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Smart Manufacturing

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Abstract

Historic manufacturing enterprises based on vertically optimized companies, practices, market share, and competitiveness are giving way to enterprises that are responsive across an entire value chain to demand dynamic markets and customized product value adds; increased expectations for environmental sustainability, reduced energy usage, and zero incidents; and faster technology and product adoption. Agile innovation and manufacturing combined with radically increased productivity become engines for competitiveness and reinvestment, not simply for decreased cost. A focus on agility, productivity, energy, and environmental sustainability produces opportunities that are far beyond reducing market volatility. Agility directly impacts innovation, time-to-market, and faster, broader exploration of the trade space. These changes, the forces driving them, and new network-based information technologies offering unprecedented insights and analysis are motivating the advent of smart manufacturing and new information technology infrastructure for manufacturing.

INTRODUCTION

Forty years of business, technical, and information technology (IT) evolution have converged on manufacturing practices built around steadiness and vertically optimized companies, operations, and tasks to form end-to-end information enterprises. Material, energy, and product orders are placed throughout a supply chain; inventories manage variations in demand, time, and/or processing; each segment addresses raw material, energy, and environmental impacts relatively independently; and manufacturing enterprises are managed as sequences of optimized segments. However, changing customer value demands, expectations for safety and environmental sustainability, cost and availability of energy and materials, global competitiveness, and a need for greater customer responsiveness have become driving forces across all industries. Over the past 10 years, early adopter manufacturers have made incremental changes in operating practices, but real transformative manufacturing approaches can now be forged with the use of new data, knowledge, and IT technologies that were not available previously (1–3, 4).

Smart manufacturing (SM) is terminology developed by the Smart Manufacturing Leadership Coalition (SMLC)[1] to define a set of manufacturing practices that respond to a new wave of networked data and information technology capability destined to shape future manufacturing operations (**https://smartmanufacturingcoalition.org**) (5). SM has been used increasingly to reference a general advanced manufacturing theme about next-generation business and operational practices with the wide adoption of advanced sensing, control, modeling, and platform technologies, i.e., advanced cyber technologies (**http://www.nist.gov/manufacturing-portal.cfm**) (6). SMLC is an industry, academic, and government coalition widely recognized for its commitment to improving US manufacturing competitiveness through comprehensive adoption of SM systems, and it has been a principal force behind the development of SM. Early in the pursuit of its mission, SMLC determined that a macro-level definition and articulation of SM systems would be required to fully incorporate the breadth of the driving forces and opportunities shaping manufacturing into the design and development of SM technology.

This review focuses on the technical architecture and deployment of IT infrastructure and platform technology emanating from the systematic macroanalysis and decision practice pursued by SMLC to define what is required for commercial adoption. The business and technical analysis of multiple SM applications has been used to build new manufacturing-wide platform infrastructure called the SM Platform and to initiate diverse demonstration test beds. The SM Platform marries cloud technologies with real-time manufacturing data and operational requirements, making it possible to build dynamic enterprise data systems, scale IT infrastructure, and manage software applications while managing their resulting actions locally. SM Platform technology opens new opportunities for platform modeling and scaled modeling methodologies, as well as emerging business models that involve development beyond individual companies. SM Platform technology changes the economics of vendor and software services while addressing new practitioner demands.

OPPORTUNITIES DEFINED FOR SM ADOPTION AND SM PLATFORM TEST BEDS

The SMLC has defined the 21st-Century SM enterprise (7–11) as data driven, knowledge enabled, and model rich with visibility across the enterprise (internal within a manufacturer and external

[1] SMLC is a nonprofit, industry-led coalition composed of manufacturers, manufacturing consortia, universities, government laboratories and agencies, and regional consortia.

Table 1 Five operational categories of smart manufacturing opportunities

Smart machine line operations	In-production high-fidelity modeling	Dynamic decisions	Enterprise and supply chain decisions	Design, planning and model development
Integrated process machine and product management	Enhanced management complex behaviors	Performance management global integrated decisions	Smart grid interoperability	Design models in production
Benchmarking machine-product interactions	Rapid qualification components products materials	Untapped enterprise degrees of freedom in efficiency, performance, and time	In situ measurement and integrated value chains	Product/material in production quality
Machine-power management	Integrated computational materials engineering	Enterprise analytics and business operational tradeoff decisions	Tracking, traceability, and genealogy	New product, material technology insertion
Adaptable machine configurations		Configurable data and analyses for rapid analytics and model development	External partner integration and interoperability	

across manufacturers), such that all operating actions are executed proactively by applying the best information and performance metrics. SM also encompasses the sophisticated practice of generating and applying data-driven manufacturing intelligence (MI) throughout the manufacturing life cycle of a product. MI is a comprehensive behavioral understanding of the manufacturing process through extensive data and modeling, which can identify untapped degrees of operational freedom and a new capacity to take action. SM's strength is in applying MI by taking a comprehensive enterprise view. In Davis et al. (11), SMLC defined SM from the point of view of a manufacturer as the use of data-driven MI in multiple real-time applications deployed throughout all operating layers across the factory and supply chain. SMLC uses the concept of manufacturer test beds to define and scope SM systems in the context of operational needs and has identified untapped opportunities across multiple manufacturing industries. Operational MI opportunities for SM applications of priority interest across numerous industries identified to date have been grouped into five categories, as shown in **Table 1**.

To illustrate how test beds are used to develop SM Platform infrastructure and enable SM implementation, we briefly describe four SM test beds. Each test bed has new corporate enterprise objectives and can be identified with some combination of the opportunities displayed in **Table 1**. However, from an operational perspective, SMLC test beds are all attempting to achieve a lowered cost of production and higher productivity while also achieving broader, integrated business and performance goals that respond to the driving forces impacting all industries.

To produce actionable outcomes and achieve their respective goals, each SM system involves processing different types of real-time data from various sources and enterprise modeling that cross or interface with multiple operating segments. The result is new MI and untapped degrees of freedom with actions that can be taken to achieve desired outcomes. Any one of the test bed systems described in this review could be built with today's technology as a one-off system, but the required IT infrastructure and modeling systems do not scale, the function is not readily expanded or grown, and costs are prohibitive as stand-alone systems.

In all of the illustrated SM test beds, success with the first application provides a set of contextualized data defined for a particular objective, deployment experience with data management, analytics and modeling, actionable use of the results relative to a metric, and decisions about standards. This foundation establishes a basis for expansion with much greater expectation of success. Additionally, success with a location can provide a template to scale the IT infrastructure to additional plant sites, which can lower the cost and risk of development and implementation. As a result, test beds together with SM Platform technology can mitigate short- and long-term investment risks, improve paybacks, provide methodologies for replication, and shorten development times for the adoption of SM systems.

Test Bed 1: Continuous Flow Process, Energy-Intensive Furnace Operations

Steam methane reforming is an energy-intensive process that uses catalytic reactions in steel tubes in large-scale furnaces heated to approximately 1,000°C to produce hydrogen, synthesis gas, ammonia, and methanol in more than 900 facilities worldwide. In the test bed, furnace operations are controlled using reduced-order models (ROMs) that are periodically validated with high-fidelity modeling. Continuous collection of furnace temperature data with infrared cameras could allow individual burners to be fine-tuned for dynamic optimization of the heat distribution. However, high-fidelity modeling for production involves different time requirements because the model cannot be solved within the response time associated with the process and control system. An SM system extension of the control system can provide real-time updates to a ROM using windows of operation validated with a high-fidelity computational fluid dynamics model running multiple parallel predictive sessions on a regular basis. A large reduction in wasted energy and corresponding improvements in productivity, fuel usage, and greenhouse gas emissions have been projected. Constructing the application using the SM Platform substantially reduces risk, brings payback within thresholds, and offers the methodology to replicate. The SM Platform also shortens the model and data management configuration process to bring the SM system into production sooner.

Test Bed 2: Discrete, Batch-Process, Energy-Intensive Fabrication Operations

Fabrication of precision metal parts involves a series of forging, heat treatment, and machining steps that convert raw material into parts with customized geometrical and metallurgical specifications. The various steps form a value chain that involves the dynamic orchestration of a number of production parameters to manufacture a range of products. The heat forging and heat treatment processes are energy intensive and frequently operate furnaces in excess of 750°C. There are numerous products with multiple process changeovers and varying orders from customers. New furnace control systems and optimization of Computer Numerical Control machining have already resulted in significant energy savings and productivity improvements. These control and management capabilities can be significantly extended with an SM system that uses in situ measurement and/or inference analysis to dynamically model the effects of heat treatment on metallurgical properties together with a range of operating situations that depend on particular orders. The data are used to enhance and dynamically manage the metallurgical structure of parts, production, and energy together to improve downstream machining productivity, reduce rejects, and dynamically manage fuel and power use in all operations. There is considerable untapped opportunity for improvement in economics, productivity, gas and electricity usage, and machine maintenance across the entire product line. The SM Platform makes in-production analytical model-based solutions an operational, business, and financial reality and is itself used to build an initial model of the line operation that can be readily grown in sophistication and capability. The SM Platform also facilitates trialing different software solutions within an assembly of models and analytics solutions and developing respective model and data configurations.

Test Bed 3: Cross-Company Food Supply Chain Interoperability

Input product qualifications from supplier to buyer, as well as traceability of product from buyer to supplier, are important manufacturing practices required by federal and state governments in the food industry. Today, the buyer processes that ensure every lot of grain meets or exceeds regulatory requirements, company requirements, and quality standards still rely heavily on a paper-based certificate of analysis (CoA) and verification of protocols from the supplier. An SM system integrates several key steps in the overall purchasing, shipping, and receiving process that include (*a*) allowing a buyer to recast the CoA for supplier product into data, (*b*) managing shared data in accordance with agreements between the supplier and buyer, (*c*) mapping the CoA data from multiple suppliers into the units and definitions required by multiple buyers, (*d*) interfacing securely so the buyer receives the supplier's data in time to incorporate variability into manufacturing readiness, and (*e*) facilitating continuous improvement of operations between the supplier and buyer. Significant cost benefits can be derived from the use of supplier product data to adjust buyer production processes in advance of material delivery, i.e., reduced inventory. The SM Platform provides initial capability for managing selected data with appropriate security, privacy, and policy for multiple companies. As an electronic CoA grows in sophistication with more sensor data, the SM Platform makes it possible to assemble analytics and modeling for cross-supplier and buyer needs and for cross-company energy, environment, transportation, opportunities, and management of regulatory requirements.

Test Bed 4: Configurable Data and Models for Rapid Analytics, Model Development, and Approaching Big Data

Product fabrication involving high-precision casting benefits from progressively developed real-time sensing, analytics, modeling, and actions across the line operation. The SM system objective is to reduce the time and effort for building models and making data-oriented enterprise decisions. As much as 90% of the effort can be devoted to setting up the right sources of diverse data, such as plant historians, real-time process state and part-quality data, equipment specifications, and supply-chain databases, and contextualizing it. The SM Platform supports the progressive development and application of MI by growing data and modeling with increasingly sophisticated but well-defined performance hypotheses to always drive contextualized data collection, aggregation, and modeling needs. High-precision casting is an example in which developing data, analytics, and models together with upstream and downstream data can be used to incrementally build MI and increasingly sophisticated dynamic management tools about the line operation. An analysis of SM Platform economics (compared with no platform) shows that cost-based risks and actual costs of developing an SM data analytics application could be reduced by as much as 25% for the first model, followed by further reductions for subsequent modeling stages. Replication and reuse of SM applications for similar operations could be reduced by as much as 60% for the first replication.

DEFINITION OF NEW OPERATIONAL REQUIREMENTS TRANSLATED INTO SM CONCEPTS

SM's new potential is centered on technology and practice that extends and scales existing infrastructure, operations, and/or applications while also scaling capability and managing complexity of enterprise SM systems built in and across highly heterogeneous environments characterized by seams. A manufacturing seam is a location at which two or more parts of a manufacturing

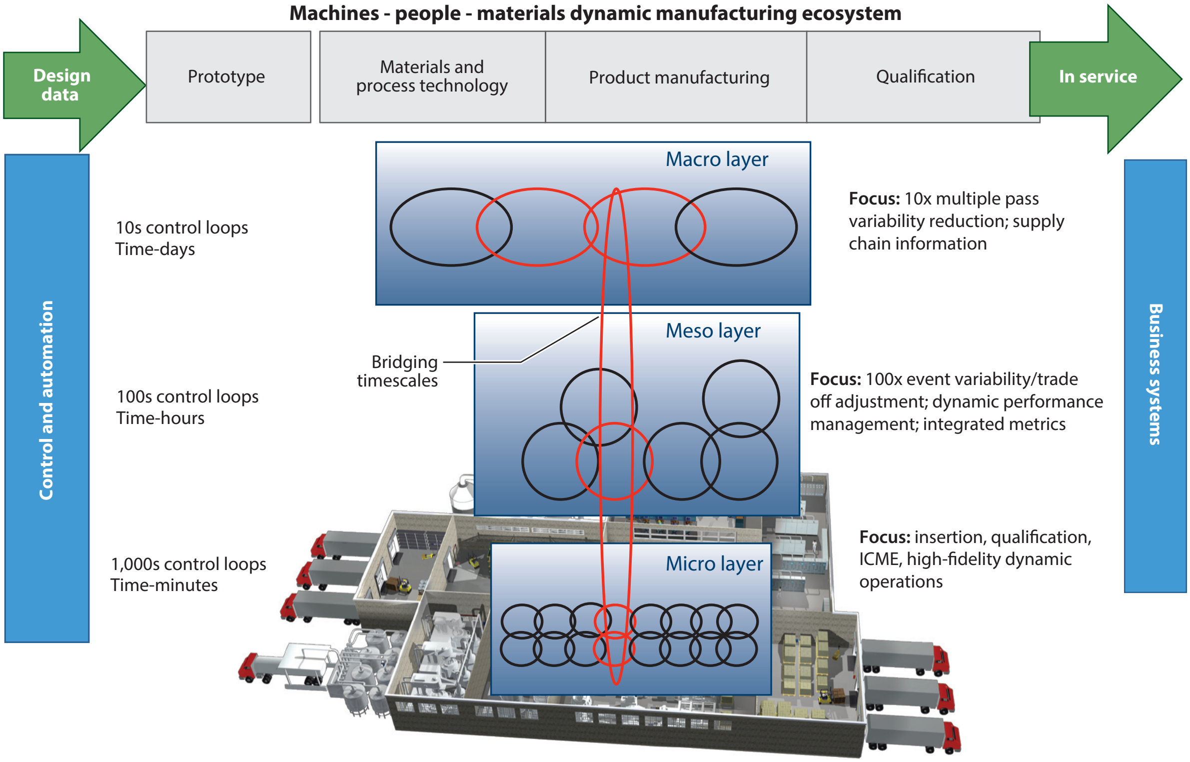

Figure 1

Smart Manufacturing: multi-layered seams, time, data, and action. Abbreviation: ICME, Integrated Computational Materials and Engineering.

enterprise or supply chain are joined together.[2] The parts so joined often differ by time horizon, lexicon, technology, culture, business drivers, or priorities.

A seam results from discontinuities or separations in manufacturing processes, physical facilities, operations, or information flows that require bridging, stitching, and joining together at the edges. Seams form as a result of variations in operational time constants, data definitions and standards, and company boundaries between factory operations and organizations. Manufacturing seams exist at the micro level [machine to machine, people to machine, and machine to people (human in the loop)], the meso level (operation to operation and cross-system decisions and management), and the macro level (cross-factory, -company, and –supply chain decisions and management). These layers reflect overarching seams that exist among and between control systems and business and performance systems. We use the term vertical systems to reference the systems on either side of a seam and the term horizontal systems to reference an overall combination of vertical systems that are bridged across the seams.

The patterns of SM opportunity in **Table 1**, when generalized with reference to these layers, are illustrated in **Figure 1** to show the foundational nature of time. An overarching seam associated with design shows time in the sense of time-to-market. The seams among the product life-cycle stages blur under the label of Digital Thread (6, 12) and are becoming more complex with

[2] This definition of seam is attributed to discussions with Evan Wallace and Frank Riddick at NIST, Gaithersburg, Maryland.

additional sustainability considerations. The Digital Manufacturing Design Innovation Institute has focused its efforts on design and Digital Thread drivers (13) (**http://dmdii.uilabs.org/**). The center of **Figure 1** identifies a significant space between business and control systems that reflects the extremes of manufacturing time associated with business transaction and a wide range of times associated with individual physical manufacturing operations and tasks. The overall space somewhat corresponds to the International Society of Automation (ISA 95) classification of systems (**https://www.isa.org/isa95/**) and the growing commercial product space that includes distributed control and model predictive control systems, manufacturing execution systems, manufacturing operations management, and collaborative production management (14–18). Unlike current manufacturing systems, SM does not compartmentalize by time but extends existing capabilities by bridging across these functions.

SM informatics focuses on the dynamic orchestration of data, analytics, and models; stitching together of data, applications, and services; and interoperable insertion or extension of capability with existing manufacturing systems through the use of decision/action workflows. Workflows in the SM sense are formed fundamentally across seams, hence the focus on heterogeneous environments. In the SM context, a manufacturing enterprise is defined as a heterogeneous cross-seam operation. SM informatics critically and fundamentally involve the variable of time. Data must be measured, conditioned, contextualized, modeled, and interfaced to perform cyber tasks that are applied to physical operations within actionable windows of time. An action is a physical manipulation of the operation and can be either human or machine centered. Cyber time is the amount of time it takes to complete a measurement and interface with a cyber task that produces an action, which must be accomplished within an appropriate actionable window in physical time defined by the heterogeneous enterprise environment. Cyber tasks can inform other cyber tasks or conditionally call them. Cyber time inherently encompasses prediction when a predictive model is incorporated in a measurement to interface with a cyber task. Synchronization refers to any aspect of and including the entire cyber task that requires coordination with data in current physical time.

The fundamental considerations of orchestrating the application of data, analytics, and models into actionable processes in heterogeneous environments defined in terms of seams and time led to SM Workflow as a foundational modeling construct for cyber tasks that interface with a physical system, generally through existing vertically located systems. An SM Workflow describes one or more manufacturing business and operational goals for a cross-seam enterprise. Workflow is a foundation for orchestrating decision making through the understanding of data across seams and time. Workflow makes it possible to provision IT infrastructure as needed for different elements of orchestrating an SM informatics system. Lastly, an SM Workflow function constitutes a data-driven manufacturing enterprise model that can be analyzed and used to generate MI.

SM Workflow–based enterprise modeling is distinct from smart control and automation modeling, which are characterized by sensor-to-actuator models and associated physical facilities that function within a common time frame. In control and automation modeling, cyber tasks, physical actions, and system resources are well defined in time and tightly integrated such that time, data collection rates, modeling, and actuation are synchronized by the needs of the fastest physical operation response requirements. SM Workflow enterprise modeling supports cross-seam modeling situations, such as human-in-the-loop involvement, and the need to address modeling and computation across different resources. SM Workflows also address modeling when there is insufficient information, when there are requirements outside or beyond modeling limits within control, and when there is a need to mix or merge different types of data and models from different sources. Although distinguished from control and automation modeling, SM Workflow modeling does leverage the sensor and data collection infrastructure of control, automation, and management systems.

MAJOR MARKET FORCES AND TECHNOLOGY TRENDS DRIVING THE NEED FOR SM

Profound transformations are coming within this decade in the way goods are manufactured. Driven by new market, regulatory, social, and competitive pressures, manufacturing is pursuing technologies and practices that (*a*) are more value oriented and responsive to customer demand throughout the entire supply chain; (*b*) substantially increase product value, industry agility, and manufacturing performance; (*c*) move toward zero field failures and zero incidents; and (*d*) radically decrease energy, material, and environmental impacts (10, 19–26) (**http://www.epsrc.ac.uk/**). Traditional metrics in manufacturing growth, market share, competitiveness, and business viability are giving way to powerful global trends in manufacturing and business that are breaking down current business models, increasing the emphasis on interoperability within and among small and medium manufacturers, requiring enterprise approaches, and demanding greater business agility (26). Manufacturers with an opportunistic view of these changes are seeing agile innovation directly impacting time-to-market, exploration of trade space, responsiveness to demand for small orders, productivity, competitiveness, and reinvestment. Vendors with proactive views are seeing rapidly expanding markets (27–34).

The SM concepts were formed to both respond to and drive these trends. With an industry pull, SM is grounded in the concept of manufacturing as a data-centric modality in which physical facilities become actionable vehicles to achieve enterprise objectives, essentially inverting the current physical facilities–centric modality. SM offers a new path in which data and models become extensive and are managed cyber assets that are just as valuable as physical manufacturing assets. Technical and business implementation of these cyber capabilities must be in this new data-centric modality to access the untapped opportunities that radically increase product innovation, quality, energy productivity, and production performance for highly variable, demand-driven products with product runs of one to many. The targets of radical productivity increases and product agility are not the existing vertical operations in large companies but increased product innovation combined with manufacturing agility, addressing the seams between vertical operations and increasing value-based interoperability within and among small, medium, and large manufacturers. The acronym ASCPM (for advanced sensing control and platforms for manufacturing) was coined in recent national discussions sponsored by the Office of Science and Technology Policy and the Advanced Manufacturing Program (AMP) 2.0 committee (6) to describe new information technologies that are used in conjunction with SM to form the modality and business basis for implementation.

The opportunities with these objectives are amplified and accelerated by macro trends in IT that include unprecedented capabilities in

- understanding of scale, scope, and substance with new networked capabilities for data aggregation and informatics;
- the ability to model materials, operations, risks, and economics to form atomic to enterprise structures with access to previously unthinkable networked computational power; and
- mobile computation in the hands of half of the world's population.

From a technological basis, SM and ASCPM offer the potential of radically improving manufacturing with front-end sensor, modeling, design, and manufacturing network infrastructure; readily affordable access to new IT applications and analytic capability; and a customizable path forward regardless of the level of technological sophistication. Realization of these improvements faces business and technical challenges that must be considered in the design of the SM Platform. An industry SM Platform should interoperate, not compete, with the vendor product space and should provide capability beyond that which is implemented within a given factory situation.

Practitioner Market Challenges

The United States has concentrated its high-value manufacturing into large manufacturing enterprises (6). The return on investment in large companies and small and medium manufacturers is interdependent but motivated differently. Unfortunately, there is little market incentive for large companies to invest in small and medium manufacturers except to drive down cost and ensure orders, and there is little market incentive for small and medium manufacturers to invest in new technologies except to cut costs and ensure transactions. The combined effect is that large companies must modernize their performance metrics for horizontal opportunities, and the small and medium manufacturers must modernize their performance with respect to building new vertical and horizontal capabilities.

Supplier Market Challenges

Overall provider market drivers have resulted in a shift away from hardware-based, large-package software solutions toward modular, cloud-based software service solutions within the vendor. Market drivers have not pushed providers toward interoperability standards, intersystem cyber security, low-cost scaled infrastructure, low-complexity technology solutions, low-barrier software and services alternatives, or low-barrier entrée to SM (6). In total, there is a significant supplier market misalignment with key dimensions of SM and ASCPM and a need for a new market model if SM adoption is to accelerate.

Practitioner and Supplier Market and Organizational Drivers

Adoption of SM and ASCPM technologies requires practitioner pull, not a supplier push. At the same time, there is need for partnerships to deliver new technologies and define new practitioner/supplier business models (34). Even though industry-demonstrated benefits of SM are emerging, an acceleration of SM adoption is still awaiting critical mass with practitioners. For those companies considering SM, acceleration is held back by depth of knowledge, complexity, market misalignment, organizational gaps between CIOs and operational technologists, and perceived and real risks (24–26). Trust, confidence, confusion, and mixed messages with security and cyberattack prevention are major challenges.

SM PLATFORM TECHNOLOGY AND FUNCTIONAL REQUIREMENTS

With the growth in complexity of enterprise integration, an industry-driven consensus for manufacturing IT platform infrastructure has become a requirement and foundation of SM. SMLC validated the importance of IT platform infrastructure for manufacturing in its June 2011 report entitled *Implementing 21st Century Manufacturing* (10, p. 9), which stated the overwhelming need for "model and computing *platforms* that are easily accessible and available to a wide range of users yet protect intellectual property." The Business Roundtable has also specified the need for platform infrastructure in manufacturing (33).

Referred to as the SM Platform, this technology is scaled IT infrastructure for broadly defined heterogeneous manufacturing environments. It is shared infrastructure that facilitates access and actionable enterprise application of real-time networked data and information applied throughout the manufacturing enterprise (34). From a technical standpoint, an open SM Platform facilitates cyber and physical technology integrations for manufacturing to achieve extensive enterprise application of SM technologies and MI in direct relation to the physical enterprise. An SM Platform must also accommodate the partnerships needed to build industrywide infrastructure that no one company can build, and that supports public and private sector interests.

In developing the technical design and specifications for the open SM Platform, computational tools need advanced functionality to support more sophisticated analysis and decision making in the enterprise environment and to enable integration with business systems and control systems wherever they exist across the manufacturing enterprise. This functionality includes integration of all key performance indicators and human factors to enable the integration of machine knowledge with human behavior and actions. The functionality must be architected to assimilate new technologies, make it possible to orchestrate actionable information, and address the provisioning of IT infrastructure and resources. The AMP 2.0 report provides an analysis of the technology gaps (6).

Orchestration references the organization and deployment of actionable data-based analytics and modeling to achieve operational goals defined by performance metrics, and provisioning references the organization and deployment of the IT services and resources necessary to achieve the orchestration. The SM Platform marries orchestration and provisioning with a design that is anchored by business and technology considerations that drive three key requirement categories and therefore features for the SM Platform:

- Progressively developed and accessible SM intelligence to
  - — support progressively developed understanding of the manufacturing process through configurable modeling and data analysis;
  - — increase access to new software capacity to observe and take action on integrated patterns of operation through networked data, information, analytics, and metrics;
  - — make possible a broader base of software solution innovators;
  - — ensure manufacturing dynamics and integrated metrics, e.g., energy and material resources together with customer demands for value and responsiveness;
  - — make MI actionable; and
  - — make it possible to share data about software applications.

- SM practice in
  - — generating and orchestrating the use of sensor-based, data-driven MI;
  - — using multiple real-time SM systems extensively deployed throughout all operating layers;
  - — integrating network-based data and information from, about, and across SM systems;
  - — modernizing existing IT infrastructure by retrofitting or extending;
  - — applying integrated performance metrics together with applications, all constructed for real-time action;
  - — applying composability and application customization balanced with invariant infrastructure to scale IT and function at lower cost and risk;
  - — reusing and scaling integrated practice through common infrastructure; and
  - — providing entry to SM at the point of readiness, risk tolerance, and local infrastructure, and progressive build-up of contextualized data, MI, breadth of analytics, and actionable use.

- SM architecture practice facilitating
  - — dynamic orchestration of decision/action workflows in heterogeneous environments without losing control of state across different time constants and seams, including supply chain;
  - — separation of data and applications;
  - — applications that can share data, data that can share applications, and applications that can connect to applications to achieve horizontal enterprise views and actions;
  - — use of Apps as code layers associated with application environments that are accessed and executed in the cloud;

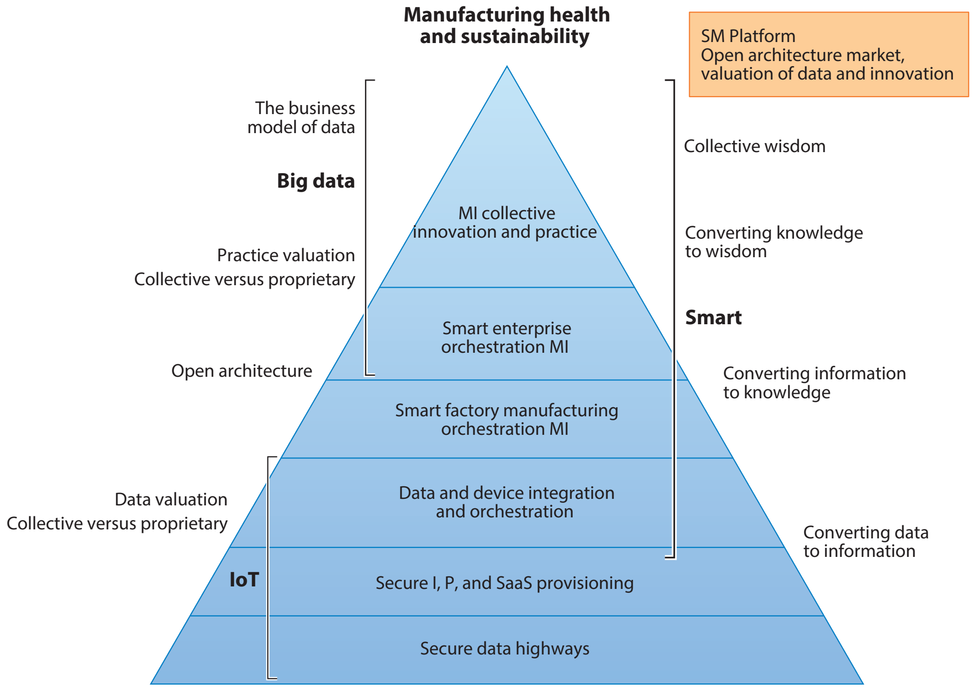

Figure 2

Smart Manufacturing Platform design definition. Abbreviation: IoT, internet of things; MI, manufacturing intelligence.

— standard structure for Apps regardless of function, selection at Apps level, composability at workflow level, customization at code parameter level, and provisioning tied to Apps and workflows;
— cyber platforms for interoperability, accessibility, scalability, affordability, and security;
— coexisting commercial and open products/services, public and private resources R&D, and academic resources;
— ready access and contribution to applications and resources both commercially and in an open-source manner;
— managed levels of community sharing of data, standards, and implementation information about applications; and
— strong data ownership, management, security, and cyber-attack protocols.

As shown in **Figure 2**, SMLC has assimilated these requirements into an SM Platform design definition that is conceived as a set of layered cloud services.

In this design concept, MI accrues when all layers operate in coordination and from a collective set of industry participants but is applied within the individual company, thereby closing the loop on the MI life cycle. SM practice is reflected in the orchestration layers that build upward from the factory, enterprise, and industries that benefit from sharing nonproprietary or precompetitive information about orchestrated software applications. The focus of SM Platform applications, however, involves applications that share data. SM assumes a progressive build of metrics, systems, and MI by integrating network-based data across SM systems. The SM Platform also will take advantage of internet-of-things technologies to further facilitate network, standards, and connector structures

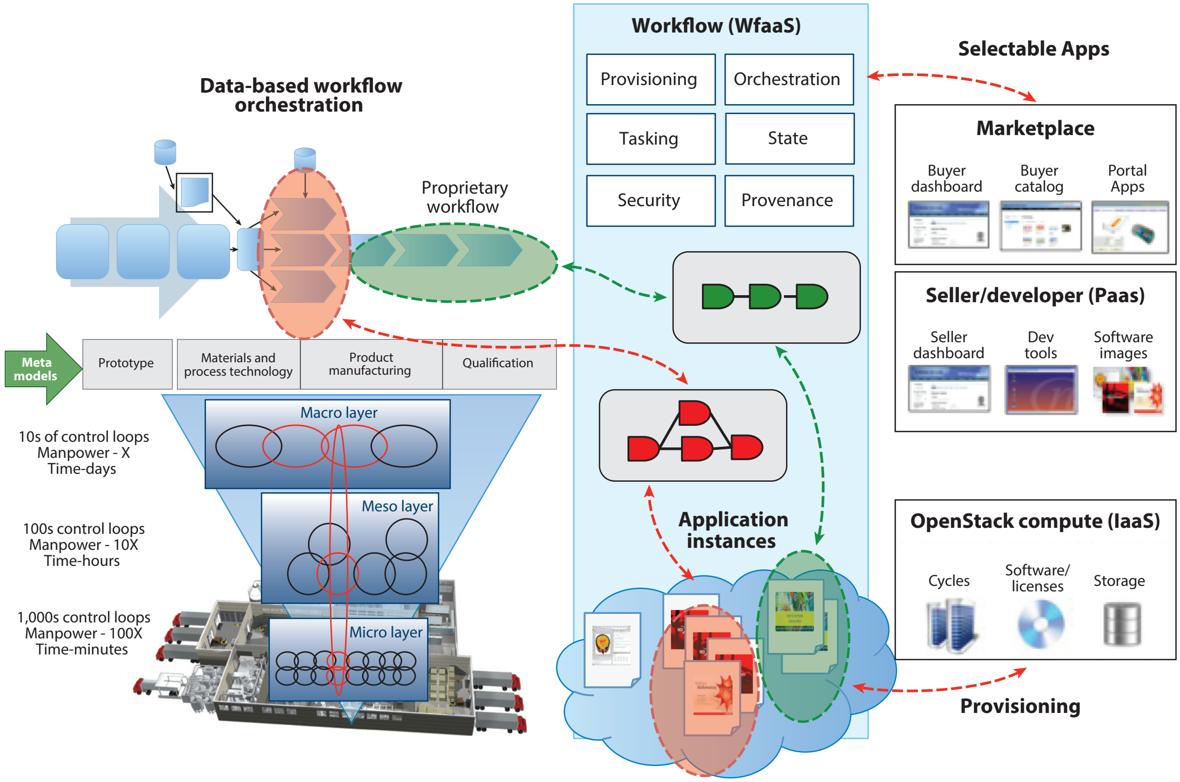

Figure 3

Smart Manufacturing Workflow as a Service (WfaaS) and marketplace as service.

for device integration. SM execution assumes inclusion of MI within vertical, typically homogeneous, manufacturing IT systems but extends capability, breadth, and reach by addressing interoperability with the structure in **Figure 2**. The design concept supports platform replication in public, private, and hybrid configurations to meet different company, regional, and industry needs.

These anchor requirements can be accommodated in an SM Platform methodology founded on an industry-managed specification of shared cloud-based infrastructure services. **Figure 3** illustrates the concept of SM Platform interoperation in a manufacturing facility, including several breakthrough concepts in the structure:

- Open architecture SM Workflow as a Service (WfaaS) provides broadly accessible infrastructure for orchestrating workflows in heterogeneous environments while simultaneously provisioning IT resources.
- Open architecture WfaaS also makes it possible to stitch together other cloud resources; interface with vendor environments; and deploy in public, private, and hybrid structures.
- A cloud services structure makes it possible to invert the historical manufacturing paradigm by bringing data to the application instead of the application to data.
- Composable SM Workflows provide context to enable enterprise modeling and real-time decision making.
- WfaaS adapts real-time requirements and customized applications through composed workflows.

- A Marketplace store offers open-source and commercial software application environments and composed, reusable SM Workflows with multiple Apps orchestrated for a specific objective.
- The SM Platform that combines open architecture orchestration, provisioning, and market-driven resources and data offers new approaches to IT infrastructure, interoperability, standards, intellectual property, and security.

The SM Platform technology specification is a shared, open-access SM application and data platform that comprises a layered set of cloud technologies with workflow as a fundamental construct, a composable WfaaS layer that is linked to provisioning services, and a Marketplace that provides access to composable data resources and information about them. From an implementation standpoint, the SM Platform is a continuously managed architectural and standards specification that supports private, shared, and hybrid operating instantiations as a layered set of secure, widely networked integrated web services, along with a widely networked Marketplace of readily accessible resources and data.

An open, nonproprietary WfaaS environment provides the core capability for the orchestration of all types of data and automated or manual insertion of software Apps in a contextualized, objectives-based form. As a core technical construct, SM Workflow describes one or more manufacturing operational goals for a cross-seam enterprise, which constitutes a data-driven manufacturing enterprise model. The operational goals of an SM Workflow define performance expectations and overall needs for data selection, contextualization, and synchronization. Each activity in an SM Workflow process[3] contains the information for that particular activity, making it possible to build workflow models containing activities with widely varying time constants. Each activity contains the information necessary to provision resources, which also aligns the use of SM Platform technology for access, interoperability, and scaling.

INSTANTIATION OF THE SM PLATFORM TECHNOLOGY

Given that an SM Workflow describes one or more manufacturing operational goals for a cross-seam enterprise, the design and implementation specifications for the SM Platform begin with the nature of workflow as a fundamental construct and the key features it brings to SM Platform infrastructure.[4] Development of the WfaaS concept is based on the Wf Reference Model by the Workflow Management Coalition (**http://www.wfmc.org/**). An SM WfProcess is a detailed description of an SM WfFunction that can be used by a workflow engine to realize that function. A WfProcess contains (*a*) one or more WfActivities, in which each WfActivity corresponds to one of the logical steps needed to realize the associated SM Workflow, and (*b*) information governing the sequential, parallel, and/or conditional execution requirements of each WfActivity in relation to the other WfActivities in the WfProcess definition.

Execution of a WfProcess occurs in terms of instances. A WfProcess instance is the entity in a workflow engine that represents the current state of a specific occurrence of the SM WfFunction. The execution of a WfProcess instance is started, monitored, and managed by a workflow engine, based on the information defined in its WfProcess description. Similarly, a WfActivity instance is the entity in a workflow engine that represents the current state of a specific occurrence of a

[3] A Workflow Process is a fully defined and instantiated workflow comprised of activities that can be executed by a workflow engine (**http://www.wfmc.org/**).

[4] This architectural description is attributed to discussions with Evan Wallace and Frank Riddick at NIST, Gaithersburg, Maryland.

WfActivity defined in the context of a WfProcess description. In a similar manner, a WfActivity instance is started, monitored, and managed by a workflow engine based on the state of its associated WfProcess instance and the information defined in its associated WfProcess and WfActivity descriptions. As is discussed later, we further recognize the need for multiple workflow engines given the diversity of operational categories for SM opportunities listed in **Table 1**.

As illustrated in **Figure 3**, the WfaaS directly addresses orchestration and tasking that occur at the functional manufacturing level. Orchestration references how an SM Workflow interfaces with a manufacturing operation, and tasking references the WfProcess description. Provisioning references the service capability of merging the necessary software, platform, and infrastructure services for the various activities and workflow processes to execute. State is a service within and about the workflow engine that tracks and reports progress, completion, and conditions of work items, WfProcesses, and associated WfActivities as workflow execution proceeds. Wf progress, state, and time across seams are available at any point during execution in an understandable form from a user perspective. A work item is an event (typically a manufacturing event) that takes place outside of the direct control of the workflow engine but defines when a workflow starts and the conditions under which it is considered complete. The completion or progress of any WfActivity as well as the overall WfProcess must be readily reportable and conditionally actionable so that conditional and/or corrective action can be taken in the case of an activity failure or unexpected condition. State as a Service is itself workflow that involves calls to update the state of WfActivities and WfProcesses and the work items associated with SM functions. Provenance is a service that records WfProcess execution instances, recognizing that they constitute important MI. Security references multiple layers of systems, information, and cyber-attack security and includes secure peering between vendor and factory network services. Methods for modeling SM Workflows and cyber task completion times as well as stability, fault tolerance, resilience, and optimization properties constitute new areas of research and development.

This WfaaS-cloud architecture has the property of being able to preinstall software packages into run time instances while they are being instantiated (booted up), a property that makes it possible to work with an App and WfActivity images as separate entities and App environments as preinstalled images that can be merged into a WfProcess instance when instructed to do so (35). This property makes it possible for an App and its App environment to be a composable software artifact with respect to building a WfProcess. An App, which is a set of computer logic instructions, can be paired with an appropriate execution environment defined within a WfActivity description and then executed, monitored, and controlled by the SM Platform. Execution of an App instance must therefore be requested by a WfActivity instance running in the SM Platform Workflow engine. The App execution environment can be stored and made ready for other App uses as a validated, secure code base. Specific interfaces and services in the SM Platform govern which WfActivity instances may run an App, how and where an App runs, and how it is monitored. This property provides two security advantages. One is that the application environment can be prevalidated for security. Secondly, this structure allows instances to be run securely in protected service spaces and removed upon completion.

A WfProcess and associated WfActivities are executed computationally to realize the intent of an SM function. Execution commences with the creation of a WfProcess instance and then proceeds with the creation, monitoring, and management of its associated WfActivity instances that call Apps. In addition to invoking Apps, complexity in function can also arise from calling an external application that is paired with the execution environment and with nesting WfProcesses—a WfProcess instance that is initiated because of a request from a WfActivity instance defined in another WfProcess instance. A nested sub WfProcess can be executed by the Wf engine controlling the WfActivity instance that requested the subprocess or another Wf engine.

These capabilities are exemplified in the Kepler workflow environment shown in **Figure 4**. Kepler, a scientific workflow tool that supports web services and grid and cloud technologies, has been implemented in a representational state transfer (REST) service architecture that runs over HTTP (36). The graphic illustrates a cloud computational view of using Kepler as a workflow service to orchestrate a temperature data analysis and furnace modeling sequence that involves Octave, MATLAB, and ANSYS Fluent software environments.

The WfActivities in this example workflow are secure and execute MATLAB, OCTAVE, and Ansys Fluent computations on virtual App and App environment instances. As shown, the WfProcess is hosted and initiated in a secure facility in Virginia.[5] The data and computational activities are requested from and executed at the University of California, Los Angeles, where the computational WfActivities are paired with a high-performance computational cluster to accommodate the computational provisioning requirements. The WfProcess is called from a REST service (WfaaS) that transfers data files to cloud computing resources and triggers the workflow from the login node. When the results of the computation are complete, they are transferred to a cloud storage resource. When called, the workflow initiates the transfer of the input files from the login node to the appropriate compute instances that run the jobs and copy the outputs back to the login node. The significance here is not a Kepler workflow per se but Kepler as WfaaS.

This WfaaS architectural concept built on Infrastructure, Platform, and Software aaS capabilities takes full shape as tightly integrated services, again referencing **Figure 3**. The major service components of the SM Platform include developer and user interfaces, a Dashboard to select WfaaS structured Apps and/or WfProcesses (multiple Apps orchestrated for function), and a Marketplace for selecting Apps and WfProcesses. A key feature of the SM platform is the exposure of data and experiences with the deployment of WfProcesses via the Marketplace. The open access and information capability provide a basis for a full range of application possibilities, from validated and tested applications to software posted for review and testing. In this way, the SM Platform facilitates a progression from model and data configuration to operation.

OpenStack is a cloud services layer that is critical to the provisioning that must be married to orchestration. OpenStack is a community source standard and cloud management environment that makes orchestration and provisioning work. In brief, OpenStack contains RESTful APIs that use HTTP protocol for secure web interfacing with other applications and eURL command line tools for making interface (API) requests. APIs are written in the Python programming language. Importantly, clients can use any language that supports REST calls. OpenStack APIs support many interrelated but standalone services that are needed to bring all the service layers into an integrated whole. From a provisioning standpoint, the SM Platform makes it possible to spin up and spin down WfProcesses and the computational and storage resources that support them.

A bold and key element of SM Platform orchestration is the ability to interface with manufacturing operations with real data exchange. SM fundamentally depends on data collected as point measurements, as well as input information in time and analyzed across defined windows in time. The SM Platform is architected for secure application of highly selective, factory data. In some cases, the data are regulated or highly proprietary; in other cases, data can be applied with appropriate security practices, and in others, sharing data with some defined community is valuable. In regulated or proprietary data use cases, the SM Platform can be built as a private cloud. For

[5]Not shown are a data collection and historian architecture that interface with proprietary manufacturer data platforms based upon agreed up protocols and security.

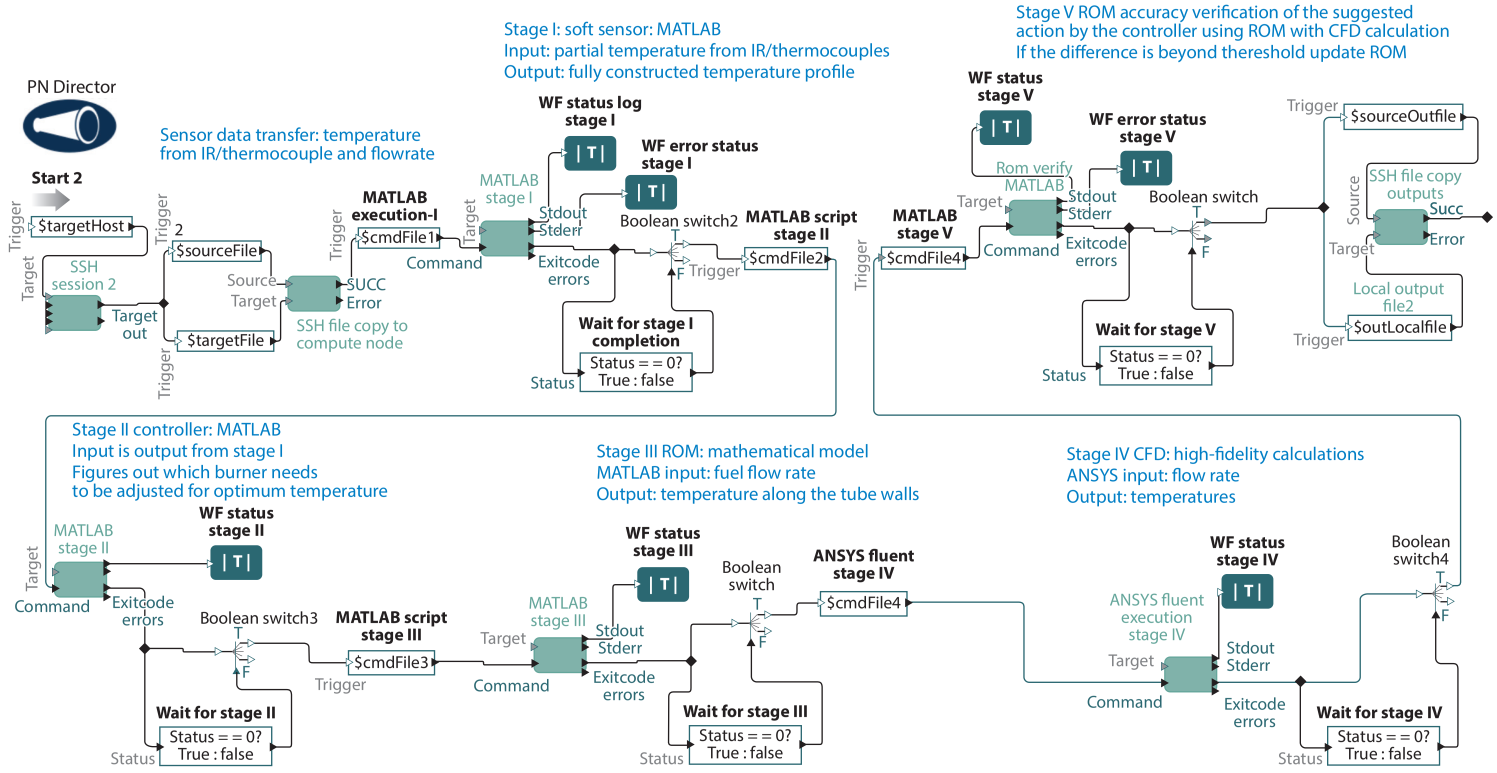

Figure 4

A Kepler Workflow as a Service (WfaaS) example.

situations in which there is value in sharing data, the SM Platform provides a secure and managed structure for this to occur. For data for which there is benefit to share, the SM Platform provides the services to make this possible in an open community manner through the Marketplace or with a managed and defined community. In no situation is the manufacturing data pulled. Rather, the SM Platform assumes a push strategy with data always managed from the factory side.

To the requirements outlined for progressive development of MI, the SM Platform, based on its WfaaS construct, addresses specific and defined workflow objectives that serve to both provide the basis for contextualizing the data and limit the need for data only to what the objective demands. Security is better addressed when it is the result of knowing exactly what data is being used and for what purpose. Data contextualization is the result of knowing the objectives and developing the data needs and definitions to address these. The SM Platform is therefore specified to those practices that progressively build toward big data analyses, with increasingly larger data sets as insights grow.

SUMMARY

The open SMLC SM Platform is not about any one technology but about systems of systems integrations of technologies to achieve broad-based capability. It is fundamentally about a platform that stays integrated regardless of the service technologies employed. In such a service ecosystem, the SM Platform provides the infrastructure to facilitate changes in technologies rather than locking onto them. The architectural specification is a critical technology development in that it (*a*) defines and embeds elements that will be invariant with time; (*b*) creates the flexibility for resource provisioning and minimum user involvement; (*c*) focuses functional composability at an Apps and Apps process level with the WfaaS environment; (*d*) focuses application customization through App selection and application-specific parameterization; (*e*) provides a Marketplace for accessing and selecting Apps and related resources; and (*f*) provides tools to readily model, orchestrate, and provision and to scale, reuse, and replicate.

The fundamental implementation objective is a managed open architecture specification and process of open selection and access to a library of Apps and importantly access to data about each App. Open architecture is attractive in that real-time orchestration and provisioning infrastructure can be available on an as-needed, pay-as-you-go basis. Open access to Marketplace resources and information and to a core set of platform orchestration and provisioning infrastructure tools creates an entirely different technology and business model than is in play today. Open access managed through an industry coalition ensures a clear industry pull in the design of the SM Platform, definitions of core services versus those charged, management of open-source and commercial resources without conflict of interest, and sharing of precompetitive data about applications with the community without conflict. The creation of a shared market space provides not only access to software application resources but noncompetitive information about them to create value in shared experiences with, e.g., implementation, range of use, and standards employed. Visibility in a market-driven setting lets successful applications and associated implementation practices become more apparent. The open-access SM Platform has the potential to open doors to dormant technologies and encourage entrepreneurs to develop manufacturing software made accessible to multiple users through the SM Platform.

This structure ties back to anchor decisions about SM practices that were defined by SMLC from a comprehensive perspective inclusive of sustainable production, agile demand-driven supply chains, and plant-wide optimization and is metrics driven, assuming the progressive application of increasingly integrated performance metrics constructed for real-time action. Metrics are critical in defining data-driven objectives that build MI. Broad-based deployment throughout all operating layers is achieved in steps in which MI progressively builds but is continuously aligned. General capability is made available at a low cost of entry and provides infrastructure for bringing public and commercial resources together in a seamless, market-driven format. SM Platform sustainability is therefore focused on bringing commercial resources and services into the Marketplace and value-added use of the SM Platform specification in an industry-driven manner.

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