

Vision: *Optimized, flexible processes for engineered operations*

Future modeling and simulation systems will provide a robust environment for designing, planning, and driving seamless assembly/disassembly/reassembly processes that enable engineered operations. Automated design for assembly (DFA) tools will enable product and process designers to rapidly compose, adjust, and decompose "micromodels" of constituent materials, parts, components, subassemblies, and assemblies. The system will enable them to determine the fastest and most effective assembly sequence, evaluate and select the best joining/attachment methods, ensure correct fit and tolerancing, and optimize the total assembly process to make the most effective use of manual and automated assembly resources from all assets available to the enterprise – including those of partners, suppliers, vendors, and remote facilities as well as the local factory.

A sound understanding of the ergonomics of assembly will enable the system to optimize both product and process for ease of manual and automated assembly, reducing the need for developing specialized assembly tools while also reducing physical issues common to human assemblers, such as muscle strain, repetitive stress, and exposure to hazardous materials and operations.

The system will also enable product and process designers to reverse-engineer products for ease of disassembly and reassembly, simplifying maintenance and support while also optimizing the product for eventual recycle, refurbishment and reuse, or disposal at the end of its useful life.

The output of the DFA system will be an electronic "script" for assembly that can be downloaded to the factory floor to both drive automated assembly systems (parts handling, pick-and-place systems, robotic riveters/welders, etc.) and provide on-line work instructions to operators in the form of animated video, textual instructions, audio guides, or other sensory cues. The electronic script will also drive the operation of maintenance and support activities, enabling repair personnel to quickly isolate problems, fix or replace them problem part/assembly, and return the product to service – or alternatively, break it down for recycle or disposal.

Goals & Requirements for Assembly/Disassembly/Reassembly

- **Goal 1: Knowledge-Based Assembly M&S Tools** – Provide knowledge-based assembly modeling tools to ensure that design-for-assembly/disassembly/reassembly issues are addressed as an integral facet in process and product design decisions.

  – **Virtual Product/Process Planning Structure** – Establish a virtual product/process planning structure that highlights key associated attributes (i.e., tolerances, constraints) of the assembly activity, in the concept stage, providing a roadmap to assure assembly issues are considered in all aspects of the design.

    * **Basic Planning Structure** – Establish a basic planning structure that addresses and associates basic attributes of assembly/disassembly/reassembly processes.
    * **Extended Planning Structure** – Extend the planning structure to include assembly tolerance stack-ups, assembly sequences, datums, ergonomics issues, assembly tooling, fixturing, assembly quality, and production rate.
    * **DFM Product/Process Models** – Develop product/process models that enable true design for manufacturing (DFM), including disassembly, reassembly, and remanufacturing processes.

  – **Assembly Operations Process Modeler** – Develop enabling M&S technologies for choosing assembly processes, enterprise configurations, material handling and logistics.

- * **Basic Assembly Process Selection Tools** – Develop and validate a set of basic tools for choosing assembly processes, with abilities to zoom up/down/in/out for visualization; highlight level of confidence in each model component; display associations across all model structure and layers.
- * **Tool Extensions for Global Resources** – Expand the basic toolset to incorporate use of assembly resources drawn from outside the immediate confines of the enterprise (i.e., from partners and suppliers world-wide).
- * **Tool Extensions for Surge** – Expand the basic toolset to provide for reserve/surge capacity to meet planned and potential peak loads.

– **Distributed Enterprise Assembly Planning System** – Establish a comprehensive M&S planning system for assembly across extended enterprises.

- * **Planning System Backbone** – Develop and validate a basic distributed M&S assembly planning system able to incorporate disassembly, reassembly, and remanufacturing considerations.
- * **Product/Process Software Interface** – Extend the planning system backbone with a uniform interface enabling plug & play integration of supporting product/process applications.
- * **Discrete Event Simulation** – Extend the planning system backbone with discrete event simulation capability to support M&S of assembly processing system availability.
- * **Advanced Tool Interfaces** – Extend the planning system backbone with a capability to interface with more detailed M&S tools to optimize assembly operations (process physics and capability) down to the lowest level of assembly.

• **Goal 2: Assembly Process Control Simulation** – Provide a comprehensive and integrated process control simulation capability for assembly, disassembly, and reassembly.

– **Generic Assembly Control Model** – Develop generic assembly process control models to provide a baseline for creation and operation of integrated Manufacturing Execution Systems. (Model-based factory control is addressed in further detail in the IMTR *Roadmap for Manufacturing Processes & Equipment*, Sections 2.3.3, 2.3.5 and 5.3).

– **Control Program Autocreation** – Develop capability to create dynamic assembly control programs directly from process and product models and simulations.

– **System Extensions** – Extend assembly simulation capability to provide support for manual and automated operations, including setup, operation, and maintenance (diagnosis, prevention, and repair).

3.3.3 Quality, Test, & Evaluation (QT&E)

Vision: ***100% quality engineered into every facet of every manufacturing process***

Over the next 10 to 15 years, "virtual testing" based on a solid foundation of science and knowledge (first-principles models coupled with experience captured in knowledge bases) will gradually eliminate the need for physical testing of processes and products in all but the most critical manufacturing operations. Today's incrementally developed physical prototypes will be replaced by true "first-article perfect" products immediately ready for customers to drive, fly, wear, consume, or switch on. In the future product creation process, requirements will be automatically converted into specifications that directly drive the design of product features, the definition of process control parameters for quality assurance, and the subsequent execution of the manufacturing processes. Knowledge-based systems will enable certification of processes, eliminating the need for after-the fact certification of virtually all products.

Goals & Requirements for Quality, Test, & Evaluation

- **Goal 1: Product Attribute Specification Capability** – Provide the capability to capture and/or generate the knowledge needed to convert functional specifications into product attribute control parameters that can be embedded in master product and process models and continuously validated and updated based on actual process performance.

  – **Functional Specifications Derivation** – Develop M&S systems that provide the capability to derive and specify all information needed to verify that products and processes meet functional specifications (physical, geometric and chemical), and which specify requirements and processes for acquiring necessary evaluation/certification information.

    * **QT&E-Aware M&S Systems** – Develop new product and process M&S systems that 1) are standards-based; 2) represent geometric design specifications with perfect fidelity; and 3) include all certification information as model attributes.

    * **QT&E Decision Support Systems** - Develop QT&E decision support systems that access attributes of the product and process model to specify and optimize quality and control requirements, and provide direct inputs to control quality/test and certification operations.

- **Goal 2: Zero Post-Process Certification** – Establish robust, science-based manufacturing process control models that enable elimination of "after-the-fact" certification by integrating certification as a real-time, integral part of individual manufacturing processes. (Also see Section 6.3 of the IMTR *Roadmap for Manufacturing Processes & Equipment*.)

  – **Adaptive, Real-Time Process/Equipment Control Models** – Develop self-tuning process and equipment control models based on first principles, validated knowledge bases, and continuous feedback of test and inspection data.

    * **Multi-Level Model Controls** – Develop multi-level controls for model tuning and verification.

    * **Capture/Use of Predefined Performance Parameters** – Develop means for automatic capture and use of historical or predefined performance parameters.

  – **QT&E Certification Models** – Develop new certification models that enable elimination of certification through the application of control strategies using real-time process information.

    * **Baseline Vendor Equipment Models** – Establish standard practice for vendors to supply baseline performance models of their test and inspection equipment.

    * **Updated Equipment Models** – Establish vendor linkages to continually update test and inspection equipment performance models based on factory floor experience.

    * **Critical Process Variables** – Use historical data or perform testing to establish relationships between process variables and final product quality specifications.

    * **Process Control Strategy** – Develop the necessary process control algorithms that provide continuous control over critical variables to ensure product quality.

3.3.4 Packaging

Vision: *Packaging seamlessly integrated into process and product design*

Future process (and product) modeling and simulation systems will enable packaging designs and processes to be fully integrated in all aspects of the design-to-manufacturing process and will provide needed functionality with minimum cost, and minimum environmental impact, with no non-value added operations. Advanced packaging M&S systems will enable product and process designers to optimize packaging designs and supporting processes for enhanced product value and performance, as well as for protection, preservation, and handling attributes. Section 7.3 of the IMTR *Roadmap for Manufacturing Processes & Equipment* provides further detail on packaging process R&D requirements.

Goals & Requirements for Packaging

- **Goal 1: Integrated Packaging Modeling** – Provide integrated M&S tools that enable packaging to be a full-fledged product design factor contributing to minimum product cost while assuring product preservation and integration with logistics systems.

  – **Extended Process M&S Systems** – Extend manufacturing product/process modeling systems to address packaging, handling, and distribution functions.

  * **Packaging/Handling Constraints Application** – Develop capability to ensure that models apply constraints of inherent preservation, differentiation, identification, and disposition throughout the product/process design function.
  * **Packaging Optimization Criteria** – Establish criteria and strategies for optimizing handling and packaging functions in process models. Include projected environmental boundary conditions and end use.
  * **Packaging Optimization Functionality** – Develop and establish criteria to include packaging/handling optimization strategies in product and process modeling and simulation systems.
  * **Environmentally Benign Packaging** – Develop M&S capability to ensure that packaging and packaging processes are environmentally benign; i.e. model includes reduce, reuse, recycle considerations and that packaging is safe, sanitary, and simple.

- **Goal 2: Integrated Life-Cycle Material Behavior Modeling** – Ensure that the material modeling frameworks and knowledge base developed under Section 3.3.1 include the materials and material properties used in packaging and packaging processes throughout the production, distribution, and end use environments.

  – **Packaging Process Models** – Develop models of best-practice packaging, marking and tracking processes.

  – **Functional Packaging Performance Modeling** – Develop common relationship model relating attributes of packaging in preserving product to packaging impacts on product functional performance.

  – **Shipping Conditions Simulation** – Develop science-based models of the effect of shipping conditions on common packaging and product types to enable elimination of transport/shipping testing.

- **Goal 3: Optimized Life-Cycle Packaging** – Establish the capability to create best packaging based on characteristics of environments throughout life cycle (package design synthesis).

– **Packaging Criteria** – Establish a packaging criteria knowledge base accessible to all manufacturers.

– **Materials Knowledge Base Interface** – Develop an interface to the shared industry materials knowledge base developed under Section 3.3.1 for use in packaging design M&S activities. Extend the shared knowledge base with data on specific life-cycle issues such as environmental and operational (end use) considerations.

– **Processes Knowledge Base Interface** – Develop an interface to a shared industry manufacturing processes knowledge base for use in packaging design M&S activities.

– **Boundary Conditions Database Interface** – Develop an interface to a shared industry database of environmental boundary conditions.

3.3.5 Remanufacture

Vision: ***Robust process design and execution for reuse, recycle, and total life-cycle efficiency***

Manufacturers in the future will reuse, recycle, and remanufacture products and materials to minimize material and energy consumption, and to maximize the total performance of manufacturing operations. Advanced modeling and simulation capabilities will enable manufacturers to explore and analyze remanufacturing options to optimize the total product realization process and product and process life cycles for efficiency, cost-effectiveness, profitability, and environmental sensitivity.

Companies in related industries will use process and enterprise integration M&S capabilities to develop integrated operations where product and process byproducts from one or more companies serve as feedstock to different companies, similar to the way paper products and plastics are recycled today. Advanced manufacturing systems will knowledgeably treat material streams with processes optimized through modeling and simulation for economical recovery, remanufacture, and reuse without sacrificing product or process quality or performance. Process M&S systems will incorporate anticipated returned/recycled material as part of the input stream and assist in making intelligent process development and process management decisions.

The products of the future will be designed from inception for remanufacture and reuse either at the whole product or the component or constituent material level. In some cases, ownership of a product may remain with the vendor (not unlike a lease), and the products may be repeatedly upgraded, maintained, and refurbished to extend their lives and add new capabilities. For further description of remanufacturing-related issues, see the IMTR *Roadmap for Manufacturing Processes & Equipment*, Section 2.3.1.

Goals & Requirements for Remanufacture

- **Goal 1: Integrated Material Stream Modeling** – Provide manufacturing process modeling systems able to identify and separate product/material streams for 1) reuse of products or constituents with little or no modification; 2) reused components (without reprocessing); 3) remanufactured components; and 4) material entirely recycled into new or similar products.

– **Intelligent Material Separation Modules** – Develop material stream design advisors that anticipate the variety, state, and quantity of materials used in complex, distributed, multi-product manufacturing operations, evaluate material reuse requirements and options, and assist product and process designers in achieving the most efficient and beneficial designs and processing approaches.

- **Material Assessment Tools** – Extend the material stream modeling advisors to use historical information about returned material to determine if a given material will perform adequately without reprocessing, or what processing steps are required for reuse.

- **Goal 2: Comprehensive Material Flow Models** – Provide material flow models for widely used processes which include the flow of materials enterprise-wide, both internal to and crossing plant boundaries, to support planning and execution of remanufacturing operations.

- **Material Flow Interfaces** – Develop generic definitions of material flow interfaces between the integrated product/process design systems and the overall material management systems that update these systems to reflect recycled/returned materials.

- **Goal 3: Remanufacturing Modeling Tool Suite** – Provide M&S applications that enable full consideration of remanufacturing issues in the original product and process design stage of the product realization cycle.

- **Reverse Engineering Applications** – Develop generic M&S application modules that are plug & play compatible with existing product and process design applications, which enable product and process designers to "reverse engineer" prototype designs to evaluate remanufacturability aspects of returned products in a wide range of condition (dysfunctional, damaged, corroded, contaminated, etc.), and which enable designers to optimize the design of both the product and its manufacturing processes to support efficient, cost-effective reprocessing, recycling, recovery, and remanufacture.

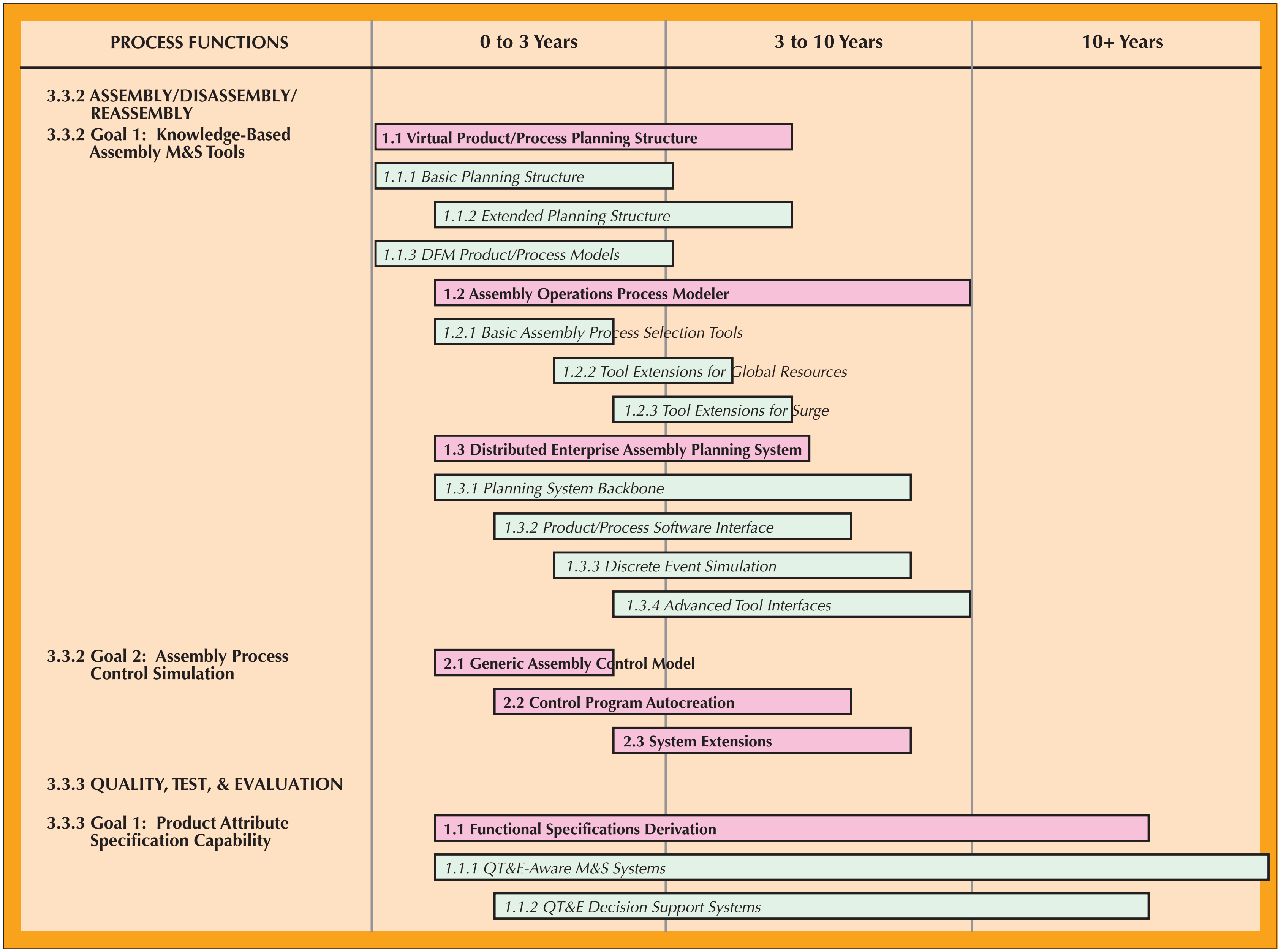
- **Remanufacturing Design Advisors** – Develop intelligent design assistant applications that automatically evaluate, or score, candidate process and product design models on the basis of their attributes to support remanufacturing, including disassembly, component/part/material recovery and reprocessing, and reassembly/reintegration, and which drawn on captured knowledge to offer recommendations for remanufacturing design optimization.

- **Automatic Remanufacturing Simulation System** – Develop a robust, integrated product and process simulation system that exercises candidate new product and process designs through a living, high-fidelity factory model and life-cycle model and automatically adjusts both product and process models to optimize them for the most efficient and cost-effective remanufacturing solution.

3.4 Roadmap for Manufacturing Process Modeling & Simulation

Using the goals outlined in Section 3.3 above, the workshop team mapped the associated requirements and R&D areas over near-, mid-, and long-term timeframes as presented on the following pages. The attached roadmap represents a "first cut" at defining a research, development, and implementation plan, and additional work is required to develop detailed task plans as well as to align dependencies among the various activities.

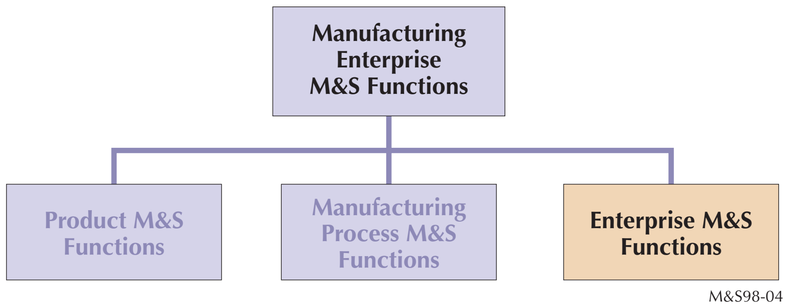
3.3 PROCESS FUNCTIONS	0 to 3 Years	3 to 10 Years	10+ Years
3.3.1 MATERIAL PROCESSING			
3.3.1 Goal 1: Broad-Based Material Modeling Framework	**1.1 Science-Based Material Modeling Knowledge Base**		
	1.1.1 Standard Info Representation Framework		
	1.1.2 Material Knowledge Gap Analysis		
	1.1.3 Expanded/Sustained Knowledge Base		
	1.2 High-Fidelity, Multi-Model Analytical Applications		
	1.2.1 Process-Specific Apps - Metal Forming		
	1.2.1.1 Conditions Definition		
	1.2.1.2 Multi-Code Integration		
	1.2.1.3 Low-Cost Dynamic Contact Modeling		
	1.3 Interactive Knowledge Base & Validation Methodology		
	1.3.1 Knowledge Capture Methodology		
	1.4 Continuum Modeling Capability		
	1.4.1 Model Validation		
	1.4.2 Parameter ID		
	1.4.3 Flagging Capability		
	1.4.4 Genetic Inheritance/Engineering of Microstructures		
3.3.1 Goal 2: Collaborative Analytical Systems	**2.1 Analytical Systems Integ**		
		2.2 Auto Parameter Abstraction	
		2.3 Contact Interface Management	


PROCESS FUNCTIONS
0 to 3 Years
3 to 10 Years
10+ Years
3.3.2 ASSEMBLY/DISASSEMBLY/ REASSEMBLY
3.3.2 Goal 1: Knowledge-Based Assembly M&S Tools
1.1 Virtual Product/Process Planning Structure
1.1.1 Basic Planning Structure
1.1.2 Extended Planning Structure
1.1.3 DFM Product/Process Models
1.2 Assembly Operations Process Modeler
1.2.1 Basic Assembly Process Selection Tools
1.2.2 Tool Extensions for Global Resources
1.2.3 Tool Extensions for Surge
1.3 Distributed Enterprise Assembly Planning System
1.3.1 Planning System Backbone
1.3.2 Product/Process Software Interface
1.3.3 Discrete Event Simulation
1.3.4 Advanced Tool Interfaces
3.3.2 Goal 2: Assembly Process Control Simulation
2.1 Generic Assembly Control Model
2.2 Control Program Autocreation
2.3 System Extensions
3.3.3 QUALITY, TEST, & EVALUATION
3.3.3 Goal 1: Product Attribute Specification Capability
1.1 Functional Specifications Derivation
1.1.1 QT&E-Aware M&S Systems
1.1.2 QT&E Decision Support Systems

3.3 PROCESS FUNCTIONS	0 to 3 Years	3 to 10 Years	10+ Years
3.3.3 Goal 2: Zero Post-Process Certification	**2.1 Adaptive, Real-Time Process/Eqpt Control Models**		
	2.1.1 Multi-Level Model Controls		
	2.1.2 Capture/Use of Predefined Performance Parameters		
	2.2 QT&E Certification Models		
	2.2.1 Baseline Vendor Equipment Models		
	2.2.2 Updated Equipment Models		
	2.2.3 Critical Process Variables		
		2.2.4 Process Control Strategy	
3.3.4 PACKAGING			
3.3.4 Goal 1: Integrated Packaging Modeling	**1.1 Extended Process M&S Systems**		
	1.1.1 Packaging/Handling Constraints Application		
	1.1.2 Packaging Optimization Criteria		
	1.1.3 Packaging Optimization Functionality		
	1.1.4 Environmentally Benign Packaging		
3.3.4 Goal 2: Integrated Life-Cycle Material Behavior Modeling	**2.1 Packaging Process Models**		
	2.2 Functional Packaging Performance Modeling		
	2.3 Shipping Conditions Sim		
3.3.4 Goal 3: Optimized Life-Cycle Packaging	**3.1 Packaging Criteria**		
	3.2 Materials Knowledge Base Interface		
	3.3 Processes Knowledge Base Interface		
	3.4 Boundary Conditions Database Interface		

PROCESS FUNCTIONS	0 to 3 Years	3 to 10 Years	10+ Years
3.3.5 REMANUFACTURE			
3.3.5 Goal 1: Integrated Material Stream Modeling	1.1 Intelligent Mat'l Separation Modules	1.1 Intelligent Mat'l Separation Modules	
		1.2 Material Assessment Tools	
3.3.5 Goal 2: Comprehensive Material Flow Models	2.1 Material Flow Interfaces	2.1 Material Flow Interfaces	
3.3.5 Goal 3: Remanufacturing Modeling Tool Suite	3.1 Reverse Engineering Apps		
	3.2 Remanufacturing Design Advisors	3.2 Remanufacturing Design Advisors	
	3.3 Automatic Remanufacturing Simulation System	3.3 Automatic Remanufacturing Simulation System	3.3 Automatic Remanufacturing Simulation System

4.0 ENTERPRISE MODELING & SIMULATION FUNCTIONS



4.1 Functional Model Definition for Enterprise Modeling & Simulation

The Enterprise Management activities of a manufacturing enterprise can be functionally divided into two major elements for evaluation purposes. The Business functions generally deal with cross-cutting, high-level strategic issues at the enterprise level. The Operations functions are more tactical, and deal with issues more specific to a discrete manufacturing facility.

Business Functions

- Strategic Positioning ⇒ Includes decisions and evaluation of business lines, retention and outsourcing of competencies, site locations, facilities, and configurations, evaluation and other strategic decision-making (incl. evaluation of legal and contractual implications and stakeholder concerns).
- Market Assessment & Positioning ⇒ Includes customer and competitive analysis for product positioning and product evolution, forecasting, business line assessment.
- Risk Management ⇒ Includes all financial, technical, schedule, regulatory, legal (incl. intellectual property control), and other risk evaluation, decision, and management processes, relative to both internal and external enterprise views.
- Financial/Cost Management ⇒ Includes all financial forecasting and trending functions, tradeoff analyses, and cost management process modeling.
- Resource Management ⇒ Includes management of all enterprise resources, including capital, manpower and skills, training, core competencies, facilities, material, and subcontractor/partner/supplier capabilities and assets, and Make/Buy decision processes, and optimization of all resources across and among all functions for all elements of the extended enterprise.
- Quality Management ⇒ Includes all quality design and specification and performance monitoring and assessment functions, incl. continuous process improvement and support of certifications.
- Enterprise Architecture Management ⇒ Includes management and integration of enterprise systems incl. physical, organizational structure, info systems, and integration of enterprise models and simulations.
- Extended Enterprise Management ⇒ Includes all aspects of teaming and partnering, such as supplier/vendor/partner assessment and selection, working interfaces, information interchange (collaboration), knowledge management (including intellectual property), contract vehicles, profit/risk sharing, and performance measurement.

Operations Functions

Resource Management	⇒	Includes identification, allocation, routing, and control of all operational resources, including manpower/skills (incl. training and certification), technology (incl. info systems), equipment, support assets, and supporting information.
Performance Management	⇒	Includes all operational performance elements, including cost, schedule, quality, throughput, productivity, risk, capture of corporate experience and knowledge, effectiveness of training/certification, and similar parameters.
Factory Operations	⇒	Includes all factory floor and related above-shop-floor operations functions, such as design change management, equipment configuration and layouts, product and material flow, manpower (incl. training) and shift usage, experience/knowledge capture, and maintenance.
Facility Infrastructure Management	⇒	Includes management of physical assets and resources required to support the core manufacturing operations, such as utilities, maintenance, calibration, standards, computers and networks, and telecommunications.

4.2 Current State Assessment for Enterprise Modeling & Simulation

Modeling and simulation have been extensively applied to product engineering and manufacturing processes over the past decade and are now evolving very rapidly in the business and operations management arena. The challenges here are more problematic than in the math and physics-based realms of engineering and manufacturing. The objects and events being modeled are largely focused on business transactions, relationships, and human intellectual operations, and models in this area are generally limited to spreadsheets for financial and resource calculations or simple graphic representations of processes and relationships. M&S capabilities in this realm are almost exclusively developed and applied on a case-specific basis and, outside of the emerging enterprise resource management (ERM) arena, there is essentially zero integration of product and process models at any level to support processes at the enterprise level.

This "softer" side of manufacturing enterprises does offers rich potential for application of modeling, simulation, and other engineering disciplines to analyzing and optimizing business operations, and there are success stories that provide confidence in the ability of M&S to provide bottom-line benefits in the enterprise management arena. The recursive executable cell (REC)[11], for example, is an architectural simulation template designed to model the relationship between organizational structure, material and information flows, and behavior within and between enterprises from a performance perspective. It is a composite template consisting of six interconnected generic components that model the execution of tasks in business enterprises.

For a large banking firm, the scaleable architecture of the REC facilitated the modeling of a multi-function and multi-location customer service environment. In this model, worker schedules were imported to describe time-dependent service capacities at a number of different physical processing centers and historical and forecasted customer demand functions were used to test the system's response to time-dependent service loads. The results of the simulation were used to fine-tune the total service delivery approach to meet customer needs at significantly lower operational costs.

4.2.1 Business Functions

There are some general observations that can be made about the current state of modeling and simulation for the business functions of a manufacturing enterprise:

[11] Peter H. Tag, The Recursive Executable Cell: An Architectural Template For Building Enterprise Simulation Models. January 1996.

- The base of modeling and simulation tools is small but growing. Most existing tools are diagnostic and analysis tools, not optimization tools. Most are costly, slow, and reliant on special expertise. The state of practice is defined by simple spreadsheet models and homegrown point applications.
- The process of validating business models is more art than science for most applications.
- Few tools exist for modeling soft, non-math/non-numerical sciences. There are few accepted standards or conventions for representing information other than financial data, and financial data standards are subject to widely varying interpretation among (and even within) different companies.
- Most tools used for modeling or simulating business enterprise functions are stand-alone, point solutions, and do not integrate with other systems or higher-level simulation functions. The lack of an complete, synchronized enterprise model is a huge barrier to optimization of the total manufacturing enterprise design.
- Three-dimensional visualization techniques such as virtual reality modeling language (VRML) have great potential to convert masses of enterprise data into useful information, but are only now being explored in the business environment.
- There is very little linkage of business models to real-time data, or even to accurate. Data collection is largely ad-hoc, and data quality is highly suspect even in the best companies.
- Little has been done to resolve pressing issues related to intellectual property, and there is no consensus on how to treat intellectual property in enterprise asset models.

4.2.1.1 Strategic Positioning

The ability of a manufacturing enterprise to stake out a strategic position in its industry and continuously adjust this position for best advantage is vital to the enterprise's long-term survival, but there are few modeling and simulation tools available to support rigorous analysis, evaluation of opportunities and challenges, and prediction of likely outcomes of decisions and events. This is due in large part to the fact that there are no "first principles" for this type of analysis; it is a soft science, subjective, and situation-dependent. Variables in decisions about positioning business lines, retaining and outsourcing of competencies, siting new facilities, and forming new relationships with suppliers and partners are not easily reduced to sets of numbers that can be run in a math-based simulation. Decision-making processes in these areas must include legal implications and the concerns of all enterprise stakeholders (customers, stockholders, employees, and the wider community). The management of a manufacturing enterprise must take account of the economic, technological, and industrial trends surrounding the enterprise in order to best plan for its future investments and development of its manufacturing capabilities. For global enterprises, strategic positioning assessment becomes even more complex, since political and cultural differences of the distributed business environment can have a great impact on the success or failure of decisions to site new plants or relocate existing ones.

Other attributes of the current state of M&S maturity for strategic positioning include:

- There are some "homegrown" applications that perform as simple models of the business environment, but they do not enable prediction of outcomes with any degree of confidence. Most possible outcomes of strategic decisions can only be expressed in terms of general likelihood, with no accurate weighting of probability.
- Some qualitative simulation techniques exist, and research is ongoing, but there are currently no widely accepted commercial tools available in this area. There is a real need to be able to augment current management techniques with robust, widely applicable models and

simulation tools in a number of functions, such as risk analysis, capital budgeting, make/buy analysis, and cash flow analysis.

- With current approaches, macro-level analysis is not possible without extensive (time-consuming and costly) accumulation of detailed data to build bottom-up models.

4.2.1.2 Market Assessment & Positioning

The challenge in this area is to predict future market conditions and strategically plan how best to position the enterprise to take advantage of those conditions. The complexity and "softness" of the information modeled in this arena are similar to that described for Strategic Positioning. The knowledge used primarily leverages personal wisdom and experience, and is closely protected for competitive advantage. Current practice is typically based on subjective assessment of options and performance against known metrics of market size, competitor rankings, and price levels. The few M&S tools available and used in corporate training or business schools are primarily based on a few quantitative techniques (such as spreadsheet tradeoffs). One such tool is the "Prosperity Game" by Pace Van Devender of Sandia National Laboratories.

Manufacturers and market analysis firms expend a great deal of time and energy analyzing potential customers in the consumer products markets. Warranty registrations, subscriptions, Internet transactions, postal "zip+4" codes, and post-purchase customer surveys are driving the creation of huge databases about individual preferences, buying habits, and trends. While data mining and analysis techniques are giving manufacturers a better picture of who their customers are and what they want in a product, current M&S applications lack the ability to do more than support basic decisions about how many to make and what color to make them. Despite the advanced tools that now exist, manufacturers continue to be surprised when a new product wildly exceeds expectations or flops miserably.

The capability to assess the impact of a competitor's products is also greatly lacking. Brisk sales of Iomega's new 100 MB "Zip" drive in 1997 gave new life to a company thought to be on the rocks, and the resulting shift in market share was a likely factor in the decision by Iomega's major competitor, Syquest, to reduce its workforce and close some production facilities in mid-1998.

4.2.1.3 Risk Management

Step-wise templates and spreadsheets are commonly used to model and assess risk in large companies, but these tools these rely almost exclusively on individual expertise and insight to identify and assign weights to risk factors. Cost risk is more easily quantified than other types (such as betting on the wrong technology or failing to meet a development milestone on schedule), but here again the risk assessment is largely dependent on individual insight in determining the magnitude of possible outcomes or the value of workarounds or fallback strategies.

Disciplines other than manufacturing have deeper investments and insights in modeling and simulation of risk factors (e.g., NASA and the FAA for space vehicle and aviation safety, DOE for nuclear materials safety and surety); their best practices are directly applicable to manufacturing, but are not widely used outside their respective agencies.

4.2.1.4 Financial/Cost Management

There are many M&S tools available for static simulation and tradeoff analysis (e.g., spreadsheet-based cost models) for financial analysis of various types and views of cost, including total ownership cost, flyaway unit cost, activity-based cost, and capital investments, but few tools exist in this area to support robust simulation. The latest enterprise resource planning (ERP) tools have deterministic modeling capabilities such as cash flow analysis, but there is a driving need to develop robust enterprise cost models that integrate all relevant factors and link to current, accurate data to enable fast, accurate analysis of cost/finance issues and opportunities.

4.2.1.5 Enterprise Resource Management

Enterprise resource management (ERM) has become a burning issue in the 1990s as increasingly complex manufacturing enterprises – formed through mergers, acquisitions and formation of virtual enterprises that bring together many partners and suppliers for a specific purpose – seek to manage all of their resources in an increasingly competitive and resource-constrained environment. The larger and more complex the enterprise, the more difficult it is to manage its resources (e.g., capital funds, facilities, and equipment, manpower and skills, core competencies, and product and material inventory) with any degree of fine control at the enterprise level. Increasing product complexity, decreasing lot sizes and lead times, and workforce reductions further drive an industry-wide sense of urgency to find ERM solutions that really deliver on their promises.

Section 4.3 of the IMTR *Roadmap for Information Systems* provides an in-depth look at the current state, vision, goals, and requirements for ERM. However, M&S technology is certainly a component of the ERM solution. Following are some general observations on the current state of M&S tools in this area:

- There are many tools available in different domains, but there are no conventions or standards for common representation schemes to collectively manage different types of resources, no means of aggregating detailed data into a high-level model, and no common understanding or definition of the terms used by the different tools.
- Development of models for any resource area is expensive and time-consuming. Current tools are complex and require highly trained operators.
- Data collection to support resource modeling is largely ad hoc, and data accuracy and currency are major problems.

Resource areas with current M&S tools and capabilities of note include:

- **Facilities resource management** has good M&S tools for operational assets such as plant HVAC and utilities systems. Some CAD tools are available to model factory layout, but they are not integrated with simulation tools for analyzing operational or business performance – and no standards exist to support such representations. In a few cases, geographic information system (GIS) tools are being used in modeling multi-plant resources or siting of distributed resources, including status monitoring and logistics support.
- **Manpower planning** has some M&S tools available for planning and prediction, but these are not integrated with simulation tools to do business analysis, and there are no standards to support such models.
- **Training** is a major area of current focus for M&S applications, particularly virtual reality training to operate complex equipment or perform hazardous processes. Simulations of manufacturing processes with complex tools enable in-process training (or man-in-the-loop training) on use of those tools. There is emerging use of web-based virtual reality training.

4.2.1.6 Quality Management

The function of quality management in manufacturing has undergone rapid evolution over the past decade as companies – spurred largely by global competitive pressures – moved from a philosophy of "inspecting quality in" to "getting it right the first time." This was done largely by designing more reliable manufacturing processes and providing capabilities such as statistical process control (SPC) to help keep processes operating within their specified parameters. The recognition that properly designed and executed processes produce quality products has extended beyond the shop floor to be applied to virtually any type of business process, from engineering to business management to product support.

Modern quality concepts have evolved through many initiatives, such as DoD's Total Quality Management doctrine and the U.S. Malcom Baldridge Quality Award criteria, and are now codified in the ISO 9000 quality standard and certification programs such as the Software Engineering Institute's Capability Maturity Models (SEI CMMs).

While these standards and requirements do serve as excellent "models" for manufacturers to enhance and assure quality in their products and processes, until recently no automated macro-level modeling or simulation tools existed to support them. This is particularly true at enterprise levels, where discrete quality attributes are more difficult to define in meaningful ways. Modeling techniques such as QFD (see page 25) are enabling companies to address subjective quality measures in a more objective way, and products such as Catalyst by Software Productivity Solutions, Inc. are providing automated means of creating QFD models.

Firms such as John Keane & Associates (JKA) currently offer a number of simulation products to support quality planning. These "virtual factories" enable managers to evaluate different plant operating scenarios, especially as they relate to quality, and evaluate the effects on plant performance. The simulators compress time [months into minutes] and reduce risk of missteps when real dollars and jobs are on the line. JKA's QMS/9000+ is set of "building blocks" which can be assembled to create a customized quality system solution for an actual plant. The software also instructs computers to execute procedures and instructions normally done by people, thereby reducing labor costs associated with quality systems.

These kinds of tools can help predict the payoff for new quality improvement programs or to evaluate the "cost of quality" and other factors, such as tradeoffs of contemplated alternative process improvements with respect to the cost, schedule, or quality improvements which would result.

4.2.1.7 Enterprise Architecture Management

Today's complex manufacturing enterprise are managed in two domains: operational (execution of business missions) and functional (management of functions to support those operations). Management actions at the enterprise level focus largely on promulgating strategic objectives, performance parameters, and constraints, and the operational and functional units of the enterprise develop and execute tactical plans to meet those objectives. The enterprise itself comprises a series of loosely interrelated physical and process architectures, such as organizational structures, financial systems, "distributed repositories" of skills, competencies, and physical resources, information and communications networks, and hierarchies of interrelated processes and facilities.

Managing this complexity occupies a tremendous portion of the enterprise's resources, and is a huge component of product costs. There are many modeling and simulation tools available to help manage various pieces of the total picture, but very few of these tools work together to any meaningful degree and there are no tools available to manage the enterprise as a whole, in all of its complexity.

At the macro level, there are some tools available for enterprise modeling, but most enterprise models are custom-built for very specific domains (e.g., finance, communications, transportation and distribution), have limited fidelity with the real world, and little or no capability to run simulations to predict the effects and impacts of planned or potential change events. A number of vendors are working in this area, and some commercial, Internet-based enterprise financial models are emerging.

One simple modeling tool freely available to help government facilities manage their information systems architectures is the GRAF system, developed by Oak Ridge National Laboratory. GRAF enables users to take simple database lists of resource objects (such as telephone repeater nodes and computer servers), map their relationships, and graphically depict those objects and their connections and interdependencies. This helps IT managers understand the "big picture" when services must be expanded, upgraded, or otherwise modified in response to changing demands.

4.2.1.8 Extended Enterprise Management

This function includes all aspects of teaming and partnering, including supplier/vendor/partner assessment and selection, establishing and managing interfaces between organizations, information interchange and collaboration, knowledge management (including intellectual property issues), contract vehicles, profit and risk sharing, and performance measurement.

Modeling or simulating the activities of extended enterprises is challenging, since most extended enterprise functions involve human activities and interactions that are impossible to quantify or predict with confidence, particularly for global enterprises which include different cultures and economic environments. The companies involved in an extended enterprise often have different knowledge representations and information flows and different accounting schemes. There are no mature tools openly available for modeling extended enterprises, though there is research ongoing in this area.

The following observations describe the current state of practice in M&S for extended enterprise management:

- The ability to build robust M&S tools for extended enterprise management is complicated by different computer languages, data structures, and ways of representing requirements and capacities among different companies. The different tools often do not have the same scope of operation, or communicate well with each other (unless using a common interface such as SAP's Business API).
- Tools are available for some functions – for example, SAP has tools for supply chain modeling using advanced planning and optimization techniques) and stochastic (deterministic) models for forecasting.
- Depending on what management problem is being addressed, different levels of information granularity are used at different times. It is difficult to integrate these levels of information, both within one company and across the extended enterprise.
- Automotive companies are doing some multilevel supplier modeling.
- The Theory of Constraints[12] is now being used in leading-edge tools such as SAP and I2 to manage and optimize use of capacity.
- Most tools are costly, inflexible, slow, limited in function, and do not integrate with other tools; some firms are partnering with others to gain strategic capabilities and move away from monolithic systems.
- Good tools to capture and represent domain knowledge (and model complex processes) so it can feed models and simulations do not exist.
- Even if knowledge is captured in some representation mechanisms, there is no good way to *use* the knowledge in business processes or integrate it with conventional simulations.
- Despite the lack of standards, it is easier to share nontechnical data (e.g., schedules and spreadsheets) than technical data (e.g., designs) across an extended enterprise.

[12] The Theory of Constraints states that every system has at least one constraint limiting its output. Therefore, by addressing the major limiting constraints of a system (e.g., cycle time), the system can be improved to realize the greatest benefit with the least investment of time and resources.

- There is presently no way to model different levels of trust and common purpose in representing the activities of different participants in virtual enterprises.

4.2.2 Operations Functions

4.2.2.1 Resource Management

This function includes identification, allocation, routing, and control of all operational resources, including manpower and skills (and associated training and certification), technology (including information systems), equipment, support assets, and supporting information. There are many tools available for modeling different types of resources, for example capacity and manpower planning and estimating, but these are not tied to simulations or the models to each other. An exception to this is that scheduling tools are tied to resource planning for assessment of resources to tasks over time. Some other observations include:

- New techniques such as genetic algorithms and neural nets are being used for schedule and control, but they are narrowly focused, user-intensive and not interoperable. Genetic algorithms provide a more efficient way of pruning the search space for potential solutions, but they are very dependent on a good starting point to get good results.
- For manpower, skills, and associated training, the same points made under Business Management (Section 4.2.1) apply here.
- It is not possible to simulate what is happening at any given time in a manufacturing shop, in order to evaluate problems. Post-event modeling and simulation are expensive, time-consuming, and does not have a high probability of success except in clearly defined situations (e.g., single machine failure).
- It is not possible to capture inspection data and superimpose it on a machine's simulation, in order to detect and correct noncompliance to specifications.

4.2.2.2 Performance Management

This function includes all operational performance elements, including cost, schedule, quality, throughput, productivity, risk, capture of corporate experience and knowledge, effectiveness of training and certification, and similar parameters. General observations include:

- The M&S tools in this area are immature. They help with planning in conjunction with captured performance information, but they do not extend to actual management, i.e., they do not support robust modeling and simulation using experience and knowledge to help reengineer and optimize processes.
- Tools do exist for cost and schedule performance (such as ProModel and Arena), but lack necessary links to real-time performance data and are limited by the fidelity of defined dependencies in making predictions.
- Only a few tools, mostly homegrown, are available to model operator effectiveness and tie in to appropriate training and certification information.

4.2.2.3 Factory Operations

This function includes all factory floor and related above-shop-floor operations functions, including design change management, equipment configuration and layouts, product and material flow, manpower (including training) and shift utilization, experience/knowledge capture, and maintenance. Observations on the current state of practice are as follows:

- Many shop floor management tools are good in their specific domain, but do not interoperate; they are expensive, time-consuming, require dedicated assets and support, and provide little or no predictive capability.

- Knowledge is hard-coded into the tools, and they offer little flexibility to adapt to business requirement or technology changes.
- Maintenance problems and remanufacturing issues are not addressed by manufacturing M&S systems.
- There are no commercial M&S tools (only customized point solutions) for distribution management, i.e., warehouse management and intersite movement and tracking of materials.

4.2.2.4 Facility Infrastructure Management

This function includes management of physical assets and resources required to support the core manufacturing operations, including utilities, maintenance, calibration, standards, computers and networks, telecommunications, etc. There are good M&S tools available for different areas of the facility infrastructure, and many can be interfaced, but they are not truly integrated. That is, they do not share or act on the same common data set.

- For physical facilities management, there are tools available for operational assets such as HVAC (real-time status, balancing, etc.). Some ERP systems have plant and facility infrastructure management tools.
- Geographical information systems (GISs) can help manage distributed sites, allowing precise location of resources, and coordination and overlaying of different resource models.
- Tools such as Computer Associates' Unicenter TNG and Tivoli Systems' TME 10 are available for modeling and managing large, heterogeneous computer networks. There are commercial tools such as ComNet for simulating telecommunications networks.

> **Flying the Factory:**
>
> ***The Enterprise Management Cockpit***
>
> **Managers need the right information at the right time to make the right decisions. They also need the ability to evaluate options and risks and have confidence in the results. Financial and market data, operations and resource needs and status, and the ability to communicate all need to be at their fingertips – in the same way that pilots of fighter aircraft need responsive controls and accurate information about direction, speed, fuel, weapons, and potential threats in order to accomplish their mission.**
>
> **The modern aircraft cockpit, with all of its sophisticated instruments and controls linked to sensors, weapons, and flight systems, provides a perfect model for enterprise management systems. Future managers at all levels of the enterprise, who now get their information from paper and e-mail, will see their desktop computers evolve into sophisticated enterprise management cockpits that are fully connected with all of the systems and operations of the enterprise. Live, 3-D factory models will be hooked directly into the factory's design and manufacturing systems, providing instant visibility into performance and status of every operation. "Click down" interfaces will enable managers to quickly delve into successively deeper levels of detail to aid decision-making, and integrated analytical tools and smart advisory systems will help them head off problems, evaluate options for change, and keep operations running at peak performance.**

4.3 Future State Vision, Goals, & Requirements for Enterprise Modeling & Simulation

The future manufacturing entity will be a totally "connected" enterprise, where all processes are tightly integrated and continuously tuned via automated systems and human decisions for optimum performance. Manufacturing companies will no longer be unwieldy, inefficient "dinosaurs" where change is a years-long process; M&S technology will transform them into lean dynamic, responsive entities that thrive on challenge and change.

Real-time data about all aspects of performance will feed detailed process and global enterprise models that provide managers with total visibility into the health of the enterprise and all of its processes and resources. Powerful, intelligent advisory and decision support systems will provide equipment operators, line and shop supervisors, operations managers, and higher-level executives with real-time awareness of performance and potential effects resulting from changing conditions, and enable them to quickly make the best decisions based on enterprise needs, goals, and objectives. Directives for changes in products, processes, and resources will automatically propagate instructions and requirements to every affected part of the enterprise, enabling the business to respond in near-real time to new and changing requirements.

The centerpiece of this vision is the master enterprise model, a virtual mirror image of the enterprise and all of its component operations and processes (including business systems as well as design, manufacturing, and support systems), which resides in the enterprise dataspace. Users at all level of the organization, from any location, will be able to interact with the model to obtain accurate forecasts of the effects of planned or potential actions – such as introduction of a new or improved manufacturing process, or a new product, or reorganization of a particular operation or business unit, or establishment of a new partnering arrangement to pursue an emerging opportunity. Since the elements of the enterprise model will be linked directly to their real-world counterparts, and kept current through links permeating the enterprise's information network, the simulations will provide a very accurate picture of real-world results. Also, since the simulation model lives entirely in the virtual realm, users will be able to rapidly evaluate many different options to arrive at the best decision in light of costs, risks, associated impacts, and return on investment.

Table 4.3-1 provides a summary-level view of where we are today and where we expect to be in the next 15 years.

4.3.1 Business Functions

4.3.1.1 Strategic Positioning

Vision: ***Deep understanding and accurate prediction of strategic issues***

In the future, manufacturing enterprise leaders will be able to quickly and accurately evaluate and explore opportunities, threats, and options – at the enterprise macro level – to make sound business decisions. They will be able to evaluate options for evolution of existing products and business lines, development of spinoffs, and creation of new products and business lines, and make accurate predictions of the results of their decisions. Fast, intuitive predictive modeling capabilities will enable managers to evaluate health and vitality of the enterprise at specific points in future time based on real-time "as is" data and probable or possible future conditions.

User interfaces to the underlying M&S capability will be easy and transparent (including graphical and verbal natural-language interfaces), and accessible from wherever they happen to be, whenever they need it.

The global enterprise model will be able to identify and respond to changes in critical resources based on accurate, current knowledge of assets, core competencies, capability, and capacity.

The enterprise model will have accurate, current knowledge of market conditions (including technology trends and political and legal considerations), from perspectives of both the customer base and the competitive environment. It will be able to detect trends from early data and provide an analysis of advantages, disadvantages, and implications of contemplated courses of action. It will interface directly with the enterprise's information systems to quickly promulgate decisions and guidance to all enterprise elements once a change is accepted for action.

Goals & Requirements for Strategic Positioning

- **Goal 1: Timely, Accurate M&S Processes for Strategic Positioning** – Provide M&S tools and techniques that enable accurate, timely, informed decisions for manufacturing enterprises based on comprehensive, useful, accurate information.

  – **Strategic Decision Modeling** – Develop mechanisms to model and evaluate the strategic decision-making process in manufacturing organizations.

Table 4.3-1.
State Map for Enterprise Modeling & Simulation Functions

Function	Current State of Practice	Current State of Art	Expected 2005 State (Major Goals)	IMTR 2015 Vision (Major Goals)
BUSINESS FUNCTIONS				
Strategic Positioning (Section 4.3.1.1)	• Little or no modeling & simulation	• Limited use of simple, "homegrown" models	• Strategic decision models • Real-time data links	• Easy, transparent modeling & simulation
Market Assessment & Positioning (Section 4.3.1.2)	• Primarily use of spreadsheets	• Some market share modeling & gaming simulations	• Domain specific models • Links to external & internal information sources	• Extensive market assessment models & tools
Risk Management (Section 4.3.1.3)	• Little or no modeling	• Spreadsheet based models based on individual expertise	• Domain & function specific risk models	• Risk assessment & avoidance models
Financial/Cost Management (Section 4.3.1.4)	• Spreadsheet-based financial modeling	• Deterministic cost models	• Predictive cost modeling	• Integrated cost & profitability models
Resource Management (Section 4.3.1.5)	• Many tools for specific uses • Expensive data collection	• No common standards or integration frameworks	• Enterprise-wide resource models	• Extended enterprise resource models
Quality Management (Section 4.3.1.6)	• Little or no modeling	• Limited "cost of quality" modeling	• Quality impact assessment & trade-off tools	• Quality no longer a discriminator – all excellent
Enterprise Architecture Management (Section 4.3.1.7)	• Little or no modeling	• Structured models (e.g., IDEF & GRAF)	• Generic enterprise architectures, metrics & modeling tools	• Full enterprise architecture models
Extended Enterprise Management (Section 4.3.1.8)	• Little or no modeling	• Supply chain modeling using proprietary or custom systems	• Techniques for modeling functions across the supply chain	• Extended enterprise models • Automated knowledge management techniques
OPERATIONS FUNCTIONS				
Operations Resource Management (Section 4.3.2.1)	• Many tools available for specific functions or resources	• Large, complex, hierarchical models	• Tools & standards for model building & integration	• In-depth resource management models
Performance Management (Section 4.3.2.2)	• Cost & schedule performance models	• Larger custom models	• Accurate data collection techniques for model building	• Self-optimizing simulation models
Factory Operations (Section 4.3.2.3)	• Many domain-specific models	• Expensive & time-consuming systems	• Data collection techniques, standards & frameworks	• Virtual factory models using real-time data
Facility Infrastructure Management (Section 4.3.2.4)	• Domain-specific systems	• Some ERP systems have infrastructure features	• Standard taxonomies & generic infrastructure models	• Integrated physical control & performance models

Note 1: There is a very wide gap between "state of practice" and "state of art" for enterprise M&S capabilities among different industries and companies. A number of the attributes of the "Expected 2005 State" and "IMTR 2015 Vision" are already emerging among leading practitioners; however, from the IMTR perspective these capabilities will not be considered mature until they are in wide use among more than a handful of companies, and meet the test of total plug & play compatibility and robust functionality to serve any industry.

Note 2: The timeframes given for various capabilities reflect application of "reasonable" R&D resources toward their attainment. The timelines for most capabilities shown could be significantly shortened through creation of focused R&D efforts with adequate funding.

  * **Gaming Algorithms for Macro Models** – Conduct research to identify and develop gaming algorithms for exercising macro models of strategic decision processes.
  * **Macro-Level Enterprise Models** – Develop macro-level manufacturing enterprise models and tools to address enterprise-level needs supported by different levels of source information (varying amount and quality of data).
  * **Capability Representation Models** – Develop manufacturing enterprise models to represent capabilities and core competencies at the enterprise and extended enterprise level.
  * **Enterprise Model Library** – Develop a library of manufacturing enterprise models that can be selected and tailored based on a manager's dialogue with the system.

– **Real-Time Model Data Links** – Develop real-time linkages to information sources internal and external to the enterprise. (Additional requirements in this area are discussed in the IMTR *Roadmap for Information Systems*, Section 5.3.2.)

  * **Basic Data Requirements Definition** – Research and develop detailed strategic data requirements to support macro-level modeling and simulation.
  * **Global Data Requirements Definition** – Define global data requirements (including technological, economic, and political information) to feed the enterprise model.
  * **Data Availability Evaluation Tools** – Develop tools to evaluate current state of data availability.
  * **Macro View Processing Tools** – Develop methods and tools for processing data at different levels and developing a unified view of the information at the macro level.

4.3.1.2 Market Assessment & Positioning

Vision: *Real-time awareness and fast, accurate response to market forces*

Future executives and managers will have timely, current, accurate visibility of market research that indicates the enterprise's position relative to its competitors. They will be able to quickly evaluate options for introducing new products, modifying product and product family attributes (price, functions, capabilities, features, etc.), and ending product offerings. They will understand the effects of different courses of action (e.g., trade off smaller market share for higher dollar volume per product, or vice-versa). They will be able to evaluate demographic, social, political, technological, and competitive trends and forecast resulting effects.

Goals & Requirements for Market Assessment & Positioning

• **Goal 1: Timely, Accurate M&S Processes for Market Assessment** – Provide the capability for manufacturers to make accurate, timely, informed market decisions based on comprehensive, useful, accurate information which includes operations, infrastructure, risk, and financial knowledge.

– **Gaming Algorithms for Macro Models** – Research and develop gaming algorithms for exercising manufacturing enterprise macro models.

– **Data Requirements Research** – Conduct research to identify data required for macro-level modeling and simulation functions to support manufacturing enterprises.

– **Opportunity Models** – Develop models to evaluate opportunities to enter or exit manufacturing markets and predict results with high confidence.

– **Qualitative Forecasting Tools** – Develop M&S tools to forecast manufacturing requirements based on more than quantitative factors, and more than just past data. Apply emerging techniques (fuzzy logic, neural nets, etc.) to enable non-quantitative analysis.

- **Goal 2: Rapid Change Response Tools** – Provide M&S tools and techniques enabling enterprises to respond quickly and opportunistically to rapid, unpredicted change.

  – **Discontinuity Event Modeling** – Develop capability to predict the impacts on the enterprise of major "inflection points" and emerging unanticipated changes in technological, economic, or political developments (such as the collapse of the Soviet Union, or the explosion of Internet use).

4.3.1.3 Risk Management

Vision: ***Complete, accurate, real-time visibility of risk issues and mitigation performance***

In the future, managers will have models with sufficient knowledge to detect potential risks, to assess the impact of a given risk, and to make a plan to mitigate or avoid a given risk. Enterprise managers will have clear visibility into potential risks and will be immediately alerted to events that create a potential risk or change the status of a previously identified risk. Project managers and operations managers will be able to quickly perform initial risk assessments for contemplated programs and activities, which take into account all applicable forms of risk (cost, technical, schedule, liability, safety, etc.).

Goals & Requirements for Risk Management

- **Goal 1: Risk Assessment & Analysis Toolset** – Provide and enhance a generic risk modeling and simulation system that supports quantification and analysis of technical, cost, and schedule risks for complex products, processes, and ventures.

  – **Risk Quantification Methodology** – Develop mechanisms and algorithms to represent, measure, monitor, and evaluate risk based on activities and their outcomes – linked to analytical models (e.g., of a product design); must be able to weigh against risk tolerance.

  – **Risk Integration Methodology** – Develop mechanisms and methods to combine the qualitative and quantitative aspects of risk in risk models.

  – **Risk Knowledge Base and Data Linking Methodology** – Develop methods and tools to establish and maintain knowledge bases of risk experience, from across the enterprise, that link into risk M&S tools.

  – **High-Risk Tradeoff Tools** – Develop, validate, and expand risk modeling tools to evaluate trade-offs, approaches, and potential payoffs for high-risk ventures.

4.3.1.4 Financial/Cost Management

Vision: ***Fast, accurate insight into financial issues and opportunities***

Future decision-makers will be able to quickly and accurately predict the financial and cost implications of any contemplated decision. Manufacturing enterprise systems and the models that drive them will accurately reflect cost and profitability, in near real-time.

Goals & Requirements for Financial/Cost Management

- **Goal 1: Enterprise Financial Simulation Environment** – Provide the capability to obtain and evaluate current financial status information and requirements, and to accurately predict effects of contemplated actions or events on capital requirements, funds flow, profitability, ROS/ROI, rates and factors, and other financial parameters.

  – **Integrated Financial Modeling** – Develop techniques to integrate cost and financial models with other models as a seamless part of the global enterprise model.

– **Multilevel Cost Modeling** – Develop methods and tools to model costs at different levels and from different perspectives (e.g., activity-based costing versus general ledger versus total cost of ownership), and integrate cost models extending down to the lowest level of granularity (e.g., down to the component and constituent material level of individual products).

– **Predictive Cost Modeling** – Develop tools and techniques for predictive cost modeling.

– **Financial Engineering Analysis Tools** – Migrate engineering analysis methods and tools to financial operations.

4.3.1.5 Enterprise Resource Management

Vision: *Total visibility, quick response, precise control of all enterprise resources*

In the future, enterprise managers will be able to quickly and accurately predict the effects of potential (planned or possible) change on enterprise resources, and evaluate the effect of changes (e.g., in cost or availability) in a given resource on all aspects of enterprise operation. Richer decision support will be available because enterprise models will address the notion of which capabilities and resources represent critical competencies for the enterprise, and extended enterprise models will include assessment of the capabilities, performance, and other characteristics of partners and suppliers as well as internal assets.

Enterprise resource models will have direct links to real-time status data about all resources available to or needed by the enterprise. Embedded resource advisors will recalculate "on the fly" the impacts of an actual or planned change in resources on all other dependent resources, and provide recommendations for corrective actions before impending resource constraints impact operational throughput.

Goals & Requirements for Enterprise Resource Management

- **Goal 1: Real-Time Resource Modeling System** – Provide enterprise resource models able to deal with multiple constraints and optimize operations to simultaneously meet multiple criteria.

– **Base Resource Models** – Develop a common framework of plug & play resource models that include the capabilities, performance and attributes of all internal and external resources, including partners and suppliers, and which can be adapted and extended by any manufacturing enterprise.

– **Resource Performance Simulation** – Develop capability to assess specific resource performance based on simulations of performance options and models of process.

– **Change Requirements Identification** – Develop enterprise operational resource models able to assess strategic plans, evaluate core competencies and existing/forecasted/planned resources, and identify where (or if) changes are required based on an internal or external change or event.

– **Multiple Constraint Processing** – Develop techniques and algorithms for identifying, capturing, and correlating multiple resource constraints.

– **Multiple-Criteria Resource Optimization** – Develop methods and tool for multiple-criteria resource optimization.

– **Resource Status Monitoring** – Integrate real-time data collection interfaces that enable the master enterprise resource model to interact with hardware and software mechanisms for resource status and usage monitoring (developed as outlined in the IMTR *Roadmap for Manufacturing Processes & Equipment*, Section 2.3.3) to maintain current understanding of resource readiness, availability, and fitness for use.

- **Goal 2: Distributed Resource Management** – Provide M&S tools and techniques to manage resources across all components of the extended enterprise.

  – **Resource Status Modeling & Linkages** – Develop methods, tools, and techniques for modeling extended enterprise and linking to current resource status information from different sites.

  – **Multi-Source Data Integration** – Develop mechanisms to integrate and exploit the usefulness of varying resource information from different sources.

  – **Distributed Resource Integration** – Develop methods and techniques for composing, integrating, and harmonizing multiple resource models across the extended enterprise.

4.3.1.6 Quality Management

Vision: ***100% quality the first time, every time***

Future manufacturers will design high-quality products from inception and precisely control their manufacturing processes to ensure that every product is 100% free of defects. Quality will therefore no longer be a competitive discriminator. Product and process designers and managers will have modeling and simulation tools that enable evaluation and prediction of quality in all aspects of enterprise operation and performance. Extremely precise product models, coupled with extremely precise process models supported by precisely monitored and controlled processes and equipment, will enable elimination of all post-process quality inspection and nonconformance correction needs.

Goals & Requirements for Quality Management

- **Goal 1: Quality Tradeoff Tools** – Provide tools and techniques to quickly trade off cost impacts and effects of contemplated improvements (i.e., cost impact of measures to incrementally improve quality).

  – **Comprehensive Quality Models** – Develop M&S tools to evaluate quality in design, manufacturing, and operations, incorporating applicable parameters of quality standards such as ISO 9001 (and its successors) using "live" quality performance data from all enterprise operations.

  – **Continuum Quality Modeling** – Develop M&S tools to evaluate the impact of individual and multiple events and parameters on total product, process, and enterprise performance.

  – **Early Problem Indication** – Develop methods and tools to quickly detect subtle influences on quality performance and suggest corrective action.

- **Goal 2: Quality Model QA Techniques** – Provide methods and tools to evaluate and assure the quality of enterprise quality models themselves.

4.3.1.7 Enterprise Architecture Management

Vision: ***Seamlessly integrated, multidimensional enterprise model for management and control***

In the future, enterprise managers will have an enterprise architecture model that provides clear, immediate visibility into any and all aspects of the enterprise – organizational, skills, core competencies, financial data, facilities, operations, databases, networks, supplier/partner relationships and capabilities, and other physical and information assets. The manager can browse conveniently through any aspect of the enterprise, drilling down for more information (current or historical enterprise data as well as forecasts) when needed to make decisions.

The model and simulations will work because the architecture guides how different component models are integrated and unified within the context of the overall enterprise structure. Based on the architecture, vendors of equipment, software and other components will see how their product fits into the overall manufacturing enterprise. There will be libraries of architectural components for different activities carried on in various manufacturing sectors. For any given enterprise, selecting the components that best fit the enterprise strategy and business plan can assemble a complete simulation capability.

The business rules captured in the model define how the enterprise does business. Managers will use the living enterprise model, with direct linkage to current data on enterprise structures, systems, and assets, to evaluate configuration options to respond to growth, consolidation, and other types of change. For some enterprises, the simulation may actually be used to control enterprise operations.

Goals & Requirements for Enterprise Architecture Management

- **Goal 1: Extendible Enterprise Model & Reference Architecture** – Provide a generic, extendible reference architecture for manufacturing enterprises, enabling managers to use a visually presented model to represent all aspects of their operations and assist in making decision. The enterprise model must depict the interrelationships of all relevant functions and knowledge bases within the enterprise.

  - **Architecture Evaluation Tools** – Develop metrics and tools for evaluating and testing candidate architecture designs.
  - **Architecture Adaptation** – Develop a methodology to tailor generic architecture to a specific enterprise.
  - **Software Implementation Tools** – Develop methods and tools for designing and implementing software systems based on the reference model architecture.

4.3.1.8 Extended Enterprise Management

Vision: ***Seamless, flexible enterprises, utterly transparent to geography and complexity***

In the future, enterprise managers will be able to look anywhere in the supply chain to instantly obtain real-time information (such as capacities or capabilities) at the desired level of detail. Modeling and simulation tools will enable rapid tradeoffs to support partnering decisions and drive the mechanisms for establishing concurrence and initiating work. Potential partners will share information freely, trusting multilevel information filtering and access mechanisms to protect proprietary information appropriately.

Goals & Requirements for Extended Enterprise Management[13]

- **Goal 1: Extended Enterprise Management System** – Provide an extended enterprise management system that enables enterprise managers to establish and manage complex supply chains.

  - **Enterprise Multi-Model Integration** – Develop a methodology to integrate multiple types of enterprise models within the framework of the extended enterprise architecture. Extended enterprise operations and interactions will be modeled and used to guide production planning and other business decisions.

[13] Additional goals and requirements for enterprise management are addressed in the IMTR *Roadmap for Information Systems*, Section 4.3.6, and in the IMTR Roadmap for *Technologies for Enterprise Integration*.

– **Extended Enterprise Modeling Tools** – Develop methods and tools for modeling extended enterprises, including evaluation of supplier and partner contributions, values, and capabilities to support teaming decisions.

– **Risk/Reward Models** – Develop models to enable modeling and equitable sharing of risks and rewards in proportion to contribution of enterprise participants to the extended enterprise operation.

– **Resource Model Integration Tools** – Develop methods, tools, and techniques for composing, integrating, and harmonizing multiple resource models across the extended enterprise.

– **Plug & Play Enterprise Process Model Library** – Develop a library of plug & play manufacturing and business process models supporting seamless extended enterprise operations.

4.3.2 OPERATIONS FUNCTIONS

4.3.2.1 Operations Resource Management

Vision: ***Full visibility, accurate prediction, real-time control of distributed operations***

In the future, operations managers and operational personnel will optimally meet their business objectives using model-based control systems that enable real-time, in-depth (and appropriately filtered) access to all factory status, performance, and capability information. The factory model will be a real-time representation of the factory, and will be used to directly control operation of the factory. Model-based control systems now in place for individual processes will evolve to provide finer control and become-plug-compatible to support integrated, hierarchical control systems for integrated process suites.

Managers will be able to quickly identify and assess performance issues (e.g., bottlenecks) and trade off resources (equipment, material, personnel) to optimize operations – both in the current state and predict with confidence the impacts of planned or potential changes to support flexible, adaptive, reconfigurable operations to meet dynamic business requirements.

Simulation- and model-based training (including immersive virtual reality) and qualification will be pervasive, applied to all skills development. The equipment models and operational simulations will be used not only for process and decision support, but also intended for training to enable workers to perform required tasks to standards.

Environmental stewardship and economic issues may become more compatible in the future with better modes of information sharing on resources. The enterprise view of resources will broaden to encompass knowledge of other nearby enterprises and their byproducts and waste materials, to allow potential reuse of these materials in the manufacturing processes. Similarly, the enterprise will make available its byproducts and waste to any other enterprises which may make effective use of them.

Goals & Requirements for Operations Resource Management

- **Goal 1: Real-Time Factory Model** – Provide factory models to provide real-time representations that also runs large portions of factory operations and is able to deal with multiple constraints and optimize operations to simultaneously meet multiple criteria.

– **Multiple Constraint Integration** – Develop techniques and algorithms for identifying, capturing and correlating multiple constraints.

– **Multi-Resource Optimization** – Develop methods and tools for multiple-criteria resource optimization.

- **Goal 2: Distributed Resource Management Tools** – Provide M&S tools and techniques to manage resources across all factory components of the extended enterprise – including partners', suppliers', and sub-tier suppliers' shops.

  – **Extended Factory Modeling** – Develop methods, tools, and techniques for modeling extended factory and linking to current resource status information from different sites.

  – **Extended Factory Integration & Optimization** – Develop methods, tools, and techniques for composing, integrating, and harmonizing multiple resource models across the extended enterprise.

- **Goal 3: Enterprise Knowledge/Skills Management** – Provide M&S tools and techniques to enable a growing store of corporate knowledge plus an integrated training and certification environment that transforms manpower assets into capable, qualified skill/knowledge workers.

  – **Model-Driven Training Systems** – Develop model-driven training systems that automatically capture shop-floor data and update models used for training. This includes model-driven training systems that draw directly from live enterprise data, and self-learning training simulators embedded on process equipment to support on-the-job training and continuous learning.

  – **Embedded Process & Equipment Simulators** – Develop training simulators that are embedded into process and equipment control systems. These simulators are updated automatically with actual operating data collected from the processes and equipment.

4.3.2.2 Performance Management

Vision: ***Real-time visibility and control of all aspects of enterprise performance***

Future operations managers will able to monitor, in real or near-real time, any time and from anywhere, all defined aspects of enterprise factory operational performance at any desired level of detail, and to evaluate the impact of performance variations or changes and potential corrective actions, against business objectives. The simulations will learn and adapt based on previous experience to produce improved behavior of the manufacturing enterprise system. Furthermore, the simulations will be "mixed initiative" systems, allowing human insights and decisions to be mixed with automatically produced system inferences to guide future operations to produce desired results.

Goals & Requirements for Performance Management

- **Goal 1: Performance Optimization Systems** – Provide models and simulations able to generate optimal performance profiles, define corrective actions (from knowledge base or input by user) to meet the profiles, and promulgate corrective action directions back into the system.

  – **Performance Data Integration & Assessment** – Develop tools and techniques to provide access to accurate, current performance data on all aspects of enterprise operations. Develop generic metrics for enterprise performance measurement, and integrate into modeling and simulation tools. (reference that IS provides the data; expand from MS perspective (application)

  – **Continuous Improvement Techniques** – Develop M&S tool and techniques that provide ability to explore alternatives for improvement and corrective action.

- **Goal 2: Adaptive Performance Management System** – Provide the capability for model-based performance management systems to adapt, to improve performance over time, and to evolve to accommodate new parameters.

  – **Self-Assessment & Learning Tools** – Develop mechanisms enabling system to learn based on self-assessment of performance (recognize recurring occurrences).

  – **Automated Reconfiguration Capability** – Develop mechanisms for system reconfiguration based on human input.

4.3.2.3 Factory Operations

Vision: *Real-time control for continuous optimization and instantaneous response*

In the future, factories will be run by control models, integrated within a complete virtual factory above the shop floor, fed by real-time, accurate information from shop-floor processes and implemented by sensors and intelligent, proactive controllers. All routine manufacturing operations will be automated, plus the models will be adaptive to modify operations in response to engineering changes. In addition, the control models will be monitoring the status of various resources, factoring in shop-floor economic considerations, and predicting or planning needed maintenance operations. In many factories, human intervention will be required only to handle unplanned events.

For geographically distributed "virtual factories," decisions on manufacturing operations will be based on best use of needed resources, wherever they are.

Goals & Requirements for Factory Operations[14]

- **Goal 1: Total Factory Control Model** – Building on the factory control model developed in Section 4.3.2.1, provide models for total factory control driven by full, complete, accurate, real-time process status and performance data.

  – **Component Operations Models** – Develop framework and tools for component-based modeling and simulation for factory operations at the machine, work cell, and line levels.

  – **Multi-View Factory Vision** – Integrate capability to view the factory at macro level with ability to zoom down to any level of detail.

- **Goal 2: Integrated Factory Monitoring & Control** – Provide methods and tools for integrating factory monitoring and control models and interfacing with enterprise management systems to enable reactive and proactive problem-solving.

  – **Integrated Manufacturing Change Management** – Develop model-based methods and tools for managing engineering changes in a fully automated manufacturing system.

  – **Data Fusion Tools** – Develop mechanisms to fuse and mine varying information from different sources (see the IMTR *Roadmap for Information Systems*, Sections 3.3.1 and 5.3.2).

  – **Predictive Maintenance Response Systems** – Develop intelligent mechanisms to use sensor information plus knowledge of shop-floor economics to monitor status and predict and plan needed maintenance operations.

[14] Additional goals and requirements for factory operations are addressed in the IMTR *Roadmap for Manufacturing Processes & Equipment*, Section 2.3.

4.3.2.4 Facility Infrastructure Management

Vision: ***Deep knowledge and responsive control of extended enterprise infrastructure***

In the future, the control models that run the factory will extend their scope and effectiveness by having total knowledge and control of the extended facility infrastructure, such as the physical plant, utilities, and telecommunications and computer networks, irrespective of geographic separation. These control models will be integrated in a complete virtual factory, fed by real-time, accurate information from all operations and support facilities and implemented by sensors and intelligent, proactive controllers. Given knowledge of the production schedule and the status of the operational facilities, the system will be able to plan maintenance and upgrade operations to minimize impact on production. Human intervention will be required only to handle required maintenance, physical upgrades and modifications, and to launch/run simulations to optimize exception situations which cannot be handled automatically.

The system will provide accurate, current information on available vs. used infrastructure capacity (e.g., space, utilities, common infrastructure and other resources) and enable evaluation of options to support new or modified operations at the individual factory level or the extended (distributed) enterprise factory level. In the case of globally distributed enterprises, the control models will incorporate knowledge of relevant cultural or economic differences which affect resources and how they can be used.

Goals & Requirements for Facility Infrastructure Management

- **Goal 1: Integrated, Distributed Factory Infrastructure Model** – Provide and enhance generic factory control models that provide robust capabilities to model and simulate operations of complex physical plants and associated infrastructure.

  – **Infrastructure Model Representation** – Develop representation mechanisms, tailorable generic models, and techniques and tools to fully, accurately model physical plant and associated infrastructure.

  – **Infrastructure Model Library** – Develop libraries of generic, knowledge-based, plug & play modules for modeling different factory infrastructure components.

  – **Live Factory Models** – Develop capability to dynamically update factory models directly from current operational status information.

  – **Facility Integration Models** – Develop methodologies and tools to integrate facility infrastructure models with operations models manufacturing process models, and enterprise models.

4.4 Roadmap for Enterprise Modeling & Simulation

Using the goals outlined in Section 4.3 above, the workshop team mapped the associated requirements and R&D areas over near-, mid-, and long-term timeframes as presented on the following pages. The attached roadmap represents a "first cut" at defining a research, development, and implementation plan, and additional work is required to develop detailed task plans as well as to align dependencies among the various activities.

4.3 ENTERPRISE FUNCTIONS	0 to 3 Years	3 to 10 Years	10+ Years

4.3.1 BUSINESS FUNCTIONS

4.3.1.1 STRATEGIC POSITIONING

4.3.1.1 Goal 1: Timely, Accurate M&S Processes for Strategic Positioning

- **1.1 Strategic Decision Modeling**
  - *1.1.1 Gaming Algorithms for Macro Models*
  - *1.1.2 Macro-Level Enterprise Models*
  - *1.1.3 Capability Representation Models*
  - *1.1.4 Enterprise Model Library*
- **1.2 Real-Time Model Data Links**
  - *1.2.1 Basic Data Requirements Definition*
  - *1.2.2 Global Data Requirements Definition*
  - *1.2.3 Data Availability Evaluation Tools*
  - *1.2.4 Macro View Processing Tools*

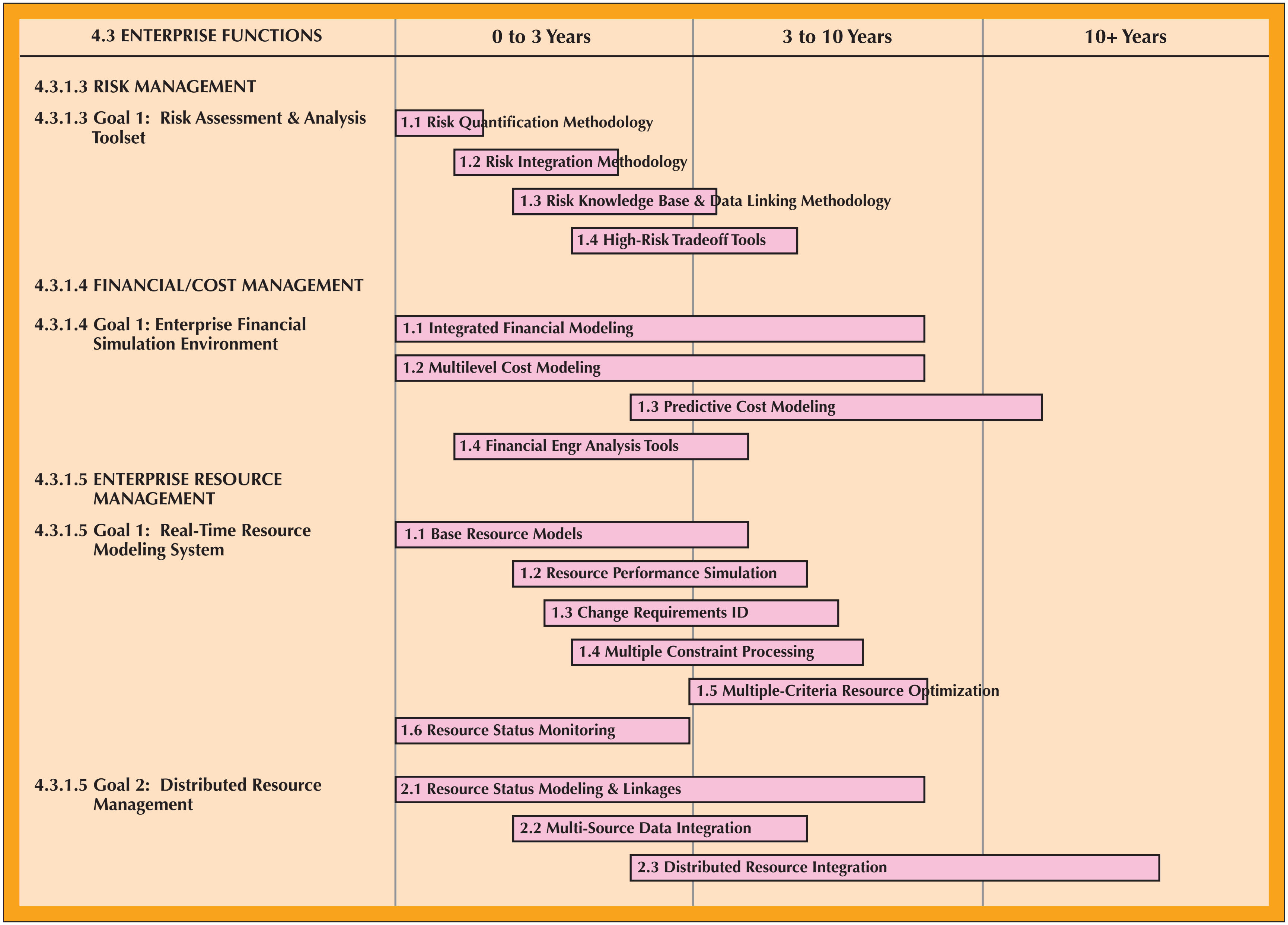
4.3.1.2 MARKET ASSESSMENT & POSITIONING

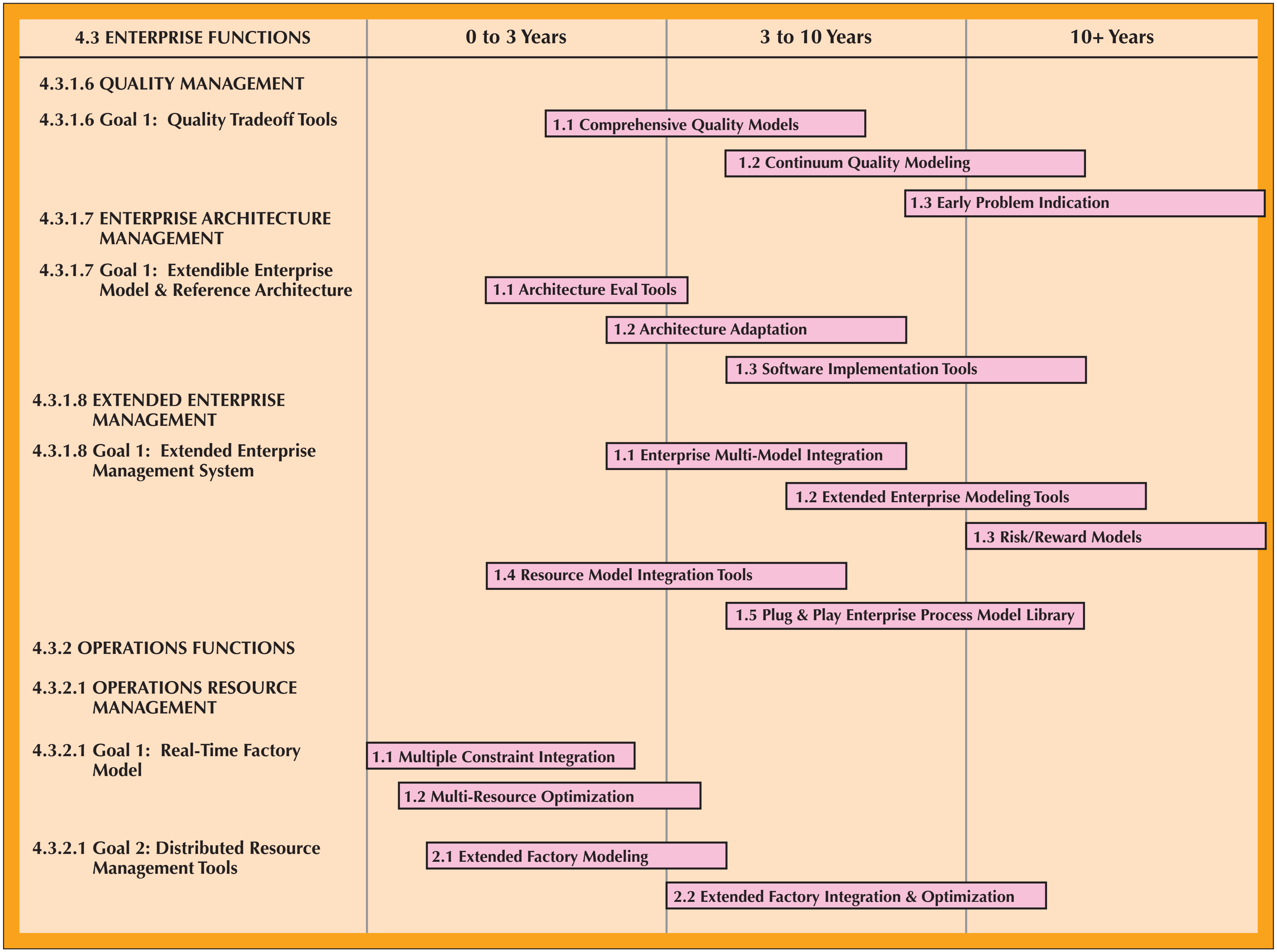
4.3.1.2 Goal 1: Timely, Accurate M&S Processes for Market Assessment

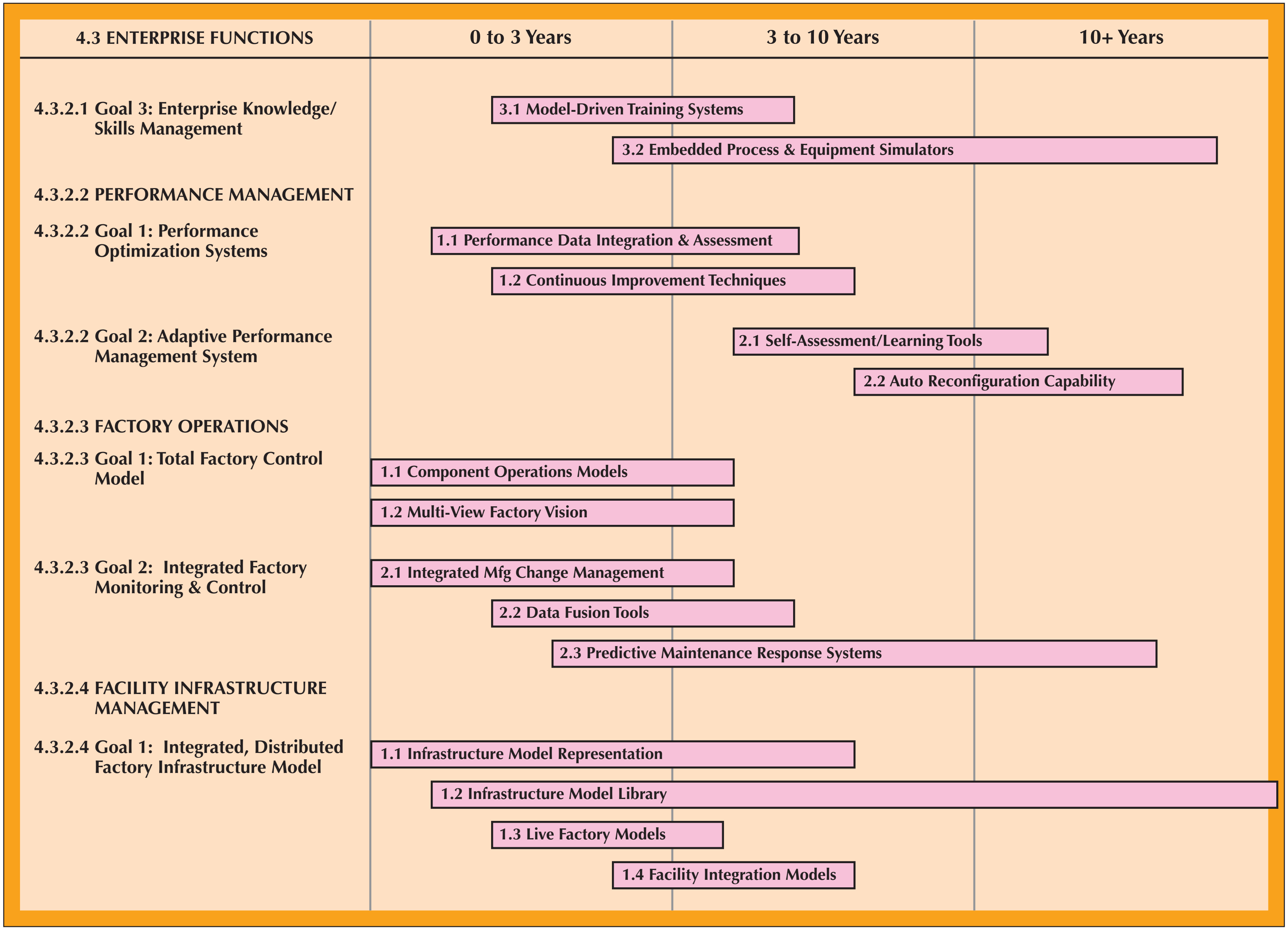
- **1.1 Gaming Algorithms for Macro Models**
- **1.2 Data Requirements Research**
- **1.3 Opportunity Models**
- **1.4 Qualitative Forecasting Tools**

4.3.1.2 Goal 2: Rapid Change Response Tools

- **1.1 Discontinuity Event Modeling**


4.3 ENTERPRISE FUNCTIONS
0 to 3 Years
3 to 10 Years
10+ Years
4.3.1.3 RISK MANAGEMENT
4.3.1.3 Goal 1: Risk Assessment & Analysis Toolset
1.1 Risk Quantification Methodology
1.2 Risk Integration Methodology
1.3 Risk Knowledge Base & Data Linking Methodology
1.4 High-Risk Tradeoff Tools
4.3.1.4 FINANCIAL/COST MANAGEMENT
4.3.1.4 Goal 1: Enterprise Financial Simulation Environment
1.1 Integrated Financial Modeling
1.2 Multilevel Cost Modeling
1.3 Predictive Cost Modeling
1.4 Financial Engr Analysis Tools
4.3.1.5 ENTERPRISE RESOURCE MANAGEMENT
4.3.1.5 Goal 1: Real-Time Resource Modeling System
1.1 Base Resource Models
1.2 Resource Performance Simulation
1.3 Change Requirements ID
1.4 Multiple Constraint Processing
1.5 Multiple-Criteria Resource Optimization
1.6 Resource Status Monitoring
4.3.1.5 Goal 2: Distributed Resource Management
2.1 Resource Status Modeling & Linkages
2.2 Multi-Source Data Integration
2.3 Distributed Resource Integration


4.3 ENTERPRISE FUNCTIONS
0 to 3 Years
3 to 10 Years
10+ Years
4.3.1.6 QUALITY MANAGEMENT
4.3.1.6 Goal 1: Quality Tradeoff Tools
1.1 Comprehensive Quality Models
1.2 Continuum Quality Modeling
1.3 Early Problem Indication
4.3.1.7 ENTERPRISE ARCHITECTURE MANAGEMENT
4.3.1.7 Goal 1: Extendible Enterprise Model & Reference Architecture
1.1 Architecture Eval Tools
1.2 Architecture Adaptation
1.3 Software Implementation Tools
4.3.1.8 EXTENDED ENTERPRISE MANAGEMENT
4.3.1.8 Goal 1: Extended Enterprise Management System
1.1 Enterprise Multi-Model Integration
1.2 Extended Enterprise Modeling Tools
1.3 Risk/Reward Models
1.4 Resource Model Integration Tools
1.5 Plug & Play Enterprise Process Model Library
4.3.2 OPERATIONS FUNCTIONS
4.3.2.1 OPERATIONS RESOURCE MANAGEMENT
4.3.2.1 Goal 1: Real-Time Factory Model
1.1 Multiple Constraint Integration
1.2 Multi-Resource Optimization
4.3.2.1 Goal 2: Distributed Resource Management Tools
2.1 Extended Factory Modeling
2.2 Extended Factory Integration & Optimization


4.3 ENTERPRISE FUNCTIONS
0 to 3 Years
3 to 10 Years
10+ Years
4.3.2.1 Goal 3: Enterprise Knowledge/ Skills Management
3.1 Model-Driven Training Systems
3.2 Embedded Process & Equipment Simulators
4.3.2.2 PERFORMANCE MANAGEMENT
4.3.2.2 Goal 1: Performance Optimization Systems
1.1 Performance Data Integration & Assessment
1.2 Continuous Improvement Techniques
4.3.2.2 Goal 2: Adaptive Performance Management System
2.1 Self-Assessment/Learning Tools
2.2 Auto Reconfiguration Capability
4.3.2.3 FACTORY OPERATIONS
4.3.2.3 Goal 1: Total Factory Control Model
1.1 Component Operations Models
1.2 Multi-View Factory Vision
4.3.2.3 Goal 2: Integrated Factory Monitoring & Control
2.1 Integrated Mfg Change Management
2.2 Data Fusion Tools
2.3 Predictive Maintenance Response Systems
4.3.2.4 FACILITY INFRASTRUCTURE MANAGEMENT
4.3.2.4 Goal 1: Integrated, Distributed Factory Infrastructure Model
1.1 Infrastructure Model Representation
1.2 Infrastructure Model Library
1.3 Live Factory Models
1.4 Facility Integration Models

APPENDIX A
NGM: An Industry-Driven Collaboration

The NGM project, completed in 1997, was a groundbreaking effort to examine long-term trends in U.S. manufacturing in light of unprecedented changes taking place in the global business environment, and to identify actions required to respond to these new challenges. More than 500 technologists and business leaders from industry, government, and academia participated in the project.

Key global drivers identified by NGM that will shape the competitive environment in the 21st century include:

- Ubiquitous availability and distribution of information
- Accelerating pace of change in technology
- Rapidly expanding technology access
- Globalization of markets and business competition
- Global wage and job skills shifts
- Environmental responsibility & resource limitations
- Increasing customer expectations.

In response to these drivers, the NGM project identified six attributes that will characterize successful manufacturing enterprises in the future, as well as a number of barriers that must be resolved to attain these attributes. These in turn led the NGM project to identify 10 interrelated "imperatives" (i.e., enabling business practices and related technologies) that will be needed to overcome the barriers and achieve the successful enterprise attributes.

One of the major recommendations from the NGM project was the need to establish technology roadmaps to guide development of the necessary technical and "cultural" solutions. The IMTR initiative represents a follow-on activity aimed at implementing this critical recommendation for the technology-related imperatives.

NGM Attributes & Imperatives:
Keys to Success for Next-Generation Manufacturers

	Success Attributes: Customer Responsiveness	Physical Plant & Equipment Responsiveness	Human Resource Responsiveness	Global Market Responsiveness	Teaming as a Core Competency	Responsive Practices & Culture
Technology-Related Imperatives						
Advanced Processes & Equipment	M	H	M	M	M	M
Pervasive Modeling & Simulation		H				
Adaptive, Responsive Information Systems	H	M	L	H	M	L
Enterprise Integration	H		M	H		M
Other Imperatives	H	M		H	M	
Workforce Flexibility			H			H
Knowledge Supply Chain	H			H	H	
Rapid Product/Process Development	L	H	H	L		H
Innovation Management	H	L	H	H	H	M
Change Management	H	M	H	H	H	
Extended Enterprise Collaboration	H		H	H	H	M

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APPENDIX B
The IMTR Roadmapping Process

The IMTR team has applied a structured methodology (Figure A-1) to develop technology roadmaps that identify the "Grand Challenges" and define specific goals and requirements to meet the defined needs of the national manufacturing infrastructure. The first step was to conduct a broad-based survey (see Appendix C) of the national manufacturing community for each technology area. This provided input for the IMTR participants to start mapping near- and long-term needs, and at identifying solution approaches to meet those needs. The IMTR team then conducted a focused workshop for each technology area to define time-based goals, requirements, and tasks for R&D to address the high-priority, cross-cutting needs of the nation's manufacturers and manufacturing infrastructure.

Based on the survey and workshop results, the roadmap documents were developed and distributed to a broad cross section of the manufacturing community for review. All of the roadmaps are maintained on the IMTR Internet website (http://www.IMTI21.org) and will be updated as progress is made against the plan.

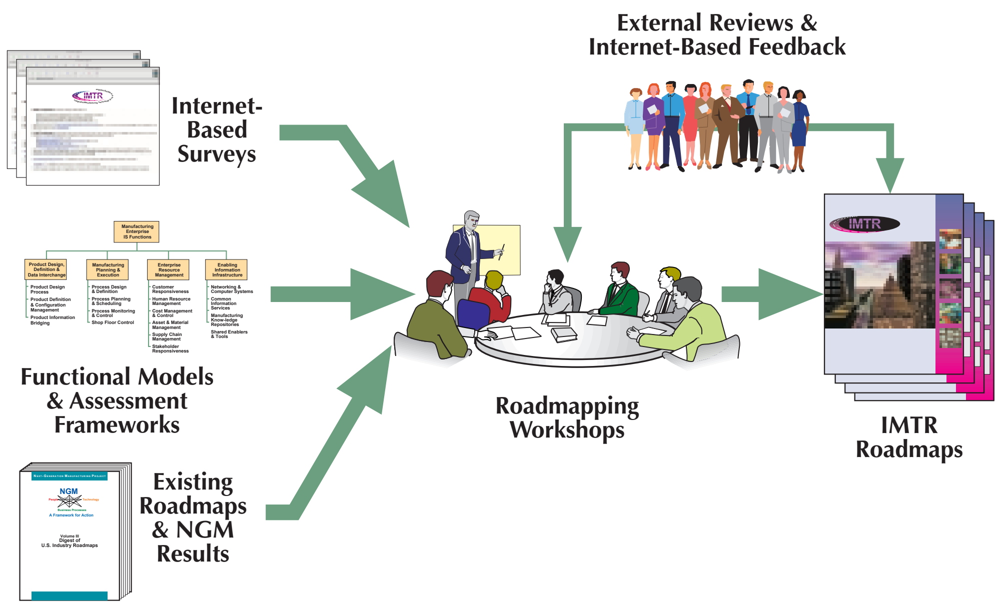

Figure A-1. The IMTR roadmapping process provides a structured methodology for identifying needs, developing plans to fulfill those requirements, & measuring progress toward the future state.

APPENDIX C
Highlights of IMTR Modeling & Simulation Survey Findings

The IMTR Modeling & Simulation questionnaire was constructed around a functional model very similar to that defined above to gather data from a wide distribution. The responses to the survey were then used to refine the functional model for use at the M&S workshop at the National Center for Manufacturing Sciences (NCMS) facility in Ann Arbor, MI. The questionnaire comprised three parts:

- Assessment of the validity and completeness of the functional model.
- Assessment of the adequacy of current technologies and identification of needs for the future.
- Suggestions on technologies and innovations that offer the potential to add significantly to current capabilities.

General Observations – The questionnaire drew fewer responses than expected (about 30) based on the team's experience with the Information Systems (IS) survey, which drew more than 80 responses. This is attributed to the fact that the M&S community is much smaller than the IS community, by several orders of magnitude. Despite the low number of responses, the quality of the input was judged very useful and served as good input by the participants in the M&S workshop in Ann Arbor.

Comments on Functional Model – The model of M&S functions of the manufacturing enterprise was expanded based on several respondents' suggestions to include some non-traditional processes. Several suggestions related to addition of various planning support functions. The lack of technology management in the baseline model also concerned some participants.

Product M&S – A large fraction of the responses described the need to develop modeling systems using sets of features whose structures are sufficiently rich to incorporate material, manufacturing (including producibility indices), and cost (predicted and experienced) information as well as geometric information. These feature definitions should also have seamless interfaces to modeling tools that generate performance information based on first principles and are correlated with real test information. Life-cycle considerations also dictate the inclusion of environmental concerns and reuse/recycle opportunities in product design.

Process M&S – Physical process models drawing from comprehensive materials databases are needed for a wide range of processes. These models must be yield accurate predictions of surfaces generated, both geometry and surface finish, and the resulting property information. The influence of tolerance stackup on assembled product performance is needed. Support tools are needed for designing workholding fixtures and material handling equipment.

Enterprise M&S – Business models are needed that acquire and interpret customer input. Cost and affordability decisions must be correlated with predicted and documented performance data. A better employment and deployment of resources – both human and other – within and across plant and company boundaries is required, including maintenance and material movement and storage functions.

APPENDIX D
Glossary

Agility – For a company, Agility is the ability to thrive and prosper in a competitive environment of continuous and unanticipated change, and to respond to rapidly changing markets driven by customer-based valuing of products and services.

Application Program Interface (API) – The interface (calling conventions) by which an application program accesses operating system and other services. An API provides a level of abstraction between applications and ensures portability of applications from different sources.

Architecture – A model of the arrangement and connectivity of the physical or conceptual components of a system.

CMM (Coordinate Measuring Machine) – A machine for automatically measuring the surface position and features of 3D parts using a touch probe or non-contact sensor.

Common Object Request Broker Architecture (CORBA) – An Object Management Group specification which provides the standard interface definition between OMG-compliant objects.

Computer Aided Design (CAD) – The use of computers in interactive engineering drawing and storage of designs. Programs complete the layout geometric transformations, projections, rotations, magnifications, and interval (cross-section) views of a part and its relationship with other parts.

Computer Aided Manufacturing (CAM) – The use of computers to program, direct, and control production equipment in the fabrication of manufactured items.

Concurrent Engineering – The process of developing products with all enterprise disciplines interacting continuously from the start of the design effort, in a manner that reduces the time and downstream changes associated with the traditional practice of first designing the product and then designing its manufacturing execution processes.

Consortium For Advanced Manufacturing International (CAM-I) – An international, not-for-profit consortium founded in 1972. Membership includes over 50 Fortune 200 companies who are recognized leaders in manufacturing. The CAM-I charter includes conducting pre-competitive, industrially based, industrial-driven applied research and development of advanced manufacturing and management systems, enabling technologies, and standards.

Core Competencies – The basic technologies, skills, and knowledge possessed and required by a company to excel in its business. A manufacturer of small power transformers may have core competencies such as transformer design, computer-aided design and manufacturing, and electrical insulation technology.

DARPA – Defense Advanced Research Projects Agency.

Distributed Enterprise – An organization that has operations in more than one geographic location.

DOD – Department of Defense.

DOE – Department of Energy.

Enterprise Architecture – The body of knowledge for designing, building, operating and modeling enterprises. The architecture contains guidelines and rules for the representation of the enterprise framework, systems, organization, resources, products and processes. (ISO TC184).

Enterprise Modeling – The generation of models of an enterprise or part of an enterprise (e.g., process models, data models, resource models).

Enterprise Resource Planning (ERP) – An ERP system is: 1) An accounting-oriented information system for identifying and planning enterprise-wide resources needed to take, make, ship, and account for customer orders. An ERP system differs from the typical MRP II system in technical requirements such as graphical user interface, relational database, use of fourth-generation language, and computer-assisted software engineering tools in development, client-server architecture, and open-system portability. 2) More generally, a method for the effective planning and control of all resources needed to make, take, ship, and account for customer orders in a manufacturing, distribution, or service company.

Expert Systems, or Knowledge-Based Systems – Interactive computer programs that help users with problems that would otherwise require the assistance of human experts. Expert systems capture knowledge in rules that can be communicated to others as advice or solutions. Programs that present the computer as an expert on some topic. The programs often simulate the reasoning process used by human experts in certain well-defined fields.

Extended Enterprise – A group of companies that work together as a team and act as a single business entity to satisfy a particular set of customer needs. Generally includes the prime manufacturer and all suppliers and vendors who contribute to creation, delivery, and support of the product to the customer.

Extranet – Linked intranets from a variety of enterprises that have agreed to share information and some business processes.

Framework – A basic structure, a frame of reference, or a systematic set of relationships. A framework does not include the art, science, style, and methodology required to develop the system, only the scope of the system and the arrangement of the components are considered.

Genetic Algorithm – A method for representing knowledge in decision support tools, based on the analogy of DNA and Darwinian "natural selection." In simple terms, a decision process involves "chains" of options from a limited set (as in the four basic compounds of DNA) and can decompose complex decisions into strings of selection of best options.

Integrated Product Realization (IPR) – A concept of totally interconnected and interrelated processes for creating product, from generation of the initial product concept and definition of its requirements, to optimization of the design of the product and its manufacturing processes, and to eventual creation of the product itself.

Integrated Product/Process Development (IPPD) – The discipline of developing products and the processes used for their manufacture in parallel, so as to reduce the time and cost of moving products from concept to production. Commonly accepted as the next step beyond the practices of concurrent engineering.

Intelligent Control Systems – Advanced control techniques that use artificial intelligence, knowledge-based, and other nonconventional approaches to control systems to autonomously achieve a specific goal.

Internet – An openly accessible network of computing systems, servers, and interconnecting communications equipment that operate using standard interfaces and protocols.

Interoperability – The ability of two or more systems, subsystems, products, or applications to work together and/or share information or inputs and outputs.

Intranet – An internal network of information systems and supporting services using Internet protocols and a common user interface such as a web browser.

Lean Manufacturing – A set of practices intended to remove all waste from a manufacturing system, especially by reducing the cost of non-value-added activities. "Lean" encompasses concepts such as just-in-time, Kaizen, Kanban, empowered teams, cycle time reduction, small lot manufacturing, and flexible manufacturing.

Life Cycle – The collective set of phases a product or system may go through during its lifetime (e.g., concept definition, development, production, operation and support, decommissioning, and disposal).

Manufacturing Execution System (MES) – A factory floor information and communication system with several functional capabilities. It includes functions such as resource allocation and status, operation/detailed scheduling, dispatching production units, document control, data collection and acquisition, labor management, quality management, process management, maintenance management, product tracking and genealogy, and performance analysis. It can provide feedback from the factory floor on a real-time basis. It interfaces with and complements accounting-oriented, resource planning systems.

Mass Customization – The manufacture of large volumes of products that are tailored to meet the specific preferences or requirements of individual customers.

Metamodel – A model in which many detail-level or micro models of different types can be quickly and easily composed to create macro models that reflect the attributes and behaviors of the whole system as well as those of the constituent parts. As an example, detailed models of the individual processes and equipment that comprise a factory can be composed to create a macro factory model. Tuning of the factory model automatically propagates appropriate changes in individual micro models, thus keeping every process in continuous tune with every other process.

Methodology – A set of instructions, rules, and/or guidelines that defines the process of achieving a specific task.

Model – A mathematical representation of an object (a part, a product, a machine, a facility, an organization, etc.) or a process (e.g., a specific manufacturing process or a business process). A mathematical model characterizes the behavior of its subject through the form of the equation(s) chosen, the variables and parameters present, and the ranges or values of those terms for which the model is considered valid.

Modular Design – A design approach or philosophy that emphasizes the use of standard modules or components to assemble equipment, products or systems.

Natural Language – Ordinary human language; unlike precisely defined computer languages, it is often ambiguous and is thus interpreted differently by different hearers.

Neural Net – A method for analyzing large amounts of data to create "convergence" (define common trends and reach conclusions) faster than conventional methods. The methodology is based on the biological model of the neurons of the human brain.

Next Generation Manufacturing (NGM) – A 1996-97 program to develop a broadly accepted, industry-driven model for a next generation manufacturing enterprise and action plans that individual companies can use to help plan, achieve, and sustain world-class manufacturing. NGM was funded by the National Science Foundation, Department of Defense, Department of Energy, National Institute of Science and Technology, and several industry sponsors and participants.

NIST – National Institute of Standards and Technology.

NSF – National Science Foundation.

Open Architecture – Information and control system structures that are well documented and non-proprietary.

Open Systems – Systems that are designed to interconnect using defined standard interfaces with a variety of products that are commonly available, thus allowing a large degree of vendor independence as to product form, fit, and function.

Process Model – The defined description and/or representation of a process.

Product Data Management (PDM) – The process of, or a system for, managing all information about a product as it moves through the engineering and manufacturing life-cycle. Generally includes function such as management of engineering drawings, processing of change notices, and configuration control.

Product Data Model – The description of data about a product (e.g., a STEP standard).

Product Model – Information about a product captured in a standard representation format (e.g., a CAD file).

Simulation – A process for exercising mathematical models through simulated time wherein one or more models can be run with varying values of input parameters to evaluate the effects of interaction among variables.

Standard – An established norm or specification against which measurements of compliance may be made.

STandard for Exchange of Product model data (STEP) – A neutral mechanism for describing product data throughout the life cycle of a product independent from any particular system (ISO 10303).

Supply Chain – A manufacturing enterprise and the tiers of subcontractors and suppliers who provide materials, parts, components, subsystems, assemblies/subassemblies, services, expertise, or other assets that enable the enterprise to create, deliver, and support its products and services.

Technologies Enabling Agile Manufacturing (TEAM) – A joint industry/government program to develop, integrate, demonstrate, and validate manufacturing technologies that support the vision of manufacturing as a seamless, tightly integrated process from concept to delivery.

Theory of Constraints – A theory that states that every system has at least one constraint limiting its output. Therefore, by addressing the major limiting constraints of a system (e.g., cycle time), the system can be improved to realize the greatest benefit with the least investment of time and resources.

Virtual Enterprise – A temporary alliance of companies, linked primarily by information technology, that join together to take advantage of a market opportunity.

Workflow – The sequencing (and often, automation) of business processes into structured movement of tasks, documents, and data among people performing different functions or responsibilities.

We gratefully acknowledge the sources of some definitions used above:

CAM-I, *Strategic Supply Chain Management*; Dictionary of Relevant Terms

APICS Dictionary, Ninth Edition

Compendium of Agility Terms created by the Agility Forum, supported by the National Science Foundation under Cooperative Agreement No. DMI-9696175

Next-Generation Manufacturing Project Report on "Enterprise Integration"; Glossary

APPENDIX E
Bibliography & Suggested Reading

Web Links of Interest

Scientific & Engineering Software, Inc.'s Links page:

http://www.ses.com/Reference/links.html

Simulation Optimization and Sensitivity Analysis Resources:

http://ubmail.ubalt.edu/~harsham/ref/RefSim.htm

General References

1. *AIT IT Reference Model*, Reference AIT-IP/WP5/d511v03.doc, AIT Integration Platform (AIT-IP), Advanced Information Technology in Design and Manufacturing, KESPRIT Project 22148, May 1997.
2. *CCE, an Integration Platform for Distributed Manufacturing Applications*. Survey for Advanced Computing Technologies, ESPRIT Consortium CCE-CNMA, eds. Berlin; New York: Springer, 1995.
3. *Data Management in the Manufacturing Enterprise*, the Yankee Group, Manufacturing Automation Planning Service. Boston, MA, 1990.
4. *Enterprise Information Exchange: a Roadmap for Electronic Data Interchange for the Manufacturing Company*, V.O. Muglia, ed. Dearborn, MI.: CASA/SME Reference Publications Division, 1993.
5. *IMPPACT Reference Model: an Approach to Integrated Product and Process Modeling for Discrete Parts Manufacturing*, W.F. Gielingh, A.K. Suhm, eds., with contributions by Michael Bohms et al. Berlin ; New York: Springer-Verlag, 1993.
6. *Information and Collaboration Models of Integration*, Shimon Y. Nof, ed. Boston: Kluwer Academic, 1994.
7. *Information Infrastructure Systems for Manufacturing*: Proceedings of the JSPE/IFIP TC5/WG5.3 Workshop on the Design of Information Infrastructure Systems for Manufacturing, DIISM '93, Tokyo, Japan, 8-10 November 1993.
8. *Integrated Product and Process Development: Methods, Tools, and Technologies,* Hamid Parsaei, John Usher, Uptal Roy eds. New York: John Wiley, 1998.
9. Kosanke, K. and J.G. Nell (eds.), *Enterprise Engineering and Integration: Building International Consensus*, Springer, 1997.
10. *Manufacturing Systems: Modeling, Management, and Control* (MIM 97): a proceedings volume from the IFAC workshop, Vienna, Austria, 3-5 February 1997. P. Kopacek, ed. Oxford, UK; New York: Published for the International Federation of Automatic Control by Pergamon, 1997.

11. New Forces at Work: Industry Views Critical Technologies, Office of Science and Technology Policy, MR-1008-OSTP, http://www.rand.org/publications/MR/MR1008/MR1008.pdf/, Rand Corporation 1998.
12. Scheer, August-Wilhelm, *CIM: Computer Integrated Manufacturing: Towards the Factory of the Future*. Berlin; New York: Springer-Verlag, 1994.
13. Vernadat, F.B., *Enterprise Modeling and Integration: Principles and Applications.* London; New York: Chapman & Hall, 1996.
14. Williams, Theodore J., *The Purdue Enterprise Reference Architecture: a Technical Guide for CIM Planning and Implementation*. Research Triangle Park, N.C.: Instrument Society of America: Industrial Computing Society, 1992.
15. Womack, James P. and Daniel T. Jones, *Lean Thinking.* Simon & Schuster, New York, NY. 1996. ISBN 0-684-81035-2.
16. *Next Generation Manufacturing: A Framework for Action*, Agility Forum, 1997.

Readings on Modeling & Simulation Technology

1. Agnetis, A., et al., *Scheduling of Flexible Flow Lines in an Automobile Assembly Plant*, European Journal of Operational Research, 97, 1997, 348-362.
2. Alessandri, A. and T. Parisini, *Nonlinear Modeling of Complex Large-Scale Plants using Neural Networks and Stochastic Approximation*, IEEE Transactions on Systems, Man, and Cybernetics: A, 27, 750-757, 1997.
3. Almgren, R., *Topological Modeling of Assembly Systems, Linking Studies in Science and Technology*, Dissertation no. 335, ISBN 91-7871-228-9, Dept. of Mechanical Engineering, Linkoping University, 1994.
4. Al-Qaq, W., M. Devetsikiotis, and J. Townsen, *Stochastic Gradient Optimization of Importance Sampling for the Efficient Simulation of Digital Communication Systems*, IEEE Transactions on Communications, 43(11), 2975-2985, 1995.
5. Ames, Arlo L., Terri L. Calton, Rondall E. Jones, Stephan G. Kaufman, Cathy A. Laguna, Randall H. Wilson, *Lessons Learned from a Second Generation Assembly Planning System*, IEEE ISATP, Aug 1995, pp. 41-47.
6. Andradóttir, S., *Optimization of Transient and Steady-State Behavior of Discrete Event Systems*, Management Science, 42, 717-737, 1996.
7. Andramonov, M., A. Rubinov, and B. Glover, *Cutting Angle Methods in Global Optimization*, Applied Mathematics Letters, 12, 95-100, 1999.
8. Arai, E. and K. Iwata, *CAD System With Product Assembly/Disassembly Planning Function*, Robotics and Computer Aided Integrated Manufacturing, vol. 10, no 1/2, 1993, pp. 41-48.
9. Armstrong, J., R. Black, D. Laxton, and D. Rose, *A Robust Method for Simulating Forward-Looking Models*, Journal of Economic Dynamics and Control, 22, 489-501, 1998.
10. Arsham, H., *A Test Sensitive to Extreme Hidden Periodicities*, Stochastic Hydrology and Hydraulics, 11, 323-330, 1997.
11. Arsham, H., *Algorithms for Sensitivity Information in Discrete-Event Systems Simulation*, Simulation Practice and Theory, 6, 1-22, 1998.
12. Arsham, H., *Goal Seeking Problem in Discrete Event Systems Simulation*, Microelectronics and Reliability, 37, 391-395, 1997.

13. Arsham, H., *Input Parameters to Achieve Target Performance in Stochastic Systems: A Simulation-Based Approach*, Inverse Problems in Engineering, 6, 1-23, 1998.

14. Au, G. and R. Paul, *A Graphical Discrete Event Simulation Environment*, INFOR, 35, 121-137, 1997.

15. Aytug, H., C. Dogan, and G. Bezmez, *Determining the Number of Kanbans: A Simulation Metamodeling Approach*, Simulation, 67, 23-32, 1996.

16. Aytug, H., S. Bhattacharyya, and G. Koehler, *Genetic Learning through Simulation: An Investigation in Shop Floor Scheduling*, Annals of Operations Research, 78, 1-29, 1998.

17. Azadivar, F., *Simulation Optimization with Qualitative Variables and Structural Model changes: A Genetic Algorithm Approach*, European Journal of Operational Research, 113, 169-182, 1998.

18. Badiru, A. and D. Sieger, *Neural Network as a Simulation Metamodel in Economic Analysis of Risky Projects*, European Journal of Operational Research, 105, 1998, 130-142.

19. Bae, Seockhoon and Kunwoo Lee, *An Analytic Approach for Generation of Assembly Sequences with Feasible Trajectory*, IEEE ISATP, Aug 1995, pp. 250-257.

20. Balci, O. (ed.), *Simulation and Modeling*, Annals of Operations Research, 53, 1994.

21. Banks, J. (ed.), *Handbook of Simulation*, John Wiley, 1998.

22. Benford, S. and L. Fahlen. *A Spatial Model of Interaction in Virtual Environments*. In Proceedings Third European Conference on Computer Supported Cooperative Work (ECSCW'93), Milano, Italy, September 1993. ftp://nyquist.cs.nott.ac.uk/pub/papers/ECSCW

23. Benson, D., *Simulation Modeling and Optimization using ProModel*, in the Proceedings of the Winter Simulation conference, 1996.

24. Bequette, B., *Process Dynamics; Modeling, Analysis and Simulation*, Prentice Hall, 1997.

25. Bettonvil, B. and J. Kleijnen, *Searching for Important Factors in Simulation Models with Many Factors: Sequential Bifurcation*, European Journal of Operational Research, 96, 1997, 180-194.

26. Biethhan J. and V. Nissen, *Combinations of Simulation and Evolutionary Algorithms in Management Science and Economics*, Annals of Operations Research, 52 (1994) 183-208.

27. Bison, P., C. Ferrari, E. Pagello, and L. Stocchiero, *Mixing Action Planning and Motion Planning in Building Representations for Assemblies*, Proceedings of the24th ISIR, Tokyo, Nov 1993, pp. 13-144.

28. Bosch, P. and A. Klauw, *Modeling, Identification and Simulation of Dynamical Systems*, CRC Press, 1994.

29. Bowman, R., *Stochastic Gradient-Based Time-Cost Tradeoffs in PERT Network using Simulation*, Annals of Operations Research, 53, 533-551, 1994.

30. Breiteneder, C., S.J. Gibbs, and C. Arapis (1996). *Teleport - An Augmented Reality Teleconferencing Environment*. In Proceedings of the Third Eurographics Workshop on Virtual Environments. New York, NY: Springer-Wein.

31. Brennan R. and P. Rogers, *Stochastic Optimization Applied to a Manufacturing System Operation Problem*, in the Proceedings of the Winter Simulation conference, 1995.

32. Broll, W (1995). *Interacting in Distributed Collaborative Virtual Environments*. In Proceedings of the Virtual Reality Annual International Symposium. VRAIS '95 (pp. 148-155). Los Alamitos, CA, IEEE Computer Society Press.

33. Brutzman, D.P., M.R. Macedonia, A. Zyda, and J. Michael (1996). *Internetwork Infrastructure Requirements for Virtual Environments*. In the Proceedings of the Virtual Reality Modeling Language (VRML) Symposium (pp. 95-104). New York, NY: ACM. ftp://taurus.cs.nps.navy.mil/pub/auv/brutzman/nii_2000.

34. Bryson, S. and Y.M. Gerald (1992). *The Distributed Virtual Windtunnel*. In Proceedings of Supercomputing '92 (pp. 275-284). Los Alamitos, CA, USA,IEEE.

35. Butler, J., *Simulation Techniques for the Sensitivity Analysis of Multi-Criteria Decision Models*, European Journal of Operational Research, 103, 1998, 531-546.

36. Cao, X-R., *Perturbation Analysis of Discrete Event Systems: Concepts, Algorithms, and Applications*, European Journal of Operational Research, 91, 1-13, 1996.

37. Capin, T.K., I.S. Pandzic, N.M. Thalmann, and D. Thalmann (1995). *Virtual Humans for Representing Participants in Immersive Virtual Environments*. Paper presented at FIVE '95 Conference, London, UK.

38. Carlsson, C. and O. Hagsand (1993). *The Distributed Interactive Virtual Environments: Architecture and Applications*. In IEE Colloquium on 'Distributed Virtual Reality', Digest Number 121 (pp. 3/1- 3). London, UK: IEE.

39. Carson, T. and A. Maria, *Simulation Optimization: Methods and Applications*, in the Proceedings of the Winter Simulation conference, 118-126, 1997.

40. Ceric, V. and L. Lakatos, *Measurement and Analysis of Input Data for Queueing Systems Models used in System Design*, System Analysis Modeling Simulation, 11, 227-232, 1993.

41. Chakrabarty, Sugato and Jan D. Wolter, *A Structure-Oriented Approach to Assembly Sequence Planning*, Tech Rept 95-006, Dept. of Computer Science, Texas A&M University, Jan 1995; IEEE Trans R&A.

42. Chakrabarty, Sugato and Jan D. Wolter, *Hierarchical Assembly Planning*, NSF Design and Manufacturing Systems Grantees Conference, Cambridge, MA, Jan 1994, pp. 27-28.

43. Chau, H.L., E.J. Derrick, H.C. Shen, and R.K. Wong, *A New Approach for the Specification of Assembly Systems*, IEEE ISATP, 1995, pp. 9-14.

44. Chen, C-H., *An Efficient Approach for Discrete Event System Decision Problems*, Ph.D. Dissertation, Harvard University, 1994.

45. Chen, F. and Y-S Zheng, *Sensitivity Analysis of an Inventory Model*, Operations Research Letters, 21, 1997, 19-23.

46. Chen, J., J.M. Moshell, C.E. Hughes, B. Blau, & L. Xin (1994). *Distributed Virtual Environment Real-Time Simulation Network.* Advances in Modelling & Analysis B, 31(1), 1- 7.

47. Chen, P-H., *Sensitivity Analysis and Bias Estimation Techniques for Simulation of Production Systems*, Ph.D. Dissertation, Northwestern University, 1993.

48. Chisman, J., *Using Discrete Simulation Modeling to Study Large-Scale System Reliability/Availability*, Computers and Operation Research, 25, 169-174, 1998.

49. Cho, D.Y. and H.S. Cho, *Inference on Robotic Assembly Precedence Constraints Using a Part Contact Level Graph*, Robotica, vol. 11, pt 2, Mar-Apr 1993, pp. 173-183.

50. Chong, E. and P. Ramadge, *Optimal Load Sharing in Soft Real-Time Systems using Likelihood Ratios*, Journal of Optimization Theory and Applications, 82, 1994, 23-48.

51. Ciscon, L.A., J.D. Wise, and D.H. Johnson (1994, Fall). *A Distributed Data Sharing Environment for Telerobotics*. Presence: Teleoperators and Virtual Environments, 3(4), 321-340.

52. Codella, C.F., R. Jalili, L. Koved, and J.B. Lewis (1993). *A Toolkit for Developing Multi-User, Distributed Virtual Environments*. In Proceedings of IEEE 1993 Virtual Reality Annual International Symposium, VRAIS '93 (pp. 401-407). Piscataway, NJ: IEEE Service Center.

53. Coit, D. and A. Smith, *Penalty Guided Genetic Search for Reliability Design Optimization*, Computers and Industrial Engineering, 30, 1996, 895-904.

54. Crites, R., *Large-Scale Dynamic Optimization using Teams of Reinforcement Learning Agents*, Doctoral Dissertation; University of Massachusetts, 1996.

55. De Fazio, T., A.C. Edsall, R.E. Gustavson, J. Hernandez, P.M. Hutchins, H-W Leung, S.C. Luby, R.W. Metzinger, J.L. Nevins, K. Tung, and D.E. Whitney, *A Prototype of Feature-Based Design for Assembly*, ASME Journal of Mechanical Design, V 115, n 4, Dec 1993, pp. 723-734.

56. Dekker, R. and P. Scarf, *On the Impact of Optimising Models in Maintenance Decision Making: A State of the Art*, Reliability Engineering and System Safety, 60, 1998, 111-119.

57. Derek A., *Performance Evaluation of Scheduling Control of Queueing Networks: Fluid model Heuristics*, Queueing Systems, 21, 1996, 391-413

58. Desrochers, A. and R. Al-Jaar, *Applications of Petri Nets in Manufacturing Systems*: Modeling, Control, and Performance Analysis, IEEE, 1994.

59. Dickens, A.R., (1993). *Distributed Representation Issues for Distributed Virtual Environments*. In Proceedings of the 1993 Summer Computer Simulation Conference, Twenty-Fifth Annual Summer Computer Simulation Conference (pp. 894-899). San Diego, CA: SCS.

60. Donohue, J., E. Houck, and R. Myers R., *Simulation Design for the Estimation of Quadratic Response Surface Gradients in the Presence of Model Misspecification*, Management Science, 41, 244-262, 1995.

61. Duenyas, I. and M. Van Oyen, *Stochastic Scheduling of Parallel Queues with Set-Up Costs*, Queueing Systems, 19, 1995, 421-444.

62. Ernst R. and S. Powell, *Optimal Inventory Policies under Service-Sensitive Demand*, European Journal of Operational Research, 87, 1995, 316-327.

63. Fishwick, P., *Simulation Model Design and Execution: Building Digital Worlds*, Prentice-Hall, Englewood Cliffs, 1995.

64. Friedman, L., *The Simulation Metamodel*, Kluwer Academic Publishers, Norwell, MA, 1996.

65. Fu, M. and J-Q. Hu, *Inventory Systems with Random Lead Times: Harris recurrence and its Implication in Sensitivity Analysis*, Probability in the Engineering and Information Sciences, 8, 355-376, 1994.

66. Fu, M. and J-Q. Hu, *Sensitivity Analysis for Monte Carlo Simulation of Option Pricing*, Probability in the Engineering and Information Sciences, 9, 417-449, 1995.

67. Fu, M. and K. Healy K., *Techniques for Optimization via Simulation: an Experimental Study on an Inventory System*, IIE Transactions, 29, 191-199, 1997.

68. Gassmann, H., *Modeling Support for Stochastic Programs*, Annals of Operations Research, 82, 1998, 107-138.

69. Gen, M. and R. Cheng, *Generic Algorithm and Engineering Design*, John Wiley & Sons, Inc., New York, 1997.

70. Gisi, M.A. and C. Sacchi (1994, Fall). *Co-CAD: A Collaborative Mechanical CAD System*. Presence: Teleoperators and Virtual Environments, 3(4), 341-350.

71. Glasserman, P. and T. Liu, *Rare-Event Simulation for Multistage Production-Inventory Systems*, Manage. Sci., 42, 1292-1307, 1995.

72. Goldberg, D., *Genetic Algorithms in Search, Optimization and Machine Learning*, Addison-Wesley, Reading, MA, 1994.

73. Gourieroux, C. and A. Monfort, *Simulation-Based Econometric Methods*, Oxford University Press, 1997.

74. Greenhalgh, C. and S. Benford (1995). *MASSIVE, A Collaborative Virtual Environment for Teleconferencing*. ACM Transactions on Computer, Human Interaction. [Special Issue on Virtual Reality Software and Technology]. 2(3), 239- 261.

75. Greenwood, A., *An Investigation of the Behavior of Simulation Response Surfaces*, European Journal of Operational Research, 111, 1998, 282-313.

76. Gross, D. and M. Juttijudata, *Sensitivity of Output Performance Measures to Input Distributions in Queueing Simulation Modeling*, in the Proceedings of the Winter Simulation Conference, 1997, 296-302.

77. Gruer, P., *Modeling and Quantitative Analysis of Discrete Event Systems: A statecharts based approach*, Simulation Practice and Theory, 6, 1998, 397-411.

78. Guariso, G., M. Hitz, and H. Werthner, *An Integrated Simulation and Optimization Modeling Environment for Decision Support*, Decision Support Systems, 16, 103-117, 1996.

79. Guibas, L.J., D. Halperin, H. Hirukawa, J-C Latombe, R. Wilson, *A Simple and Efficient Procedure for Polyhedral Assembly Partitioning under Infinitesimal Motions*, IEEE ICRA, May 1995, vol. 3, pp. 2553-2560.

80. Guide Jr., V. and R. Srivastava, *Repairable Inventory Theory: Models and applications*, European Journal of Operational Research, 102, 1997, 1-20.

81. Gutjahr, W. and G. Pflug, *Simulated Annealing for Noisy Cost Functions*, Journal of Global Optimization, 8, 1996, 1-13.

82. Haurie, A., P. L'Ecuyer, and C. van Delft, *Convergence of Stochastic Approximation Coupled with Perturbation Analysis in a Class of Manufacturing Flow Control Models*, Discrete Event Dynamic Systems: Theory and Applications, 4, 1994, 87-111.

83. Hazra, M., D. Morrice, and S. Park, *A Simulation Clock-Based Solution to the Frequency Domain Experiment Indexing Problem*, IIE Transactions, 29, 769-782, 1997.

84. Heidelberger, P., P. Shahabuddin, and V. Nicola, *Bounded Relative Error in Estimating Transient Measures of Highly Dependable non-Markovian Systems*, ACM Transactions on Modeling and Computer Simulation, 4, 137-164, 1994.

85. Higle J., W. Lowe, and R. Odio, *Conditional Stochastic Decomposition: An Algorithmic Interface for Optimization and Simulation*, Operations Research, 42, 1994, 311-322.

86. Hisham, Al-Mharmah H. and J. Calvin, *Comparison of Monte Carlo and Deterministic Methods for Non-Adaptive Optimization*, in the Proceedings of the Winter Simulation conference, 348-351, 1997.

87. Ho, Y., *Heuristics, Rules of Thumb, and the 80/20 Proposition*, IEEE Trans. on Automatic Control, 39,1025-1027, 1994.

88. Hoehmann, Axel, *Finding Stable Subassemblies with Backtracking Divide and Conquer on Strongly Connected Components*, IEEE ICRA, vol. 2, May 1995, pp. 1599-1604.

89. Honda, Y., K. Matsuda, J. Rekimoto, and R. Lea (1996). *Virtual Society: Extending the WWW to Support a Multi-User Interactive Shared 3D Environment*. In Proceedings of Virtual Reality Modeling Language (VRML) Symposium '96 (pp. 109-116). New York, NY, ACM. http://www.csl.sony.co.jp/project/VS/VRML95.

90. Horibe, D., *Application of Smoothed Perturbation Analysis to a Discrete-Time Stationary Queue*, Journal of the Operations Research Society of Japan, 41, 1998, 152-165.

91. Hu, J-Q. and D. Xiang, *Structural Properties of Optimal Controllers for Failure Prone Manufacturing Systems*, IEEE Transactions on Automatic Control, 39, 1994, 640-642.

92. Hu, J-Q., P. Vakili, and G. Yu, *Optimality of Hedging Point Policies in the Production Control of Failure Prone Manufacturing Systems*, IEEE Transactions on Automatic Control, 39, 1994, 1875-1880.

93. Huang, K-I, *Development of an Assembly Planner Using Decomposition Approach*, IEEE ICRA, pp. 63-68, May 1993.

94. Hurrion, R., *An Example of Simulation Optimization using a Neural Network Metamodel: Finding the Optimum Number of Kanbans in a Manufacturing System*, Journal of the Operational Research Society, 48, 1105-1112, 1997.

95. Hurrion, R., *Visual Interactive Meta-Simulation using Neural Networks*, International Transactions in Operational Research, 5, 261-27.

96. Ishii, M., M. Nakata, and M. Sato (1994, Fall). *Networked SPIDAR: a Networked Virtual Environment with Visual, Auditory, and Haptic Interactions*. Presence: Teleoperators and Virtual Environments, 3(4), 351-359.

97. Jacobson, S., *Analyzing the M/M/1 Queue in Frequency Domain Experiments*, Applied Mathematics and Computation, 69, 185-194, 1995.

98. Jones, C., *Visualization and Optimization*, Kluwer Academic Pub., 1996.

99. Kalashnikov, V. and V. Sedunov, *Sensitivity Analysis of Regenerative Queueing Models*, Queueing Systems, 19, 1995, 247-268.

100. Kalasky, D., *Simulation-Based Supply-Chain Optimization for Consumer Products*, in the Proceedings of the Winter Simulation conference, 1996.

101. Kamrani, A., K. Hubbard, H. Parsaei, and H. Leep, *Simulation-Based Methodology for Machine Cell Design*, Computers and Industrial Engineering, 34, 1998, 173-188.

102. Kao, C., W. Song, and S. Chen, *A modified quasi-newton method for optimization in simulation*, International Transactions in Operational Research, 4, 223-233, 1997.

103. Karaboga, D. and D. Pham, *Intelligent Optimisation Techniques : Genetic Algorithms, Tabu Search, Simulated Annealing and Neural Networks*, Springer-Verlag, London, 1998.

104. Karacal, S., *A Novel Approach to Simulation Modeling*, Computers and Industrial Engineering, 34, 573-587, 1998.

105. Karim A., J. Hershauer, and W. Perkins, *A Simulation of Partial Information Use in Decision Making: Implications for DSS Design*, Decision Sciences, 29, 1998, 53-85.

106. Kashyap, R., C. Blaydon, and K. Fu, *Stochastic Approximation*, in “A Prelude to Neural Networks: Adaptive and Learning Systems,” J. Mendel (ed.), Prentice Hall, 329-355, 1994.

107. Khobotov, E., *The Optimization Simulation Approach to Modeling of Sophisticated Manufacturing Systems*, II, Journal of Computer and Systems Sciences International, 35, 273, 1996.

108. Kleijnen, J. and R. Rubinstein, *Optimization and Sensitivity Analysis of Computer Simulation Models by Score Function Method*, European Journal of Operational Research, 88, 413-427, 1996.

109. Kleijnen, J. and R. Sargent, *A Methodology for Fitting and Validating Metamodels in Simulation*, Working paper, Tilburg University, Netherlands, 1997.

110. Koehler, G., *New Directions in Genetic Algorithm Theory*, Annals of Operations Research 75, 49-68, 1997.

111. Kouikoglou, V. and Y. Phillis, *A Continuous-Flow Model for Production Networks with Finite Buffers, Unreliable Machines, and Multiple Products*, International Journal of Production Research, 35, 1997, 381-397.

112. Kouikoglou, V. and Y. Phillis, *Discrete Event Modeling and Optimization of Production Lines with Random Rates*, IEEE Transactions on Robotics and Automation, 10, 1994, 153-159.

113. Kroll, E. and Jan Wolter, *Toward Assembly Sequence Planning with Flexible Parts*, IEEE Symposium on Assembly and Task Planning, Aug 1995.

114. Kroll, E., *Intelligent Assembly Planning of Triaxial Products*, Concurrent Engineering: Research and Applications, vol. 2, 1994, pp. 311-319.

115. Kwon, C. and J. Tew, *Strategies for Combining Antithetic Variates and Control Variates in Designed Simulation Experiments*, Management Science, 40, 1994, 1021-34.

116. Lacksonen, T. and P. Anussornnitisarn, *Empirical Comparison of Discrete Event Simulation Optimization Techniques*, Proceedings of the 27th Annual Summer Computer Simulation Conference, 96-101, 1995.

117. Latombe, J-C, and R. Wilson, *Assembly Sequencing with Toleranced Parts*, Third ACM Symp. on Solid Modeling and Applications, April 1995.

118. Le Van Gong, H., M. Soto, and F. Breant (1994). *Architecture For Virtual Environments Cooperation and Interoperability*. In Proceedings of 1994 IEEE International Conference on Systems, Man, and Cybernetics, Humans, Information and Technology (pp. 1036-1041). New York, NY, IEEE.

119. L'Ecuyer, P. and G. Yin, *Rates of Convergence for Budget Dependent Stochastic Optimization Algorithms*, Proceedings of the 35th IEEE Conference on Decision and Control, 1069-1070, 1996.

120. Lee, Y., K. Kyung, and C. Jung, *On-Line Determination of Steady State in Simulation Outputs,* Computers & Industrial Engineering, 33, 805-808, 1997.

121. Lee, J., *Faster Simulated Annealing Techniques for Stochastic Optimization Problems, with Application to Queueing Network Simulation*, Ph.D. Dissertation, Statistics and Operations Research, North Carolina State University, 1995.

122. Lee, S., G. Kim, and G. Bekey, *Combining Assembly Planning with Redesign: An Approach for More Effective DFA*, IEEE ICRA, May 1993.

123. Lee, Y., K-J. Park, and Y. Kim, *Single Run Optimization using the Reverse-Simulation Method*, in the Proceedings of the Winter Simulation Conference, 187-193, 1997.

124. Lei, X., E. Lerch, D. Povh, and B. Kulicke, *Optimization: A New Tool in Simulation Program System*, IEEE Power Engineering Review, 17, p55, 1997.

125. Leung, D. and Y-G Wang, *Bias Reduction using Stochastic Approximation*, Australian & New Zealand Journal of Statistics, 40, 43-52, 1998.

126. Levitin, G. and A. Lisnianski, *Joint Redundancy and Maintenance Optimization for Multistate Series-Parallel Systems*, Reliability Engineering and System Safety, 64, 33-42, 1999.

127. Li, W., *On Stochastic Machine Scheduling with General Distributional Assumptions*, European Journal of Operations Research, 105, 1998, 525-536.

128. Liang, F., *Weighted Markov Chain Monte Carlo and Optimization*, Doctoral Dissertation, Chinese University of Hong Kong, 1997.

129. Lin, A.C. and T.C. Chang, *An Integrated Approach to Automated Assembly Planning for Three-Dimensional Mechanical Products*, International Journal of Production Research, Vol. 31, No 5, 1993, pp. 1201-1227.

130. Lindemann, C., *Performance Modeling with Deterministic and Stochastic Petri Nets*, John Wiley & Sons, 1998.

131. Liptak, B., *Optimization of Industrial Unit Processes*, CRC Pr., 1998.

132. Liu, C. and J. Sanders, *Stochastic Design Optimization of Asynchronous Flexible Assembly Systems*, Annals of Operations Research, 15, 131-154.

133. Logdson, J., *Discrete Event Dynamic Systems: Gradient-Based Optimal Control Versus Passive Adaptive Control*, Doctoral Dissertation; University of Illinois, Chicago, 1995.

134. Lozano-Pérez, T. and R. Wilson, *Assembly Sequencing for Arbitrary Motions*, IEEE Intl. Conf. on Robotics and Automation, 1993, volume 2, pp. 527-532.

135. Luman, R., *Quantitative Decision Support for Upgrading Complex Systems of Systems*, 1997, Ph.D. thesis, School of Engineering and Applied Science, George Washington University.

136. Lüthi, J. and G. Haring, *Mean Value Analysis for Queueing Network Models with Intervals as Input Parameters*, Performance Evaluation, 32, 1998, 185-215.

137. Macedonia, M.R., M.J. Zyda, D.R. Pratt et al (1995). *Exploiting Reality with Multicast Groups: A Network Architecture for Large, Scale Virtual Environments*. In Proceedings of the Virtual Reality Annual International Symposium. VRAIS '95 (pp. 2-10). Los Alamitos, CA, IEEE Computer Society Press.

138. Macedonia, Michael R. and Michael J. Zyda (1995). *A Taxonomy for Networked Virtual Environments*. In the Proceedings of the 1995 Workshop on Networked Realities, Boston, MA, October 26-28, 1995.

139. Maxfield, J., T. Fernando, and P. Dew (1995). *A Distributed Virtual Environment for Concurrent Engineering*. In Proceedings of the Virtual Reality Annual International Symposium. VRAIS '95 (pp. 162-171). Los Alamitos, CA, IEEE Computer Society Press.

140. McCarty, W.D., S. Sheasby, P. Amburn et al (1994, January). *A Virtual Cockpit for a Distributed Interactive Simulation*. IEEE Computer Graphics and Applications, 14 (1), 49-54.

141. Merkuryev, G. and Y. Merkuryev, *Knowledge Based Simulation Systems-A Review*, Simulation, 62, 74-89, 1994.

142. Merkuryev, Y. *Integral Optimization in Simulation Modeling of Discrete Systems*, Automatic Control and Computer Sciences, 31, 27-38, 1997.

143. Merkuryev, Y., L. Rastrigin, and V. Visipkov, *Knowledge-Based Selection and Adaptation of Optimization Algorithms in Discrete System Simulation*, Proceedings of the 1995 Summer Computer Simulation Conference, ed. by Louis Birta and Tuncer Oren. 1995, 82-85.

144. Michalewicz, Z., *Evolutionary Computation Techniques for Non-Linear Programming Problems*, International Transactions in Operational Research, 1, 1994, 233-240.

145. Minami, Shunsuke, K. Francisco Pahng, M. Jakiela, and Alok Srivastava, *A Cellular Automata Representation for Assembly Simulation and Sequence Generation*, IEEE ISATP, Aug 1995, pp. 56-65.

146. Moddy, J., *Petri Net Supervisors for Discrete Event* Systems, Doctoral Dissertation; University of Notre Dame, 1998.

147. Noorhosseinii, S. and A. Malowany, *Robot Action Planning Using State Matrix Representation*, Proceedings of the1994 Canadian Conference on Electrical and Computer Engineering, Halifax, Sept 1994.

148. Okada, M., S. Hara, S. Komaki, and N. Morinaga, *An Application of Simulated Annealing to the Design of Block Coded Modulation*, IEICE Transactions on Communications, E79-b, 1, 88-91, 1996.

149. Otto, J. et al., *Bayesian-Validated Computer-Simulation Surrogates for Optimization and Design: Error Estimates and Applications*, Mathematics and Computers in Simulation, 44, 347-367, 1997.

150. Park, J.H. and M. J. Chung, *Automatic Generation of Assembly Sequences for Multi-Robot Workcell*, Robotics & Computer-Integrated Manufacturing vol. 10, no 2, 1993, pp. 355-363.

151. Park, J.H., M.J. Chung, K.Y. Lim, *Acquisition of Assembly Constraints Without Redundancies*, IEEE ICRA, May 1993, pp. 69-74.

152. Park, M. and Y. Kim, *A Systematic Procedure for Setting Parameters in Simulated Annealing Algorithms*, Computers and Operation Research, 25, 1998, 207-217.

153. Park, Y. and E. Chong, *Distributed Inversion in Timed Discrete Event Systems*, Discrete Event Dynamic Systems: Theory and Applications, 5, 1995, 219-241.

154. Passino, K. and K. Burgess, *Stability Analysis of Discrete Event Systems*, Wiley, 1998.

155. Paul, R., *Simulation Optimisation using a Genetic Algorithm*, Simulation Practice and Theory, 6, 601-611, 1998.

156. Petrovic, D., *Modeling and Simulation of a Supply Chain in an Uncertain Environment*, European Journal of Operational Research, 109, 1998, 299-309.

157. Phillis, Y., V. Kouikoglou, D. Sourlas, and V. Manousiouthakis, *Design of serial Production Systems using Discrete Event Simulation and Nonconvex Programming Techniques*, International Journal of Production Research, 35, 1997, 753-766.

158. Pierreval, H. and Tautou, *Using Evolutionary Algorithm and Simulation for the Optimization of Manufacturing Systems*, IIE Transactions, 29(3), 1997, 181-189.

159. Polis, M.F., S.J. Gifford, and D.M. McKeown (1995, July). *Automating the Construction of Large-Scale Virtual Worlds*. Computer, 29(7), pp. 57-65.

160. Pouliquen, D. (1994). *Integrating Several Operators in a Synthetic Environment, a Real Time Technique for a Realistic Behaviour*. In Proceedings of Oria 94, From Telepresence Towards Virtual Reality (pp. 149-151). Marseille, France: Inst. Int. Robotique & Intelligence Artificielle.

161. Pratt, D.R. and M.A. Johnson (1995). *Constructive and Virtual Model Linkage.* In Proceedings of 1995 Winter Simulation Conference (pp. 1222-1228). New York, NY: IEEE.

162. Pu, P. and L. Purvis, *Assembly Planning Using Case Adaptation Models*, IEEE ICRA, vol. 1, May 1995, pp. 982-987.

163. Purvis, L., *Constraint Satisfaction Combined with Case-Based Reasoning for Assembly Sequence Planning*, Tech Rept CSE-TR-93-20, University of Connecticut, 1993.

164. Qian, W-H and E. Pagello, *On the Scenario and Heuristics of Dissassemblies*, IEEE ICRA, May 1994, pp. 264-271.

165. Ramachandran, K., V. Sivakumar, K. Sathiyanarayanan, and S. Chandraskekaran, *Genetic Based Redundancy Optimization*, Journal of Microelectronics and Reliability, 37, (1997) 661-663.

166. Rea, P. and S. Whalley (1993). *Advanced Interface into Network Management Workstations*. In Proceedings of IEE Colloquium on 'Distributed Virtual Reality' (Digest No.121), (pp. 7/1-7/3). London, UK.: IEE.

167. Rezayat, F., *On the Use of an SPSA-Based Model-Free Controller in Quality Improvement*, Automatica, 31, 1995, 913-915.

168. Ricotti, M. and E. Zio, *A Neural Network Approach to Sensitivity and Uncertainty Analysis*, Reliability Engineering and System Safety, 64, 59-71, 1999.

169. Roberts, D. J., M.P. Griffin, and R.J. Mitchell, (1993). *LOKI- 2: An Architecture for Distributed Virtual Reality*. In Proceedings of IEE Colloquium on 'Distributed Virtual Reality', Digest Number 121 (pp. 8/1-5). London, UK: IEE.

170. Rollans, R., *Sensitivity Analysis of Simulations and the Monte-Carlo Optimization of Stochastic Systems*, Ph.D. Thesis, University of Waterloo, 1993.

171. Rosenblatt, M., Y. Roll, and V. Zyse, *A Combined Optimization and Simulation Approach for Designing Automated Storage/Retrieval Systems*, IIE Transactions, 25(1), 1993, 40-50.

172. Rossetti, M. and G. Clark, *Evaluating a Queueing Approximation for the Machine Interference Problem with Two Types of Stoppages via Simulation Optimization*, Computers and Industrial Engineering, 34, 655-668, 1998.

173. Rubinstein, R., *Optimization of Computer Simulation Models with Rare Events*, European Journal of Operations Research, 99, 1997, 89-112.

174. Sadiku, M. and M. Ilyas, *Simulation of Local Area Networks*, Springer, 1994.

175. Saltelli, A., K. Chan, and M. Scott (eds.), *Mathematical and Statistical Methods for Sensitivity Analysis*, New York: Wiley, 1999.

176. Sanchez, S., P. Sanchez, J. Ramberg, and F. Moeeni, *Effective Engineering Design through Simulation*, Transactions in Operational Research, 3, (1997), 169-185.

177. Satelli, A. and R. Bolado, *An Alternative Way to Compute Fourier Amplitude Sensitivity Test (FAST),* Computational Statistics & Data Analysis, 26, (1998), 445-460.

178. Sayers, C.P. and R.P. Paul (1994, Fall). *An Operator Interface for Teleprogramming Employing Synthetic Fixtures*. Presence: Teleoperators and Virtual Environments, 3(4), 309-320.

179. Schmeiser, B. and J. Wang, *On the Performance of Pure Adaptive Search*, Proceedings of the Winter Simulation Conference, 353-356, 1995.

180. Schruben, L., *Simulation Optimization using Simultaneous Replications and Event Time Dilation*, in the Proceedings of the Winter Simulation conference, 177-180, 1997.

181. Schweikard, A. and R.H. Wilson, *Assembly Sequences for Polyhedra*, Algorithmica, vol. 13, 1995, pp. 539-552.

182. Scott, E., *Uncertainty and Sensitivity Studies of Models of Environmental Systems*, in the Proceedings of the Winter Simulation conference, 1996.

183. Scott, M. and A. Saltelli (eds), *Special Issue on Sensitivity Analysis in the Journal of Statistical Computation and Simulations*, 57(1-4), 1997.

184. Seow, K.T. and Rajagopalan Devanathan, *A Temporal Framework for Assembly Sequence Representation and Analysis*, IEEE Trans R&A, vol. 10 no 2, April 1994, pp. 220-229.

185. Shapiro, A., *Simulation-Based Optimization-Convergence Analysis and Statistical inference*, Communications in Statistics: Stochastic Models, 12, 1996, 425-435.

186. Shin, C.K., D.S. Hong, and H.S. Cho, *Disassemblability Analysis for Generating Robotic Assembly Sequences*, IEEE ICRA, vol. 2, May 1995, pp. 1284-1289.

187. Shorter, J. and H. Rabitz, *Risk Analysis by the Guided Monte Carlo Technique*, Journal of Statistical Computation and Simulation, 57, 1997, 321-336.

188. Sichman, J., R. Conte, and N. Gilbert (eds), *Multi-Agent Systems and Agent-Based Simulation*, Berlin, Springer-Verlag, 1998.

189. Sodhi, R. (ed.), *Advances in Manufacturing Systems: Design, Modeling and Analysis*, Elsevier Science Ltd, 1994.

190. Song, W., *A Three-Class Variance Swapping Technique for Simulation Experiments*, Operations Research Letters, 23, 63-70, 1999.

191. Spall, J., *Implementation of the Simultaneous Perturbation Algorithm for Stochastic Optimization*, IEEE Transactions on Aerospace and Electronic Systems, 34, 817-823, 1998.

192. Stadzisz, P.C. and J-M Henrioud, *Integrated Design of Product Families and Assembly Systems*, IEEE ICRA, vol. 2, May 1995, pp. 1290-1295.

193. Stanger, V.J (1993). *Networked Virtual Reality Applications*. Paper presented at the IEE Colloquium on 'Distributed Virtual Reality' (Digest No.121, pp. 1/1-1/4). London, UK.: IEE.

194. Stone, S., M. Zyda, D. Brutzman, and J. Falby (1995). *Mobile Agents and Smart Networks for Distributed Simulations.* In Proceedings of the 14th Distributed Simulations Conference, Orlando, FL, March 11, 15, 1995.

195. Strickland, S., *Gradient/Sensitivity Estimation in Discrete-Event Simulation*, Proceedings of the Winter Simulation Conference, 1993, 97-105.

196. Sugihara, K., *A Case Study on Tuning of Genetic Algorithms by using Performance Evaluation based on Experimental Design*, in Proceedings of the 1997 Joint Conference on Information Sciences, 1997.

197. Suri, R. and B-R Fu, *On Using Continuous Flow Lines to Model Discrete Production Lines*, Discrete Dynamic Systems, 4, 129-169, 1994.

198. Swaminathan, A. and K.S. Barber, APE: *An Experience-based Assembly Sequence Planner for Mechanical Assemblies*, IEEE ICRA, vol. 2, May 1995, pp. 1278-1283.

199. Tag, Peter H., *The Recursive Executable Cell: An Architectural Template For Building Enterprise Simulation Models*. January 1996.

200. Takemura, H., Y. Kitamura, F. Kishino, and J. Ohya (1993). *Distributed Processing Architecture for Virtual Space Teleconferencing System*. In Proceedings of the Third International Conference on Artificial Reality and Tele, Existence, ICAT '93 (pp. 27-32). Tokyo, Japan, Japan Technology Transfer Association.

201. Tambe, M., M. Lewis-Johnson, R.M. Jones, F. Koss, J.E. Laird, P.S. Rosenbloom, and K. Schwamb (1995). *Intelligent Agents for Interactive Simulation Environments*. AI Magazine, 16(1), pp. 15-39.

202. Tang, Q. and H. Chen, *Convergence of Perturbation Analysis Based Optimization Algorithm with Fixed Number of Customers*, Discrete Event Dynamic Systems: Theory and Applications, 4, 1994, 359-375.

203. Teleb, R. and F. Azadivar, *A Methodology for Solving Multi-Objective Simulation-Optimization Problems*, European Journal of Operational Research, 27, (1994), 135-145.

204. Thomas, J.P. and P.N. Nissanke, *A Graph-based Framework for Assembly Tasks*, IEEE ICRA, vol. 2, May 1995, pp. 1296-1301.

205. Thomas, J.P., *A Framework for the Generation of Assembly Plans*, Internal Report, CS Dept, U of Reading, 1994.

206. Tompkins, G. and F. Azadivar, *Genetic Algorithms in Optimizing Simulated Systems*, Proceedings of the Winter Simulation Conference, 757-762, 1995.

207. Tsao, Jungfu, and Jan D. Wolter, *Assembly Planning with Intermediate States*, IEEE ICRA, Atlanta, May 1993, pp. 71-76.

208. Ulrich, E., V. Agrawal, and J. Arabian, *Concurrent and Comparative Discrete Event Simulation*, Kluwer Academic, Boston, 1994.

209. van den Bosch, P. and A. van der Klauw, *Modeling, Identification and Simulation of Dynamical Systems*, CRC Press, 1994.

210. Venuvinod, P.K., *Automatic Analysis of 3-D Polyhedral Assembly Directions and Sequences*, Journal of Manufacturing Systems, vol. 12, no 3, 1993, pp. 246-252.

211. Wang, T., H. Lin, and K. Wu, *An Improved Simulated Annealing for Facility Layout Problems in Cellular Manufacturing Systems*, Computers and Industrial Engineering, 34, 1998, 309-319.

212. Watson, E., P. Chawda, B. McCarthy, M. Drevna, and R. Sadowski, *A Simulation Metamodel for Response-Time Planning*, Decision Sciences, 29, 1998, 217-241.

213. Wilson, R. and J-C Latombe, *Geometric Reasoning about Mechanical Assembly*, Artificial Intelligence, 71 (2): 371-396, 1994.

214. Wilson, R., L. Kavraki, T. Lozano-Pérez, and J-C Latombe, *Two-Handed Assembly Sequencing*, Tech Report STAN-CS-93-1478, Dept. of Computer Science, Stanford University, 1993.

215. Winsch, B.J., N.K. Atwood, and K.A. Quinkert (1994). *Using a Distributed Interactive Simulation Environment to Investigate Machine Interface and Training Requirements*. In Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting (pp. 1033-1037). Santa Monica, CA: Human Factors and Ergonomics Society.

216. Yang K-K, and C-C. Sum, *An Evaluation of Due Date, Resource Allocation, Project Release, and Activity Scheduling Rules in a Multiproject Environment*, European Journal of Operational Research, 103, 1997, 139-154.

217. Yang, J-M, and J-H Kim, *Optimization of Discrete Event Systems Using Evolutionary Programming*, Proceedings of 1996 IEEE International Conference on Evolutionary Computation, 131-134, 1996.

218. Yoon, A., *Randomized Algorithms and Global Optimization for Optimal and Robust Control*, Doctoral Dissertation, University of Michigan, 1998.

219. Yu, B. and K. Popplewell, *Metamodels in Manufacturing: A Review*, Int. J. Prod. Res., 32, 1994, 787-796.

220. Yucesan, E. and S. Jacobson, *The Complexity of Rapid Learning in Discrete Event Simulation*, IIE Transactions, 29, 1997, 783-790.

221. Yunker, J. and J. Tew, *Simulation Optimization Search*, Journal of Mathematics and Computers in Simulation, 37, 17-28, 1994.

222. Zenios, S. (ed.), *Financial Optimization*, Cambridge University Press, 1993.

223. Zhang, J. and X. Xu, *An Efficient Evolutionary Programming Algorithm*, Computers & Operations Research, 26, 645-663, 1999.

224. Zhou, M. and F. Dicesare, *Petri Net Synthesis for Discrete Event Control of Manufacturing Systems*, Kluwer Academic Pub, 1993.

225. Zyda, Michael J., David R., Pratt, Shirley M. Pratt, Paul T. Barham, and John S. Falby (1995). *NPSNET-HUMAN: Inserting the Human into the Networked Synthetic Environment*. In the Proceedings of the 13th DIS Workshop, 18-22 September, 1995, Orlando, Florida.

APPENDIX F
M&S Cross-Walks for IMTR Nuggets

The "Nugget" roadmaps presented in Section 1.3 of each of the IMTR documents identify 40 critical capabilities that collectively underpin the IMTR visions for Information Systems, for Modeling & Simulation, for Manufacturing Processes & Equipment, and for Technologies for Enterprise Integration.

Each of the Nugget roadmaps identifies a sampling of goals from the various IMTR roadmaps that support each Nugget. The following "cross-walk" matrix provides a more comprehensive listing of goals from the M&S document that support each of the 10 Nuggets from the M&S, IS, MPE, and TEI roadmaps.

Nugget Cross-Walk for Modeling & Simulation

M&S Nuggets	Related M&S Roadmap Goals (By Document Section & Goal Number)
1. Micro to Macro Continuum Modeling	2.3.1, G1: Flexible, Complex Representation 3.3.1, G1: Broad-Based Material Modeling Framework
2. Science-Based Models Integrated with Living Knowledge/Experience Bases	2.3.2, G1: Robust Performance Modeling Environment 2.3.3, G2: Enterprise-Wide Product Cost Models 2.3.5, G1: Integrated Life-Cycle Modeling Capability 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.2, G1: Knowledge-Based Assembly Modeling & Simulation Tools 3.3.4, G1: Integrated Packaging Modeling 3.3.5, G1: Integrated Material Stream Modeling 4.3.1.3, G1: Risk Assessment/Analysis Toolset 4.3.1.5, G1: Real-Time Resource Modeling System
3. M&S Is Rule, Not Exception	2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.3, G2: Enterprise-Wide Product Cost Models 2.3.4, G1: Producibility Requirements Integration 2.3.5, G2: Total Service Modeling Environment 3.3.4, G2: Integrated Life-Cycle Material Behavior Modeling 3.3.5, G3: Remanufacturing Modeling Tool Suite 4.3.1.1, G1: Timely, Accurate Modeling & Simulation for Strategic Positioning 4.3.1.3, G1: Risk Assessment/Analysis Toolset 4.3.1.4, G1: Enterprise Financial Simulation Environment 4.3.2.1, G2: Distributed Resource Management Tools
4. Intelligent Design & Analysis Advisors	2.3.1, G3: Direct Product Model Design 2.3.2, G1: Robust Performance Modeling Environment 2.3.4, G2: Parallel Multi-Attribute Producibility Evaluation 2.3.5, G1: Integrated Life-Cycle Modeling Capability 3.3.1, G2: Collaborative Analytical Systems 3.3.5, G3: Remanufacturing Modeling Tool Suite

5. M&S as Real Time Enterprise Controller	3.3.2, G2: Assembly Process Control Simulation 4.3.1.5, G1: Real-Time Resource Modeling System 4.3.1.8, G1: Extended Enterprise Management System 4.3.2.1, G1: Real-Time Factory Model 4.3.2.1, G3: Enterprise Knowledge/Skills Management 4.3.2.3, G1: Total Factory Control Model 4.3.2.3, G2: Integrated Factory Monitoring & Control
6. Smart, Self-Learning Models	2.3.3, G1: Robust Cost Modeling 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.2, G2: Assembly Process Control Simulation 4.3.1.5, G2: Distributed Resource Management 4.3.2.2, G2: Adaptive Performance Management System
7. Open, Shared Repositories & Validation Centers	2.3.3, G2: Enterprise-Wide Product Cost Models 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.3, G2: Zero Post-Process Certification 4.3.1.1, G1: Timely, Accurate M&S Processes for Strategic Positioning
8. Integrated, Robust Product & Process Models Supporting All Domains & Applications	2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.4, G1: Producibility Requirements Integration 2.3.5, G2: Total Service Modeling Environment 3.3.1, G2: Collaborative Analytical Systems 3.3.2, G1: Knowledge-Based Assembly Modeling & Simulation Tools 3.3.3, G2: Zero Post-Process Certification 3.3.5, G1: Integrated Material Stream Modeling 4.3.1.1, G1: Timely, Accurate M&S Processes for Strategic Positioning 4.3.1.4, G1: Enterprise Financial Simulation Environment 4.3.1.8, G1: Extended Enterprise Management System
9. Total, Seamless Model Interoperability	2.3.1, G1: Flexible, Complex Representation 2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.3, G1: Robust Cost Modeling 3.3.1, G1: Broad-Based Material Modeling Framework
10. Real Time, Interactive, Performance-Based Models	2.3.1, G1: Flexible, Complex Representation 2.3.2, G1: Robust Performance Modeling Environment 2.3.3, G1: Robust Cost Modeling 2.3.5, G1: Integrated Life-Cycle Modeling Capability 3.3.1, G2: Collaborative Analytical Systems 3.3.2, G2: Assembly Process Control Simulation 3.3.3, G2: Zero Post-Process Certification 3.3.5, G3: Remanufacturing Modeling Tool Suite 4.3.1.1, G1: Timely, Accurate M&S Processes for Strategic Positioning 4.3.1.5, G1: Real-Time Resource Modeling System 4.3.1.8, G1: Extended Enterprise Management System 4.3.2.1, G1: Real-Time Factory Model

Nugget Cross-Walk for Information Systems

IS Nuggets	Related M&S Roadmap Goals (By Document Section & Goal Number)
1. Information-Driven Seamless Enterprises	2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.2, G1: Robust Performance Modeling Environment 2.3.3, G1: Robust Cost Modeling 2.3.3, G2: Enterprise-Wide Product Cost Models 2.3.4, G1: Producibility Requirements Integration 2.3.5, G1: Integrated Life-Cycle Modeling Capability 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.2, G1: Knowledge-Based Assembly M&S Tools 3.3.3, G1: Product Attribute Specification Capability 3.3.3, G2: Zero Post-Process Certification 3.3.4, G2: Integrated Life-Cycle Material Behavior Modeling 4.3.1.4, G1: Enterprise Financial Simulation Environment 4.3.1.5, G1: Real-Time Resource Modeling System 4.3.1.5, G2: Distributed Resource Management 4.3.1.7, G1: Extendible Enterprise Model & Reference Architecture 4.3.1.8, G1: Extended Enterprise Management System 4.3.2.1, G2: Distributed Resource Management Tools 4.3.2.2, G1: Performance Optimization Systems 4.3.2.2, G2: Adaptive Performance Management System 4.3.2.3, G1: Total Factory Control Model 4.3.2.3, G2: Integrated Factory Monitoring & Control 4.3.2.4, G1: Integrated Distributed Factory Infrastructure Model
2. Shared Knowledge Repositories	2.3.1, G1: Flexible, Complex Representation 2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.3, G2: Enterprise-Wide Product Cost Models 2.3.5, G1: Integrated Life-Cycle Modeling Capability 3.3.1, G1: Science-Based Material Modeling Knowledge Base 3.3.3, G2: Zero Post-Process Certification 3.3.4, G2: Integrated Life-Cycle Material Behavior Modeling 4.3.1.3, G1: Risk Assessment & Analysis Toolset 4.3.1.5, G1: Real-Time Resource Modeling System 4.3.1.5, G2: Distributed Resource Management 4.3.1.8, G1: Extended Enterprise Management System 4.3.2.1, G3: Enterprise Knowledge/Skills Management 4.3.2.3, G1: Total Factory Control Model 4.3.2.4, G1: Integrated Distributed Factory Infrastructure Model
3. Customer/Requirements-Driven Manufacturing	2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.1, G3: Direct Product Model Design 2.3.2, G1: Robust Performance Modeling Environment 2.3.3, G1: Robust Cost Modeling 2.3.3, G2: Enterprise-Wide Product Cost Models 2.3.4, G1: Producibility Requirements Integration 2.3.4, G2: Parallel Multi-Attribute Producibility Evaluation 2.3.5, G1: Integrated Life-Cycle Modeling Capability 2.3.5, G2: Total Service Modeling Environment 3.3.2, G1: Knowledge-Based Assembly M&S Tools 3.3.3, G1: Product Attribute Specification Capability 3.3.3, G2: Zero Post-Process Certification 3.3.4, G1: Integrated Packaging Modeling 3.3.4, G2: Integrated Life-Cycle Material Behavior Modeling 3.3.4, G2: Optimized Life-Cycle Packaging 3.3.5, G1: Integrated Material Stream Modeling 3.3.5, G3: Remanufacturing Modeling Tool Suite 4.3.1.2, G1: Timely Accurate M&S Processes for Market Assessment

	4.3.1.5, G1: Real-Time Resource Modeling System 4.3.1.5, G2: Distributed Resource Management 4.3.1.6, G1: Quality Tradeoff Tools
4. Mature Integrated Product/Process Development	2.3.1, G1: Flexible, Complex Representation 2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.1, G3: Direct Product Model Design 2.3.2, G1: Robust Performance Modeling Environment 2.3.2, G2: Fast Background Performance Simulation 2.3.3, G1: Robust Cost Modeling 2.3.3, G2: Enterprise-Wide Product Cost Models 2.3.4, G1: Producibility Requirements Integration 2.3.5, G1: Integrated Life-Cycle Modeling Capability 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.2, G1: Knowledge-Based Assembly M&S Tools 3.3.4, G1: Integrated Packaging Modeling 3.3.4, G2: Integrated Life-Cycle Material Behavior Modeling 3.3.5, G3: Remanufacturing Modeling Tool Suite 4.3.1.4, G1: Enterprise Financial Simulation Environment
5. Totally Connected Extended Enterprise	2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.3, G2: Enterprise-Wide Product Cost Models 2.3.3, G2: Distributed Enterprise Assembly Planning System 4.3.1.1, G1: Timely, Accurate M&S Processes for Strategic Positioning 4.3.1.2, G1: Timely, Accurate M&S Processes for Market Assessment 4.3.1.4, G1: Enterprise Financial Simulation Environment 4.3.1.5, G1: Real-Time Resource Modeling System 4.3.1.5, G2: Distributed Resource Management 4.3.1.7, G1: Extendible Enterprise Model & Reference Architecture 4.3.1.8, G1: Extended Enterprise Management System 4.3.2.1, G2: Distributed Resource Management Tools 4.3.2.3, G2: Integrated Factory Monitoring & Control 4.3.2.4, G1: Integrated Distributed Factory Infrastructure Model
6. Plug-&-Play, Interoperable Systems Components	2.3.1, G1: Flexible, Complex Representation 2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.2, G1: Robust Performance Modeling Environment 2.3.3, G1: Robust Cost Modeling 2.3.3, G2: Enterprise-Wide Product Cost Models 4.3.1.7, G1: Extendible Enterprise Model & Reference Architecture
7. Design & Operation Advisors	2.3.1, G3: Direct Product Model Design 2.3.3, G1: Robust Cost Modeling 2.3.2, G1: Robust Performance Modeling Environment 2.3.3, G1: Robust Cost Modeling 2.3.4, G2: Parallel Multi-Attribute Producibility Evaluation 3.3.2, G1: Knowledge-Based Assembly Modeling & Simulation Tools 3.3.2, G2: Assembly Process Control Simulation 3.3.1, G1: Product Attribute Specification Capability 3.3.4, G2: Integrated Life-Cycle Material Behavior Modeling 3.3.5, G1: Integrated Material Stream Modeling 3.3.5, G3: Remanufacturing Modeling Tool Suite 4.3.2.2, G1: Performance Optimization Systems 4.3.2.2, G2: Adaptive Performance Management System 4.3.2.3, G2: Integrated Factory Monitoring & Control
8. Self-Correcting, Adaptive Operational Systems	3.3.2, G1: Knowledge-Based Assembly Modeling & Simulation Tools 3.3.3, G2: Adaptive, Real-Time Equipment/Process Control Models 2.3.3, G2: Real-Time Factory Operations Optimization Model 4.3.2.2, G1: Performance Optimization Systems 4.3.2.2, G2: Adaptive Performance Management System 4.3.2.3, G1: Total Factory Control Model 4.3.2.3, G2: Integrated Factory Monitoring & Control

9. Self-Learning Systems	2.3.1, G3: Direct Product Model Design 2.3.3, G1: Robust Cost Modeling 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.3, G2: Zero Post-Process Certification 3.3.5, G1 Integrated Material Stream Modeling 4.3.1.3, G1: Risk Assessment & Analysis Toolset 4.3.2.2, G1: Performance Optimization Systems 4.3.2.2, G2: Adaptive Performance Management Systems
10. Integration of Multiple Design Domains	2.3.1, G1: Flexible, Complex Representation 2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.2, G1: Robust Performance Modeling Environment 2.3.3, G1: Robust Cost Modeling 2.3.4, G2: Parallel Multi-Attribute Producibility Evaluation 2.3.5, G1: Integrated Life-Cycle Modeling Capability

Nugget Cross-Walk for Manufacturing Processes & Equipment

MPE Nuggets	Related M&S Roadmap Goals (By Document Section & Goal Number)
1. Zero Net Life-Cycle Waste	2.3.1, G3: Direct Product Model Design 2.3.3, G2: Enterprise-Wide Product Cost Models 2.3.5, G1: Integrated Life-Cycle Modeling Capability 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.4, G3: Optimized Life-Cycle Packaging 3.3.5, G1: Integrated Material Stream Modeling 3.3.5, G2: Comprehensive Material Flow Models 3.3.5, G3: Remanufacturing Modeling Tool Suite 4.3.1.5, G1: Real-Time Resource Modeling System 4.3.2.1, G2: Distributed Resource Management Tools 4.3.2.3, G1: Total Factory Control Model 4.3.2.4, G1: Integrated Distributed Factory Infrastructure Model
2. First Part Correct	2.3.1, G1: Flexible, Complex Representation 2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.1, G3: Direct Product Model Design 2.3.2, G1: Robust Performance Modeling Environment 2.3.3, G1: Robust Cost Modeling 2.3.4, G1: Producibility Requirements Integration 2.3.4, G2: Parallel Multi-Attribute Producibility Evaluation 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.1, G2: Collaborative Analytical Systems 3.3.2, G1: Knowledge-Based Assembly Modeling & Simulation Tools 3.3.2, G2: Assembly Process Control Simulation 3.3.3, G2: Zero Post-Process Certification
3. Intelligent Control Systems	2.3.1, G1: Flexible, Complex Representation 3.3.2, G1: Knowledge-Based Assembly Modeling & Simulation Tools 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.2, G1: Knowledge-Based Assembly Modeling & Simulation Tools 3.3.2, G2: Assembly Process Control Simulation 3.3.3, G2: Zero Post-Process Certification 4.3.1.5, G2: Distributed Resource Management 4.3.1.8, G1: Extended Enterprise Management System 4.3.2.1, G1: Real-Time Factory Model 4.3.2.1, G2: Distributed Resource Management Tools 4.3.2.3, G1: Total Factory Control Model 4.3.2.3, G2: Integrated Factory Monitoring & Control 4.3.2.4, G1: Integrated Distributed Factory Infrastructure Model

4. Innovative Breakthrough Processes	2.3.1, G3: Direct Product Model Design 3.3.1, G2: Collaborative Analytical Systems 3.3.2, G2: Assembly Process Control Simulation 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.1, G2: Collaborative Analytical Systems 3.3.5, G3: Remanufacturing Modeling Tool Suite
5. Science-Based Manufacturing	2.3.1, G1: Flexible, Complex Representation 2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.1, G3: Direct Product Model Design 2.3.2, G1: Robust Performance Modeling Environment 2.3.4, G2: Parallel Multi-Attribute Producibility Evaluation 2.3.5, G1: Integrated Life-Cycle Modeling Capability 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.1, G2: Collaborative Analytical Systems 3.3.2, G1: Knowledge-Based Assembly M&S Tools 3.3.2, G2: Assembly Process Control Simulation 3.3.3, G2: Zero Post-Process Certification
6. Intelligent Design & Process Advisors	2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.1, G3: Direct Product Model Design 2.3.2, G1: Robust Performance Modeling Environment 2.3.3, G1: Robust Cost Modeling 2.3.3, G2: Enterprise-Wide Product Cost Models 2.3.4, G2: Parallel Multi-Attribute Producibility Evaluation 3.3.1, G1: Product Attribute Specification Capability 3.3.2, G1: Knowledge-Based Assembly Modeling & Simulation Tools 3.3.2, G2: Assembly Process Control Simulation 3.3.4, G2: Integrated Life-Cycle Material Behavior Modeling 3.3.5, G1: Integrated Material Stream Modeling 3.3.5, G3: Remanufacturing Modeling Tool Suite 4.3.2.2, G1: Performance Optimization Systems 4.3.2.2, G2: Adaptive Performance Management System 4.3.2.3, G2: Integrated Factory Monitoring & Control
7. Knowledge Repositories & Validation Centers	2.3.1, G1: Flexible, Complex Representation 2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.3, G2: Enterprise-Wide Product Cost Models 2.3.5, G1: Integrated Life-Cycle Modeling Capability 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.3, G2: Zero Post-Process Certification 3.3.4, G2: Integrated Life-Cycle Material Behavior Modeling 4.3.1.3, G1: Risk Assessment & Analysis Toolset 4.3.2.1, G3: Enterprise Knowledge/Skills Management 4.3.2.3, G1: Total Factory Control Model 4.3.1.5, G1: Real-Time Resource Modeling System 4.3.1.5, G2: Distributed Resource Management 4.3.2.4, G1: Integrated Distributed Factory Infrastructure Model 4.3.1.8, G1: Extended Enterprise Management System
8. Distributed Control Across Extended Enterprises	4.3.1.5, G1: Real-Time Resource Modeling System 4.3.1.5, G2: Distributed Resource Management 4.3.1.7, G1: Extendible Enterprise Model & Reference Architecture 4.3.1.8, G1: Extended Enterprise Management System 4.3.2.1, G1: Real-Time Factory Model 4.3.2.1, G2: Distributed Resource Management Tools 4.3.2.2, G1: Performance Optimization Systems 4.3.2.2, G2: Adaptive Performance Management System 4.3.2.3, G1: Total Factory Control Model 4.3.2.3, G2: Integrated Factory Monitoring & Control 4.3.2.4, G1: Integrated, Distributed Factory Infrastructure Model

9. Engineered Materials & Surfaces	2.3.4, G2: Parallel Multi-Attribute Producibility Evaluation 3.3.1, G1: Broad-Based Material Modeling Framework 2.3.2, G1: Robust Performance Modeling Environment 2.3.1, G1: Flexible, Complex Representation
10. Freeform Manufacturing	3.3.1, G1: Science-Based Material Modeling Knowledge Base 2.3.1, G3: Direct Product Model Design 2.3.1, G1: Flexible, Complex Representation

Nugget Cross-Walk for Technologies for Enterprise Integration

TEI Nuggets	Related M&S Roadmap Goals (By Document Section & Goal Number)
1. Coupling of Business & Production in Enterprises	2.3.1, G1: Flexible, Complex Representation 2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.1, G3: Direct Product Model Design 2.3.3, G1: Robust Cost Modeling 2.3.3, G2: Enterprise-Wide Product Cost Models 2.3.4, G1: Producibility Requirements Integration 2.3.5, G1: Integrated Life-Cycle Modeling Capability 2.3.5, G2: Total Service Modeling Environment 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.2, G1: Knowledge-Based Assembly M&S Tools 4.3.1.1, G1: Timely, Accurate M&S Processes for Strategic Positioning 4.3.1.2, G1: Timely, Accurate M&S Processes for Market Assessment 4.3.1.2, G2: Rapid Change Response Tools 4.3.1.3, G1: Risk Assessment & Analysis Toolset 4.3.1.4, G1: Enterprise Financial Simulation Environment 4.3.1.5, G1: Real-Time Resource Modeling System 4.3.1.5, G2: Distributed Resource Management 4.3.1.6, G1: Quality Tradeoff Tools 4.3.1.6, G2: Quality Model QA Techniques 4.3.1.7, G1: Extendible Enterprise Model & Reference Architecture 4.3.1.8, G1: Extended Enterprise Management System 4.3.2.1, G1: Real-Time Factory Model 4.3.2.1, G2: Distributed Resource Management Tools 4.3.2.1, G3: Enterprise Knowledge/Skills Management 4.3.2.2, G1: Performance Optimization Systems 4.3.2.2, G2: Adaptive Performance Management System 4.3.2.3, G1: Total Factory Control Model 4.3.2.3, G2: Integrated Factory Monitoring & Control 4.3.2.4, G1: Integrated, Distributed Factory Infrastructure Model
2. Seamlessly Integrated & Interoperable Supply Chains	2.3.1, G1: Flexible, Complex Representation 2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.1, G3: Direct Product Model Design 2.3.2, G1: Robust Performance Modeling Environment 2.3.3, G1: Robust Cost Modeling 2.3.3, G2: Enterprise-Wide Product Cost Models 2.3.4, G1: Producibility Requirements Integration 2.3.5, G2: Total Service Modeling Environment 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.1, G2: Collaborative Analytical Systems 4.3.1.2, G2: Rapid Change Response Tools 4.3.1.3, G1: Risk Assessment & Analysis Toolset 4.3.1.4, G1: Enterprise Financial Simulation Environment 4.3.1.5, G1: Real-Time Resource Modeling System 4.3.1.5, G2: Distributed Resource Management 4.3.1.6, G1: Quality Tradeoff Tools 4.3.1.6, G2: Quality Model QA Techniques 4.3.1.7, G1: Extendible Enterprise Model & Reference Architecture 4.3.1.8, G1: Extended Enterprise Management System 4.3.2.1, G1: Real-Time Factory Model 4.3.2.1, G2: Distributed Resource Management Tools

	4.3.2.1, G3: Enterprise Knowledge/Skills Management 4.3.2.2, G1: Performance Optimization Systems 4.3.2.2, G2: Adaptive Performance Management System 4.3.2.3, G1: Total Factory Control Model 4.3.2.3, G2: Integrated Factory Monitoring & Control 4.3.2.4, G1: Integrated, Distributed Factory Infrastructure Model
3. Manufacturing as an Integrated System (Integrated Product Realization)	2.3.1, G1: Flexible, Complex Representation 2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.1, G3: Direct Product Model Design 2.3.2, G1: Robust Performance Modeling Environment 2.3.2, G2: Fast Background Performance Simulation 2.3.3, G1: Robust Cost Modeling 2.3.4, G1: Producibility Requirements Integration 2.3.5, G1: Integrated Life-Cycle Modeling Capability 2.3.5, G2: Total Service Modeling Environment 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.1, G2: Collaborative Analytical Systems 3.3.2, G1: Knowledge-Based Assembly M&S Tools 3.3.2, G2: Assembly Process Control Simulation 3.3.3, G2: Zero Post-Process Certification 4.3.2.1, G1: Real-Time Factory Model 4.3.2.1, G2: Distributed Resource Management Tools 4.3.2.1, G3: Enterprise Knowledge/Skills Management 4.3.2.2, G1: Performance Optimization Systems 4.3.2.2, G2: Adaptive Performance Management System 4.3.2.3, G1: Total Factory Control Model 4.3.2.3, G2: Integrated Factory Monitoring & Control 4.3.2.4, G1: Integrated, Distributed Factory Infrastructure Model
4. Totally Integrated Life-Cycle Management	2.3.1, G1: Flexible, Complex Representation 2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.1, G3: Direct Product Model Design 2.3.2, G1: Robust Performance Modeling Environment 2.3.3, G1: Robust Cost Modeling 2.3.3, G2: Enterprise-Wide Product Cost Models 2.3.4, G1: Producibility Requirements Integration 2.3.5, G1: Integrated Life-Cycle Modeling Capability 2.3.5, G2: Total Service Modeling Environment 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.4, G2: Integrated Life-Cycle Material Behavior Modeling 3.3.4, G3: Optimized Life-Cycle Packaging 3.3.5, G1: Integrated Material Stream Modeling 3.3.5, G2: Comprehensive Material Flow Models 3.3.5, G3: Remanufacturing Modeling Tool Suite
5. Self-Integrating Systems & Processes	2.3.1, G1: Flexible, Complex Representation 2.3.1, G2: Distributed Product Modeling Collaboration Environment 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.1, G2: Collaborative Analytical Systems
6. Web-Based Manufacturing	2.3.1, G1: Flexible, Complex Representation 2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.1, G3: Direct Product Model Design 2.3.4, G1: Producibility Requirements Integration 4.3.1.7, G1: Extendible Enterprise Model & Reference Architecture 4.3.1.8, G1: Extended Enterprise Management System 4.3.2.1, G1: Real-Time Factory Model 4.3.2.1, G2: Distributed Resource Management Tools 4.3.2.1, G3: Enterprise Knowledge/Skills Management 4.3.2.2, G1: Performance Optimization Systems 4.3.2.2, G2: Adaptive Performance Management System 4.3.2.3, G1: Total Factory Control Model 4.3.2.3, G2: Integrated Factory Monitoring & Control 4.3.2.4, G1: Integrated, Distributed Factory Infrastructure Model

7. Seamless Knowledge Management Across Extended Enterprises	2.3.1, G2: Distributed Product Modeling Collaboration Environment 3.3.1, G1: Broad-Based Material Modeling Framework 3.3.1, G2: Collaborative Analytical Systems 3.3.2, G1: Knowledge-Based Assembly M&S Tools 4.3.1.8, G1: Extended Enterprise Management System 4.3.2.1, G3: Enterprise Knowledge/Skills Management
8. Mature Electronic Commerce	4.3.1.8, G1: Extended Enterprise Management System
9. Human Enablement via Technology	2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.1, G3: Direct Product Model Design 2.3.2, G1: Robust Performance Modeling Environment 3.3.2, G1: Knowledge-Based Assembly M&S Tools 3.3.3, G2: Zero Post-Process Certification
10. Customer-Responsive Concept Development	2.3.1, G1: Flexible, Complex Representation 2.3.1, G2: Distributed Product Modeling Collaboration Environment 2.3.2, G1: Robust Performance Modeling Environment 2.3.3, G1: Robust Cost Modeling 2.3.3, G2: Enterprise-Wide Product Cost Models 2.3.4, G1: Producibility Requirements Integration 2.3.5, G1: Integrated Life-Cycle Modeling Capability 2.3.5, G2: Total Service Modeling Environment