SMART MANUFACTURING, MANUFACTURING INTELLIGENCE AND DEMAND-DYNAMIC PERFORMANCE

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Abstract

Smart Manufacturing is the dramatically intensified and pervasive application of networked information-based technologies throughout the manufacturing and supply chain enterprise. It responds and leads to a dramatic and fundamental business transformation to demand-dynamic economics keyed on customers, partners and the public; enterprise performance; demand-driven supply chain services; and broad-based workforce involvement. IT-enabled *Smart* factories and supply networks can better respond to national interests and strategic imperatives and can revitalize the industrial sector by facilitating global competitiveness and exports, providing sustainable jobs, radically improving performance, and facilitating manufacturing innovation.

Keywords

Smart manufacturing, advanced manufacturing, performance-based enterprises, supply chain performance, demand-dynamics, energy productivity, sustainability

Smart Manufacturing

Greater manufacturing complexity, dynamics-based economics and radically different performance objectives will require the pervasive application of networked information-based technologies that transform a facilities focus to knowledge-embedded facilities, a reactive operational approach to one that is predictive, incident response to incident prevention, compliance to performance, and vertical decision making to local decision-making with global impact. Existing assets will need to become globally competitive while the installed base of equipment runs its investment life cycle. Capital and operating costs will need to be lowered. Performance will need to be responsive to multi-faceted objectives. Advanced manufacturing and advanced networked information and computation technology will become synonymous (SMLC 2009; SMLC 2011, Warren, 2011).

The manufacturing workforce with substantially more advanced training and skills will not only be fundamental but will also be the key competitive advantage as dynamic management and operation of demand-driven product profiles increase and as innovation and faster time-to-market for new products becomes a key economic driver. Small, medium and large manufacturers will depend on college level training and skills and the manufacturing workforce will re-distribute throughout the supply chain, advanced technology suppliers, innovation and start-up companies. (Kaushal, et. al. 2011, Devol et. al., 2010; Nosbusch and Wince Smith, 2010). Talent and workforce training will no longer be about vertical factory operations but about dynamic interaction, innovation, rapid product changes, and new products to market all with safe and sustainable operations spread across a widely distributed base of small, medium and large companies. Not only will talent and workforce training need to address a dramatically distributed manufacturing approach but also the technologies that support it.

In response, a coalition of companies, universities, manufacturing consortia and consultants called the Smart Manufacturing Leadership Coalition (SMLC) has been on a five year 'journey' to define, plan and implement the game changing roles for networked data and information within and across the manufacturing process. Through a set of consensus-driven processes, Smart Manufacturing has been defined as the dramatically intensified application of '*manufacturing intelligence*' throughout the manufacturing and supply chain enterprise to both lead and respond to a dramatic and fundamental business transformation toward *demand-dynamic* economics, *performance-based* enterprises, *demand-driven* supply chain services and broad-based *workforce involvement and innovation*. This intensification of 'manufacturing intelligence' comprises of the real-time understanding, reasoning, planning and management of all aspects of the enterprise manufacturing process and is facilitated by the pervasive use of advanced sensor-based data analytics, modeling, and simulation (Caminiti, 2011; Chand and Davis, 2010 a & b)

Smart Manufacturing envisions the enterprise that integrates the intelligence of the customer, its partners and the public. It responds as a coordinated, performance-oriented enterprise, minimizing energy and material usage while maximizing environmental sustainability, health and safety and economic competitiveness. Business, operations, management, workforce and manufacturing process transformations are in response to new ways of reasoning about the manufacturing process. These same transformations are facilitated by the application of manufacturing intelligence in a "generate-plan-apply" cycle that is sufficiently accelerated to produce a new demand-dynamic performance orientation.

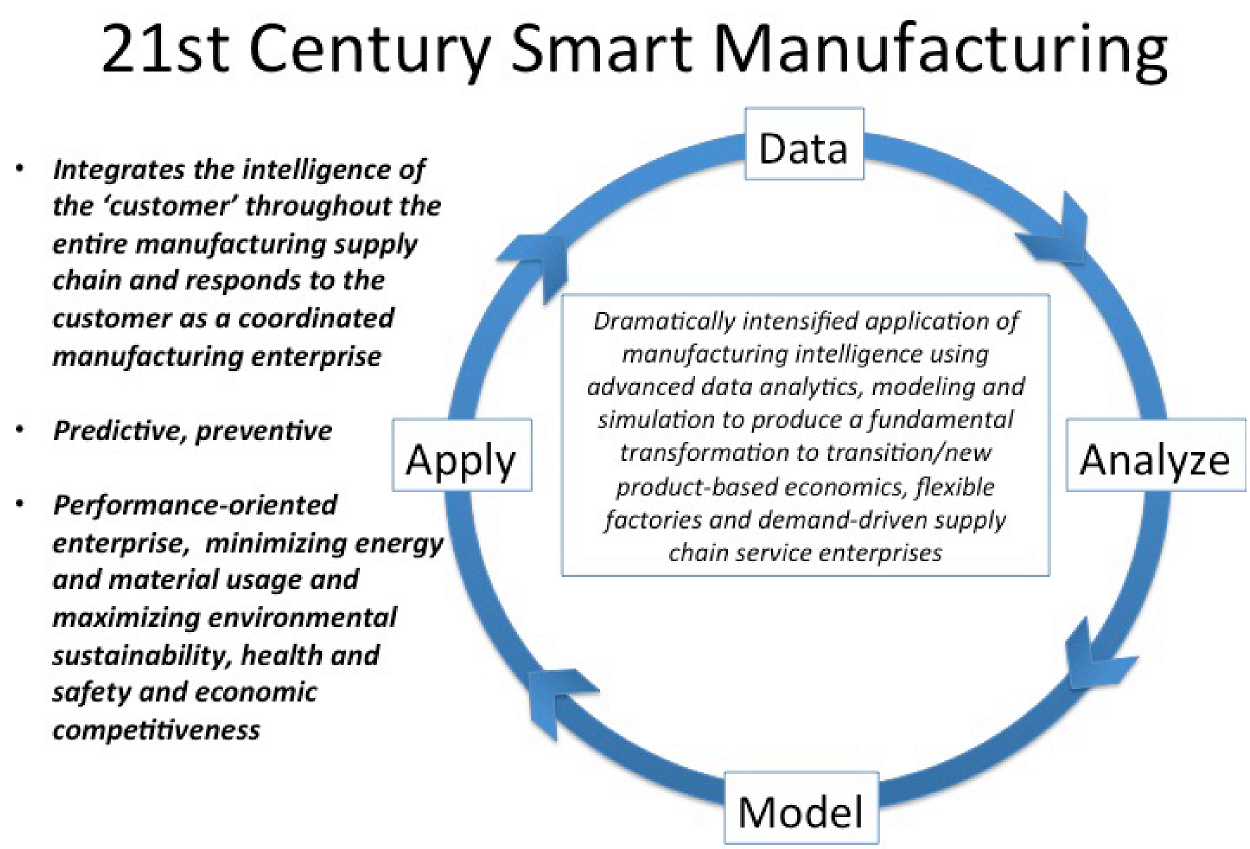

Figure 1: Manufacturing Intelligence

The Smart Manufacturing Leadership Coalition (SMLC)

The SMLC is comprised of 25 large global companies, 8 manufacturing consortia, 6 universities, 1 government lab and 4 high performance computing centers. It has built on earlier NSF funded work by 20 companies and 20 universities to develop a roadmap for Smart Manufacturing (SMLC, 2009). The SMLC is committed to a comprehensive vision in which technology and the business, operating and workforce models are transformed in concert to achieve a steep change in manufacturing productivity with respect to value add product economics. There is no doubt that the deployment of smart manufacturing involves complex on-the-ground detail, difficult applications of technical and operational approaches, difficult business models, the management of significant risk, and the need for research and development in new technologies, business models and organization engineering. The coalition comes together around a set of goals that no one company (even large and global) can accomplish alone (SMLC, 2011):

- Integrate the intelligence of the customer, partner and public throughout the manufacturing supply chain
- Develop the collective capacity to respond as coordinated factory and supply chain enterprises
- Perform against new cross factory and supply chain Key Performance Indicators (KPIs) that are radically different from traditional output/input metrics
- Increase the base of workforce innovation
- Radically increase productivity and quality by lowering the cost of IT infrastructure, sensing and the pervasive deployment of modeling and simulation
- Build equivalent capability across small, medium and large enterprises together
- Build a workforce that is trained in performance oriented decision making
- Define the technology research and development that is needed to achieve the full vision

In June 2011 the SMLC released its latest report entitled, "Implementing 21st Century Smart Manufacturing." The SMLC's comprehensive vision is summarized in six areas of emphasis:

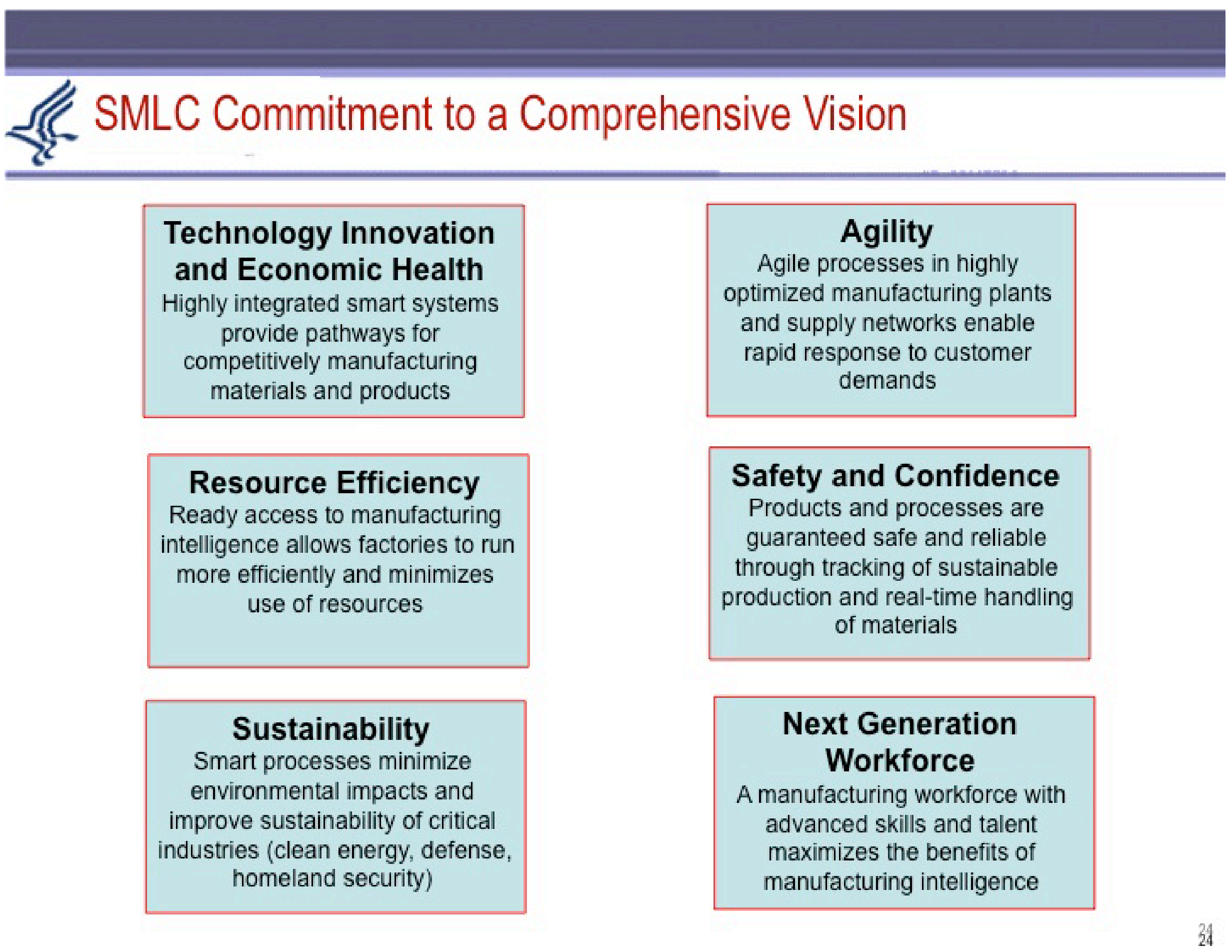

Figure 2: The SMLC's Comprehensive Vision

The report captures the SMLC's consideration of the most *meaningful impact*s in intensifying stage wise application of manufacturing intelligence over a ten-year time horizon:

- *Resources & optimized networks* - 25% reduction safety incidents, 25% improvement energy efficiency, 10% improvement overall operating efficiency, 40% reduction cycle times
- *Product* - Product tracking and traceability throughout the supply chain; pinpoint product recalls that are dynamically managed; product trustworthiness, e.g. defense products
- *Transition economics* - 10x improvement in time to market in target industries
- *U.S. industrial innovation base* - 25% revenue in new products and services; 2x current small and medium enterprises (SMEs) addressing total market; more highly skilled sustainable jobs created.

Game Changing IT

The SMLC has strongly underscored the premise that manufacturing continues to be data rich and knowledge poor, and as a result, operates with constricted decision processes, even in operations using sophisticated modeling and control technologies. New information technologies have been applied to optimize individual unit processes, but Smart Manufacturing (SM) systems that integrate manufacturing intelligence in real-time across an entire production operation remain rare in large companies, and virtually non-existent in small and medium size organizations. Real time management of energy consumption is a perfect example of the contradiction between the potential benefits and barriers to the implementation of SM technology. In many industries, energy is frequently the second largest operating cost; but many companies lack cost effective measurement systems and modeling tools and/or performance and management tools to optimize energy use in individual production operations, much less in real-time across multiple operations, facilities, or an entire supply chain. As a result, business plans and day-to-day management decisions are being implemented with incomplete knowledge of the relationship between product output, energy use and environmental impact, while approximately 30% of the energy delivered to U.S. manufacturing sites is lost as waste heat. Generally speaking, a cost effective infrastructure to integrate real-time manufacturing intelligence and active management above and across the control systems of an entire production operation does not exist today.

Clearly there is a recognized interest and a base of literature on flexible and adaptive enterprise wide optimization and decision making (e.g. Stephanopoulos and Reklaitis, 2011; Wassick, 2009; Engell, 2007, Christofides, et. al. 2007; Grossmann, 2005; Ydstie, 2004). To help distinguish Smart Manufacturing, as a 21st century advanced manufacturing model, from the prior 40 years of implementing information, modeling, control and optimization technologies, advanced robotics and automation systems, and financial and business systems, etc., we can draw some important parallels with the recent Health Care IT initiative especially as it relates to the increasingly broad and pervasive access to health care information and its *meaningful use*. Referring to the December 2010 Report from the President's Council of Advisors on Science and Technology (PCAST, 2010) to the President and Congress entitled, "Designing a Digital Future: Federally Funded Research and Development in Networking and Information Technology", there are meaningful use scenarios for information technology that fundamentally change the existing health care model. We use two of these to draw some analogies for manufacturing;

An 'enterprise' health care record for each patient – There is considerable healthcare related data about each of us that exists across caregivers, treatments, facilities, pharmacists, etc. and across time. Sensors and other observational tools add to a data record of health and state and there is additional important data that we could contribute to our own record. The sheer value of a comprehensive record of history and state is evident with respect to tracking and traceability of therapies, having full information for decision-making, having the information to better gage and manage risk and the basis for verifying the viability of actions and avoiding consistency and interaction errors.

The application of health care intelligence – Data across populations of patients, caregivers, and facilities can be combined with data, information and studies from other sources to produce new insights, educational needs, alternative approaches, etc. Information can grow as scientific and medical knowledge progresses. Data from simulated and virtual clinical studies can continuously grow through validation and update processes. Aggregated data can be used to produce populations of disease or therapy situations that are otherwise impossible to generate locally. "Analyses can apply information to individuals, populations and public health situations and event monitoring carried out with knowledgeable healthcare professionals can detect situations requiring attention and trigger proactive interventions."

By casting these healthcare objectives using smart manufacturing terminology, some parallels with manufacturing are evident when one equates *patient* and *product,* and *health care intelligence* and *manufacturing intelligence*. By analogy, smart manufacturing objectives are not just about applying IT but about game-changing promise to energize innovation, address productivity, achieve new and structurally different performance goals, and drive the competitive advantage of investments.

An 'enterprise' manufacturing record for each product – Sensor data, procedures, specifications, task records and other observational data across a manufacturer and its suppliers create an enterprise data record of history, state, quality and characteristics of each product. These are data that include supply chain, energy grid, business systems, factory, distribution center, and the customer that can be used to build models and new key performance indicators. For example, supply chain data provides the source of raw materials or assembly components. Energy, transportation, distribution, raw material, process, etc. data can be used to build the carbon footprint of the product. The product record provides the global performance perspective for automated and workforce decisions at local points and the basis for optimally balancing global and local management.

Passage of the Food Safety Modernization Act is an illustrative example. The Act essentially requires the Secretary of Health and Human Services to create a national food tracing system to streamline the process of finding the source of contamination in the food supply chain in days rather than weeks or months, should an outbreak occur. Smart Manufacturing provides the enterprise technology, interoperability, operational infrastructure, and approaches for tracking raw materials in plants and the entire supply chain that are needed to address this requirement. A major multi-billion dollar investment for a separate food safety tracking system should not be necessary.

The application of manufacturing intelligence – Armed with information about the product and ability to shape it toward individual requirements, customers become active participants and push demands that ripple in reverse through the supply chain. These demands are responsive to cost, quality, value added customization, environmental effectiveness, etc. Smart manufacturing enterprises adjust with more flexible production of variable volumes of products, become less vertically integrated and more informationally driven. Over the long term, traditional performance metrics based on output/input productivity give way to performance measures related to customization, flexibility, responsiveness, energy efficiency, and environmental effectiveness. The traditional source-to-customer directed supply chain is inverted to form a demand-dynamic supply chain. Additionally, real-time data across products, manufacturing facilities, small and medium enterprises in the supply chain, distribution and customer response can be combined with data, information, models and studies from other sources to produce new insights, educational needs, alternative approaches, etc. Similarly, better data and models of manufacturing processes can be used to predict, plan and/or manage risk around product transitions, dynamic material and energy source situations, and machine operations.

The comprehensive patient record, the aggregation of the data and direct patient involvement all together change a fundamentally centralized process for health care delivery into a highly distributed approach across many kinds of caregivers, including the patient. The information-based processes create a greater base of information and new data for the study of healthcare therapies and techniques. However, this pervasive application of healthcare intelligence remains orthogonal to the complex, expertise-driven diagnoses, therapies and techniques. Their administration remains the responsibility of healthcare professionals to provide and/or manage the facilities required. Similarly for manufacturing, the experience and expertise to address the complexities of tasks and operations that involve chemical, mechanical, material and energy transformations and the various equipment and facilities assets to make and/or assemble a particular product remain with the manufacturers, suppliers, OEMs, etc.

The application of manufacturing intelligence does not change specific manufacturing technologies per se. However, it facilitates their review, improvement, integration, role, effectiveness and dynamic management, and it is the basis for innovations in the overall process of manufacturing a good or product. These *meaningful* impacts of manufacturing intelligence are supported by the "attributes of the smart enterprise" updated from the SMLC's 2009 Smart Manufacturing Operations and Technology Roadmap.

The analogy with Health IT is an attempt to illustrate the role of manufacturing intelligence in the manufacturing process. There are of course notable precedents in the design and engineering domain. For example, there is the collaborative standards and infrastructure work by the FIATECH consortium (FIATECH, 2011), which has made considerable progress in managing data, information and intelligence in the design, engineering and construction of capital facilities. Smart Manufacturing is in fact an extension or continuation of the FIATECH capital program domain (SMLC, 2009)

Alignment of Smart Manufacturing and Advanced Manufacturing

Advanced manufacturing in a U.S. context, its scope, and the need to focus attention on new models of competitiveness have been defined and established through an extensive process conducted by the President's Council of Advisors on Science and Technology (PCAST). The roll up of many discussions and the overall findings are in the June, 2011 PCAST report on Advanced Manufacturing:

> "In this report, we focus in particular on advanced manufacturing, which we believe offers the path forward for revitalizing manufacturing in the United States. The term refers to a family of activities that (a) depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or (b) make use of cutting edge materials and emerging capabilities enabled by the physical and biological sciences, for example nanotechnology, chemistry, and biology. This involves both new ways to manufacture existing products, and especially the manufacture of new products emerging from new advanced technologies."

This report was preceded and supported by a number of earlier federally generated reports (NEC, 2011, PCAST, 2010, STPI, 2010, NSTC, 2008).

These reports thread the roles for networked information systems for advanced manufacturing into (1) discovery and innovation, (2) design and engineering, and the (3) manufacturing process. *Discovery and Innovation* refers to the use of modeling, simulation and data analytics for entrepreneurial discovery, prediction and innovation, especially with respect to new products and new materials. *Design and Engineering* encompasses manufacturing process design, the engineering and design of specific manufacturing tasks or operations and digital engineering that refers to direct design to product approaches. *Manufacturing* refers to the set of ordered tasks, the facilities, and the workforces that are required across factories and supply chains to generate a product from raw material to customer distribution.

Most importantly, and as the PCAST report states, these three roles are linked. New material discovery, product innovation, design and engineering are activities that are facilitated by the manufacturing process. Similarly innovation in the manufacturing process is facilitated by new material and product innovations. Stated alternatively, economic viability and competitiveness is not achievable by invention alone. It is innovation in combination with the economics of product customization, value-add and quality manufacturing that drive competitiveness. Manufacturing is a central and irreplaceable core of a strong, secure economy and manufacturing competitiveness involves attention, investment and research in all. These points are brought out not only in the PCAST reports but also in the Council on Competitiveness Ignite reports (2011) and the 2010 NAM and NCMS reports.

The 2011-2012 critical issues recently published by the Manufacturing Executive Board (2011) provides an industry articulation of how manufacturing needs to change:

- **The Adaptive Organization** responds to the increasingly dynamic nature of competition.
- **Global Value Chain Optimization** recognizes that manufacturing plants, organizations, technologies, customers, and people are nodes in large, complex global supply and demand networks.
- **The Innovative Enterprise** responds to accelerating change faster and the manufacturing function becomes a source of innovation.

- **Factories of the Future** build the products that are needed, when they are needed, and in the quantities in which they are needed.
- **Next Generation Leadership and Culture** responds to rapid market, business, and technological change.
- **The New Workforce** drives industrial change, corporate growth and professional excellence.
- **The Sustainability Imperative** requires companies to embrace innovative sustainability strategies to survive.
- **Game-Changing Technologies** continue to set new standards for the way manufacturing companies innovate, create, source, manage and deliver their products.

How to enact these changes is in significant discussion and/or action at the level of governments. In the U.S., resolution is still in debate and ranging from "leave it to industry and the market" to a set of government activities that could include tax policies, visa changes, patent process changes, new workforce education and training and public-private partnerships (Council on Competitiveness, 2011). Other countries have enacted government level plans to invest and accelerate changes in manufacturing (Science and Technology Policy Institute, 2009; European Commission, 2009, EPSRC, 2011, Fraunhofer, 2011).

Game Changing Examples

There are several excellent examples that provide a glimpse into the full potential of applying manufacturing intelligence across the factory and supply chain enterprise and changing the fundamental manufacturing process.

ExxonMobil has and continues to build an information infrastructure that facilitates the sharing of information and management practices across its units globally. Already deployed are standards and cyber security, life cycle cost and life expectancy management, remote access and data visualization. In progress are global application engineering standards and tools, consistent models, global RTO, refinery and regional planning and scheduling tools, next generator operator tools, global console level monitoring tools and wireless (Sarli, 2006). Under a banner of "Operational Excellence and Sustainability", ExxonMobil is managing approximately 100 cogeneration plants in more than 30 facilities together (Pryor, 2009). It is leveraging scale and integration with 75% of the refining capacity integrated with its lubes and chemical businesses. At the same time it is emphasizing a culture of safety through an Operations Integrity Management System. Finally ExxonMobil is reaping significant benefit through a composition-based refining program that is designed to capture the best value of every molecule at every point in the refinery (Glass, 2009; Quann, 1998). By modeling the real-time process operations with a significantly greater fidelity and building a greater detailed understanding, ExxonMobil is able to radically improve the ability to plan and schedule its product portfolio (Kushnerick, 2005).

Procter and Gamble uses "super computing" to model complex problems while avoiding the need for expensive mock-ups or experimentation (Lange, 2010). P&G uses the phrase "Atoms to the Enterprise" to describe their vision (N.B. the similarity to ExxonMobil's "Molecule Management" phrase.) High performance computing arrays host complex, rigorous calculations such as computational fluid dynamics algorithms to model and solve problems such as the scale-up of the mixing of fluids in commercial scale equipment. Dynamics problems such as the behavior of bottles (full or empty) on a conveying system can also be modeled, avoiding the need to produce physical specimens of a new bottle design. These capabilities allow P&G to answer critical manufacturing questions, e.g. What if, Why not and How Much? faster and at a lower cost.

In Gujarat, India, Tata Motors Ltd. built a $417 million smart factory to manufacture its market-changing Tata Nano – the world's least expensive car, selling at $2,500 in India. The factory in India was designed to incorporate smart manufacturing technologies at every turn – technologies that enable the company to accept custom orders from dealers and adapt on the spot to customers' preferences. Those same technologies have allowed the company to track every part to its source and to confine a recall to just a few cars by having the part tracking and traceability capability to identify where a malfunctioning part was made, what shipments contained the part and what cars had used the part. The enterprise has a manufacturing execution system that captures data and optimizes operations across the entire production process. When smart grids become available, the factory will be ready to connect to them to optimize production to times that energy is most plentiful or least expensive.

In China, Shougang Steel is an example of applying smart manufacturing to an enterprise of 20,000 workers with 100 college-educated workers running blast furnaces from a NASA-like command center. The plant produces 9+M tons of high-grade steel per year, recycles 99.5% of its solid waste and 98% of its water. Particulate matter is reduced to .44 kg per ton, and the steel has a low carbon footprint. There are 10,000+ workers in surrounding small and medium enterprise (SME) businesses and a million new jobs is expected as this smart steel plant becomes a magnet for the Caofeidian industrial eco-city. This is compared to Xinhua Steel as an example of current factory centric manufacturing technology. 65,000 employees with 1000 workers on dangerous blast furnaces produce 6 M tons of average quality steel per year. The plant was closed during the Olympics to reduce particulate matter in the atmosphere by 18,000 tons.

The Smart Manufacturing Business Conundrum

The fact that the enterprise scale implementations of smart manufacturing are outside the U.S. is indicative of the advantages of starting with greenfield vs. brownfield applications. This effect is aggravated with the lack of current market drivers in the U.S and compounded with direct government involvement in other countries that is accelerating change to smart manufacturing (i.e. European Commission, 2009). The overall result is exemplified with numerous examples of company-level deployments of smart manufacturing elements but a limited number of deployments where core change in enterprise manufacturing infrastructure or process is pursued (SMLC, 2009). These are significant implementations of smart manufacturing and illustrate that efficiencies, competitive cost/per unit reductions, and productivity increases are possible and can be sufficiently large to justify investment..

However, ***"if Smart Manufacturing is such a smart idea, why aren't companies already doing it?"*:** Despite major projected impacts of Smart Manufacturing, U.S. businesses continue to hold off, as long as possible, replacing 20 - 40 year old Distributed Control Systems that by their basic architecture preclude the use of many "Smart Manufacturing" Technologies. New long life-cycle investments are further hampered by business, political and regulatory uncertainties. At the company and factory level, vertically segmented investments in (1) compartmentalized infrastructure, (2) uncoordinated applications on replicated infrastructure, and (3) operational assimilation of non standards based modeling and simulation remain more easily justified relative to risky (perceived), expensive, longer term ROI smart manufacturing infrastructure investments. In general, investment in process control and IT is associated with high disruption and cost factors while the value is low when implemented incrementally and in a compartmentalized manner. This is in contrast, for example, to consumer-based electronics in which incremental changes can have high value across a large customer base with minimal disruption. For manufacturing, it is critical to target implementation for more than incremental value and at the same time lower disruption and cost with industry standards, collaboratively developed infrastructure and shared risk. Currently, an investment may be scaled enough to be justified and cost affordable for large companies. Access to the technology by small and medium manufacturers remains essentially prohibited.

Without a modern industrial infrastructure for Smart Manufacturing, incentives will at best push toward uncoordinated applications on replicated infrastructure and non-standards-based modeling and simulation implemented in a piecemeal fashion. The breadth and scale of Smart Manufacturing infrastructure and the technological transformation necessary to achieve industry-wide, company-agnostic benefits is too great a leap in investment for any single or even group of companies to take on (see SMLC, 2011 and Council on Competitiveness Reports, 2011).

Raising the level of Abstraction

The application of manufacturing intelligence is a journey. There is considerable need for new information, modeling and simulation technology research, development and application, and there may be short term advantages gained through proprietary application. However, the primary advantage to investment in smart manufacturing comes from building the competitive experience base of practice collaboratively as these information technologies spread globally. The competitive advantage is not with the technology itself nor is the technology the limiting factor. The competitive advantage is with the workforce and the operational practice in applying the technology to drive supply chain productivity, energy conservation, EH&S and sustainability performance, and competitiveness. Embracing demand-dynamic economics also requires engaging the small and medium, as well as large enterprises in the supply chain.

Immediate gains are expected in material, energy and operating efficiencies, improved EH&S performance, tighter supply chain coupling, and new integrated operating performance metrics. These give way quickly to product tracking and traceability, dynamically managed product trustworthiness and pinpoint product recalls throughout the supply chain. With substantially increased intelligence capabilities, the participation of small and medium enterprises is drastically enhanced to address the total product objective, production surge, transition planning, time to market, and new demand-dynamic performance metrics. Smart manufacturing ultimately becomes the platform for new product and manufacturing innovations. Early priorities for the smart manufacturing enterprise are local-global dashboard performance tools deployed across the enterprise to manage dynamic production, use and storage of essential resources (energy, water, air) (see SMLC 2011).

While there are excellent examples of smart manufacturing elements deployed within some companies, by and large, the U.S. smart manufacturing infrastructure remains balkanized with limited factory and supply chain effectiveness along with significant replicated but uncoordinated investment in information technology, modeling and simulation. It is estimated that as much as 70% of the average cost to manufacture a product goes to non-value-add aspects. Information technology is a significant and growing portion of this, especially when investments cannot be leveraged toward enterprise business or performance goals. It is currently very expensive if not cost prohibitive to deploy information technology and it is certainly financially and operationally risky to trust and assimilate new roles for information-based approaches to operations. Of the 300,000 manufacturers in the U.S. over 95% are small and medium sized enterprises (SME's) that are often suppliers to the larger corporations (NCMS, 2010). For all practical purposes, the cost and capability barriers prohibit the use of modeling and simulation of any kind for these SMEs.

Yet, the industry as whole can benefit if small, medium and large companies have access to modeling and simulation tools together and can become part of network of shared information. Additionally, there are aspects to the IT infrastructure that cannot be solved by a single company no matter how large. Approaching smart manufacturing in a piecemeal fashion further pushes out the benefits and therefore the ROI of a comprehensive approach increasing the financial risk of deploying. All of this is aggravated by the fact that retrofit application of smart manufacturing in U.S. brownfield plants is a much more difficult IT investment than for new greenfield plants which are mostly deployed in other countries.

The central theme of the SMLC is this goal of addressing a radically more aggressive and comprehensive deployment of Smart Manufacturing by raising the level of problem abstraction and solution across large industry segments. As shown in Figure 3 the objective is to bend the curve toward smart manufacturing by addressing key barriers, mitigating risks and demonstrating potential. While transitioning into a coordinated, multi-company collaboration, Smart Manufacturing must also sustain individual company competitiveness.

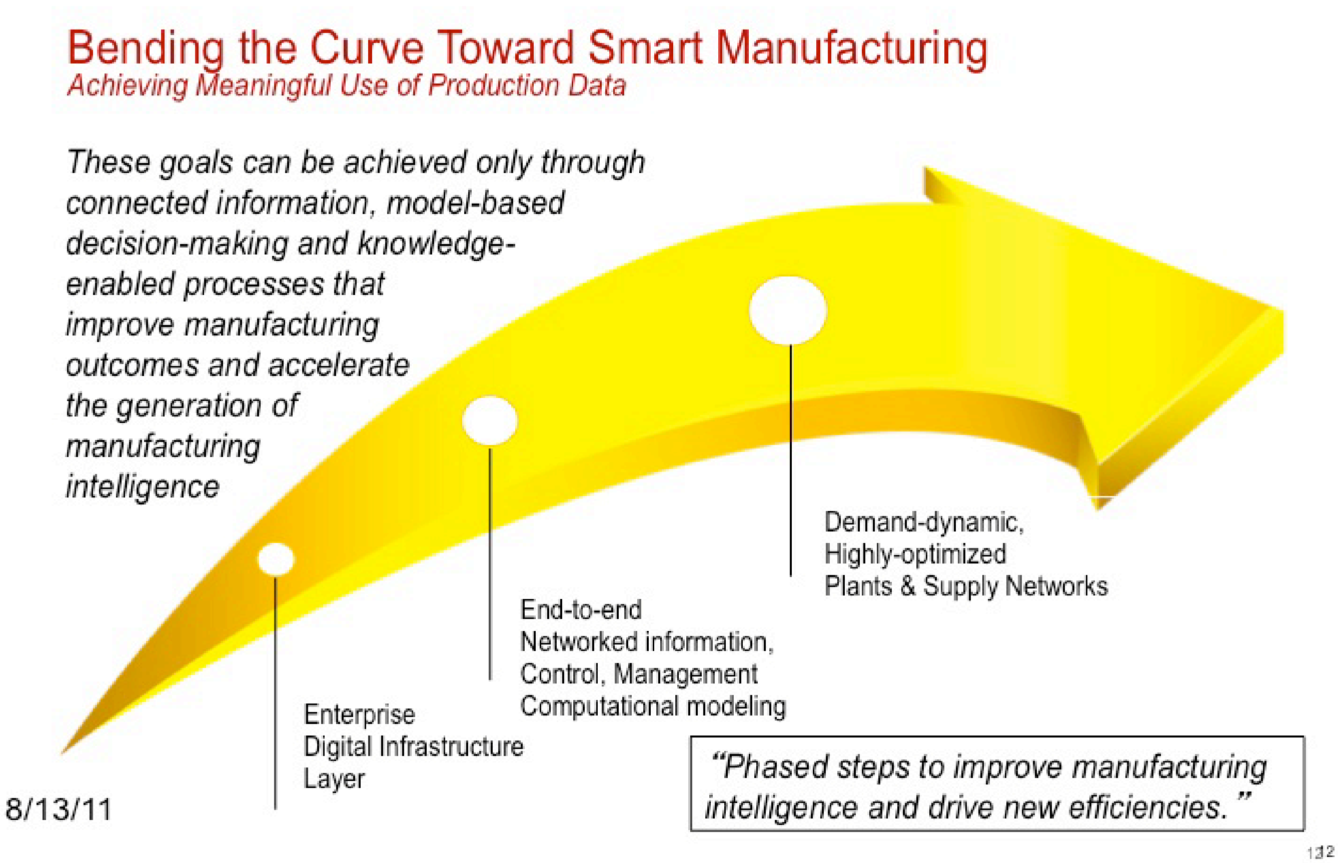

Figure 3: Stage Wise Implementation

To achieve new enterprise demand-dynamic performance, there is a need to collectively hold the vision and progressively work through several key phases, beginning with the foundations of an enterprise digital infrastructure. Each phase needs to define real implementation benefits that start small but maintain a view of the comprehensive end game. Costs need to be substantially lowered through pre-competitive shared infrastructure and a broadened base of innovation, and risk needs to be mitigated through test beds and pre-competitive collaborations on practice.

From a business and operations standpoint, there needs to be a pathway to focus and test new technologies and practices in combinations. The Smart Manufacturing Operations and Technology Roadmap (2009) defines the components as shown:

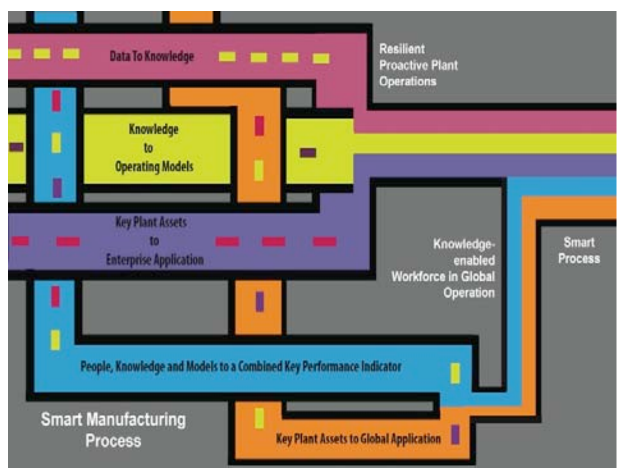

Figure 4: Operations and Technology Roadmap

In terms of application tools and practice, there is the need to establish how to distribute and apply business and operating intelligence through integrated information across tasks, units and companies so that local decisions roll up into global performance objectives. This in turn requires building an involved workforce that is using manufacturing intelligence 'on the ground' to make decisions that drive performance and objectives and not tasks. Moving into a dynamic distributed intelligent manufacturing and innovation model also demands the ability to calculate and manage risk and uncertainty within very different operating structures.

To address the roadmap and the business objectives, the SMLC has raised the level of abstraction focusing on the business model that creates true collaboration to lower costs, share pre-competitive practices and technologies, collectively define research and development areas and facilitate innovation around these. These are captured in a program agenda (SMLC, 2011) that the SMLC is proceeding to implement:

SMLC Program Agenda
Lower the cost for applying advanced data analysis, modeling, and simulation in core manufacturing processes
Build pre-competitive infrastructure including network and information technology, interoperability, and shared business data
Establish an industry-shared, community-source platform and associated software that functions as an "apps" store and clearinghouse
Create and provide broad access to next-generation sensors, including low-cost sensing and sensor fusion technologies
Establish test beds for smart manufacturing concepts and make them available to companies of all sizes

Table 1: The SMLC Program Agenda

A Smart Manufacturing Platform (SM Platform)

The SMLC has focused its immediate action agenda on an SM Platform of shared capacity and capability for (1) substantially reducing development and deployment costs for manufacturing oriented modeling and simulation, (2) reducing costs for IT infrastructure, (3) access to smart manufacturing 'apps' and new models for innovation, (4) an enterprise digital layer for applied manufacturing intelligence and applied Key Performance Indicator (KPI) dashboards, (5) test bed demonstrations, and (6) dynamic involvement of small, medium and large enterprises. These foundational capabilities are supporting application efforts directed at efficiency, environment, product quality, and productivity improvements in the short term. Longer term, smart enterprises can target the dramatic and fundamental shift in manufacturing processes toward demand-dynamic economics, flexible factories and demand-driven supply chain service enterprises as the experience with applying manufacturing intelligence grows.

The SM Platform is an approach that integrates information technology, sensor-driven modeling and simulation, and comprehensive performance metrics in a framework that allows manufacturing organizations to assemble situational awareness, decision support, active management and/or integrated control systems. These management systems can be deployed at a much lower cost than is possible today, and they can extract new levels of intelligence to optimize performance on multiple fronts.

A key aspect of the SM Platform is performance metrics. An overall objective is an open platform that enables active, real-time decisions to manage performance in conjunction with new production performance metrics, and in so doing, establishs new key drivers in business decisions that can be applied across multiple manufacturers. The use of common metrics to measure and benchmark performance characteristics across an entire enterprise can be a powerful management tool and can ultimately be used to form basic operating principles in a company. For example, a broad based, industry defined energy productivity metric available through an application tool kit would allow manufacturers of all types and sizes to assemble customized energy productivity metrics in an energy management dashboard that addresses their specific business needs, e.g. key variables, weighting factors, and ranges of measurement best suited to a particular process or production operation. Where there are collaborative business benefits, relevant data can be shared or used to provide benchmarks.

In information technology terms, the SM Platform contemplates the vision that manufacturing processes, tasks, steps, equipment items, suppliers, and products (through various transformations from raw material to customer products) that are related can be coupled in data and models as nodes on a secure network. Each node is both a producer and consumer of real-time data and information. The pervasive internet availability of this data and information about the manufacturing process opens untapped opportunities for radically improving manufacturing productivity and performance with new manufacturing intelligence that results from tapping new, yet highly targeted, data and information not previously used. By selecting and integrating data and information around specific performance metrics, it is possible to anticipate, plan, manage risk and optimize across manufacturing tasks and suppliers. New degrees of freedom for performance, efficiency and productivity open with the global management of collections of manufacturing units. New forms of benchmarking from equipment to process levels are now possible. The network provides an infrastructure for tracking and traceability of product and product attributes from source to sale and there is now capability to operate with new, global performance metrics in real-time situations. The network is a flexible structure in which the nodes can be aggregated into managed and secure domains such that a domain can be a factory, multiple factories or multiple physically distributed units within a company. Internet domains can also be established for specified kinds of data and information across companies and suppliers or specified kinds of equipment operations for integrated operations, shared metric management or benchmarking.

As importantly, the SM Platform provides a standard protocol for building the internet modeling, simulation and data analytic applications that put the manufacturing internet data into actionable forms. An industry driven SM Platform will provide and manage the protocols and standards for data and the plug and play standards for internet applications. The platform will provide an applications development capability for building common application toolkits, open source and proprietary applications and an “apps store” for distribution and commerce. The platform will also provide cloud computation and repository services for managing particular data and application domains for both company and cross-company situations. Lastly, the platform will provide training, consultation and support for building and applying the internet applications and assimilating them into useful deployment.

A key premise of the SM Platform draws from an analogy with the smartphone operating systems offered by Apple or Google. These systems provide a standardized architecture that promotes rapid, low cost development of compatible applications (“Apps”) by numerous third parties, while maintaining an understood level of security for individual users and the basic operating system. With literally thousands of Apps available to download, smartphone owners can customize the capability of their phone to match their specific interests and needs; discarding, upgrading, and adding new Apps as their personal situation evolves. As in the smartphone example, the SM Platform will act as an overall operating system for manufacturing situational awareness, decision support and management systems. The SM Platform will be open to industry and contain standardized interfaces for compatibility with existing process control systems and data platforms, kits for development of new management applications by third parties, models and simulation software, and energy productivity metrics as Apps in the store. The content and open architecture of the SM Platform will allow manufacturers to evaluate and assemble a combination of controls, models, and energy productivity metrics with the appropriate scope and degree of rigor for their company, regardless of industry or organization size.

Building the SM Platform

Building the SM Platform is non-trivial requiring significant cross-industry collaboration and agreement and it depends on acceptable internet and cyber security protocols and practices already in place. Figure 5 shows four additional ‘Difficult Problem’ areas described as a stack of application and infrastructure layers that require industry coordination. The four ‘meta’ bubbles describe areas of definition and involvement for manufacturing facilities. The integration of activities to address these difficult problems in a coordinated way with suppliers and cross-linked manufacturing facilities forms a *Smart Manufacturing System.*

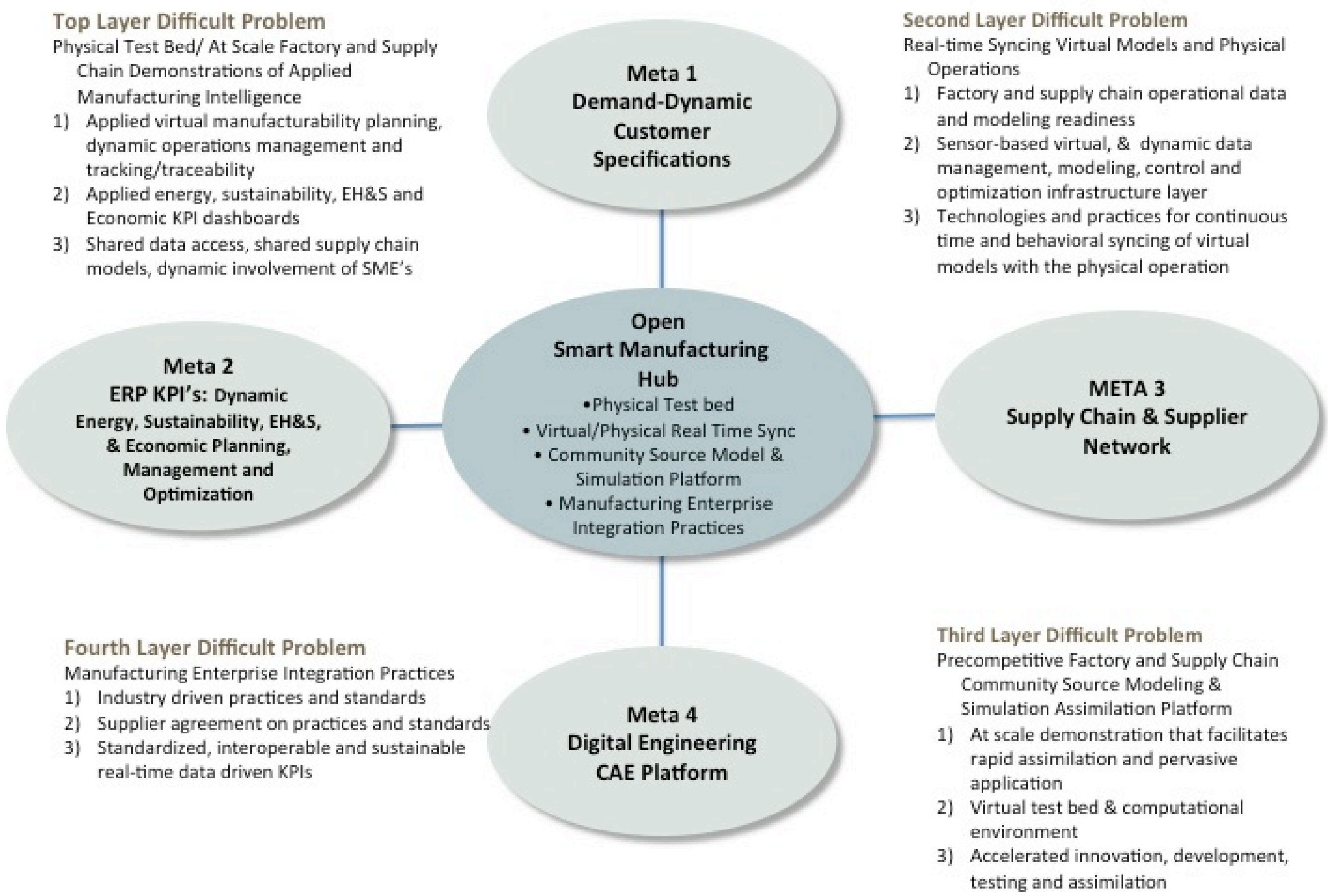

Figure 5: The SM Platform

More specifically, the four meta areas define key enterprise outcomes that set the stage for new business and operating models for manufacturing that recognize the interconnected roles of all entities in the manufacturing enterprise. The primary objective is to establish a shared pre-competitive component to the business model and then organize/develop the technology to support it. Proceeding from 4 to 1, there is a need to draw upon distributed digital engineering and computer-aided engineering information and interface, combining this knowledge with the dynamics of the manufacturing process. Meta 3 describes the need to collectively address information and decision making across the supply chain and the supplier network forming the overall enterprise that impacts various new Key Performance Indicators. Meta 2 is about the definition and collective agreement on KPI's that drive dynamic performance management. These will certainly include energy, sustainability, EH&S, productivity and economics. At the highest level, the enterprise is responsive to demand-dynamic customer specifications. To achieve these goals, there is a need to address cross industry enterprise integration practices, pre-competitive and competitive modeling and simulation assimilation, real-time syncing of virtual and physical models and the development of at scale demonstrations.

Figure 6 illustrates the function of the SM Hub. Bringing pre-competitive and competitive spaces seamlessly together to facilitate new collaboration models produces a construct in which an industry-driven Virtual Smart Manufacturing Hub (V-SMH) provides the 'heart' and the 'circulatory system' that brings the platform to life. The V-SMH links manufacturers to form physical test bed enterprises where knowledge is managed and exchanged within competitive and intellectual property constraints. It provides a clearinghouse for integration practices and it facilitates the collaboration business models to bring the players appropriately together.

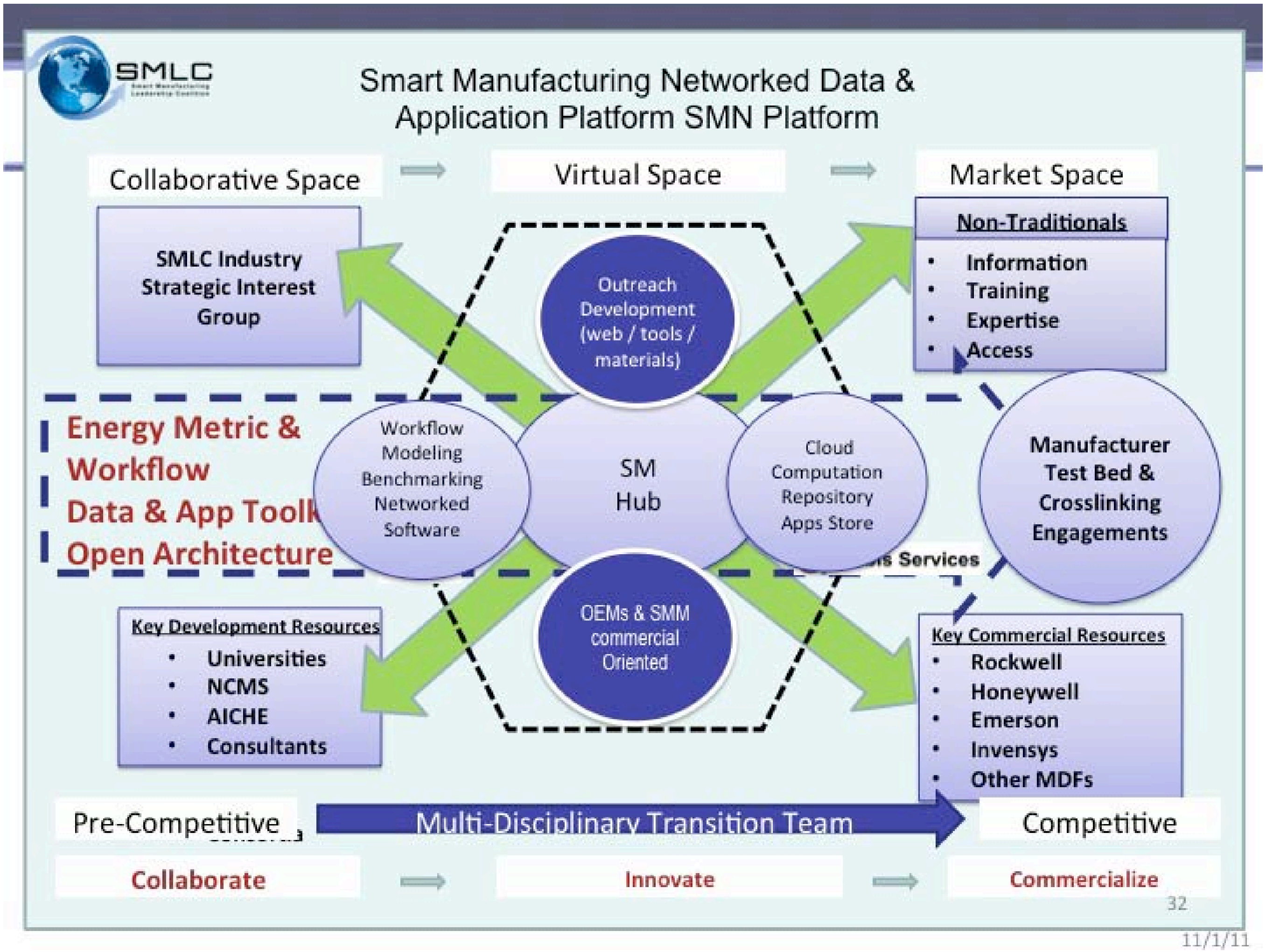

Figure 6: The Hub of SM Platform

To address the high cost of software, its customization for individual manufacturing facilities, and the difficulties of on-going support, the V-SMH provides industry-driven processes, workflow toolkits and/or cloud facilities by which a manufacturing enterprise can come together within a business model to define a global management need, e.g. active energy management, or product tracking and traceability function. The V-SMH addresses standards and protocols to work across multiple vendor platforms and to deploy software that is not easily applied across sectors or that is cost prohibitive. Lastly, the necessary application and software development, certification, verification and validation capacity to design, develop, distribute and implement sensor-driven modeling and simulation applications and workflows are provided.

Specifically, the V-SMH will:

- Provide workflow tools that will make it possible to assemble and stage the real-time data supporting application models and metric calculations into coherent active performance management dashboards
- Support workflow compatible applications for validating data, projecting performance, and scenario-based decision risks
- Provide rapid evaluation of models and toolkits to determine the “right” rigor of the model and the “right” timeliness of data to meet performance objectives with the goals of using the right model and right real-time time data to achieve a specific objective
- Making it possible to progress in increasing levels of modeling sophistication as business needs and experience grows

- Enable manufacturers (from small to large) to adopt and customize software
- Standardize models to enable consistent use and results, and enable exchange of model input/output across various enterprises along the supply chain
- Make software development faster, easier, and cheaper
- Improve usability in diverse environments
- Engage entrepreneurs to develop new software modules

Building on an industry-driven reference architecture that ensures proprietary platform interoperability, the V-SMH comprises of integrated precompetitive and competitive spaces to provide a comprehensive array of services and resources that include collaboration tools, application and expertise markets, software development, an apps store, resources and facilities, direct operational tools and manufacturing facility cross-linking. The SMLC has demonstrated that manufacturers, suppliers and IT providers can come together to establish new collaborative business models for the SM Platform and to work through considerable intellectual property and competition barriers to facilitate collaboration on the pre-competitive infrastructure provided by the Platform.

The V-SMH uses workflow and services to seamlessly integrate:

- Research with application functions
- Precompetitive collaboration with proprietary and competitive value-added processes
- Virtual and physical integration with synchronization tools and processes
- Community-source with production software practices
- Research with secure commercial computational environments
- Open-source distribution, apps store with comprehensive packaged software access

The competitive aspects of the infrastructure and the SM Platform are needed to manage the production design requirements for manufacturers and large original equipment manufacturers (OEMs). Cyber security is a major requirement that needs to be addressed with state of the art practices that meet user requirements. While the workflow toolkits can become general apps, the workflows themselves remain proprietary to a particular manufacturer. Additionally, there can be ITAR export control, proprietary data requirements on the modeling and simulation results and/or service-level agreements for computer resources that may be needed to guarantee a certain processing capacity, uptime, backup, or auditing requirement. Materials or simulation models might only be available to specific licensed customers, or can be linked for simulation inside some workflow while the source code remains on a protected IP. Authentication, authorization, auditing, reservation, metering, billing all have to be coordinated.

New Technology R & D

Smart manufacturing fundamentally depends on networked-based information technology, modeling and simulation. In raising the level of abstraction, smart manufacturing is seen as a new enterprise operating model in which demand-dynamic economics, active, performance-driven management, and broad-based innovation are achieved by using technology to distribute global business and operating intelligence throughout the enterprise to the local point of decision. Greater operating complexity and resiliency involve greater levels of automation, while greater strategic management and innovation require a new, involved workforce making decisions that drive performance and objectives, and not tasks. Predictive modeling and simulation are used to explicitly manage risk and uncertainty (i.e. Christofides et. al, 2007).

This leads to a view of the manufacturing enterprise as a cyber physical system itself. With each task, process, company, supplier and person as a node on an overall network, technology needs to be researched, developed and constructed from a different perspective than it is today. Examples in discussion or planning today by the SMLC include:

1. The long-term success of smart manufacturing depends on new economic, business, performance and collaboration models such that at any given time the economics carries phased objectives forward. There is considerable need to research, develop, prototype, practice and build experience with new collaboration business models that can evolve in a coordinated manner together with the development and application of existing technology that gives way to new technologies.
2. There is considerable need for focusing education and training so that the science, engineering and operating practices for smart manufacturing and the necessary skills and expectations for the workforce are always in concert.

3. Monolithic static and real-time modeling structures need to be redesigned for shared infrastructures, requiring architectures that are oriented toward plug and play modules, apps store-like distribution models, competitive and pre-competitive management and managed crowdsourcing development approaches.
4. Software development and application architectures that support easier, lower cost management and operational sustainability are vital.
5. Richer, lower cost sensing and actuation technologies need to be combined with richer real-time analytics, fusion and interpretation to build greater manufacturing intelligence.
6. There is a need for tools and rapid evaluation procedures for assessing the 'right' rigor of a model for a particular objective as well as the means to progress stepwise with model sophistication, i.e. how to deploy the right model for the objective at hand. Similarly there is a need to assess and adjust for the right time for data collection and computation to take appropriate action, i.e. what is the right 'real time'.
7. The calculation and projection of global and local decision and/or action risk is a critical requirement. Recognizing this is an operational dependent activity, there needs to be tools that allow risk calculations to be implemented and tuned.
8. Modeling, control, optimization and planning applications must become integrated to an extent that they become indistinct and at the same time they must be distributable for local responsive actions but in the context of global impacts.
9. Modeling and simulation architectures need to be redesigned to accommodate modern processor architectures allowing breakthroughs in higher fidelity, real-time modeling.
10. Computer process architectures themselves need to be redesigned for assured real-time actions involved with greater levels of active management and automation.
11. There is a need for new technologies and approaches that facilitate real-time synchronization, verification and validation of enterprise data and models with the current state of the physical operation.
12. Human-centered dashboards and interfaces need to reflect new expectations for distributed decision-making.

Conclusions

The global market and global forces are driving threshold changes in all segments of a world-wide manufacturing industry. Innovation and customer demand-dynamics will be key to economic value, pushing toward faster and more frequent product transitions while operating globally and at the same time responding to local markets with greater resiliency. The vertical organization of factories will give way to significantly more business-to-business interaction among small, medium and large enterprises. Job growth will not depend on policies that promote increasing unskilled, high labor oriented manufacturing but on policies that build the business climate. The focus on environment, health and safety compliance will increase and there will be increased risks of non-compliance. Social conscientiousness will be heightened while the demands of a growing world population increase. There will be greater pressure to manage risk and uncertainty and a heightened need for radical improvements in energy and raw materials productivity. Energy, environment, sustainability and safety performance will become significant economic and competitive advantages.

The Smart Manufacturing Leadership Coalition has reached a consensus on the essential need for an industry-driven collaboration via an SM Platform that is centered on a Virtual Smart Manufacturing Hub as the construct to move business and technology change forward in tandem. Applying the construct addresses large industry-shared challenges that no single company, however large, can fully address. Most importantly, the SM Platform recognizes that Smart Manufacturing is most responsive if networked sensor-driven modeling and simulation are applied pervasively in the context of new demand-dynamic, performance and innovation oriented business and operating metrics.

The SM Platform is, therefore, designed to address barriers to technology integration across all functions and people, break through the continued focus on optimizing individual unit processes and move away from a "more of the same" focus that is reaching a point of diminishing returns from future investments in advanced manufacturing technology. The SM Platform is also designed to extend modeling and simulation capabilities to small and medium enterprises that do not have the capacity to deploy. It addresses these issues with a new approach to the way technology and data are used throughout a manufacturing company, from business planning, to the production facility, to modeling and control, to improved work processes, all driven by empowering people with actionable information in real-time. The Platform uses untapped manufacturing intelligence, removes constraints in the decision process, and delivers information in the right context, at the right time, to the right user (whether a machine or person). This transformational approach can lead to new levels of business optimization as organizations become smarter about the performance metrics and the way they collect information to measure optimal performance.

The Smart Manufacturing Leadership Coalition (SMLC) have combined respective efforts and strengths to begin building the V-SMH, the foundational construct for the V-SMH as an industry, university, and government collaboration that facilitates the necessary capabilities, processes and structures.

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