Critical National Need: Intelligent and Integrated Manufacturing Systems

A White Paper for the National Institute of Standards & Technology Technology Investment Program

Submitted by:

Integrated Manufacturing Technology Initiative, Inc.
2025 Castaic Lane
Knoxville, TN 37832

Contact Information:

Richard E. Neal, IMTI, Inc.
2025 Castaic Lane
Knoxville, TN 37832
Phone: (865) 862-5668
Fax: (865) 862-5697
email: RichardNeal@imti21.org

Contributing Organizations:

100s of leaders from American companies and organizations of all sizes have contributed to the IIMS vision and documents

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1.0 Introduction

There is an urgent and critical national need to address the declining competitiveness of the U.S. manufacturing base through aggressive collaborative development of breakthrough, crosscutting technologies that support a strong manufacturing infrastructure. Many societal and technological factors have contributed to the current state of the industry. Globalization has altered the manufacturing landscape forever by blurring the geographic and cultural distinctions that once separated one country's markets and industries from another. Changes, such as shifting low-value manufacturing to low-wage countries, have been gradual. However, the trend that started in the 1980s with "offshoring" of higher-tech and higher-value products continues to accelerate and now threatens the U.S. manufacturing base and hence, the economic strength and health of our nation.

America faces an increasingly urgent challenge in addressing these problems. As detailed in Section 2, numerous studies and reports by government and private-sector organizations have sounded warnings over the past several years. These warnings are underpinned by deeply disturbing statistics:[1]

- Manufacturing lost 2.8 million jobs between 2000 and 2004.
- The cost of doing business in the U.S. is 25% above the world average. China's index is 3%, and the "China price" of a product is 30% to 50% lower than the "U.S. price".
- The trade deficient shot from $100 billion in 1997 to $700 billion in 2007 (Figure 1).
- Domestic content in U.S. manufactured products dropped from 83% in 1973 to 24% in 2004.

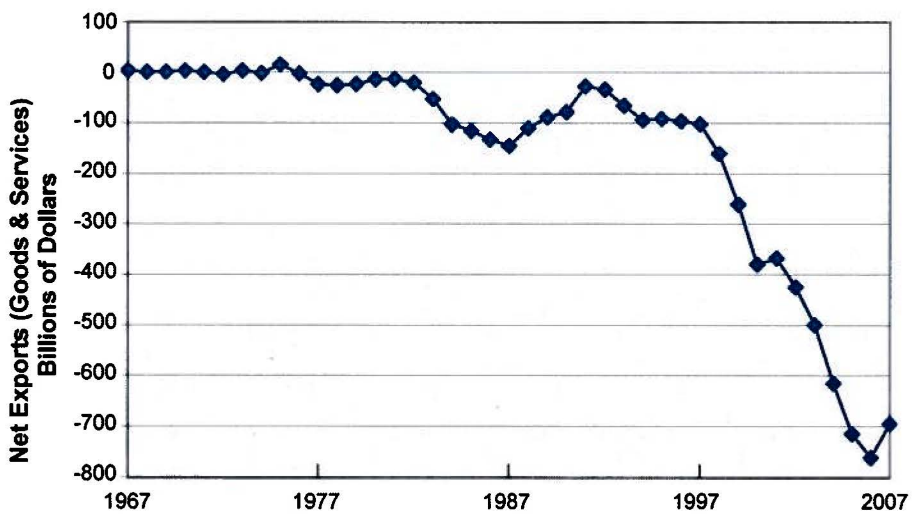

Figure 1. The dramatic decline in balance of payments presents a national crisis. The present situation is not sustainable.

These statistics are even more telling given that the ability to manufacture is critical to our economic well being:

- Manufacturing creates wealth. Every dollar generated by manufacturing spawns another $1.43 for the economy – by far the highest multiplier in any sector of the economy.
- Manufacturing supports two-thirds of the private R&D investment – more than $150 billion a year.
- Manufactured products account for over two-thirds of our exports.

[1] Compiled from data provided by the Bureau of Labor Statistics.

The decline of our economic competitiveness has been slowed only slightly by the efforts of U.S. manufacturers to increase productivity and reduce costs by downsizing, consolidation, outsourcing, and application of Lean and Six Sigma techniques to reduce waste and inefficiency. These approaches have now been largely tapped out, but only given a temporary respite. Without disruptive and game-changing improvement, the decline of our economic competitiveness will accelerate.

The concept of intelligent, integrated manufacturing systems (IIMS) offers great potential to deliver the needed breakthrough change in industrial competitiveness. While many manufacturers have made significant investments in automation and information technologies to improve their manufacturing systems and capabilities, the solutions have generally been limited to purchasing proprietary, off-the-shelf equipment and software or developing their own point solutions to solve a specific problem. Few of these technologies are able to integrate with each other in meaningful ways or to share data and information in ways that enable the systems to operate with any degree of intelligence.

IIMS embraces a holistic view of the product life cycle: a seamless, continuous flow from requirements, to design, to production, to use and end-of-life disposition. Critical information is available when, where, and in the form it is needed. All functions are controlled at the level dictated for total value optimization.

IIMS offers the potential to solve these intractable issues through a radical change in the methodology of design and manufacturing and through the development and deployment of a toolset to support that methodology. The methodology embraces a "multispectral" integration of technologies across the full product life cycle (Figure 2). The process begins with the innovation and conceptualization step, which starts an information and data flow that contributes to the growing model set. In this stage, product and business requirements, maturity, and capabilities assessments lead to possible solutions – scenarios – to be explored and evaluated in an intelligent environment. This environment may take the form of a "dashboard" or "cockpit" where the user specifies parameters and sees the resulting products/process take shape in real time. The visualization process also includes analysis. The user can specify a material to use in a product and instantly see how this material will affect product cost, performance, and robustness. By linking the cockpit to a rich set of scientific and experiential data, models, and simulations, the user may evaluate all design and manufacturing options and explore opportunities for innovation and optimization. It is emphasized that the growing model set provides the foundation for all design and manufacturing decisions, life-cycle support, and end-of-life management. This model-based approach is the key innovation of the IIMS paradigm shift.

The design process extends seamlessly from the conceptualization phase. During this phase, the product definition and process design are enriched to support full design specification. Knowledge-based intelligent design advisors, "trained" for specific design processes and continually learning from operational information, automatically produce the design definitions and requirements for both products and processes. The individual design disciplines (mechanical, electrical, structural, etc.) are integrated into a master design system. Knowledge management systems store the information in repositories where it is readily available for all who need it. The designs automatically flow to, and are pulled by, all involved process systems based on manufacturing requirements and a master schedule generated during the design process. The master schedule is continually updated, so a part of the environment is the "traffic cop" that ensures that the information is at the right place at the right time.

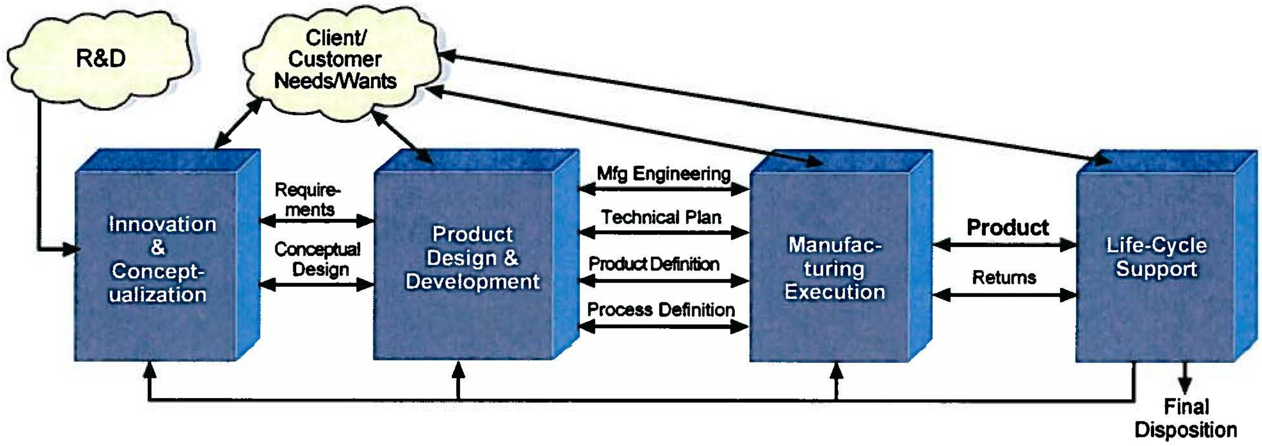

Figure 2. Integrated, Intelligent, Manufacturing Systems Life Cycle Environment

The production environment is an intelligent, closed-loop operation to the fullest extent that makes business sense. A hierarchical architecture ensures that information and control is concentrated where it is needed and only there, resulting in an efficient and well-informed environment. Decisions are made and information is managed at the point of use, with only the information needed passed to the next higher level in the architecture.

The Intelligent, Integrated Manufacturing System will sense and understand the current production environment automatically. This includes everything from the product specifications to available supply network capabilities. The IIMS will assess the currently available information and determine any additional information required for successful operation. The system will then acquire and integrate information from multiple systems or sources (both internal and external) to enable decision-making and control of manufacturing processes and associated business operations of the enterprise and its suppliers. Autonomy is the norm of the IIMS, with the human in the production control loop only for non-routine conditions or situations beyond the bounds of system knowledge.

As the IIMS performs production operations, it continuously monitors events and compares real-time measurements to expected values based on experience and predictive models. When deviations occur, the IIMS detects and assesses the deviations to either take corrective action (e.g., reconfiguring processes or product specifications), or to "learn" from the events and update the models to reflect improved understanding of reality. This is based on real-time status knowledge of all production resources (facilities, equipment, personnel, and materials (raw, in process, finished) and the in-process orders and the demand state of the supply network.

One of the breakthrough technological discriminators in an IIMS is the concept of the self-aware, intelligent model. Each of the intelligent models has the reasoning ability to configure itself to perform the needed function. Each intelligent model in the IIMS owns, maintains, and protects its own data. The intelligent model knows how to ask other models for the information it needs for its own function, and distributes data to other models for their use at the level of detail required and allowed. For example, the product design models may issue a broad request for information about deviations experienced with similar products. The detailed scheduling and process control models on the factory floor answer that request only if they have relevant information to share. The information given to the requesting models is provided in standard formats where available. In the full realization of the IIMS vision, text and data mining systems coupled with intelligent processing capability will negotiate common exchange protocols where standards do not resolve differences.

During these operations, the IIMS generates and manages all of the manufacturing information needed, from product and unit process details through the full production load and related enterprise business processes. The "learning chain" extends all the way to the strategic planning and management functions of the enterprise. The IIMS will understand and represent information in order to assess the needs and security privileges of all requesting functions and to provide information responses at the appropriate level of detail.

The IIMS adds information, knowledge, and additional model fidelity to the development process through each step of the operation. Hence, product and process development becomes a learning environment in which the model set is enriched since it is fully connected to the shop floor and the enterprise. At the point of production operation, the models are rich enough that they become the actual work process controller, distributing to a hierarchy of nodes and decision points all of the information needed for intelligent operation. As the products are made, information continues to flow – between processes, to higher-level processes, and to the strategic and enterprise functions. The mature IIMS is a self-diagnosing, self-maintaining system.

The vision presented above is futuristic, but elements of the tools and technologies to begin realizing this vision exist. R&D requirements that support IIMS development must be defined and satisfied to make the vision a reality – as a cornerstone of a national competitiveness agenda.

2.0 Alignment to TIP Selection Criteria

2.1 Maps to Administration Guidance

> *"In a world where advanced knowledge is widespread and low-cost labor is readily available, U.S. advantages in the marketplace and in science and technology have begun to erode. A comprehensive and coordinated federal effort is urgently needed to bolster U.S. competitiveness and pre-eminence in these areas."*
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> ***Rising Above The Gathering Storm: Energizing and Employing America for Brighter Economic Future***
> National Academy of Science, 2005[2]
>
> *"Americans should not fear our economic future, because we intend to shape it....With more research in both the public and private sectors, we will improve our quality of life and ensure that America will lead the world in opportunity and innovation for decades to come."*
>
> **President George W. Bush**
> State of the Union Address, 31 January 2006
>
> *"We're now playing in a tougher league...China and India are competing for our jobs. The best way to keep those jobs in America is to maintain our brainpower edge in science and technology. We asked the experts who should know exactly what we should do. They've told us. Now we should do it."*
>
> **Senator Lamar Alexander**
> Press Conference, 25 January 2006

The manufacturing competitiveness problem is huge and complex, and far outstrips the ability and resources of a handful of companies, or the Government alone, to solve. The societal challenges that need to be overcome are not being addressed head-on, with the focus and intensity

[2] *RISING ABOVE THE GATHERING STORM*; National Academy of Science, National Academy of Engineering, National Academies Press, 2005.

required to deliver workable solutions having dramatic impact. Specific, high-risk research and development is required to define and deploy critical enabling technologies that support the IIMS vision. Innovation is likewise critical to success: many of the IIMS concepts are not complex, but the technology to make them a reality does not exist.

The IIMS scope is very broad, and touches on a very wide range of technologies, including modeling and simulation, intelligent control, factory automation, enterprise information management, sensing, product life-cycle management, materials science, and knowledge management being foremost. Dozens of companies are working to advanced these and other underlying technologies, as are NIST, DoD, DOE/NNSA, NASA, and other federal agencies. Although it is not possible to realistically quantify specific investments, IMTI estimates the collective national outlay for manufacturing R&D at more than $ 2.5 billion a year. The core issue is, these investments are focused on incremental and stovepiped advances – and are not being coordinated to deliver the holistic and synergistic breakthroughs need to deliver dramatic impact.

The following reference documents key needs identified by government and industry that the IIMS TIP program is intended to address.

In his January 2006 State of the Union address, President Bush called for the establishment of an American Competitiveness Initiative to reassert U.S. leadership in science and technology. Elements of the President's Initiative include expanded investments in math and science education, and a doubling of federal investments in basic research.

The National Academy report, *Rising Above The Gathering Storm*, concludes that our world economic leadership will erode in the coming years if the nation doesn't proactively seek to improve the scientific and technological expertise of its workforce. Recommendation D of the report states, *"Ensure that the United States is the premier place in the world to innovate; invest in downstream activities such as manufacturing and marketing, and create high-paying jobs based on innovation by such actions as modernizing the patent system, realigning tax policies to encourage innovation, and ensuring affordable broadband access."*

A white paper prepared by the National Defense Industries Association, entitled Maintaining a Viable Defense Industrial Base, states that, *"If we lose our preeminence in manufacturing technology, then we lose our national security. The U.S. must accelerate its development of new innovative manufacturing technologies and processes. This is the only thing that will allow us to enable product development and maintain a competitive industrial base."*[3]

The following section provides additional reference data and citations that describe the nature and substantiate the magnitude of the societal challenges relevant to IIMS.

2.2 Justifies Government Attention

Data from Government and industry clearly outline the magnitude of the problem and justify the need to Government attention. According to a study by the Manufacturers Alliance, of the nine largest U.S. trading partners, the overhead cost of manufacturing in the **U.S. is 22% higher** than the average of these partners.[4] Such factors have caused the loss of some 3 million U.S. manufacturing jobs and a continued decline in manufacturing as a percentage of gross domestic product (GDP) – from about 30% of the GDP in the 1950s to about 15% today. Domestic content in

[3] "Maintaining a Viable Industrial Base," National Defense Industries Association, August 1, 2008.

[4] Jeremy A. Leonard, "How Structural Costs Imposed on U.S. Manufacturers Harm Workers and Threaten Competitiveness," Manufacturers Alliance/MAPI, 2003.

U.S. manufactured products has dropped from 83% in 1973 to 24% in 2004, and the "China price" of a product is 30% to 50% lower than the "U.S. price".

More recently, the Bureau of Labor Statistics reported that the U.S. lost 28,000 manufacturing jobs in January 2008. These losses were a leading contributor to the overall loss of 17,000 jobs in the U.S. economy for the month.[5]

Despite the loss of 3.432 million jobs since December 2000, the U.S. manufacturing sector still employs nearly 14 million Americans. The average annual pay in 2006 for a U.S. manufacturing worker was $51,427 compared to $25,567 for retail trade workers, $39,115 for education and health services workers, and $17,781 for leisure and hospitality workers.[6]

Liability and legal costs, regulatory compliance, and tax structures add to the cost equation for U.S. manufacturers. Even though the productivity of U.S. workers improves about 5% per year, these incremental improvements cannot offset the "cost penalty" of doing business in the U.S.[7]

The situation would be much worse if not for the efforts of our manufacturers to retrench, evolve, and improve their productivity. Over the last 15 years, there has been a dramatic shift from original equipment manufacturers (OEMs) as the creators, producers, and marketers of the products, to OEMs as integrators – assemblers and managers of the supply base. This shift results from pressures to increase productivity and efficiency, which has been enabled by both the greatly improved ability to transfer and share information and the exploding ability of the global supply chain to deliver quality materials and components. Because of this change, suppliers such as small machine shops around the world have developed the capability to accept product definition files electronically, plan processing operations, and manufacture the products. Production costs have declined, and the prices for durable goods have not inflated as in other sectors of the economy.

While generally successful, the shift to the global enterprise and supply networks does have difficulties. The communication of technical and business information through the supply chain primarily relies on a paper and electronic paper trail. The lack of interoperability of these systems costs literally billions of dollars each year and is the primary barrier to adaptability and growth for U.S. manufacturers.[8,9,10] Beyond manufacturing, the Center for Information Technology Leadership found that moving to standardizing healthcare information exchange and interoperability would deliver $77.8 billion in annual savings in the United States.[11]

Implementation of the recommendations defined in National Academy report must face the fact that the "gathering storm" is already upon us. Any strategic response MUST be coupled with an immediate "tactical" response to protect the American economy and American jobs until the strategic actions can take effect. The IIMS program, as defined in a reference document pro-

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[5] Manufacturing Job Loss Drives January's Negative Employment Numbers; Congressional Response to U.S. Manufacturing Job Loss Crisis Needed Now, American Manufacturing Trade Action Coalition (AMTAC) Press Release, February 1, 2008.

[6] Source for wage data is the U.S. Census Bureau's Quarterly Census of Employment and Wages.

[7] Next-Generation Manufacturing Technology Initiative, *Strategic Investment Plan for Emerging Process Technologies*, Executive Summary. IMTI, Inc., October 2006.

[8] Michael P. Gallaher, et. al., "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry," www.bfrl.nist.gov/oae/publications/gcrs/04867.pdf.

[9] S.B. Brunnermeier and S.A. Martin, "Interoperability Cost Analysis of the U.S. Automotive Supply Chain," Research Triangle Institute, March 1999, www.rti.org/publications/cer/7007-3-auto.pdf.

[10] The 2006 Kubotek USA Interoperability Survey, www.kubotekusa.com/news_events/press_releases/pr_10_18_2006.html.

[11] Jan Walker, Eric Pan, Douglas Johnston, Julia Adler-Milstein, David W. Bates, and Blackford Middleton, *The Value Of Health Care Information Exchange and Interoperability*, January 2005, www.healthaffairs.org/indexhw.php.

duced by IMTI for NIST, defines an aggressive visionary technical agenda coupled with a migration plan from today's current state to the realization of tomorrow's vision.[12]

2.3 Essentials for TIP Funding

The societal challenges upon which IIMS is focused are not being adequately addressed or sufficiently funded. As previous discussed, industry and Government are investing many millions of dollars annually in relevant technologies, but these investments are not coordinated to deliver a systemic solution. By embracing the IIMS vision under the TIP program, these investments can be better aligned, retargeted, and refocused for a far greater return on the R&D investment. The need for critical enabling technologies such as intelligent, self-defining and self-interfacing models and intelligent sensor networks presents challenges that strongly stimulate the nation's scientific frontiers. These and other IIMS technologies offer tremendous potential beyond the bounds of manufacturing, particularly in the arenas of defense and national security.

The challenges of IIMS are far beyond the scope or ability of any company, or even any industry sector, to address. In the absence of TIP funding, progress will continue with the current state of fragmented, stovepiped, nonaligned technology investments that focus only on specific problems or proprietary business opportunities for technology providers. IMTI has worked for the past several years to develop the IIMS concept, vision, and requirements, leveraging funding from NIST, DoD, and others on aspects of the problem. These efforts include the DoD-sponsored NGMTI strategic investment plans for the model-based enterprise; the NIST- and NSF-funded First Product Correct and Smart Machining projects; the NASA and NIST supply chain integration project; the NNSA Model-Based Enterprise project; and the NASA knowledge applications project. Clearly, the federal Government is the only entity with the perspective to fund a national strategic initiative of this scope and complexity. Likewise, within the Government, NIST is the only agency with the charter and mission to spearhead the nation's response to the societal and technology challenges posed by the IIMS vision. The TIP program stands alone as a alternative for funding high-risk, high-payback infrastructure initiatives such as IIMS.

It should be noted that the authors of this paper understand that a comprehensive IIMS initiative would be beyond the means of present TIP funding. However, defining key components within the context of the IIMS and moving those key enablers forward would provide a critical foundation for a national revival in manufacturing technology.

Potential for Impacts and Transformations

IIMS embraces a holistic view of the product life cycle: a seamless, continuous flow from requirements, to design, to production, to use and end-of-life disposition. Critical information is available when, where, and in the form it is needed. All functions are controlled at the level dictated for total value optimization.

The strongest promise for future manufacturing competitiveness lies in the full realization of intelligent and integrated manufacturing systems supported by a knowledge-enabled workforce that adapts to the changing environment with evolving skills. *Integrated, intelligent models* will help the manufacturers of the future develop the best products that move quickly to market and with predictable cost and performance. The products, processes, manufacturing equipment, resources, and associated business processes will be accurately modeled in a system that simulates the product creation and delivery reality. The modeling environment will address the complete product realization cycle – from innovation and conceptualization, to de-

[12] "Intelligent and Integrated Manufacturing Systems", IMTI, Inc. Last release on August 30, 2008.

sign, to detailed planning, through production, and on through life-cycle support and ultimate product disposition or recycle. The models will apply scientific principles, historical information, and knowledge derived from real-time experience to the extent that the models become accurate predictors of consequences, trusted decision support tools, and controllers of all manufacturing processes. The models will understand the protocols of the various components of the enterprise systems and serve as translators to ensure that systems talk to each other in a plug-and-play environment – hence achieving the elusive enterprise-wide interoperability.

An IIMS will:

1. Autonomously sense and understand the current production environment (everything from product specifications to supply chain capabilities)
2. Determine the information required for successful operation and decision-making, and then acquire and integrate that information from internal and external systems
3. Autonomously make needed decisions and control the manufacturing processes and associated business operations of the enterprise
4. Detect and correct operational deviations from expected results
5. Learn from experience and update underlying models to reflect an improved understanding of reality
6. Generate and manage all the manufacturing information needs – from product and process details through enterprise business and operational processes
7. Provide information on demand in a suitable format and at the appropriate level of detail to all requesting individuals and functions.

The IIMS initiative offers the potential to revolutionize the U.S. manufacturing base, providing manufacturing systems that use the best of human knowledge; augment that knowledge with computer-based systems operating on a set of intelligent models that can "learn;" and optimize every step of the design and manufacturing life cycle. If the technological challenges of IIMS can be met, our manufacturers will produce products with increasing efficiency and bring new, innovative products to market faster, restoring the U.S. to world leadership in manufacturing.

While the vision is in place and the potential benefits are defined, it is appropriate to address how these benefits will be realized. The total task will not be accomplished by any one organization working alone, nor will it be accomplished through any single project. It will require a cooperative effort. The foundation in the IIMS document, funded by the NIST Manufacturing Engineering Laboratory, is in place. Multiple agencies are interested in the work and more than 150 people from many organizations have already been engaged in creating the vision and the plan. NIST TIP funding for IIMS would provide the critical seed that could be cultivated to grow a national program that would transform the nation's manufacturing infrastructure for unprecedented success in the global economy. The results will be measured in the ability to reverse the $700 billion deficit in balance of payments by taking away market share from our offshore competitors – both for U.S. markets and in the expanding global economy.