Mapping Smart Manufacturing System Architectural Drivers to Smart Factory Architectural Requirements: A Planned SMLC-NIST Partnership Study (2012-2015)

Project Summary

Smart Manufacturing is the dramatically intensified and pervasive application of networked information-based technologies throughout the manufacturing and supply chain enterprise. It is both responsive and leads to a dramatic and fundamental business transformation to demand-dynamic economics keyed off of customers, partners and the public; enterprise sustainability, energy, health, safety and economic performance; demand-driven supply chain services; and broad-based workforce involvement. Sensor-measurement driven modeling and simulation provide the capture, generation, access, application, and innovation vehicles for building actionable and progressively sophisticated manufacturing intelligence that underpins the transformation. IT-enabled *Smart* factories and supply networks can better respond to national interests and U.S. strategic imperatives and can revitalize America's industrial sector by facilitating global competitiveness and exports, providing sustainable jobs, radically improving performance and facilitating manufacturing innovation [4].

The Smart Manufacturing Leadership Coalition (SMLC) is a coalition of 25 companies, seven universities, eight consortia, and one government lab encompassing the chemicals, refining, auto, food, pharmaceutical, software, and automation industry sectors. Based on industry input, the SMLC has identified a number of operational management needs with significant economic and performance benefit that are priority interests by cross-sections of companies across a number of industry segments - refining, gas, food, automotive, power generation, and heating/forging/machining. These define objectives of Smart Manufacturing Systems that have been defined today and can be grouped as follows:

Smart Machine Operations

- In production machine-product management
- Benchmarking machine-product interactions
- Integrated dynamic management of machine-electrical power interactions
- Adaptable machine configurations

In Production Use of High Fidelity Modeling and Simulation

- High fidelity modeling for better management
- Rapid qualification of components and products
- In Production Integrated Computational Materials Engineering

Dynamic Business and Operational Tradeoff Decision-Making

- Dynamic performance management of global integrated metrics
- Untapped cross factory degrees of freedom for optimizing efficiency and performance and compressing time

Supply Chain Management

- Supply chain variability reduction and management of risk
- Tracking and traceability

The defining common technical threads are time, sensor-based data collection and management, model synchronization, integrated performance metrics and workforce-cyber-physical requirements. Multiple layers of data management and modeling are needed to cover the full scope of automation, control, decision, management and optimization and still achieve a computationally tractable, actionable and real-time data driven modeling and simulation capability at scale.

The SMLC has identified that the U.S. manufacturing industry could construct foundational pre-competitive infrastructure for deploying multiple, integrated Smart Manufacturing systems (SM systems), thereby enabling multiple simultaneous operating objectives. These SM systems, when constructed on foundational infrastructure; integrated and deployed vertically and horizontally throughout the enterprise, produce untapped manufacturing intelligence for further performance innovation. Provisioning this foundational infrastructure as a shared Smart Manufacturing Platform (SM Platform) lowers the barriers to implementing sensor-measurement-driven modeling and simulation around cost, complexity, ease-of-use, and measurement availability. By lowering the cost and effort to implement and support these technologies, small and medium sized companies are incentivized to adopt new manufacturing practices that improve their performance. The SM Platform supports the integration of operational intelligence in real-time across an entire manufacturing operation, providing the potential to achieve transformational advances in a variety of performance metrics, including energy productivity, yield, production cycle time, quality, supply chain integration, and environmental performance. The infusion of information and the ensuing actions whether automation and control or decision and management need to be integrated in time and fully synchronized [1].

The SMLC vision is to establish an initial SM Platform of sufficient capability to support near term development and application of SM systems with well-defined performance metrics and use of existing technologies and models. The objective is to take a “first step” with the SM architecture and build first experiences with the most basic applications that ensure measurable benefits. With experience, objectives can move to next levels, metrics can be more aggressive and SM systems can be more sophisticated and greater in scope.

The SMLC has identified four foundational architectural drivers for the SM platform: (1) Build SM Systems as customizable workflows constructed from composable apps, (2) Drive the construction of SM Systems with composable metrics, (3) Reduce the cost of deploying SM Systems with shared pre-competitive infrastructure, concentrating IP in an application layer, and (4) Develop an architecture that supports a broader base of application developers. Overall, the architecture needs to be able to scale and have the flexibility to grow with increasing sophistication. The SMLC has tested feasibility of an SM Platform that reflects these drivers simultaneously.

The proposed SMLC-NIST study is a $100,000 per year, three-year study that progressively addresses definitional, qualification and validation of common functional drivers for a workflow-based application code deployment architecture that simultaneously underpins the shared SM Platform and the associated Smart Factory Platforms and ensures their interoperability. Over three years, the study will focus on the smart manufacturing objective categories, “Smart Machine Operations” and “In-Production Use of High Fidelity Modeling” that are factory centric. Addressing these defined objective categories provides key foundational architecture for the other two objective categories that are cross-factory in nature.

By analyzing particular example smart manufacturing system problem areas in consultation with our SMLC partners as well as in the literature, the study will identify industry-developed drivers that define the architectural needs of a platform. Industry-described drivers of the platform architecture include but are not limited to (1) desired performance opportunities and objectives, (2) the kinds of performance metrics that define those objectives, (3) what constitutes an actionable window in time, (4) expanse and scale of real-time sensor-based measurement data, (5) where and how modeling and simulation are used, (6) the roles of people in decision-making and actions (7) modeling and simulation requirements, (8) measurement and data requirements, (9) workflow structures, (10) the physical and virtual roles of time, (11) where standards would be beneficial, (12) security requirements and the (13) baseline qualifications for the smart factory. These industry-oriented architectural drivers will then be mapped into a next level set of functional requirements for the SM Platform and Factory architectures.

Year 1 - 2 – Define and develop the common workflow-based data management, modeling and simulation and performance metric architectural drivers for smart machine operations and benchmarking. Map these drivers into a draft set of functional requirements for the platform architecture. In consultation with NIST, identify major gaps and barriers.

The nature of machine benchmarking is expected to result in a focus on defining the architectural drivers for machine and process level sensor-based data collection, validation and management of data, the use of data for dynamic management and adaptability of the in-production use and performance of the machine for different product manufacturing uses and definition of machine and process level performance metric components and measurements.

Year 2 - 3 – Define and develop the common workflow-based data management, modeling and simulation and performance metric architectural drivers for in-production use of high fidelity modeling and simulation based on industry problem examples. Similar to that described above, map these drivers into an extended set of functional requirements for the platform architecture and, in consultation with NIST, identify major gaps and barriers.

The nature of in-production use of high fidelity models is expected to extend the architectural requirements to include more stringent constraints on point in time existence of measurements, their validation, the time and completion expectations of workflows, the use of reduced order models, the use of data to synchronize models with physical operations, and verification, validation and trustworthiness of cyber workflow systems.

Project Background

The Smart Manufacturing Leadership Coalition (SMLC): The SMLC is a coalition of 25 companies, seven universities, eight consortia, and one government lab encompassing the chemicals, refining, auto, food, pharmaceutical, software, and automation industry sectors. It is organized around an implementation agenda for Smart and Collaborative Manufacturing and is currently comprised of the following that have expressed interest in co-investment partnerships: Air Liquide, Alcoa, Applied Materials, CH2MHill, Cisco, Dow, DuPont, Eli Lilly, Emerson, ExxonMobil, Ford, General Dynamics, General Mills, Inc., General Motors, Honeywell International, Invensys, Kraft, Merck, Microsoft, Owens-Corning, Procter & Gamble, Pfizer, Praxair, Rockwell Automation, Sustainable Operations Solutions, Carnegie Mellon University, Purdue, Georgia Tech, RENCI/North Carolina Chapel Hill, UCLA, University of Texas Austin, U. Wisconsin Milwaukee School of Management, American Council for an Energy Efficient Economy, American Institute of Chemical Engineers, Council on Competitiveness, Institute of Paper Science & Technology – Georgia Tech, Manufacturing Institute, National Center for Manufacturing Sciences, National Council for Advanced Manufacturing, Putman Media, Denise Swink, Spitzer and Boyes, and Oakridge National Laboratory.

The SMLC brings a sustained collaboration of practitioner and IT provider companies reflecting a cross section of continuous, batch and discrete manufacturing structures as well as supply chain and energy intensive industries. The SMLC has identified a cross section of practitioner company test bed sites and a partnership for SM platform commercialization focusing on radical improvement in sustainability performance, radical reduction of design to production times; extreme flexibility for large scale to small scale production - including ultimate flexibility in component changes and insertion; ensuring trusted sources and contained product recalls, substantially improved risk management across integrated operations and knitted relationships with suppliers throughout all enterprise operations. The development and planning by the SMLC has identified a number of categories of Smart Manufacturing system opportunities as previously described. Several of these will provide industry basis for identifying architectural drivers.

Defining the Key Elements of a Smart Manufacturing Systems Architecture: Smart Manufacturing is the dramatically intensified and pervasive application of networked information-based technologies throughout the manufacturing and supply chain enterprise. Sensor-driven modeling and simulation provide the capture, generation, access, application, and innovation vehicles for building actionable and progressively sophisticated manufacturing intelligence that underpins the transformation. A **Smart Manufacturing System (SM System)** is the operational deployment, business assimilation and manufacturing transformation associated with the pervasive application of manufacturing intelligence to address one or more performance and/or business objectives [4].

The SMLC has further defined SM as a multi-dimensional approach that is applied vertically across layers and horizontally across the manufacturing process, and involves all aspects of the manufacturing product lifecycle. This is illustrated in Figure 1. The defining technical threads in SM are time, synchronization, integrated performance metrics and workforce-cyber-physical requirements. The SMLC asserts that, foundationally, multiple layers of data management and modeling are needed to cover the full scope of automation, control, decision, management and optimization and still achieve a computationally tractable, actionable and real-time data driven modeling and simulation capability of such a large scale. Layers are formed as a result of spatial and temporal scale limitations on real-time modeling, delineators on human-centered interaction vs. automation and synchronization and computational tractability requirements and how these factors combine to achieve defined performance objectives. These need to be taken into account as architectural drivers.

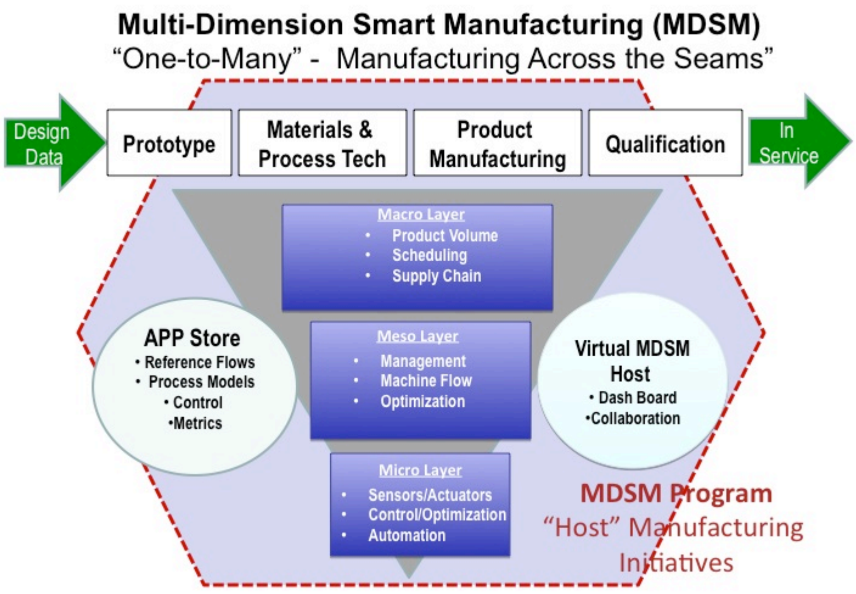
The SMLC has empirically agreed on the existence of at least three manufacturing layers to accommodate the time scales and cyber-physical requirements in a production operation. The micro production layer involves compartmentalized control and automation installations, the meso' layer involves real-time management of the tradeoffs in operating performance across multiple process units within an entire factory, while the macro layer reaches across an entire factory and supply chain enterprise. Achieving real time, dynamic interfacing of all levels (micro, meso, and macro) in breadth and depth is the ultimate of what is defined as Smart Manufacturing ("SM"). In this context, SM is the application of networked based manufacturing intelligence and integrated performance metrics throughout all layers, also shown in Figure 1.

A Smart Manufacturing Platform: The SMLC has identified that the U.S. manufacturing industry could construct foundational infrastructure for deploying vertically and horizontally oriented manufacturing intelligence to collectively strengthen capability. Building a shared Smart Manufacturing Platform (SM Platform) would lower the barriers to implementing data-driven modeling and simulation around cost, complexity, ease-of-use, and measurement availability. By lowering the cost and effort to implement and support these technologies, small and medium sized companies are incentivized to adopt new manufacturing practices that improve their performance. Creating an open architecture platform to market and use models is key to stimulating entrepreneurs to develop and license their IP in the form of models that can be plugged into the platform [1].

The SM Platform integrates operational intelligence in real-time across an entire manufacturing operation, providing the potential to achieve transformational advances in a variety of performance metrics, including energy productivity, yield, production cycle time, quality, supply chain integration, and environmental performance. The infusion of information and the ensuing actions (whether automation and control or decision and management) need to be integrated in time and fully synchronized. This enabling infrastructure involves a multidimensional virtual shared platform that provides access to the tools and capabilities that are needed to interface with the physical and human systems but also can become an integral virtual element of a cyber-physical workforce system ("CPWS").

The Smart Factory can interoperate with the SM Platform as a locally deployed Virtual Manufacturing Demonstration Facility (VMDF). To effectively scale across small, medium and large enterprises, the virtual platform needs to be shared. This vision of a multi-dimension smart manufacturing ("MDSM") host is illustrated in Figure 1.

Figure 1: Multi-Dimension Smart Manufacturing applied across manufacturing layers



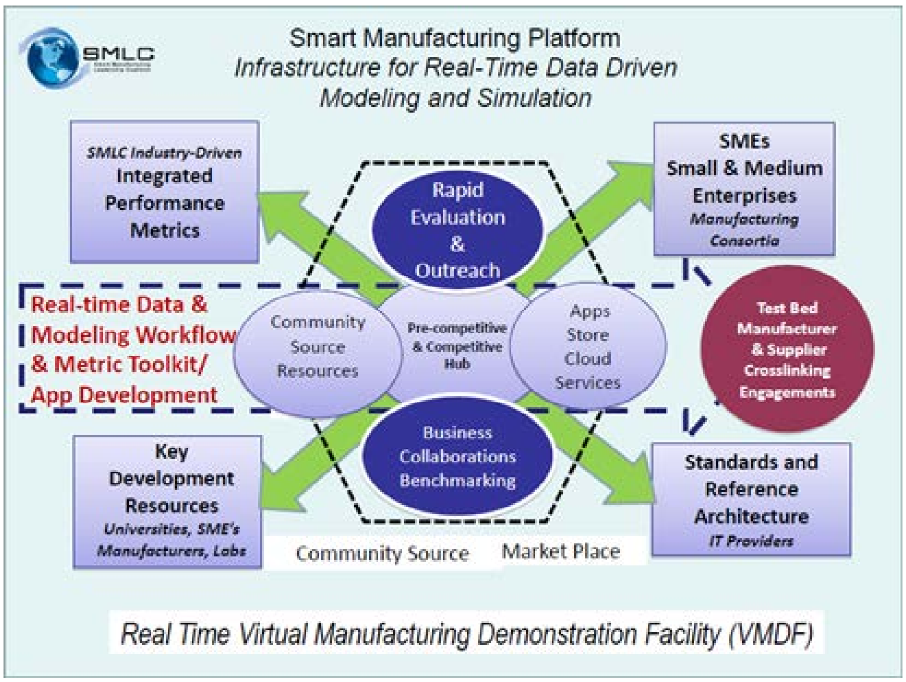
The SM Platform has the potential to enable the commercial use of SM systems across all U.S. based manufacturing operations. It enables first time use of advanced fusion sensors, reduced order models, and integrated performance metrics simultaneously and adaptively in manufacturing environments, as well as provides support to merge ICME assets and capabilities into manufacturing operations. Transformational advances in a variety of performance metrics can be achieved, including energy productivity, yield, production cycle time, quality, supply chain integration, rapid qualification, additive manufacturing, and environmental performance. Large and small companies alike can have network access to run or download applications and choose more complex configurations as necessary for specific operations. Applied R&D defined by the platform addresses richer sensor measurement and data capture technologies; real time modeling; control and/or simulation tools that incorporate a fuller complement of first principles; statistical, knowledge-based modeling and data interpretation methods; new and integrated Key Performance Indicators (KPIs); active management dashboards for distributed management and automation; a cyber physical systems approach to Smart Manufacturing; and human-centered interfaces that support new workforce skills.

While existing technologies and applications deployed through the SM Platform can produce near term benefits, a broad based R & D agenda builds from the design, implementation, and application of a shared Platform that supports and complements the physical and workforce systems to form a scaled workforce, cyber-physical manufacturing system. There are significant architectural, interoperability, synchronization, time scale, information, and task service requirements; and human and machined centered interface requirements for a virtual system that spans computational processor to the data and model synchronization with the physical sensor and the operation. In order to drive out variability risk to achieve high levels of dynamic responsiveness, there is a need to integrate information and to interoperate across the layers in real-time through the differing levels of automation, breadth of coverage, workforce involvement and actionable windows in time. Multidimensionality considers the physical and workforce systems across the micro, meso, and macro layers and factory and supply chain operations to transform manufacturing enterprise.

Solidifying the SM Platform as a Collaborative Manufacturing Solution: The SM Platform is a collaborative manufacturing innovation base that integrates information technology, models and simulations driven by real-time operating data, and comprehensive Key Performance Indicators (KPIs) in a framework that allows manufacturing organizations to assemble and run new SM systems at low cost. There are four key collaborative requirements that set the stage for new business and operating models for manufacturing that recognize the interconnected roles of all entities in the manufacturing enterprise. Clockwise in **Figure 2**, there is a need for definition and collective agreement on new KPIs for energy and economic productivity performance, sustainability, EH&S, etc. to drive dynamic performance management. These metrics need to be composable to meet varying objectives of manufacturers. The ability to collectively address critical information, technology and practice across the supply chain and the supplier network is significant to manufacturing enterprises of all sizes. This platform allows for small and medium enterprises (*SMEs*) to have this capability in addition to large enterprises.. To achieve these goals, there is a need for the IT Providers to address cross industry enterprise integration practices through a *Standards based Reference Architecture.* IT Providers must also develop *Key Shared Resources* for using modeling and simulation applications to address real-time syncing of virtual and physical models and to develop at scale demonstrations. These developments come together as *Workflow Toolkit and Application Development Processes* for development, evaluation and implementation to achieve a manufacturing objective, i.e. manage to a new energy performance metric..

The function of the SM Platform as a Virtual Manufacturing Demonstration Facility (VMDF) is to bring community source, market place, pre-competitive and competitive spaces seamlessly together to facilitate a range of collaboration models. The Platform facilitates bringing community source and proprietary software applications together for distribution through an apps store. It provides secure computational facilities for individual manufacturer use and can link manufacturers to form physical test bed enterprises where knowledge is managed and exchanged within competitive and intellectual property constraints. The Platform also provides a clearinghouse for integration practices and facilitates the collaboration business models to bring the players appropriately together.

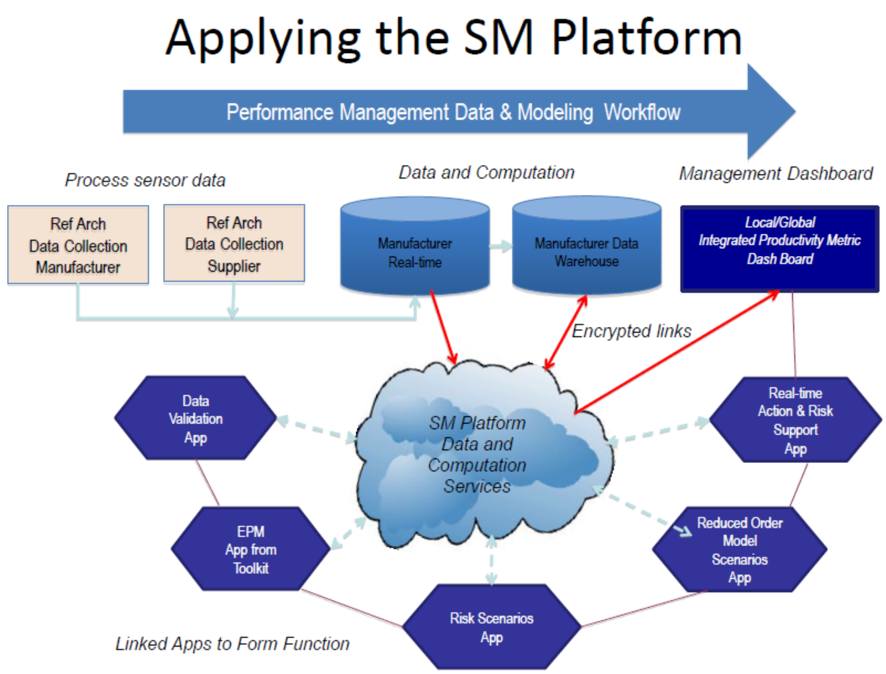
Figure 2: The SMLC specification for the SM Platform



Specifying an SM Platform Architecture for Deploying Modeling and Simulation Application: The SMLC has tested the feasibility of a fully scaled, comprehensive SM Platform by developing the first level specification for an approach and architecture for constructing customizable real-time data driven modeling applications as composable apps and composable metrics. These composable apps and metrics can be assembled, scheduled and managed in a workflow framework. **Figure 3** illustrates a fundamental design premise that all in-production, data driven modeling and simulation-based applications are decomposable into individual apps that can be reassembled. Individual apps can include data management, analysis and predictive modeling and simulation routines, performance metrics and distributed dashboards. Complex apps like reduced order modeling and integrated performance metrics can be assembled from toolkits. The SMLC has tested this premise for a range of micro, meso and macro applications.

The SM Platform provides a standardized architecture that promotes very rapid, low cost development of compatible apps by numerous third parties, while maintaining consistency and security for individual users and the basic operating system. What sets the SM Platform apart from the smartphone and application "Apps" store platform offered by Apple and Google, are the real-time data management, modeling, and KPI apps that can be assembled into a workflow to inform real-time management decisions. The content and open architecture of the SM Platform will allow manufacturers to evaluate and assemble a combination of controls, models, and KPIs into a system with the appropriate scope and degree of rigor for their company, regardless of industry or organization size. The approach builds on and extends the use of Kepler workflow on the grid [2, 3]

Figure 3: Assembling an SM application using the SM Platform



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