

SMART PROCESS MANUFACTURING

AN OPERATIONS AND TECHNOLOGY ROADMAP



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ABOUT THE REPORT

This Executive Summary is the first installment of a series of report sections that, when brought together, will describe a framework for Smart Process Manufacturing and a consensus-based Operating and Technology Roadmap that reflects priority areas of attention and transition. The report reflects the consensus of a national cross-section of industry leaders involved with planning the future of the process industry, vendors that supply technology solutions for manufacturing operations and academic researchers engaged in a range of associated systems research. The information forming the basis of this report was generated during a workshop held in April 2008 and a number of subsequent discussions. Details of the workshop results and the list of participants can be found at:

[HTTP://WWW.OIT.UCLA.EDU/SMART_PROCESS_MANUFACTURING/](http://www.oit.ucla.edu/smart_process_manufacturing/)

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MOTIVATING SMART PROCESS MANUFACTURING

1.0 A TECHNOLOGY ROADMAP BY A NATIONAL VIRTUAL ORGANIZATION

The world is experiencing trends and events that are having profound implications for the process manufacturing industry in a global economy. The understanding of uncertainty and risk has become fundamental to managing processes and ensuring optimum economic and environmental operation within a safe and responsible operating envelope. Uncertainties in the availability and cost of oil and natural gas, the exponential growth in data storage, communications and information technology, and the relentless pressure of global competition have led to an unprecedented shift toward the business of change, just-in-time processing, high performance cross-disciplinary teams, and the economics of rapid product, operation and management transitions. Sustainability, environment, health and safety have become major areas of performance emphasis.

These are forces that push toward economic and performance metrics of rapid product innovation, proactive situational response, tightly managed product transitions, performance with zero environmental impact and predictive management of production, supply chain, environmental and energy dynamics.

The solution to these challenges and opportunities is found in a quantum change in the application and intrinsic assimilation of a model-based, knowledge-enabled environment that addresses a full spectrum of enterprise product, operational and management life cycles. “Smart Process Manufacturing” (SPM) describes the technology and applied capability in which computationally enabled models are the integrating points for data, expertise, decision and discovery. It is the means of casting data and knowledge into useful forms that can be broadly applied. The knowledge and expertise embodied in SPM need to become key next-generation operating assets and investments so industry can achieve a globally competitive capability.

There is already a trend toward SPM and progress is being made, but needed systemic infrastructural capabilities are yet to be delivered to mobilize a knowledge- and model-enabled process industry environment over the entire product and process life cycle. This report frames the priorities for SPM and articulates an industry-academic consensus on the operating and technological roadmap as well as the priority areas of action for achieving infrastructure capability. Specifically, the focus of this SPM roadmap is on the need for fundamental and broad transformation in thinking and approach. Incremental improvements, while useful, will not achieve the full vision and do not lead to the breakthrough innovation and quantum capability shifts that are needed.

To support, continue and refine the development of the SPM roadmap, we have formed an industry, academic and government Engineering Virtual Organization (EVO) with start-up funding through the National Science Foundation (NSF). The EVO partnership seeks to define the future state of operational excellence, build a consensus around that definition and move toward the fulfillment of the vision.

This report documents the consensus of a national cross-section of industry leaders involved with planning the future of the process industry, vendors that supply technology solutions for manufacturing operations and academic institutions engaged in a range of associated systems research. This report defines Smart Process Manufacturing, establishes the vision and business

case and presents a detailed technology and operating roadmap of priority areas of action for transitioning to *smart* operations.

Several themes in this report were additionally discussed more generally for U.S. industry in a separate but related workshop on Simulation Based Engineering and Science held in April 2009. The specific statements that coincide have been coordinated, integrated and similarly stated in this related but broader report.¹

1.1 THE ESSENTIAL ROLE OF MODELS IN SMART PROCESS MANUFACTURING

A wide range of *smart* technologies are already being pursued, including Smart Manufacturing, Smart Energy Grids, Smart Water Resources, Smart Equipment, Smart Buildings, and Smart Cities. All are outgrowths of the integrated application of a full spectrum of monitoring, measurement and the application of models and simulations. Smart industries have only begun to embrace the enterprise-wide application of “smart” technologies. Knowledge-enabled personnel coupled with knowledge-rich tools and systems are innovating, planning, designing, building, operating, maintaining, supporting and managing facilities in significantly improved ways. It has become clear that holistic, integrated and enterprise approaches to using models provide the basis for a sea-change transition to a fundamentally more predictive mode of decision-making and operation – an operation with a much swifter and more proactive economic and incident-response capability.

The full scope of Smart Process Manufacturing extends from requirements, product and process design to execution, delivery and life-cycle support. For our purposes, the major emphasis is on the *processing* environment, in which raw materials are converted to products via mechanical, chemical or biological processes. This includes both continuous and batch manufacturing, web/film/sheet processes as well as operations that produce intermediates that are essential to the manufacturing processes. In further defining the SPM environment we include planning, scheduling, optimization, monitoring, control and the ability to respond effectively to changing performance drivers. We are interested in the capability, tools and infrastructure that ensure that processes are seeking, at every instant in time, the optimum delivery of the best possible product without interruption, incident or cause for alarm. We are further interested in a high level of responsiveness to market shifts, customer demand, global economics and political and socioeconomic factors.

Models are integral and pervasive in the SPM vision. Models provide new capabilities in assessing risk and uncertainty with decisions and the means to transition into proactive, preventive and innovative modes of operation. The “smart” industry is committed to knowledge, discovery and innovation and the ability to validate and rapidly deploy new developments, making it better equipped to drive toward zero emissions and zero incidents. It does this with the full recognition of people as essential resources for success. For SPM to be an economic and performance differentiator, models must be developed, managed and supported as essential infrastructure and key knowledge assets whose value to the organization is perceived as equivalent to physical and human assets.

¹ Workshop Report, “Research Directions: Vision for Research and Development in Simulation-Based Engineering and Science in the Next Decade, S.C. Glotzer and P. T. Cummings, April 22,23, 2009. Also please see Panel Report on International Assessment of Research and Developing in Simulation-Based Engineering and Science, S.C Glotzer, chair and S. Kim, vice chair, World Technology Evaluation Center, Baltimore, Maryland, 2009.

In summary, we define Smart Process Manufacturing as:

an integrated, knowledge-enabled, model-rich enterprise in which all operating actions are determined and executed proactively applying the best possible information and a wide range of performance metrics.

1.2 THE ROLE OF CYBERINFRASTRUCTURE IN SMART PROCESS MANUFACTURING

Smart technologies can be applied today in full concert with the business and manufacturing missions of multiple enterprises and their interconnected supply chains. SPM can enable industry cooperation *and* enterprise competitiveness for broader economic and social benefit. The development, application and management of models and their consistent and coordinated use across the process enterprise create new skill set requirements. With the investment, commitment and will to deploy for competitiveness, SPM becomes a new market and economic force. Over the next decade, those industries that develop and tap the power *of knowledge in models and knowledge through models* will be the most competitive.

We therefore recognize that SPM is, in itself not sufficient. We must also recognize the key foundational role of cyberinfrastructure (CI), which has been defined by NSF as:

the coordinated aggregation of software, hardware and other technologies as well as human expertise to support current and future discoveries and to integrate relevant and often disparate resources to provide a useful, usable and enabling computational and data framework characterized by broad access.

With the recognition that CI is a key shared enabler, achieving the goals of smart manufacturing will require excellence in data and information management, knowledge management and communications across an enterprise and the industry. We identify several technology areas that are essential to this CI:

Data interoperability provides the ability to seamlessly exchange electronic product, process and project data between collaborating groups or companies and across design, construction, maintenance and business systems.

Networked sensors in massive numbers throughout the enterprise and the surrounding environment will serve data collection workhorses supporting data communications; automated control systems; long- and short-term planning; predictive modeling; optimization; environmental, health and safety (EH&S) management; and other functions. Data fusion and information integration to create useful, accessible knowledge is essential in a network-centric manufacturing environment.

A physics- and mathematics-based understanding of material properties underlies the ability to create a rich model-based environment.

Multi-scale dynamic modeling and simulation and large-scale optimization are based on understanding and practical development at the detailed level of the process, but applied at the macro/global level of the process, the product, the manufacturing system and the manufacturing enterprise. This capability addresses large-scale cross-company, cross-industry and supply chain problems at strategic, tactical and operational levels. Business planning and scheduling are fully integrated with operational optimization so that decisions and actions are fully informed but made within an operational time window that can have proactive impact. The SPM CI requires significant network, computation, algorithmic and data management capabilities.

Scalable, requirements-based multi-level security will enable protection (without impairment of functionality) of systems and information from the vulnerabilities inherent in using commercial off-the-shelf technology networked throughout the manufacturing enterprise and supply chain. Security will be transparent to the user.

1.3 KEY “SMART” MANUFACTURING ATTRIBUTES

We summarize the vision of Smart Process Manufacturing in terms of 10 key attributes:

1. Smart processes are capable of *intelligent actions and responses*. They maximize performance, cost effectiveness, and profit by planning, continuously monitoring status and impacts of responses and applying learning to determine and implement appropriate action for planned and unplanned situations. Actions and decisions are adaptive, predictive and proactive.
2. Operating assets – people, plant, equipment, knowledge, models, databases, etc. – are *integrated and self-aware* (via sensors) of their state. Field devices, actuators and operating equipment have intelligent processing capability with the sensors needed for self-awareness. Every system is able to recognize its condition and publish that information so it, and all other interoperating devices can take immediate and appropriate action.
3. A smart manufacturing process can detect and adapt to new situations or perturbations (i.e., abnormal events). By evaluating the present circumstances and applying continuously updated knowledge, processes can determine the best response to any change in operating conditions, such as a process upset or feedstock variations due to supply chain changes, business changes or disturbances. Processes have the capacity and flexibility for robust actuation.
4. Smart processes have all pertinent information available, accessible and understandable to the parties or functions that need the information. All needed information is available *when* it is needed, *where* it is needed and in the *form* in which it is most useful.
5. As proactive operations, smart manufacturing incorporates real-time data sensing to eliminate failure before it happens, to the extent possible.
6. Rapid response is especially important because many material transformations occur in millisecond time frames and require extensive sensing and proactive control.
7. Smart manufacturing processes are environmentally *sustainable*. Sustainable manufacturing includes reuse, with a life-cycle view of products and processes. A minimal environmental footprint (energy, water, emissions) is more readily attainable in a smart manufacturing environment because smart processes are designed to monitor and adjust themselves to minimize any and all adverse external impacts.
8. Although intelligent automation is a vital component of the smart process environment, the human resource is essential. In the smart environment, human resources (people) are knowledgeable, well-trained, empowered, connected (via cyber tools) and able to adapt/improve the system’s performance.
9. Smart systems recognize the limitations of automation. They provide information and analyses to trained operators and managers who use human experience to determine and bring about the needed action.

10. People are trained and deployed to drive strategic enterprise performance. The smart processing environment combines the well-prepared and technology-enabled human with the best technological capabilities to produce the best response in an environment of dynamic change, uncertainty and risk.

Although some of the attributes listed above can be achieved by using best practices in limited venues, applying these technologies in an integrated manner dramatically expands the capability and capacity of the smart process environment. In the future, a smart manufacturing process will effectively screen among the information available for operation and acquire and integrate that information from both internal and external systems in order to optimize the performance of the manufacturing system. It will have the capability to “self-integrate” within an interoperable environment. Models and information systems will plug and play to achieve instant interoperability and allow the selection and use of best-in-class tools, regardless of the vendor.

1.4 THE PATHWAY TO A SMART PROCESS MANUFACTURING PROGRAM

The roots of the SPM activity can be found in the vision of leaders from major process industries, universities and government who came together in support of the goal of a new level of dynamic responsiveness in the chemical processing industry. An NSF-sponsored workshop to examine the interaction of cyberinfrastructure and chemical and biological processes in U.S. competitiveness was conducted in September 2006. One of the major findings was that Smart Process Manufacturing represents a national priority and a “grand challenge” worthy of priority pursuit by industry, academia and government.

An NSF grant was awarded to create an industry-academic steering committee and national Engineering Virtual Organization with the stated objectives of building a constituency to develop the SPM initiative, generate a technology roadmap and move toward implementation. A roadmap development workshop was conducted at NSF in April 2008 to develop objective goals and requirements structured around the operational model shown in Figure 1.

In presenting the results of that workshop and related research as a technology roadmap, this document becomes the basis for focused discussion on the vision, technology and operating changes that are needed, the path forward and a guide to future technology investments.

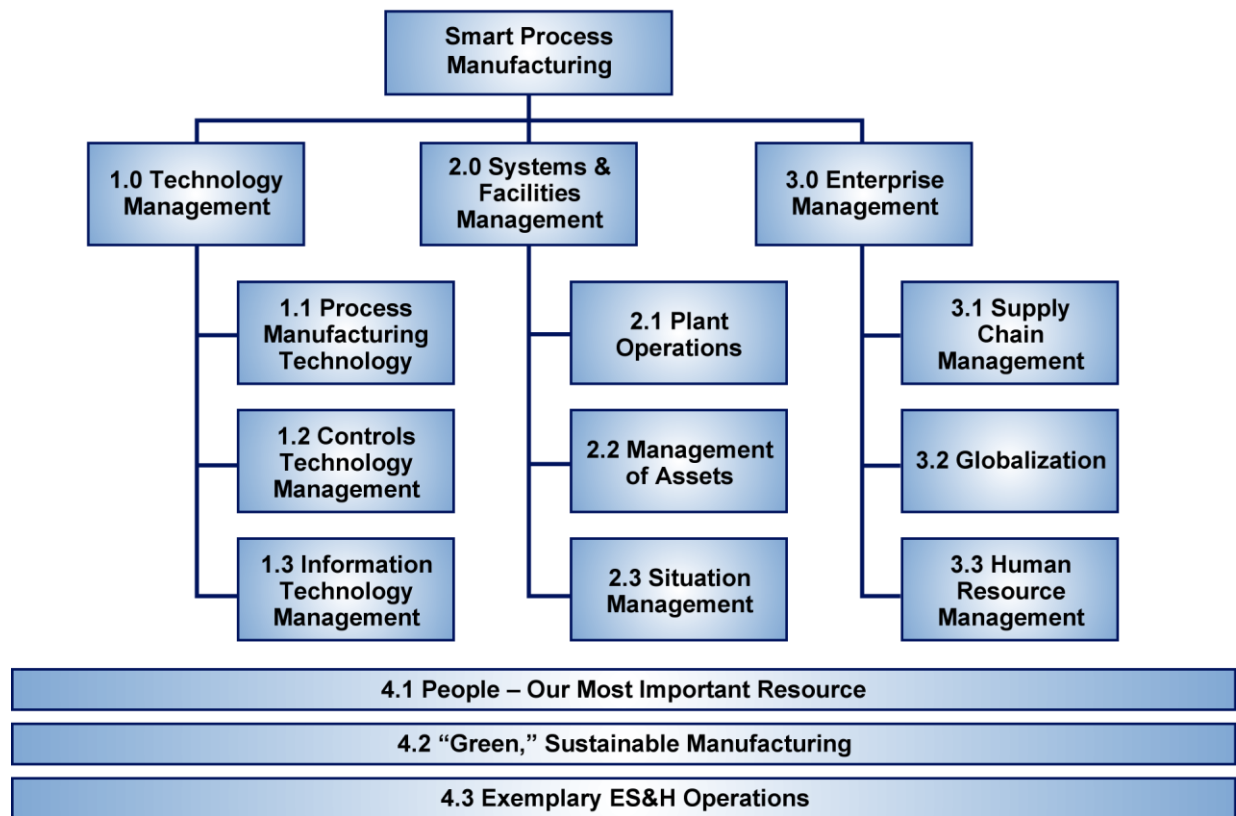


Figure 1. The Smart Process Manufacturing functional model provides a logical, hierarchical framework for development of a technology roadmap.

To facilitate information gathering in the April workshop, three major management areas, as shown, were designated as the “pillars” of process manufacturing operations.

Technology Management addresses the technological resources required to sustain, protect and improve the operations of the manufacturing enterprise.

Systems and Facilities Management provides the oversight and assurance of readiness of the plant assets to execute all needed functions within the defined operating envelope.

Enterprise Management takes an integrated view of all enterprise activities, including the integration of various functions within and across organizational boundaries.

Equally applicable to each of the pillars, key *cross-cutting enablers* were identified. The enablers include people, sustainable manufacturing practices and exemplary ES&H practices:

- People are the most important asset. Creation of a skilled and trusted workforce requires a strategic commitment to education and training, and to changing the mind-set and culture to support the future-state vision. A significant aspect of valuing knowledgeable workers is the capture and reuse of their knowledge and experience.
- “Green,” sustainable practices must be instilled in all management areas of the operation to the point that they are core business drivers that guide all planning and operations.
- A Smart Process Manufacturing facility is not only cost effective, but also safe and healthy, because safety is a core business driver that guides operations and cannot be

compromised. SPM operations see EH&S goals as performance objectives and develop capability to quickly, efficiently and safely deal with both actual and potential faults, whether accidental or deliberate.

1.5 THE TRANSFORMATIONS TO SMART PROCESS MANUFACTURING

A full realization of the SPM environment involves revolutionary and transformational change in both the business and technical arenas (Tables 1 and 2). The technology roadmap for Smart Process Manufacturing provides a migration plan and research agenda to expedite the realization of these visionary ideas.

Table 1.
Smart Process Manufacturing Business Transformations

From	To	Results
Investment in Facilities	Investment in Knowledge-Embedded Facilities	Investment and management of facilities and knowledge are equally important.
Reactive	Proactive	Economic optimization is achieved by anticipation and decision, understanding probability, risk and impact.
Response	Prevention	Sensing, modeling and analysis are used to predict events and operations are controlled to mitigate the impact.
Compliance	Performance	Zero-incident EH&S is part of the performance culture.
Tactical	Strategic	Requirements become opportunities, optimizing total enterprise operation.
Local	Global	Every decision must be made in the context of a globally competitive environment.

Table 2.
Smart Process Manufacturing Technical Transformations

From	To	Results
One-Off Models in Operations	Models Integrated Into Operations	There must be pervasive, coordinated, consistent and managed application of models.
Dispersed Intelligence	Distributed Intelligence	Data, information, knowledge, models and expertise are available and used to make decisions at the right time and place.
Unintelligent Systems	Self-Aware Systems	There must be autonomous systems that understand their role and performance in the enterprise and systems that take action to optimize performance.
Proprietary Systems	Interoperable Systems	Systems must communicate through standard protocols for information sharing, capability and best-in-class components.
Unpredictable Industry	Predictable Industry	Operations within defined operating envelopes must be performed with predictable impacts.

We have characterized the technologies, practices and resources needed to achieve the transformations as five “roadmap lanes” to convey the need to develop and implement operational technology and practice in five distinct areas and to commit to a journey of activity to achieve SPM.

Data to Knowledge

Knowledge to Operating Models

Operating Models to Key Plant Assets

Models as Key Plant Assets to Global Application

People, Knowledge and Models to a Combined Key Performance Indicator

The “lane” concept emphasizes that although there will be sequential and dependent activities the “lanes” must be addressed with an integrated and coordinated plan.

Lane 1: Data to Knowledge – In an SPM environment, the right data will be collected from the right sources in ways that are far more efficient than possible today. The data will be analyzed and compiled to produce useful information. When information is used in the context of the design, expectations, experience, rules, models and forecasts, it can become knowledge that accelerates the attainment of business and operational objectives with more effective adaptation to novel situations.

Smart Process Manufacturing dictates that the *data to knowledge* lane be “wide” enough and time-dependent to assimilate all of the data and knowledge needed to realize a smart operation. For the smart process, knowledge must support appropriate decision-making in a continuously changing environment with management of uncertainty and risk being a high-priority requirement.

It is important to note that knowledge acquisition has many pathways. Some knowledge is processed from available data and information; some is mined from data sources; and other knowledge is captured from experience or directly from subject-matter experts. This roadmap lane accommodates knowledge acquired from all sources.

Lane 2: Knowledge to Operating Models – An operating model is an applied representation of knowledge. It describes the necessary levels of integration and standardization needed to achieve the smart process goals. We can visualize the capture and application of knowledge to create models that accurately represent the components and materials in a process, and the operations, interactions and transformations of these materials and components. The application of knowledge will provide the capability to build operating models that provide real-time, dynamic management and control.

Lane 3: Operating Models to Key Plant Assets – Roadmap Lane 3 represents a milestone level moving the use of multi-scale operating models into a knowledge-based level of integrated plant usage. Models embody operating knowledge and experience that is as critically important as the physical facilities. There is a critical and integrated system of models that will need to be managed as key plant assets. There are two important dimensions to this roadmap lane: 1) aggregated operating models are used to plan, create, operate and manage the long term quality of plant performance through enhanced coordination of people, models and facilities; and 2) detailed *models* are key plant assets along with the facilities, data, material technology and the expert, trained and experienced workforce that are used to plan, control and manage each of the components of the SPM enterprise.

Lane 4: Models as Key Plant Assets to Global Application – Leading process manufacturing companies are increasing the use of modeling, smart facilities and knowledge-based systems to integrate, manage and control their operations, yielding enterprise-wide optimization with cost and performance breakthroughs. Process industries see the entire world as both their market and their operating locations. Hence, the concept of plant assets must be scalable to global application and beyond enterprise walls through smart collaboration processes. An obvious next step is to exploit and integrate continuing advances in process control, situation analysis and production management to similarly benefit and expedite these wider external relationships beyond traditional enterprise boundaries. Language, cultural, regulatory and other differences must be addressed. The success of global business relationships requires that companies reach consensus on communications among their operational systems, share information while protecting their intellectual property and competitive advantage, and create flexible and

responsive systems to optimize their mutual business operations. The challenges created by these international relationships have thus far exceeded the capabilities of most supply chain management systems.

Lane 5: People, Knowledge and Models to a Combined Key Performance Indicator – The SPM environment efficiently and effectively coordinates human skills, knowledge (both human and digitally captured) and an integrated system of models. All of these skills, capabilities and knowledge will blend into an integrated environment where manufacturing yields and other production goals are attained, EH&S compliance is assured, and key performance indicators continuously measure enterprise success. The result will be manufacturing enterprises that fully and expertly use all available knowledge and experience, augment that knowledge with computer-based systems using intelligent models that can “learn”, and optimize multiple objectives in every step of the design and manufacturing life cycle.

2.0 SMART PROCESS MANUFACTURING

THE BUSINESS CASE AND THE BUSINESS TRANSFORMATION

2.1 SMART PROCESS MANUFACTURING: THE BUSINESS CASE AND THE BUSINESS TRANSFORMATION IN DETAIL

Historically, process manufacturing plants have been operated so that steady-state operations are maintained in the face of multiple disturbances and rate or grade changes. Operations involve doing what is required to keep the plant running and meet production schedule and product quality specifications in a safe and environmentally acceptable way. Although some facilities operate in this mode, the next-generation plant does not. The economics of steady-state operations are being replaced with a dynamic economic environment where the adaptation to changing supply streams, creation of multiple products and frequent transition from product to product or grade to grade are the norm. This dynamic environment is also more constrained not only by tighter quality specifications and the need for minimum inventories but also by more stringent process safety measures, cybersecurity standards and environmental regulations. Managing this dynamic and highly constrained environment requires highly operable processes, reliable instrumentation, high availability of automation assets, excellent data, efficient information systems, accurate and predictive models, rapid and firm decisions and precise control. It also requires that uncertainty and risks are well understood and managed in every aspect of the decision-making process.

The future of smart process manufacturing can be summed up with the following statement from the 2008 Workshop:

In the future, smart process plants will be conceived, designed, and operated using “molecularly informed” engineering. Smart plants will be robust, proactive and seamlessly integrated. Systems and facilities will achieve and ensure optimum availability and performance, always delivering the best total-value product in a zero-incident, zero-emissions environment. Models and knowledge will guide the product and process design and support both automated and assisted decision-making. Enterprise tools will enable U.S.-based manufacturers to successfully collaborate and compete in the global economy.

This is achievable only when both business practices and technologies are transformed. The vision and business case for these transformations is outlined in the following sections.

2.1.1 THE BUSINESS BASELINE

The basic methodology for establishing a business case is to create a baseline, define the vision, quantify the associated cost, risk and benefits and evaluate alternatives against the baseline. In the case of SPM, the detailed data needed to conduct a rigorous analysis are company and supply-chain specific and thus cannot be directly extrapolated to the industry as a whole. However, certain observations can be made that articulate the value of SPM and indicate the potential of broader integrative application, recognizing that an integrated SPM environment broadly embraces technology, business issues and cultural change.

THE CURRENT STATE BASELINE

The current baseline for process manufacturing includes frequent use of intelligence and knowledge via the workforce but limited use of modeling and simulation. Modeling and simulation systems have been applied from the conceptualization stage, through the detailed design process and finally to the operating plant. However, application is often limited to specific instances of prediction and problem solving instead of providing the backbone for the operating environment. In the future, modeling and simulation systems will be used in the development of integrated facilities and process operations, so that process design becomes a larger driver for capital projects and investment. Facilities will be specifically developed to optimize execution of processes instead of “housing” for production operations. Production operations will be monitored for adherence to control limits, and abnormal situations and deviations from expectations will result in responses that range from simple alarm signals to decision analysis and corrective action.

Predictive maintenance systems are already becoming established in industry to move from a reactive to a proactive environment. Advanced concepts of intelligent maintenance systems that monitor critical parameters and predict the probabilities of failure are being adopted in more advanced companies. Agent-based approaches, focused on specific component, function or abnormality monitoring yet integrated into distributed reliability management systems, enable distributed assessment of the health of the processing environment. Life-cycle management is rapidly gaining prominence, especially as more government agencies transfer responsibility for life cycle and end-of-life management to the manufacturer and more attention is applied to environmental issues. The goals of closed-cycle operations and zero-emission plants are becoming pervasive, and the trend will increase. These model-enabled systems, operating jointly, can provide probability assessments for achieving defined performance (such as time to failure or the ability to complete a processing requirement). These systems, however, are in the early stages of maturation and deployment and applied only as value-added point solutions like smart instrumentation, sophisticated automation technologies, quality systems and optimizations.

Information systems are also strongly supporting all business functions of the process industry. For example, enterprise resource planning and management systems have become much friendlier over the past decade and are now an accepted part of the business landscape. However, interoperability issues continue to cause difficulties in information exchange and result in added operational costs. Software tools that can claim ubiquitous access to all data from any source, sorted to meet the needs of the user, offer the potential to revolutionize the information management arena. The elimination of interoperability barriers will produce dramatic improvement in information availability and in the cost of data management. Although numbers are not available for the process industry, extrapolations can be made from other industries.

The current state of the process industry represents a strong start toward the strategic goal of smart process manufacturing. Pieces of the smart process manufacturing mosaic are being implemented by leading companies, and movement toward integrated, smart manufacturing systems is underway in those organizations. The challenge for the future state is to develop the crosscutting enablers that expedite the journey and support global achievement.

The vision and direction are to realize a knowledge-enabled, model-rich, and intelligent manufacturing enterprise in which optimal decisions are made and executed in a totally controlled, integrated environment.

2.1.2 SMART PROCESS MANUFACTURING: THE VISION AND TRANSFORMATION IN DETAIL

Table 1 in the summary outlines the key business transformations that need to occur to move from current operations to the smart process environment. A third type of transformation – cultural – must also take place. We have, however, considered it as embedded in the business and technical transformations.

In the future, corporations and enterprises within the process industry will operate as strategic organisms that exploit a strong knowledge base to produce useful products without interruption or failure. Business functions will be seamlessly integrated to coordinate all enterprise operations and activities for total value optimization.

With reference to Table 1, the transformations in business operations to smart process manufacturing can be broken down into six categories:

1. From Investment in Facilities to Investment in Knowledge Embedded in Facilities

The mindset of investing in a facility that houses process equipment to produce a product or product line will be replaced by the mindset of the capital facility, specifically aligned to the process needs. The knowledge-rich facility embeds and continuously updates process knowledge that is applied to execute processes and deliver the best product value. Knowledge permeates this new processing environment.

With this knowledge embedded conceptualization, product and process knowledge will drive a robust scenario-based environment. The management of knowledge for optimized operation will become a priority. From the best scenarios, knowledge-supported design systems will enable process-operation factors to be evaluated in concert with other factors – with the imperative of maximized profit over the facility life cycle and operation always within acceptable operating limits. For example, the structural design will be integrated with the piping design, which will be integrated with equipment placement and support processes optimized for total value, including compliance with all regulatory constraints. Process flow, human access, material flow and all manufacturing and support logistics functions will be integrated and optimized. Operation of the facility will involve executing in a knowledge-enabled modeling and simulation environment in which models are implemented in support of the output of product. The result will be processing facilities that embed the best knowledge that is available from conceptualization, through design through construction and in operation. The embedded knowledge will continually inform the operation of the facility, and the knowledge base will be continually updated as the operational script plays out over time. Facilities will be failure tolerant.

2. From Reactive to Proactive

Both the facilities and the business functions themselves will be operated with embedded knowledge and the ability to proactively sense and respond to changing external and internal conditions. The enterprise will have a keen ability to accurately forecast risks and track all factors influencing the health and viability of the operation. The total environment in which the enterprise conducts business will be understood and modeled to the point that the impact of a change, whether a threat or an opportunity, is quickly and fully understood to the extent possible. All possible responses, probable outcomes, risks and impacts will be clear and the best course of

action, based on this understanding, will be delivered. Knowledge-enabled decision support and failure tolerant systems will guide the human decision makers to ensure the best choices are made based on all available knowledge. The business function will respond to both the highly predictable (deterministic) situations and those in which the outcome is not directly calculable due to a changing (stochastic) environment. Better understanding of uncertainty through the application of techniques such as emergent behavior modeling will guide responses to the stochastic circumstances.

3. From Compliance to Performance

Addressing the spirit and the law of regulatory requirements as well as actions prioritized for positive social impact and the safety and well being of the operating staff will become an integral aspect of the performance culture. Driving towards zero-incident, Environmental, Health, Safety and Cybersecurity will become an integral part of the operating culture for the entire workforce, transitioning from constraints for which minimum conditions need to be met to quality performance indicators that are integrated among the other KPIs.

4. From Response to Prevention

The smart process operation will have sensors and analysis to predict operating and facility events and to mitigate impacts. Closely related to items 2 and 3 above, Response to Prevention addresses how sensors and knowledge-enabled capabilities will be organized and oriented. Every component of the enterprise will operate in a dynamic, proactive environment enabled by intelligent, model-based systems that are vigilant in monitoring plant and asset status. Any deviations from expected norms will be noted and if adverse trends are detected, the intelligent control systems will gather needed information and autonomously take preventive actions and in so doing exhibit high a high degree of fault tolerance. This proactive system extends far beyond the plant's core production operations and includes safety, health, environmental protection and human resources. The future plant will operate with zero accidents; zero negative impact on the health of the workers, the community or the users of the product; zero cybersecurity incidents, and zero impact on the environment. Employees will be flexible, enabled by technology, and adaptable (through training and technology-based knowledge enhancement) so that they are constantly meeting the needs of the present and the future. The business environment will always be forward-looking and prepared to take the actions needed to ensure continuing business success. From the human resources perspective, the business will be managed within a context of social responsibility.

5. From Tactical to Strategic

The smart process manufacturing enterprise will meet today's challenges, but always in the context of strategic success. A clear vision of the future will be embedded in the organization at every level – in both the people and the systems that manage the operation of the enterprise. The vision will be captured in strategic plans and roadmaps that point the way to the future. Migration plans from where we now are to where we need to be will be managed as living plans, supported by information and knowledge systems to ensure the best decisions along the path to the future. The response to daily challenges will always stand the test of consistency with strategic direction.

Strategic thinking will permeate every aspect of business management. Marketing and sales will focus on the best positioning in the marketplace, empowered by information and knowledge that

allow the sales force to confidently pursue potential opportunities. Workforce planning and human resource management will ensure the ability to meet the strategic demands. Material and asset management will support the broad view of enterprise operations, including management of risk and uncertainty, as well as response to change. Technology management will ensure that the technology portfolio delivers and sustains the critical capabilities and core competencies that support the strategic positioning. Information management will ensure the availability of data and knowledge to manage present operations and support decisions that influence strategic success.

6. From Local to Global

The smart process manufacturing enterprise will be connected and scalable from the unit level of the single machine to global operation beyond the enterprise walls. Distributed business environments will ensure that the information needed for operation is available at the location and level at which it is needed, and that the business operations of all members of the enterprise are synchronized. Language barriers, regulatory differences, financial management differences and human resource management will all be coordinated by business systems that facilitate location transparency.

2.2 THE BUSINESS CASE QUANTIFICATION

The challenge in developing the business case for SPM is in defining and quantifying the benefits. Since the 1980s, companies like Shell Oil have recognized that tools such as optimization can provide 3% to 5% of the value-added (products vs. raw materials) when applied in a real-time environment. However, smart process manufacturing has impact at every stage of the life cycle, from innovation through production, customer support and end-of-life disposition. The smart environment reduces the cost of moving from idea to production, cuts operating costs and maximizes return on assets.

The following discussion highlights areas of benefit from smart process manufacturing and some vignettes are provided to indicate areas of significant value that are now being exploited. Although impressive, these examples generally represent point solutions implemented with existing technologies. To realize the transformation, one must think about these all together and in so doing consider significantly increased benefit and what is required with a *holistic, integrated, interoperable and sustainable* approach.

The justification of smart process manufacturing in the context of business decision-making may include increased product throughput and yield of higher-valued products; improved safety and operability; decreased energy consumption and pollution; decreased off-specification product and production labor; and extended life of equipment. These are discussed in more detail below.

1. Improved Product Quality

Smart manufacturing operations that consistently make on-specification products can eliminate the need for costly and labor-intensive (manual) quality assurance operations, which are imperfect because they are sample-based and cannot test all material from the process. In the smart manufacturing environment, sensors can inspect process and product characteristics against quality specifications throughout the entire run and allow for manual inspections only where warranted. Benefits include lower costs, assured quality, assured customer satisfaction and customer retention, and reduced product liability exposure.

Lower variability means that the process can be operated closer to constraints to maximize throughput. Making the specified product also maximizes equipment utilization and reduces energy consumption because equipment doesn't have to be shut down for blending or rework. With lower product variability, cycle time (the elapsed time between receipt of raw materials and shipping finished products) can be minimized. The effectiveness of the control system in ensuring consistent product quality depends on speed of response of the controllers and the effectiveness of the control strategy and the measurement system (i.e., all product quality variables are measured on-line). A 1988 study by E.I. DuPont de Nemours estimated that increased profits of \$200 million to \$500 million dollars a year could be realized in its facilities through implementation of advanced control and optimized operating conditions.

Model predictive control is an advanced multivariable control technique based on nonlinear programming that has been implemented in refineries and petrochemicals manufacturing. Major companies such as Exxon Mobil, Eastman Chemical, Shell Oil and Praxair have reported many successful applications of this technology. Overall profits of \$500 million to \$800 million per year have been reported in ethylene manufacturing, achieved primarily by improved product quality and decreased energy usage.

J.B. Rawlings, "Predictive Control from Practice to Theory", AIChE Annual Meeting, Philadelphia, PA, Nov. 2008

In 2005, Alcoa World Chemicals completed implementation of control and optimization on five out of the six kilns that are part of the aluminum fluoride plant at Alcoa's Point Comfort, Texas facility. The solution addressed the production of alumina fluoride that is used as a fluxing agent of aluminum smelting. The project goal was to reduce the amount of calcium fluoride left in the gypsum co-product which discharges from the kilns, thus maximizing the use of the raw material and enhancing the quality parameters of the gypsum co-product. In just six months the company deployed control solutions on five kilns and exceeded performance goals (return on investment of 12 months). In addition, the installation decreased the amount of unreacted calcium fluoride by a factor of almost three and reduced the process variability in critical downstream process by 75%.

<http://www.allbusiness.com/manufacturing/primary-metal-mfg-alumina/5027886-1.html>

2. Lower Cost of Plant Operations

Enhanced use of operations information and improved process control reduces energy consumption (usually the second-highest operating cost) and feedstock or raw material usage (typically the highest cost in process industry manufacturing). The reductions are accomplished through elimination of off-specification material and the ability of smart process systems to produce higher-quality products with greater adherence to the increasingly tighter specifications that drive improved margins and achieve environmental, health and safety goals. Making the right products correctly results in less rework, waste and labor input; higher quality; and better use of all assets in the manufacturing space. Shell Oil and other companies have estimated that 3% to 5% of value added (value of products minus the cost of raw materials) in a refinery or chemical plant can be obtained in additional profits through the application of modern optimization tools. This would amount to about \$15 billion dollars a year for the 400 largest oil, gas and chemical companies.

At the Chevron refinery near Salt Lake City, Utah, normal refinery operation allowed significant quantities of light hydrocarbons to enter the refinery fuel gas system. These hydrocarbons reduced operating efficiencies for fired heaters and boilers by increasing plugging and fouling

of the gas burner tips. It was feasible to recover the hydrocarbons from the fuel gas system and to sell them. Chevron used process simulation models of its light ends distillation columns and associated reboilers and condensers to predict the performance of potential equipment configuration changes and process modifications. The simulations projected that more than 25,000 MMBtu in natural gas could be saved annually if a debutanizer upgrade project and a new saturated gas plant project were completed. Together, these projects would save \$4.4 million annually.

http://www1.eere.energy.gov/industry/bestpractices/pdfs/petrol_cs_chevron_utah.pdf

ICI, and later Huntsman Petrochemicals, decided to completely replace the cracker control system on one of the largest single train ethylene units in Europe. This cracker is one of the largest of its type in Europe with 17 cracking furnaces, and it feeds a number of downstream users as well as exporting ethylene by pipeline to other UK locations. Advanced control and optimization, coupled with a high-fidelity process historian, yields sufficient benefits from increased production and plant reliability and reduced off-specification production and energy consumption to support the significant capital investment cost of a new, distributed control system (DCS). The combination of a new DCS and the more profitable projects would allow ICI to meet the following business objectives: (1) producing the maximum amount of ethylene and propylene; (2) reducing production disruptions, upsets and flaring; (3) decreasing cracker energy consumption.

http://www.aspentech.com/case_files/Huntsman%20SS%20129.pdf

Valero Energy Corporation recently undertook a plant-wide energy assessment at its refinery in Houston, Texas. The assessment consisted of an energy systems review to identify the primary natural gas and refinery fuel gas users, electricity- and steam-producing equipment and cooling water systems, and to develop an energy optimization and management system. It also addressed ways to reduce water use and environmental emissions. If all the projects identified during the study were implemented, the assessment team estimated that total annual energy savings at the Houston refinery would be about 1.3 million MMBtu (fuel) and more than 5 million kWh (electricity). Total annual cost savings would be about \$5 million. Assessment data and energy system information were gathered to develop a computer model of the primary refinery processes and the energy production and distribution systems. The model was used to determine the most efficient loading of individual pieces of equipment and to optimize energy usage. The model-based, equation-oriented simulation and optimization software tool optimizes the purchase, supply and use of fuel, steam and power at the refinery, based on process unit energy demands and system constraints caused by equipment or environmental regulations. The software analyzes conditions such as supply contract variability, alternative fuel options, optimum loading of steam boiler equipment, motor vs. turbine driver decisions, and importing vs. exporting of steam, fuel and power.

<http://www1.eere.energy.gov/industry/bestpractices/pdfs/valero.pdf>

3. More Effective Supply Chain Management

Smart systems that reach across company boundaries provide tremendous competitive advantage. The benefits flowing from the extended knowledge infrastructure add value for all trading partners. Smart collaboration can reduce operating costs in both the serving and served companies and provide sustainable competitive advantage. These advantages, which build on the knowledge base of the smart process manufacturing supply chain, include reduced cost due to harmonization of common processes (planning, inventory management, administration, etc.); enhanced supply chain efficiency (through reduced out-of-stock or oversupply inventories); reduced inventory in both supplier and customer locations; improved product quality; and faster development and introduction of new products and services. It is estimated that the total value of

manufacturing inventories in the United States is about \$0.5 trillion with an inefficiency of up to 50%, providing an economic opportunity of \$250 billion. Supply chain management tools build on the tremendous advances in computing for solving optimization problems. Computers are faster (due to Moore's law), and optimization software has made speed improvements of 100x to 1000x during the past 15 years. The ability to sell what you make – and make what you sell – can best be achieved in a knowledge-rich environment. Closer integration of manufacturing capacity and capability with sales and marketing functions will increase sales and margins and lower product costs. All businesses are striving to reduce working capital requirements and move to a make-to-order model. This is difficult to do in process manufacturing, where asset utilization is key to competitive advantage and shutting down assets is rarely a viable short-term strategy.

PPG Industries provides specialty products to tens of thousands of body shops and refinishers through distributors in more than 100 countries that repair 30 million cars per year. PPG needed a system to address supply chain issues including lack of visibility across the supply chain, with each manufacturing plant operating independently; poor customer service for export markets; long lead times; and high inventory of the wrong products. To address these issues, PPG implemented a supply chain management solution that reduced inventory by 20% and increased product availability to 98% in the UK and 85% to 100% in other parts of Europe. Dow Chemical implemented supply chain management software and reduced inventory by 10% in the polyethylene business, decreased planning manpower by 50%, reduced off-grade material and moved into new market areas due to increased visibility.

www.logility.com/library/success-stories.cfm

4. Improved Reliability

The ability to keep a process running is imperative for success. Nothing in a process company is more serious than losing a critical production asset, which can quickly result in lost sales, increased capital costs for repair and the increased potential for environmental upsets. When the process is down, sales are not being generated while fixed and variable costs continue to accrue, severely reducing profitability. Measuring and quantifying the ability to make product and to predict failure before it happens – and prevent its occurrence – is delivering dramatic cost savings and return on investment. Increasingly, maintenance engineers are able to monitor plant operations data and predict equipment failures, thus allowing preventive maintenance to reduce downtime and improve efficiency of maintenance personnel (a significant cost element in process plants), which leads to improved safety. These techniques can reduce plant operating costs by millions of dollars annually and prevent shutdowns that can cripple or destroy a business.

The goal of “zero-incident operations” encompasses the following performance targets:

- No injuries to facility, maintenance or other personnel
- No losses of primary containment or releases of toxic materials to the environment
- No negative impact to communities adjacent to operating facilities
- No physical or cyber-security breaches
- No unplanned outages

It has been estimated that at least \$10 billion a year is lost due to abnormal situations in the U.S. petrochemical industry, with about half of this total caused by human error. The cognitive demands on human operators in today's process control environment are rising dramatically. Process control systems have been designed with a focus on the technical issues of process automation and not on supporting the operator's tasks. This sometimes results in automation that seems non-intuitive and requires more complex decision-making from the operator. Reliable process systems cannot be totally automated and must account for human interaction. SPM in the future must integrate the human component as completely as the technical components.

The Abnormal Situation Management (ASM) Consortium is a joint industrial/academic organization that focuses on creation of knowledge, tools, and products designed to prevent, detect, and mitigate abnormal situations that affect process safety in the plant operations environment. Solutions to address abnormal incidents need to consider the human operator's role, the process technology, the system design, and the environment. Joint research with Nova Chemicals indicates that when the automation system includes consideration of human factors, substantial improvements in operator performance can be realized. Using the ASM concepts such as effective alarm management and display design, Nova realized more than 35% improvement in recognizing process deviations before an alarm, 25% improvement in the operator's ability to solve the problem, and 35-48% improvement in operator response time to deviations. Improved operator performance translates into savings of approximately \$1 million per year in safer, more reliable operations.

http://applyhcs.com/publications/workplace_design/DesignForASM-AICHE98.pdf

Honeywell Specialty Materials, at its Geismar, Louisiana, site, implemented a security system that is totally integrated with process control and automation systems. By doing so, it is able to reduce risks and increase safety preparedness. Benefits include the ability to:

- Identify and control who enters and exits the facility.
- Locate and track movement of building occupants and assets.
- Protect process automation and networks from cyber threats.
- Respond proactively to alarms and events.

— Honeywell Success Stories, http://hpsweb.honeywell.com/Cultures/en-US/NewsEvents/SuccessStories/success_geismar

5. Environment, Health, and Safety

The theme of zero incidents and zero emissions has clear value in a world where environmental sensitivity is an increasingly important business imperative. The cost of noncompliance or unsafe operation can be the loss of the right to do business. Improved integration of plant environmental information can improve upset prevention, reduce energy and maintenance costs, and avoid potential fines and costs for out-of-specification operating conditions. Energy usage and production go hand-in-hand in process manufacturing. Smart manufacturing addresses the need to minimize energy usage while also providing tools for energy production – which itself is a process that is often co-located with the plant. Coal and biomass-based energy will play a dominant role in the process industries in the future as conventional oil and gas supplies

diminish. Advanced coal combustion systems can competitively produce low-cost electricity at efficiencies higher than those of current coal power plants. Such facilities can be designed as near-zero discharge energy plants, with minimal emissions escaping into the environment. Carbon dioxide could be concentrated and disposed of in a geologically permanent manner or converted into industrially useful products. Sustainable energy solutions will be necessary to achieve the goal of zero emissions, which will in turn cause significant changes in how plants are designed and operated. Development and application of Process Systems Engineering tools will be crucial to making such a transition.

During chemical plant turnaround operations (plant startup and shutdown) and process upset management, off-spec product streams will be produced, which usually have to be sent for flaring. Flaring is a passive and end-of-pipe means to protect personnel and equipment safety in the chemical process industry. However, flaring inevitably generates huge amounts of CO, CO₂, NO_x, and some extremely hazardous volatile organic compounds (VOCs), which will cause severe air pollution problems and negative societal impacts. Meanwhile, it also results in tremendous raw material and energy loss that could generate additional products. Thus, flare minimization has great significance on environmental, societal, and economic advancement toward the sustainability of the chemical process industry. The key idea is to reduce the startup time and pursue the “balanced” reuse of off-spec products from a plant-wide systematic point of view. A general methodology framework based on dynamic simulation has been developed by Lamar University and has been applied at a Lyondell chemicals olefin plant with a 75% reduction in flaring during startup. At a Huntsman petrochemical ethylene plant, flaring time was reduced to less than 3.5 hours, and at BASF-TOTAL flaring was reduced by half

[http://dept.lamar.edu/chemicalengineering/www/Lou/IJEP%2029\(1-3\)%20Paper%2003.pdf](http://dept.lamar.edu/chemicalengineering/www/Lou/IJEP%2029(1-3)%20Paper%2003.pdf)

Rohm and Haas at its Knoxville, Tennessee, plant carried out a project to reduce energy costs and water consumption. The engineers constructed a model of the steam system to evaluate potential benefits from piping and control changes, use of letdown turbines and cogeneration alternatives. Heat and material balances were developed for the process units to establish preliminary energy targets for use in pinch analysis. The staff used pinch analysis to provide an order-of-magnitude energy savings potential and to identify conservation projects. The analysis identified several heat exchange opportunities between waste streams and feed streams. The cooling systems analysis included consideration of flow balancing and refrigeration equipment loading. The compressed air systems analysis included optimal compressor sizing and operational control. Productivity gains, environmental benefits and labor savings were also identified. The assessment team used a water pinch analysis to identify opportunities to recycle water streams and to reduce water flow and sewer discharge by approximately 20%. One non-energy benefit the assessment team identified was reducing environmental impacts by decreasing nitrogen oxide (NO_x) at the boiler house.

http://www1.eere.energy.gov/industry/bestpractices/pdfs/ch_cs_rohmhaas_drpk.pdf

Georgia-Pacific Corporation employed water-reduction analysis and thermal pinch studies to identify water and energy conservation projects in its Palatka, Florida, paper mill. It used the principles of water and thermal pinch to identify water and energy conservation projects. Using Process Flow Diagrams and dynamic simulation models, assessment personnel were able to examine direct matches between hot and cold water flows. Direct matches (such as reuse of combined condensate for brownstock washing) could be identified immediately.

http://www1.eere.energy.gov/industry/bestpractices/pdfs/fp_cs_georgia_pacific.pdf

6. *Enhanced Innovation in the Workforce*

Although metrics regarding innovation are difficult to quantify, the technology- and knowledge-enabled workforce that is central to the smart processes vision will have the training needed to equip it to perform its jobs, and the information and knowledge to guarantee that the job is done correctly. Real-time monitoring systems will ensure that every important function is done properly. An “infrastructure of innovation” and ready access to accurate models, data and other information and knowledge will radically improve the ability of workers to analyze problems, explore new ideas for improvements to products and processes, and evaluate opportunities for innovations. Such ideas form the basis for better business decisions in the future, leading to sustainable competitive advantage.

Enhancing Innovation

BP found “spikes of innovation” within its enterprise, but these were not shared across the corporation. To address this issue, more than 12,000 employees created their own websites to share their knowledge and experience. Desktop videoconferencing created “globally available local experts.” Management encouraged and incentivized employees to share information and to use the knowledge resources. The company documented more than \$100 million in impact.

<http://www.bepknowledgesystem.org/Search/ShowCase.asp?CaseTitleID=65&CaseID=477>

2.3 THE BUSINESS CASE FOR COLLABORATIVE RESEARCH ON SMART PROCESS MANUFACTURING

The challenge of the smart process manufacturing vision is daunting. Many companies have been successful in developing and implementing individual solutions. However, the business transformations associated with evolution of the smart process enterprise require a foundation that can be achieved only through cooperative and focused activity. Standards, technological breakthroughs and business process development can be achieved only by working together. This situation is amplified when emerging technologies are considered. The breakthrough changes required to move to “smart” and “intelligent” manufacturing include self-aware systems, automated interoperability and intelligent control based on very complex prognostics. Developing these capabilities is costly, and the risk is high. These enablers can be realized only with collaborative activity and strong government support.

Although the definition of a “U.S. company” has changed from that of factories located on our shores to corporations that are headquartered or substantially doing business in the United States, the need for national focus is as real as ever. The U.S. government spends more than \$150 billion a year on direct R&D. Many additional billions are spent in R&D associated with individual programs. Although unfettered discovery is an important component of an R&D strategy, the nation’s R&D investments must be balanced by focusing on achieving “grand challenge” successes. There is likewise great value to industry and to the research community in focusing their investments on shared challenges. A good example of this type of effort is in the capital project arena (see www.fiotech.org).

There are therefore three compelling arguments for collaborative activity in smart process manufacturing:

- 1) The challenges are too large and complex (with many external dependencies) for any single organization to solve the total smart process manufacturing challenge alone.

- 2) There is both necessity and opportunity to focus and leverage government and private investment to accomplish bigger goals.
- 3) Collaborative activities open up avenues for cooperation that are not otherwise possible.

A final reason for collective activity is the value of collaboration within the chemical process industry. As representatives from industry come together with the research community, the pool of knowledge increases. Opportunities for collaboration beyond the pre-competitive arena are identified. Partnerships between companies and between companies and researchers will deliver results that would not be realized in any other way.

3.0 SMART PROCESS MANUFACTURING THE TECHNICAL TRANSFORMATION

3.1 SMART PROCESS MANUFACTURING: THE VISION AND THE TECHNICAL TRANSFORMATION IN DETAIL

The overall operation of process plants takes place at many levels of granularity, e.g., the properties of an individual material component at a point in time and location, the operations of systems of process equipment, management and control of the plant operation, decisions on product types and grades across multiple plant sites, and environmental impacts that are the result of multiple companies operating in a particular geographical region. Both automated and human-centered decisions affecting the plant operation are made at all levels of production granularity in response to a myriad of planned and unplanned conditions. There is risk and uncertainty with every decision and with every response to a changed condition.

The 2008 Workshop summarized the future technology vision of the smart process manufacturing as follows:

Manufacturing operations will be knowledge-enabled and model-based through the conceptualization and engineering of facilities, the design and construction processes, and operations and maintenance, including full life-cycle responsibilities. The information flow will be seamless, with no redundant entry of data. Interoperable systems will act with and from the data to support modeling tools and decision support systems that create the right information to ensure safe, optimum process design and execution. Operations will be closed-loop, with automatic sensing of all critical parameters, and will operate under distributed control, ensuring that all parameters that affect the business of the enterprise are maintained within control limits. The workforce will be technology-enabled and seamlessly connected to the enterprise's information and knowledge processes and will be a powerful resource in ensuring mission success.

In this section we establish a baseline for the current state of technology in operations and discuss the technical transformations that are presented in Table 2.

3.2 THE TECHNICAL BASELINE

A *technical baseline* necessarily draws from the business and operational objectives. As discussed previously, the U.S. process manufacturing industry is operating in a climate that is dramatically different from what it faced in the late 20th century. Economic viability in global markets is requiring increasingly faster transitions among products and shorter, more market-responsive product runs. Plant operations must increasingly be components of a global enterprise that respond quickly to regional product demands. Integrated supply chains themselves are vulnerable to climate and regional situations and must more rapidly adapt to ever changing situations. Increased social consciousness and mounting concerns about worker safety and

health, greenhouse gas emissions and global climate change are adding to already strong pressures on reducing environment impact and energy usage. Preventing or minimizing abnormal situations that could impact the safety of the operating staff or the surrounding community is critical. Business and operational decisions must be made with a clearer understanding of risk of operational instability so that uncertainty can be better managed.

A basic technical concept advanced in smart process manufacturing is the distributed intelligent manufacturing unit as an intelligent agent itself. The intelligent unit makes decisions and takes actions to achieve greater robustness to uncertainty with changing situations and greater flexibility and responsiveness to the overall goals of a complex process system. This concept implies a fundamental change to operating facilities where, through the use of models, technology and different roles for the workforce, the facilities themselves have distributed business and operating intelligence and decision-making authority at appropriate but more detailed levels of process granularity. A fundamental technical/operational question is the granularity of distributed intelligence and the spectrum of system complexity when predicting or understanding the overall collective behavior of autonomous but coordinated smart units.

We use the term *unit* to refer to any appropriate structural abstraction of a process operation. A *unit* could be a full process plant constructed to produce a particular grouping of products in a multi-plant enterprise, a major plant level system that produces a particular product, or a subsystem that produces a key chemical, material or energy transformation. In the limit, this abstraction can be taken to an individual operating equipment item.

In the SPM environment, the process unit becomes ‘intelligent’ through the use of models that optimally manage the process goals of the unit and communicate with other intelligent process elements to collectively accomplish goals of the overall operation. An intelligent unit understands what needs to be accomplished and how to accomplish it, and it understands its information needs and how to acquire that information. We can envision distributed decision and control systems that operate with the appropriate level of automation, autonomy and human centered involvement. Every smart unit in the distributed environment will have the information and knowledge that it needs from all activities and systems with which it interacts. All decisions and process control actions that impact other operations will be made with the full understanding of the impacts on total operational value optimization. Knowledge will be applied to address uncertainty and risk with the goal of substantially reducing the impact of unplanned events and/or rapidly changing situations. It will also be applied to create a more predictable and controlled but still dynamic environment, which is more responsive to deviations, situations and transitions within a predictable and manageable level of risk.

In today’s typical process manufacturing enterprise, business planning, optimization and scheduling intelligence are concentrated into centrally managed organization and system control structures. Business decisions tend not to be informed with day-to-day operations nor are optimal operational decisions aligned and coordinated with strategic business decisions. There is also poor alignment between business and operations when for example, business decisions may be impeded by the lack of operator capability or there are life cycle issues with critical consumable materials like catalysts that are not accounted for in the overall business process. Furthermore, there is a major discontinuity in time-scale between operation and business decisions that confounds integration. As faster and faster product transitions are required to

realize economic value, this misalignment between business and operation levels is becoming increasingly pronounced. Today, both batch and continuous processes are myopically focused on maintaining a prescribed set of conditions, variables and/or procedures. This emphasis forces a more pronounced reactive, instead of proactive or preventive, approach to economic, environmental, health and safety key performance indicators.

SPM therefore presents a unifying operations framework by considering a new integration of the mathematics and models involved in plant operations that are based on the distribution of intelligence for decision-making in chemical plants. The notion of distributed intelligence in operations and control is itself not new to process manufacturing. Multi-agent systems associate well with the spatial and hierarchical nature of process operations and suggest architectures for control and monitoring as well as higher level decision functions. Agent-based architectures and holonic systems have been discussed as cooperating autonomous entities applied to integrated manufacturing. What is new is fundamental change in the business and operations control structure in process manufacturing from centralized planning and control to a decentralized approach based on the concept of distributed intelligent units.

3.3 SMART PROCESS MANUFACTURING: THE TECHNICAL TRANSFORMATION IN DETAIL

With reference to Table 2, the transformation of current technical operations to smart process manufacturing falls into five categories:

1. From Operations Plus Models to Models in Operations

The smart process manufacturing environment will be model-based and the model set will grow and evolve as the environment matures to the point that integrated process models will serve as master controllers for ensuring 100% in-control processes, 100% of the time.

Model development and deployment will move from a parallel, disconnected activity to an integrated strategy that drives smart process development. Process and facility development will take place in a model-based environment, with every component and every decision evaluated and validated in the virtual space. The model set will grow as an integrated resource along with the process design, and model development will drive process development. Realization of the facility, the process and the product will be achieved through the deployment of a rich set of models that have grown into a near real capability. The as-built facility will be the physical realization of a fully tested and mathematically accurate model set. The process will immediately run in the facility as designed and modeled. Material flow and human interaction will be as designed and as modeled, and the rich operations model set will guide the functioning of all plant processes.

2. From Dispersed Intelligence to Distributed Intelligence

The smart process environment will ensure that the right knowledge is available and applied when and where it is needed. It will store and manage only the data and information that are necessary and useful, organized in or accessible through models that enable virtual operation,

monitoring and problem solving. The intelligence, properly controlled, will be available to all units and people who need it to execute their respective functions.

Distributed decision and control systems will operate with the appropriate level of automation and autonomy. Every node in the distributed environment will receive all the intelligence it needs from all activities and systems with which it interacts. Reciprocally, each node will provide all information and intelligence relevant to the activities and systems with which it interacts. All decisions and process control actions that affect other operations will be made with the full understanding of the impacts to the total operational state. Decisions and process control actions that are local and have no external effects will be managed locally. Decisions that affect other functions will be communicated to those functions. The enterprise will be knowledge-rich, with intelligence applied at the point of need. The operational workforce trained in knowledge-enabled, knowledge rich operations will interact seamlessly with intelligent units and will take on more strategic decision-making roles.

3. From Unintelligent Systems to Self-Aware Systems

Goal seeking, readily updated, and self-learning systems will mature as key components of the smart process manufacturing enterprise. Self-aware systems will understand their function in the enterprise and the needs of systems with which they interact. As a result of this understanding, self-aware systems will have the ability to configure or alter themselves for optimal operation within the context of the enterprise – with the ability to adapt their interconnections and working protocols to both the sources of information and the information targets. The result will be flexible systems that continuously learn and improve in their ability to meet individual and collective system goals. The individual systems will interoperate in a system-of-systems and systems-and-workforce environment delivering unprecedented intelligence, control and adaptability.

The SPM enterprise is a model-based enterprise. The concept of self-aware units, operating with rich knowledge content, opens the door to an intelligent environment in which models can configure themselves and communicate with other elements of the enterprise to accomplish goals. An intelligent unit understands what needs to be accomplished and how to accomplish it, and it understands its information needs and how to acquire that information. Intelligent units cut through the barrier of the cost of creating and managing individual models to enable classes of models that are configurable to specific applications and adaptable for modeling integrated processes instead of only process components.

4. From Proprietary Systems to Interoperable Systems

The transformation from proprietary systems to interoperable systems is critical to the success of the smart process manufacturing enterprise. In the future, the user community will work together to define the system capability required, and proprietary protocols will not be a barrier to realizing that functionality. The technology suppliers will understand that competition is based on performance in the interoperable enterprise and doesn't require proprietary restrictions on needed data and information. The use of service-oriented architectures will evolve into a set of interoperability standards – across domains, applications and industries – that will be used by all technology suppliers. Text and data mining systems, coupled with self-aware systems and intelligent models, will eliminate the technical barriers of proprietary protocols, and self-regulation of the free market will eliminate the legal barriers that now inhibit automated mapping of data structures between different vendors' applications.

While the technical capability to interoperate will be provided, compliance with standard practices will be essential. Design standards and conventions, standard frameworks and architectures, and other business enablers will ensure that the resulting systems plug-and-play for radically improved speed and efficiency in information management and operations exists.

5. From Unpredictable Industry to Predictable Industry

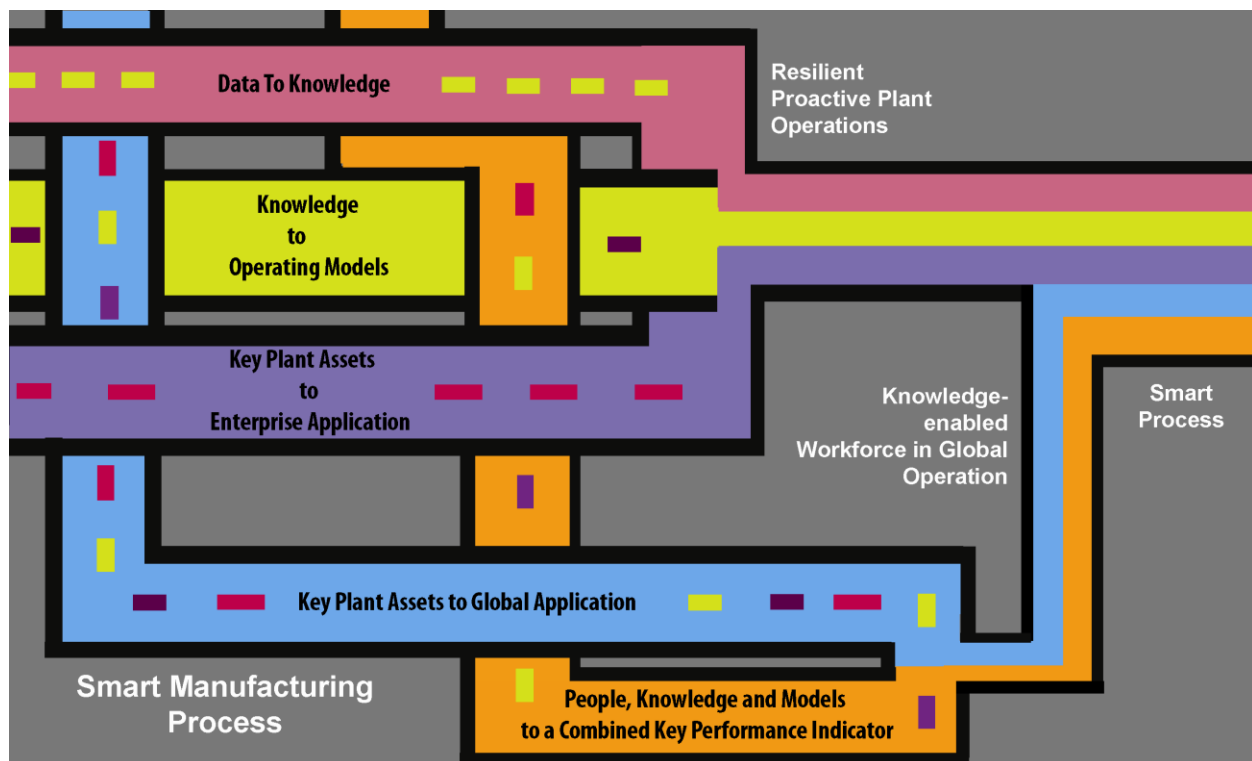
The dynamic environment will not be a chaotic environment. Unplanned change orders, failures in process operation, material shortages, product failures, environmental incidents and accidents will be eliminated in the smart process operation. The level of understanding embedded and encoded into every system within the operation, and the extent to which that knowledge addresses uncertainty and risk, will eliminate surprises and lead to a predictable and controlled environment that responds swiftly and surely to unexpected events. Truly unpredictable occurrences will be quickly, and largely automatically, accommodated with minimal disruption or delay. While this vision may never be fully realized, the smart process manufacturing environment will be knowledge-rich and forward-looking to the point that every deviation that occurs will fall within the statistical window of manageable risk.

4.0 THE SMART PROCESS MANUFACTURING ROADMAP

ACHIEVING THE VISION – THE ROADMAP LANES

The business and technical transformations describe the vision of and transformation to smart process manufacturing. What needs to be accomplished to get there, and how will it be done? This section is dedicated to an operational and technology roadmap.

Here, we provide a roadmap for organizing the thinking about areas of action in terms of operational and management outcomes. As illustrated in the roadmap graphic, by focusing attention on gathering and interpreting data (“Data to Knowledge”); determining what models and simulations are needed for plant operations (“Knowledge to Operating Models”); and then moving these into an integrated plant operation (“Key Plant Assets to Enterprise Application”), a plant operations will have taken significant steps toward “Resilient, Proactive Plant Operations.” While the initial focus is on the plant and its operation, significant attention must be paid to workforce training and transitions, as well as global thinking and decision-making.



Smart process manufacturing requires accomplishments in all five lanes.

In the approach to the resilient, proactive plant operation, there is increased consideration of new ways of management and decision-making, a knowledge-enabled workforce and the need to embrace global operations and global competitiveness. When these are fully embraced -

(“People, Knowledge and Models to a Combined Key Performance Indicator”) and (“Key Plant Assets to Global Application”), a new type of workforce becomes merged with resilient, proactive operations in a global context and the vision of Smart Processing Manufacturing takes final shape.

The roadmap is far from complete in that it represents the *start* of more extensive joint industry, academia and government discussions. It is a working map that requires further development, greater granularity and more definition and prioritization of action areas. ***It is significant that the roadmap represents a consensus of leading practitioners, providers and academics.***

User companies should employ this roadmap to test or shape their internal initiatives, but also should begin to consider where there is benefit in working together as an industry. Key industry and company considerations are how to:

- Achieve global competitiveness with existing assets
- Build new plants with more sustained and higher value
- Address multiple objectives that include:
 - Zero incidents
 - Reliability and risk management
 - Reliability and flexibility about product objectives
 - Resilient and fault-tolerant operations
 - Management of product transitions and maintenance of product quality

Suppliers should use the roadmap to:

- Understand and help define a multi-company industry vision for first-to-market and service development
- Build on the opportunity that there is a large base of automation equipment nearing obsolescence
- Understand how the concepts of safety, reliability and profitability must interrelate
- Understand future needs and cooperate with users on early developments
- Understand and take the lead on industry standards

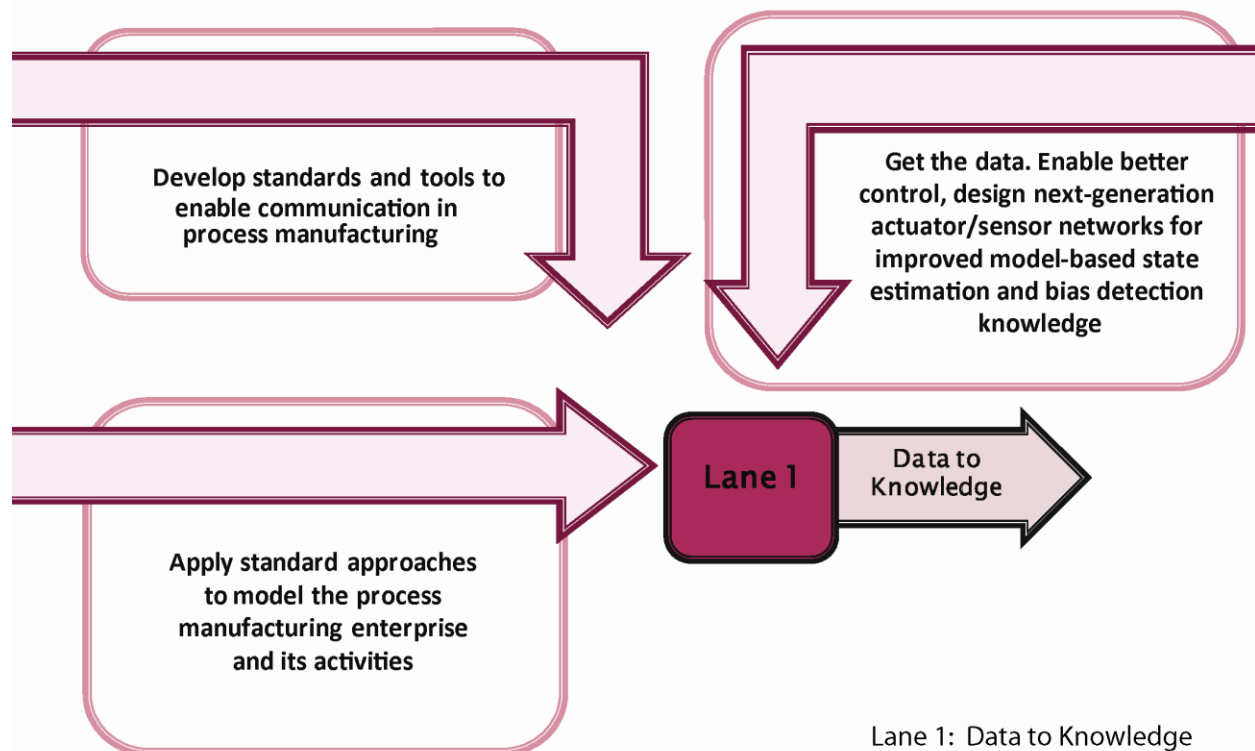
Academia and national funding agencies should use the roadmap to test or shape technological improvements and training and workforce-development. The smart process manufacturing vision will require considerable technological research and development. There will be a need for funding that targets simulation-based engineering science, systems and engineering. The funding cannot be limited to emerging technologies. Investment will be needed in approaches to managing and supporting knowledge and software as critical assets in production operations, how to accommodate new management and operational structures, and how to build, train and

transition to a new, knowledge-enabled workforce. Funding agencies and university researchers must be responsive.

The remainder of this document is dedicated to the specifics of the roadmap at its current level of development – referred to as Phase I development. The Roadmap Lanes that follow represent the conclusions of the April 2008 Smart Process Manufacturing workshop. These conclusions are divided into five key areas that, once fully studied, will facilitate the required transformations. As discussions and further development of the roadmap by the Process Systems Engineering community proceed, the roadmap will be updated.

4.1 ROADMAP LANE 1: FROM DATA TO KNOWLEDGE

In an SPM environment, the right data are collected from the right sources in ways that are more efficient than possible today. In the future, much more data from wired and wireless networks is expected and sensors will communicate with each other. The data initially are analyzed and compiled to produce useful information. That information is then processed based on past experience, rules, standards and forecasts to modify process and product models appropriately, and to create and deliver the knowledge needed for the right decisions and actions. The information transformation environment must also account for risks and uncertainty.



Advances in technology have made it possible to place sensors in almost any conceivable part of a process, taking data continuously or at time-based intervals. These sensors can be expensive

and complex, but many are inexpensive and readily available. Far from needing *more* data, the problem typically is one of filtering through the plethora of data to find the information needed to create useful knowledge and contribute to the right decisions. The challenge is to gain a better understanding of the value of different types of sensed information, then focus on acquiring that data and using it to improve process performance.

Not all data that can be collected contribute to useful knowledge about processes or plants. For example, sensor data that validate local actuator functions may or may not have value beyond that function. On the other hand, data associated with successful performance can be incorporated into process models to steer them toward improved process management and control. The challenges are to distinguish the differences in roles; to apply the appropriate methods for data, information and knowledge management; and to sustain, adapt and improve the performance of the underlying models over time. Data mining techniques and tools are being developed for other fields, such as particle physics and bioinformatics. These techniques should be leveraged and further developed for process manufacturing to mine the masses of data, provide visualizations for human operators and engineers, extract useful knowledge, and transmit the meaningful results to guide decision-making.

When a system has the ability to automatically determine what knowledge is needed to solve the current problem and takes steps to acquire it, process manufacturing will be able to go beyond data mining to discover new knowledge and achieve truly intelligent processing behavior. In such an environment, learning occurs from combining and correlating new information with knowledge from prior experience and external sources. Getting to that point is not technologically or operationally easy. It is difficult to collect and validate the right information to support the development of models that inform ongoing business decisions for the manufacturing enterprise. Only with targeted, validated data, aggregated into well-understood models and algorithms, can the right knowledge be obtained to assess the true state of the manufacturing processes and support intelligent control decisions.

The ability to accurately integrate data from different sources for automated use and sharing among multiple software systems, or among multiple organizations, is difficult and largely done manually. Performing such integration automatically and securely, with confidence in the results, requires focused coordination, provision of standards and supporting infrastructure, and a widespread trend toward conversion, compliance and cooperation. Moreover, even with the ability to communicate and integrate data toward gathering the knowledge needed to model and operate the process manufacturing facility, the challenge becomes one of designing the sensing and communications systems to provide information on the state of the process that can be employed in the operating models.

While this roadmap lane primarily addresses the transformation path from data collection to actionable knowledge, other forms of capturing and accessing knowledge must be considered. Text and data mining techniques can lead to knowledge discovery. Knowledge capture from individuals or systems can lead to encoded rules that guide decision processes. Expert systems can be developed to assist the human in decision making and, in many cases, automate decision processes and support failure tolerance.

Lane 1: Solution Plan for Data to Knowledge	
Develop standards and tools to enable communication in process manufacturing	
	Cross-industry language standards
	Standards-based information exchange for data optimization & integration
	Simplified information sharing between functional organizations
	Secure electronic data and information exchange
Apply standard approaches to model the process manufacturing enterprise and its activities	
	Common framework and models for integration of manufacturing tools and functions
	Science-based modeling and simulation environment
	Data and modeling standards for optimization applications
	Multi-scale material modeling capability
	Process adaptability to material parameters
	Scenario-based analysis
	Modular, reconfigurable enterprise modeling systems
Get the data: To enable better control, design next generation actuator/sensor networks for improved model-based state estimation and bias detection knowledge	
	Sensor networks for plant status
	Development of sensor/actuator-based control designs
	Network design for sensor/actuator-based control

A. Develop standards and tools to enable communication in process manufacturing

- 1) **Cross-industry language standards** – Develop cross-industry standards for terminology, protocols, processes and ontologies to enable clear understanding and unambiguous communication among supply networks and other industry groups. Develop an evolving standard language and indexing approach to make process knowledge directly accessible and usable by mainstream enterprise functions in all manufacturing sectors. Extend the resulting library of processes and their attributes to support real-time process planning in a learning environment in which advances in best practices are incorporated into the knowledge base.
- 2) **Standards-based information exchange for data optimization and integration** – Evaluate standards for process manufacturing data formatting and integration that are embraced by industry and required of technology and equipment vendors. Develop a standards-based baseline data/information exchange format that optimizes and integrates the data flow between different systems and platforms, and create incentives to accomplish this mission. Provide a common data specification/architecture for access to and management of data, information and models. This specification should evolve to include semantic understanding and intelligent data/model management.
- 3) **Simplified information sharing between functional organizations** – Provide tools that unify data and information systems and support interoperability to enable communication and decision-making across functions (“from the shop floor to the top floor”). Provide seamless, secure and dynamic information exchange between and among organizations that enables smooth handling of anticipated demand, surges and changes in requirements.

- 4) **Secure information exchange** – Develop secure capabilities for interoperability, protecting sensitive information with minimal impact on operations so that only those with a need to know will see the data. This work should be aligned with standards effort ISA-99, Integrating Electronic Security into the Manufacturing and Control Systems Environment.

B. Apply standard approaches to model the process manufacturing enterprise and its activities

- 1) **Common framework and models for integration of manufacturing tools and functions** – Provide a standards-based collaboration environment that supports the integration of complex product/process models using materials and processes from multiple sources, where any model is completely interoperable and plug-compatible with any other model and with any standards-compliant simulation model. Align existing and emerging standards to support this capability, including those for description of products, processes and the operations in manufacturing enterprises (e.g., ISO/TC 184, Industrial Automation Systems and Integration). Develop standard representation schemes for common product, process and support concepts used within and across multiple industry sectors to enable transparent sharing and exchange of model-based knowledge. Provide a common framework and models for manufacturing functions and information (software, technologies and methodologies) to integrate all enterprise manufacturing activities and allow companies to participate in an integrated supply chain.
- 2) **Science-based modeling and simulation environment** – Provide real-time access to a rich suite of math- and physics-based modeling and simulation tools that are accessed by the user or the system to fully evaluate process alternatives in the time required to be useful.
- 3) **Data and modeling standards for optimization applications** – Develop data standards and modeling approaches that enable the cost-effective development of modeling and optimization applications whose components mediate or avoid conflicts among key performance indicators (KPIs) and develop synergy across different applications and functions.
- 4) **Multi-scale material modeling capability** – Develop material modeling and analysis technologies enabling scaling of properties and behaviors from micro (e.g., molecular) to macro (product) levels and from laboratory to production scales, understanding and modeling all transformations. These technologies will support development of robust process models that accurately reflect the influence of real-world material properties. Provide the capability to characterize raw, intermediate, consumable and finished material streams and link those analyses to expected product quality and processing alternatives.
- 5) **Process adaptability to material parameters** – Provide the capability to adapt processes in response to real-time evaluation of the state of the material stream, including material characterization, environmental issues and process attributes.
- 6) **Scenario-based analysis** – Provide a model-rich environment that enables real-time evaluation of various options for product and process definition and supports selection of the best options for total value optimization.

- 7) **Modular, reconfigurable enterprise modeling systems** – Develop plug-and-play vendor models with standards and protocols that enable detailed configuration to support corporate system relationships. Systematically develop and integrate data models to support life-cycle business and manufacturing processes and decision-making.

C. Acquire the data: Design next-generation actuator/sensor networks for improved model-based state estimation and bias detection to enable better control

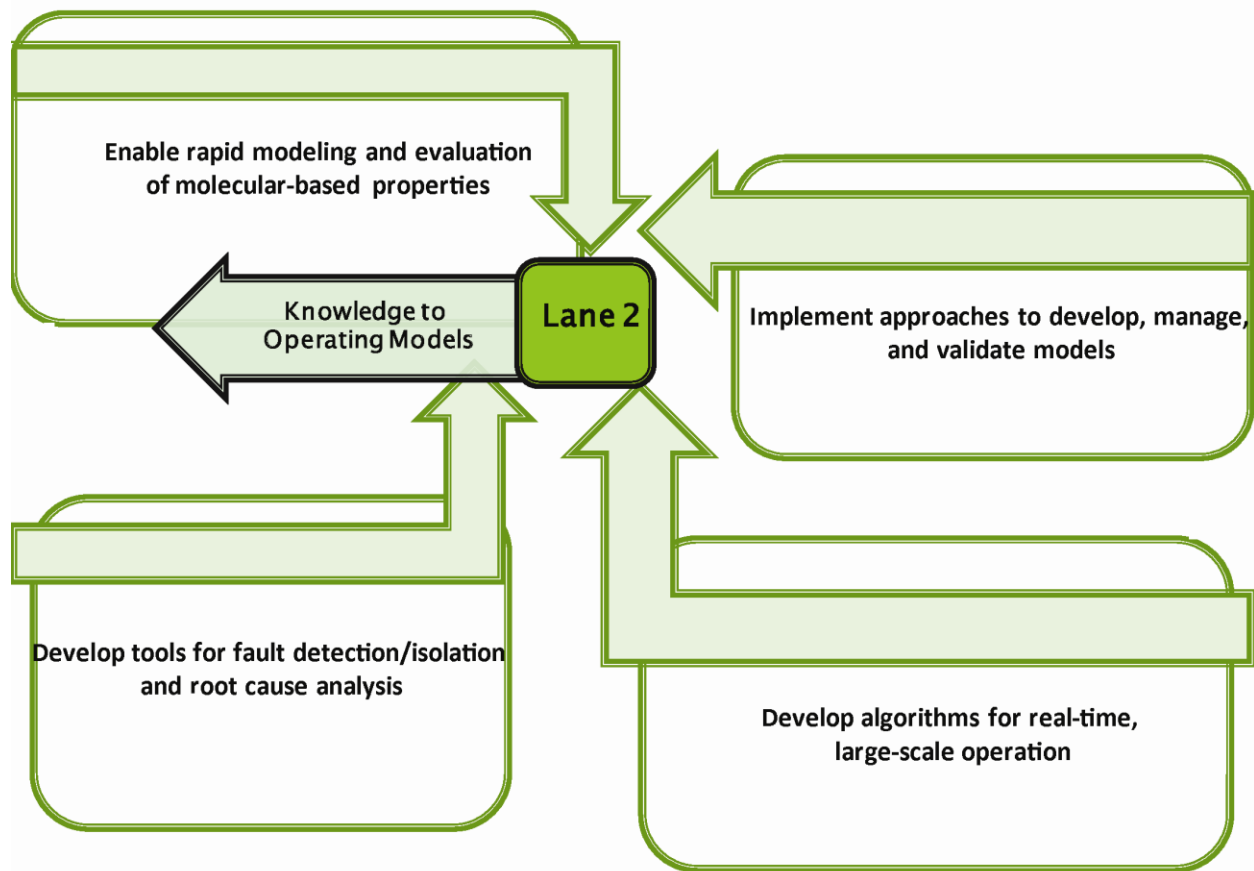
- 1) **Sensor networks for plant status** – Design sensor networks to improve plant observability and bias-free state estimation and control.
- 2) **Network design for sensor/actuator-based control** – Develop associated actuator and sensor instrumentation networks for fault-tolerant control that is compatible with other functions such as quality control, production accounting and on-line optimization.
- 3) **Exploit wireless sensor/actuator-based control designs** – Develop methods for design of control systems using wireless sensors and actuators.

4.2 ROADMAP LANE 2: FROM KNOWLEDGE TO OPERATING MODELS

If an operating model is defined as a representation of objects, assets or processes and their interactions, we can visualize a future in which knowledge is obtained and applied to creating such models – models that accurately represent the components and materials in a process as well as their functions and interactions within the process. In the future state, models of standard materials and transformation processes will be shared across the process industry. These models will be validated and integrated to populate the basic framework of a Virtual Process Organization for the process manufacturing enterprise, and will be used to make business decisions and operate the physical facility. Operation based on validated models will yield earlier and better understanding of problems and costs, enabling total value optimization.

The level of detail required to create useful models will depend on the economic value of the detail and on the technical limitations of knowledge about the modeled process or material. For some manufacturing processes and materials, modeling at the level of molecular properties may be essential for successful performance and competition in the marketplace. For other processes and products, much less detailed modeling may be sufficient to maintain quality control and production efficiency. Modeling detail for the business processes of the enterprise will show similar variability.

The smart process manufacturing facility will take into account uncertainty, so the models will use the available information to support decisions that account for that uncertainty. The more uncertainty in the environment, the more investment in data and knowledge collection that is required to monitor and control the facility's processes. The system of models must be built to detect, isolate and fix or compensate for faults without interrupting operations.



Lane 2: Knowledge to Operating Models

Management of unexpected or off-normal situations in complex process systems requires special skills and understanding of risks and mitigation options. With intelligent models, a process manufacturing system will recognize what information and knowledge is needed to manage the situation, then acquire that information autonomously and determine the correct solution steps. Achieving the level of understanding required for automatic situation management may be a distant goal; in the interim, though, the modeled environment can support decision-making by assisting human staff in finding the root cause of the multitude of potential alarms and sensor notifications. Finding and codifying the information needed to determine the problem and the proper response may require analysis of process data or mining of a shared repository of industry-specific experience and information.

Lane 2: Solution Plan for Knowledge to Operating Models	
Implement approaches to develop, manage and validate models	
	“Master Model” approach
	Standards for process specification
	Verification and validation models for applications
	Shared model libraries for process design
Enable rapid modeling and evaluation of molecular-based properties	
	Molecular models for thermophysical properties
	Multi-scale material modeling capability
	Algorithms for thermophysical analysis
Develop algorithms for real-time, large-scale operation	
	Advanced algorithms for model-based control
	Automated process planning
	Comprehensive material flow modeling across processes
	Optimal automation levels
	Self-configuring, self-integrating production operations models
Develop tools for fault detection/isolation and root cause analysis	
	Fault detection from multiple sources
	Process analysis and controller design for fault tolerance
	Root cause modeling and analysis
	Tools for situation response
	Closed-loop intelligent programming

A. Implement approaches to develop, manage and validate models

- 4) **“Master Model” approach** – Adopt a “master model” approach able to support a hierarchy of modeling needs through the ability to generate specific abstractions (e.g., views). This will lead to the ability to provide the right level of detail, the right model and the right data for each application.
- 5) **Standards for process specification** – Characterize traditional and emerging manufacturing processes. Establish standard process models that enable first-time success and optimization. Provide access to up-to-date process models for industries of any scale.
- 6) **Verification and validation models for applications** – Verify and validate models for targeted applications with specified operating ranges and boundary conditions.
- 7) **Shared model libraries for process design** – Establish an industry-wide network of shared libraries holding validated, well-characterized models of common materials, processes, and manufacturing equipment to support plug-and-play simulation, proprietary tailoring, and optimization of process designs.

B. Enable rapid modeling and evaluation of molecular-based properties

- 1) **Molecular models for thermophysical properties** – Develop molecular models that can provide quantitatively accurate descriptions of a broad range of thermophysical properties applicable over variations in the thermodynamic phase, mixture composition and reactions, and thermodynamic state.
- 2) **Multi-scale material modeling capability** – Develop material modeling and analysis technologies that enable scaling of properties and behaviors from micro (i.e., molecular) to macro (product) levels. These techniques will support the development of robust process models that accurately reflect the influence and physics of real-world material properties.
- 3) **Algorithms for thermophysical analysis** – Develop algorithms that enable the rapid evaluation of a molecular model's thermophysical properties in a way that exploits emerging hardware and software technologies.

C. Develop algorithms for real-time, large-scale operation

- 1) **Advanced algorithms for model-based control** – Update existing algorithms and develop new algorithms for model-based control of both discrete and continuous processes, taking advantage of parallel computing/multi-core processors.
- 2) **Automated process planning** – Establish the ability to automatically generate process plans as the product is being developed, consistent with product requirements, processing capabilities, existing enterprise resources, supply chain resources, and the strategic objectives of the enterprise. Develop a conceptual framework and implementation roadmap for deployment of standard or reference core processes and technologies to achieve optimal manufacturing efficiency.
- 3) **Comprehensive material flow modeling across processes** – Provide tools to develop and manage enterprise-wide material flow models that support planning and execution of complex manufacturing operations.
- 4) **Optimal automation levels** – Apply the maximum appropriate level of automation, especially on the critical development path for integrated systems operation. Examples of these critical-path processes include on-line analysis, data communication, actuation, and high-frequency decision-making.
- 5) **Self-configuring, self-integrating production operations models** – Develop intelligent systems (e.g. agent based) that are able to monitor process and control functions, make decisions based on the total body of collected information, and take the proper action to maintain optimal process performance and build maximum fault tolerance. Create software-based process advisors that determine the best means of using manufacturing resources and select the optimal process parameters to meet product specifications. Establish self-organizing production operations models able to integrate all applications, systems, equipment, and process instructions, ensuring readiness to satisfy all requirements for manufacturing the appropriate product. These models automatically adapt to changes in requirements.

D. Develop tools for fault detection/isolation and root cause analysis

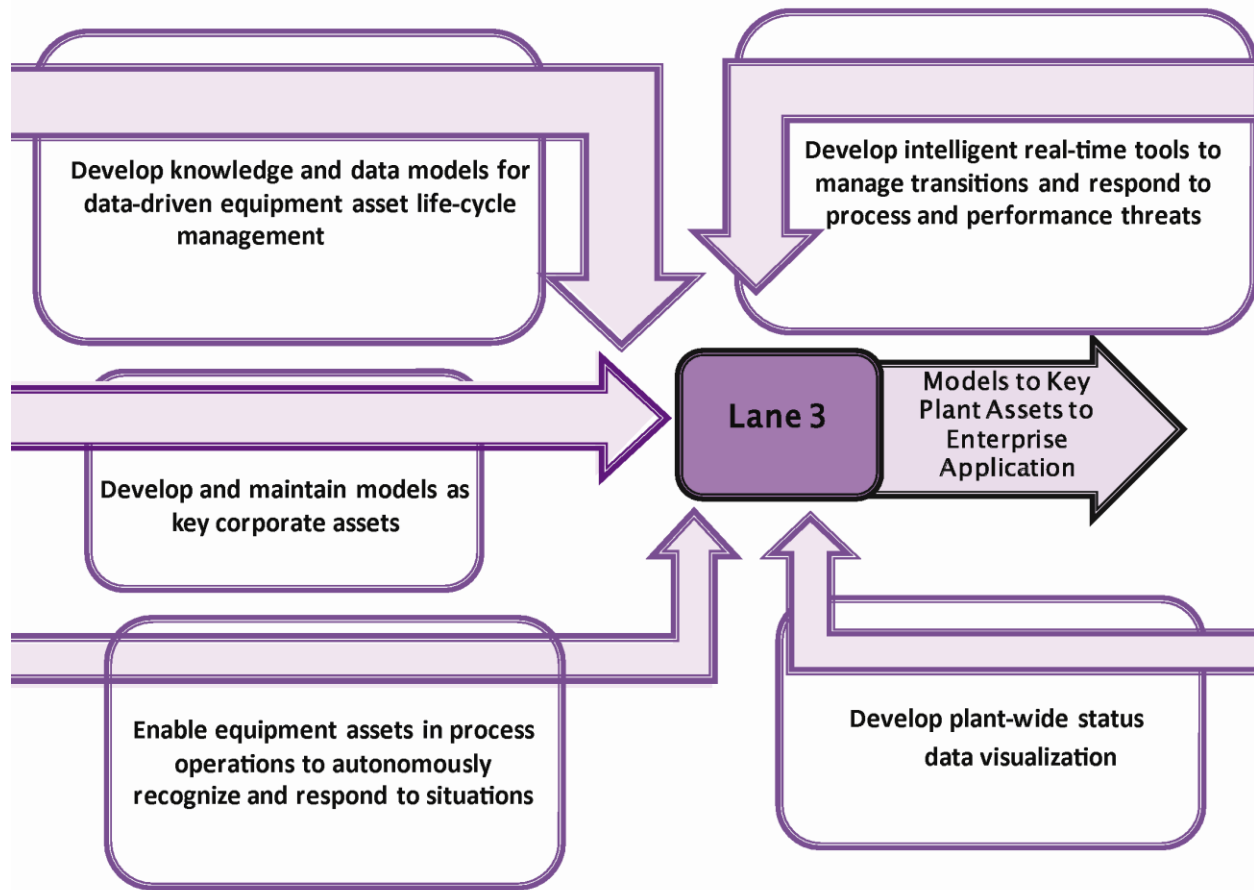
- 1) **Fault detection from multiple sources** – Develop state estimation, fault detection, and fault isolation capabilities using multiple heterogeneous and asynchronous inputs. Create methods for fault detection and isolation, accounting explicitly for both controller design and fault-tolerant control.
- 2) **Process analysis and controller design for fault tolerance** – Develop tools that rate the fault tolerance of an initial process design. Apply process design methodologies that use dynamic simulation to minimize and isolate faults and evaluate process operability on a real-world scale.
- 3) **Root cause modeling and analysis** – Establish tools for creating fundamental models for automated root-cause analysis. These should provide entire plant coverage and present information in a manner that can be easily understood and acted on by operations personnel.
- 4) **Tools for situation response** – Create scenario-based tools to enable real-time evaluation and risk assessment of responses to off-normal situations, along with determination of the best courses of action.
- 5) **Closed-loop intelligent programming** – Provide the capability of monitoring critical process parameters and dynamically altering machine programs to ensure an acceptable operation. Characterize processes to determine critical parameters and the effect of deviations on process performance and product quality. Develop systems that accurately and dynamically correct for deviations.

4.3 ROADMAP LANE 3: FROM OPERATING MODELS TO KEY PLANT ASSETS IN ENTERPRISE APPLICATION

Roadmap Lane 3 takes the operating models and the data and information and integrates them into the plant in a way that recognizes that the knowledge and experience embodied in these models are as important as the physical facilities. As such, this critical and integrated system of models will need to be managed as key plant assets. There are two important dimensions to this roadmap lane: 1) the use of operating models to plan, create, operate and manage plant performance at a high level and quality by orchestrating the roles of people, models and facilities; and 2) use of the integrated system of operating models themselves as key plant assets – along with the facilities, data, material technology and expert, trained and experienced workforce that are used to plan, control and manage the smart process manufacturing enterprise.

In the first dimension, operating models are used to predict desired operations and performance results by visualizing and simulating what is needed to realize these outcomes. These models drive a virtual environment both for initial design and, during operation, for scenario-based training and the real-time evaluation of possible actions. Long before any plant is constructed, operating models support the conceptualization and innovation environment in which process and physical requirements become feasible plant operations that are ultimately optimized in plant designs and configurations. Other models support the design of production and business processes, scheduling and acquisition of materials, delivery logistics, and other facets of the

operation. After a manufacturing facility is physically in place and production starts, models serve to control, monitor and manage the operations.



Lane 3: Models to Key Plant Assets to Enterprise Application

These models all rely on the same process and equipment knowledge, experience, expertise, and understanding. Operationally, though, they take on many forms to accomplish a full spectrum of tasks: data-driven, parametric, first-principles, statistical, dynamic, state, predictive, mathematical, logical, qualitative, quantitative, etc. Furthermore, bringing production operations models together with strategic models of the business environment enables the integration of business and operational objectives and generates much greater capacity for predictive consideration of alternatives and the proactive selection of the best solutions for both operational and business decisions. These large-scale, agile, dynamic, and adaptable model systems manage at multiple levels: strategic, tactical, operational, and practical at the shop-floor level. As the modeling environment and information management systems mature, a logical flow into Enterprise Resource Planning (ERP), Manufacturing Engineering Systems (MES) and industrial control models will be realized.

In the second dimension, the models themselves become key plant assets. The overall management and operation of a process plant can be viewed at many levels of granularity: in the properties of an individual material component at a point in time and location; the operations of systems of process equipment; management and control of the plant operation; decisions on

product types and grades across multiple plant units; and environmental impacts that are the result of multiple companies operating in a particular geographical region. Both automated and human-instigated decisions affecting the plant operation are made at all levels of production granularity in response to a myriad of planned and unplanned conditions. There is risk and uncertainty with every decision and with every response to a changed condition.

As process manufacturing is transformed to an interdependent system of integrated models, a key visionary goal of smart process manufacturing can be achieved - *a resilient, proactive process*. The integrated manufacturing enterprise consists of an interacting network of manufacturing units whose operations are coordinated through a planning function, which in turn is informed by supporting functions such as marketing and sales, inventory management and logistics, sourcing and procurement, and financial planning and control. Enterprise planning serves the strategic role of ensuring that input supply requirements and product demands are met, production runs and inventory levels are effectively balanced and, above all, corporate financial viability is sustained through optimization of cash flows and working capital. Each manufacturing entity is driven by a scheduling function that has the tactical role of coordinating with both the planning function and the real-time management function. In turn, the real-time management framework involves multiple levels of operational decision-making, spanning regulatory time control, process monitoring, exceptional events management, and real-time optimization. In this vision, operations consist of facilities, embedded models, and a knowledge-driven workforce, all of which serve as key plant assets.

Roadmap Lane 3 envisions distributed decision and control systems that operate with the appropriate level of automation, autonomy and human-centered involvement. Augmented with “smart” capabilities, the operational facilities will be managed according to their contribution, risk, and level of uncertainty to ensure the best total value to the enterprise and the optimal degree of automation. Smart units integrated with intelligent models of the process facility will be able to assess their operating environment and configure themselves for optimized operation. Devices, sensors, and equipment will have self-assessment and predictive capabilities that allow detection of performance anomalies and determination of the impact of requirements changes. The information from the current environment will be correlated with experience and operator interaction to adjust the processes for optimal contribution to plant operation. The models will learn and improve based on performance outcomes.

Once intelligent operating models are in place, skilled operators will be supported with analysis and advice that augment their insights and experience to ensure optimal performance. Note that optimal performance doesn’t always mean bringing complete scientific knowledge down to the molecular level. Smart units will assess what level of knowledge is needed to perform the current function, and acquire and provide the appropriate information.

Lane 3: Solution Plan for Operating Models to Key Plant Assets in Enterprise Applications	
Develop knowledge and data models for data-driven equipment asset life-cycle management and decision-making	
	Unified, intelligent manufacturing operations management database
	Critical resource performance indicators
	Knowledge-based asset management
	Critical operations procedures
	Intelligent manufacturing resources
Enable equipment assets in process operations to autonomously recognize and respond to situations	
	Self-aware assets
	Asset performance analysis tools
	100% uptime strategies
	Rapid transition management
Develop plant-wide status data visualization	
	Capture, archive, and make equipment status information available
	Plant-wide process status
	Full sensory plant status simulation
	Virtual reality based plant scenarios
Develop intelligent real-time tools to manage transitions and respond to process and performance threats	
	Models for performance tracking
	Risk and uncertainty assessment
	Intelligent monitoring and control systems
	Off-normal situation response
	Distributed intelligent operating units
	Cyber-attack protection
Develop and maintain models as key corporate assets	
	Business case analysis for models
	Enterprise management of models
	Systematic model development and automated model generation
	Integrating architecture

A. Develop knowledge and data models for data-driven equipment asset life-cycle management and decision-making

- 1) **Unified, intelligent manufacturing operations management database** – Develop a data model and unified manufacturing production facility database that integrates information on all resources (equipment, buildings, utility systems, etc.) and manages their maintenance and status changes. This database will be used in both design and support optimization of facility management (including production/maintenance scheduling, training and certifications) in view of anticipated production loads.
- 2) **Critical resource performance indicators** – Establish the ability to monitor and evaluate the variables and parameters that characterize all facility resources during operations. Determine which variables and parameters invoke what outcomes in the facility's performance. Evaluate how these performance indicators affect the upstream and downstream environments of the manufacturing facility enterprise, and incorporate that knowledge into enterprise models to improve future performance.

- 3) **Knowledge-based asset management** – Develop knowledge-based decision support systems for life-cycle asset management and collaborative decision-making that includes risk and uncertainty analysis.
- 4) **Critical operations procedures** – Provide practical, readily accessible and useful procedures for all critical operations at the level of detail needed by the operators, according to their experience and certification level.
- 5) **Intelligent manufacturing resources** – Develop intelligent manufacturing resources that provide information about their capabilities.
 - *Decision support for effective resource utilization* – Support operations and resource decisions by providing intelligence about capability, errors, utilization, availability, condition, etc., – and, importantly, an assessment of uncertainty and risk involved in each possible decision.
 - *Self-characterization* – Bring sensors and monitoring systems together to enable self-characterization of manufacturing resources for control, decision-making and maintenance, and for populating the manufacturing resources database. Create advisory systems and procedures that support the characterization of process systems.
 - *Self-management of the capabilities model* – Build the capability for equipment to apply self-characterization knowledge to maintain an up-to-date model of its performance capability.
 - *Vendor-supplied models as baseline* – Establish standards and conventions for vendors to deliver complete equipment models for all new purchases, as well as supporting services for existing equipment.
 - *Libraries of validated process and equipment models* – Develop and maintain a managed inventory of validated, well-characterized models and simulations for all processes and equipment.

B. Enable equipment assets in process operations to autonomously recognize and respond to situations

- 1) **Self-aware assets** – Provide technology (models, sensors, wireless, network architecture, security) that enables equipment process assets to self-diagnose, publish information on state, self-heal, reconfigure and initiate a proper safe response.
- 2) **Asset performance analysis tools** – Use operating data and advanced data analysis tools for performance pattern/behavior recognition and early detection and prediction.
- 3) **100% uptime** – Develop actuator robustness and implement self-diagnosis, fault-tolerant and self-repair capabilities for all critical manufacturing equipment and support systems.
- 4) **Rapid transition management** – Sense situations, assess risk and stability and dynamically respond, enabling the plant to optimize performance during transitions – from one product to another, during feedstock changes, in response to situations, etc.

C. Develop plant-wide status data visualization

- 1) **Capture, archive and make equipment status information available** – Provide the data and reporting capability to capture, archive and make information available about equipment resources – state, transition, expected state, diagnosis, and state of activities for reporting – and the ability to query to understand and validate.
- 2) **Plant-wide process status** – Aggregate data and provide plant-wide visualization of critical information based on analysis and correlation of process and other sensor data.
- 3) **Full sensory plant status simulation** – Develop game-quality simulation and animation systems that enable a hands-on, fully tactile experience in a virtual environment that is directly transferable to the physical environment.
- 4) **Virtual reality based plant scenarios** – Provide virtual reality-based experiences wherein various process scenarios can be reviewed with full analysis, risk assessment, and ready awareness of the consequences of choices.

D. Develop intelligent real-time tools to manage transitions and respond to process and performance threats

- 1) **Models for performance tracking** – Develop models and tools to track changes in process performance, including the performance of control systems.
- 2) **Cyber attack protection** – Improve real-time tools to identify and respond to cyber attacks while maintaining process integrity.
- 3) **Risk and uncertainty assessment** – Develop models and tools for dynamically assessing risk and uncertainty so that decisions and actions are always made with this knowledge.
- 4) **Intelligent monitoring and control systems** – Develop intelligent (e.g., agent-based) systems that are trained to monitor process and control functions and to take proper action for maintaining in-control operation. Create expert process advisors that capture the knowledge and scientific basis for process operations and present interpreted, real-time advice for best actions.
- 5) **Abnormal situation response** – Provide scenario-based tools to enable evaluation of responses to off-normal situations and determine the best courses of action, which includes risk assessment. In addition to methods for fault detection and isolation, provide capability within the controller design for dynamically reconfigurable control and automated fault-tolerant control actions.
- 6) **Distributed intelligent operating units** – Enable the process unit itself to become “intelligent” through the use of models that optimally manage the process goals of the unit and communicate with other intelligent process units and devices to collectively accomplish goals of the overall enterprise. Develop the operational management structures to take advantage of distributed intelligence and actuation.

E. Develop and maintain models as key corporate assets

- 1) **Business case analysis for models** – Provide the capability and capacity to efficiently perform business-case analysis to support the investment in creation, use and management of models.

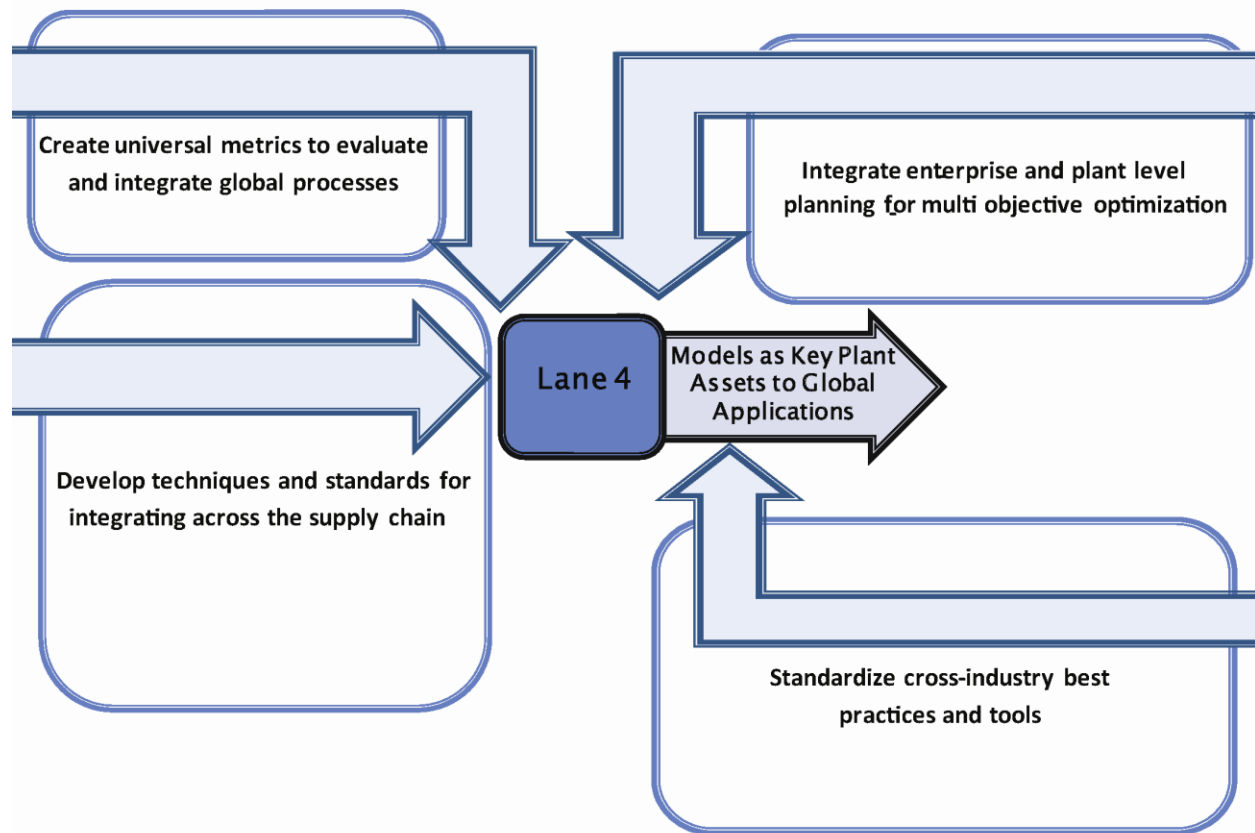
- 2) **Enterprise management of models** – Develop a management and technology structure for maintaining models as corporate assets and making them available for use across the enterprise.
- 3) **Systematic model development and automated model generation** – Develop systematic methods for building data models (plant semantic reference data models) to support business processes related to asset life-cycle management. Provide automated model generation capabilities based on the functions to be performed, the data that are required/available, and the need to be applied consistently across multiple applications.
- 4) **Integrating architecture** – Provide a common data specification/architecture for access and management of plant data, information and models – a plant reference model. This specification may be based on semantic understanding and intelligent data/model management.

4.4 ROADMAP LANE 4: FROM MODELS AS KEY PLANT ASSETS TO GLOBAL APPLICATION

Leading process manufacturing companies are increasing their use of modeling, smart assets and knowledge-based systems to integrate and control their operations – and this is resulting in cost and performance breakthroughs. Most continuous process manufacturers look internationally when considering both their potential market and operating locations. Hence, the concept of plant assets must be scalable to global application. An obvious next step for achieving this objective is to exploit technological advances in process control, situation analysis and production management to similarly benefit and expedite these wider external relationships beyond traditional enterprise boundaries.

The global technical and business requirements demand that linguistic, cultural, regulatory and other differences must be addressed. The success of global business relationships requires the industry to achieve consensus on communication among its operational systems, share information but protect its intellectual property and competitive advantage, and create flexible and quickly responsive systems to optimize mutual business operations. The challenges of these international relationships exceed the ability of most present supply-chain management systems to accommodate them. However, standards efforts are under way to create common communication and infrastructure interoperability agreements.

Even in U.S. domestic supply chains, different companies may operate under different quality and environmental constraints. External relationships generate additional uncertainty and risk in production planning and scheduling. With international relationships, these differences are more substantial. Technical issues with different toolsets and technologies to be integrated magnify the complexities. There are also complications with export control, varying safety and health requirements, different economic and cultural situations and unique definitions of business success, along with the practical logistical issues of time-zone differences and geographically remote locations.



Lane 4: Models as Key Plant Assests to Global Applications

Faced with concerns about the use of intellectual property across national boundaries, most companies employ local staff as much as possible and limit the need for exposure of intellectual property in foreign environments. However, the desire for closer communication among business partners means that knowledge as well as materials must flow across plant boundaries. The integration of shared information in a collaborative environment is a key enabler for successful operations. But there is a shortage of models and application integration standards to facilitate this communication in appropriate detail while ensuring the protection of sensitive information.

Beyond the traditional communication concerns of materials, prices and schedules, supplier/customer collaboration should broaden to address growing energy and environmental issues such as the carbon footprint of their products and processes. The goal is symbiotic reuse (with zero emissions) of waste and reclaimed materials across the material/product life span, down to the molecular level, by integrating interacting processes among neighboring process facilities.

Lane 4: Solution Plan for Models as Key Plant Assets to Global Applications	
Create universal metrics to evaluate and integrate global processes	
	Universal metrics for processes
	Collaborative evaluation tools
	Environmental, health, and safety metrics
	Process design evaluation rules
	Applying uncertainty in key performance indicators
	Energy and carbon footprint modeling
Develop techniques and standards for integrating across the supply chain	
	Cross-industry language standards
	Plug and play collaborative modeling and simulation environment
	Supply chain integration tools
	Automated translator for models
	Cost and risk assessment models for interoperability
	Ubiquitous cost data access across the enterprise and life cycle
	Object mapping and aggregation
	Models for supply chain agility
Integrate enterprise- and plant-level planning for multi objective optimization	
	Enterprise-level multi-model integration
	Multi-scale, multi-objective modeling
	Extended business intelligence management
	Enterprise-wide process cost modeling
	Enablers for sharing best practices for facilities
Standardize cross-industry best practices and tools	
	Universally applicable best practices and tools
	Enablers for sharing best practices for sectors
	Environmental, health, and safety best practices
	Universal cost/price models
	Universal material/workforce models
	Framework for optimal manufacturing efficiency

A. Create universal metrics to evaluate and integrate global processes

- 5) **Universal metrics for processes** – Charter an independent group of academic and industry participants to create a universal set of metrics for evaluating the economic impact of process robustness, fault tolerance, and flexibility (i.e., the ability for the process to handle multiple feed stocks).
- 6) **Collaborative evaluation tools** – Develop methods for analyzing the risks, rewards, viability and value of alternative collaborative relationships across the extended enterprise.
- 7) **Environmental health and safety metrics** – Create a common set of metrics that can be used by industry to understand and evaluate the economic impact of environmental, health and safety considerations as well as social responsibility.
- 8) **Process design evaluation rules** – Develop rules and standards for evaluating process designs that include additional factors as well as performance, cost and quality.

- 9) **Applying uncertainty for key performance indicators** – Assess and model how structured uncertainty (disruption) and parametric uncertainty can be treated to address key performance indicators in the supply chain (e.g., profit, sustainability, carbon footprint).
- 10) **Energy and carbon footprint modeling** – Model energy use across the supply chain, evaluate the carbon footprint and determine optimal abatement strategies for carbon footprint.

B. Develop techniques and standards for integrating across the supply chain

- 11) **Cross-industry language standards** – Develop cross-industry standards for terminologies, protocols, processes and ontologies to enable unambiguous communication about, and interconnection of, model-based processes among supply networks and other industry groups.
- 12) **Plug-and-play collaborative modeling and simulation environment** – Create a standards-based environment that fosters collaboration to optimize the value chain by supporting convenient, inexpensive integration of complex process models. These models will use processes and materials from multiple supply network members, where any model is interoperable and plug-compatible with any standards-compliant application.
- 13) **Supply chain integration tools** – Create an integrated core set of standards, processes and tools, aligned with the business enterprise that can be applied universally. The standards, processes and tools should contain enough flexibility to enable detailed configuration that supports corporate system relationships and adapts to specific local contexts.
- 14) **Automated translator for models** – Use self-learning and adaptive techniques to develop standard meta-models or semantic models that address lack of standardization and differing terminology across the supply chain. Include the ability to reconcile different terms, automate mapping between different languages, merge databases automatically, rationalize unstructured data and extract needed features, and map process components of supply partners to the models.
- 15) **Shared, secure product and process models** – Develop information management methods that enable all members of the supply network to provide input into, access, and manipulate shared models in accordance with appropriate permissions and security of every data element. Include the ability to provide an audit trail of all actions and automatically communicate changes to affected partners and personnel.
- 16) **Cost and risk assessment models for interoperability** – Develop total cost and risk-assessment models that aid investment decision processes by quantifying the potential benefits and value of interoperability to all U.S. manufacturers.
- 17) **Ubiquitous cost data access across the enterprise and life cycle** – Provide access to cost data for everyone who needs to know and for every element and activity in the product life cycle. Make detailed cost analyses by process, material, equipment utilization, human resource requirements, and other attributes accessible.
- 18) **Object mapping and aggregation** – Develop new theories for automatically performing mapping and aggregation of objects in supply chain management.

- 19) **Models for supply chain agility** – Develop standards and APIs for mathematical process models of varying complexity so that the supply chain can be made more agile.

C. Integrate enterprise- and plant-level planning for multi-objective optimization

- 20) **Enterprise-level multi-model integration** – Develop a methodology to integrate different companies' enterprise models within the framework of an extended enterprise architecture, providing point-to-point connectivity of interdependent operations. This methodology should include requirements management, process design, configuration management, manufacturing planning, cost estimating, scheduling, and performance management.
- 21) **Multi-scale, multi-objective modeling** – Develop multi-scale methods for the enterprise and plant levels by integrating planning and scheduling and identifying key manufacturing constraints that need to be accounted for. Develop algorithms and a framework for addressing multiple objectives (e.g., due date vs. capacity utilization) and multiple time periods.
- 22) **Extended business intelligence management** – Develop modeling tools and techniques to identify, monitor and respond to internal and external forces acting on the supply chain, including the capability to predict the impact an event may have on each of its members.
- 23) **Enterprise-wide process cost modeling** – Develop cost modeling systems and techniques to integrate all required data, from within and external to the enterprise, to support high-fidelity analysis of development costs, production costs, profitability, financial risk, and other cost attributes of process design.
- 24) **Enablers for sharing best practices for facilities** – Develop forums, mechanisms and functional enablers for sharing best practices and lessons learned across different manufacturing facilities within an enterprise. Facilitate normalization, standardization, communication, validation and collaboration between and among manufacturing facilities (internal to enterprise).

D. Standardize cross-industry best practices and tools

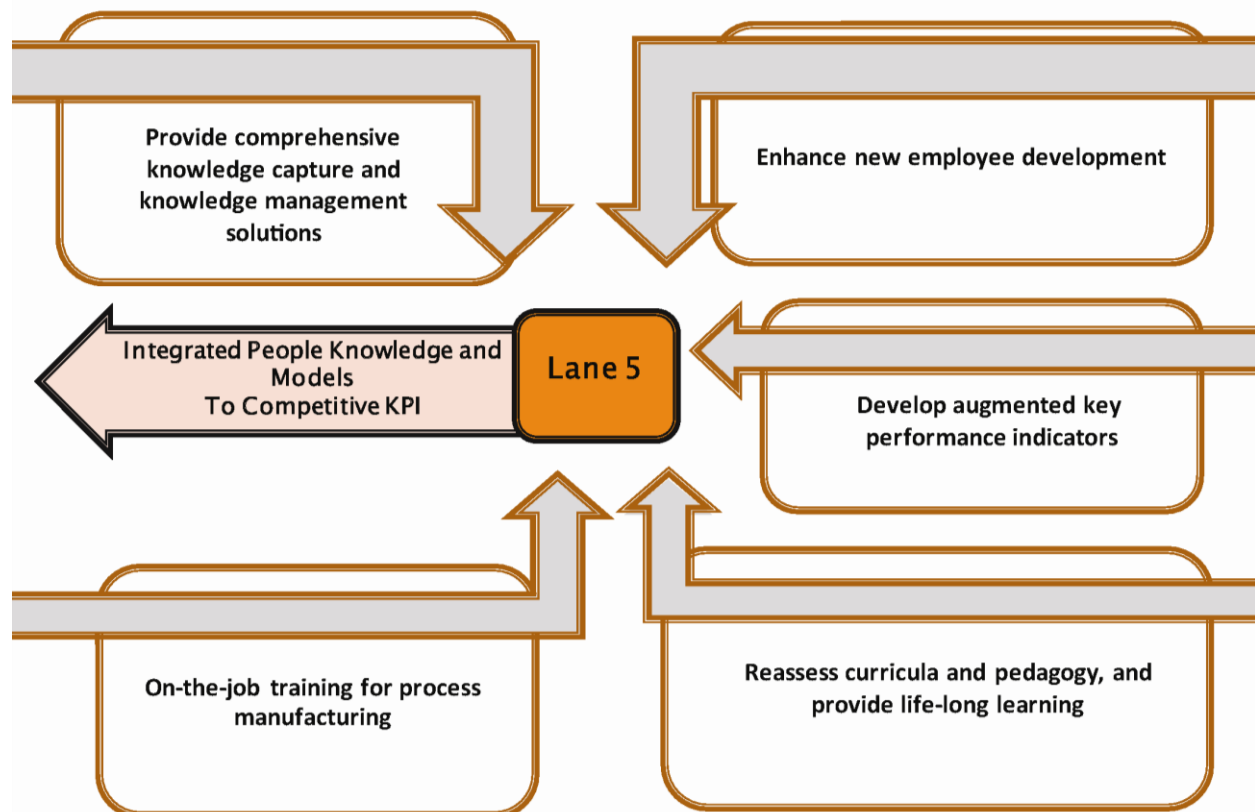
- 25) **Universally applicable best practices and tools** – Create a core set of standards, best practices, common processes and toolsets that can be applied universally, and that contain enough levels of flexibility to adapt to specific local contexts.
- 26) **Enablers for sharing best practices for sectors** – Develop forums, mechanisms and other functional enablers for sharing best practices and lessons learned across different industry sectors to allow normalization, standardization, communication, validation and collaboration between and among sectors (external to the enterprise).
- 27) **Environmental health and safety best practices** – Define a core set of EH&S best practices to reduce risk and incidents and raise living standards on a global scale.
- 28) **Universal cost/price models** – Develop costing and pricing models that incorporate local input more formally and explicitly, and that establish economic assumptions reflecting the local context in order to address the high level of variability in cost and pricing at the local/regional levels.

- 29) **Universal material/workforce models** – Develop economic models for global acquisition and distribution of material resources as well as a framework and practices for a global workforce that can be deployed locally – in each case reconciling a global perspective for optimal manufacturing efficiency with the local-level reality.
- 30) **Framework for optimal manufacturing efficiency** – Develop a conceptual framework and implementation roadmap for deployment of standard core processes and technologies locally for optimal manufacturing efficiency.

4.5 ROADMAP LANE 5: FROM PEOPLE, KNOWLEDGE AND MODELS TO A COMBINED KEY PERFORMANCE INDICATOR

The SPM environment will be an efficient machine in which human skills, knowledge (both human and digitally captured), and model-based systems operate in unison. All of the skills, capabilities and knowledge will support an integrated environment in which the excellent performance of the components contributes to 100% achievement of projected results.

Realization of this envisioned environment will require: 1) development of robust knowledge capture and management systems; 2) enhanced recruitment, training and support of process systems engineers; 3) integration of all the sources of available knowledge, both internal and external to the enterprise; and 4) taking advantage of the ability to learn and adapt to new situations.



Lane 5: Integrated People Knowledge and Models to Competitive KPI

The process manufacturing industry workforce is gradually retiring, and the retirees are taking their wealth of accumulated experience and knowledge with them. This knowledge must be captured in ways and forms that can be accessed when it is needed, and encoded in models that can control increasing levels of process operations automatically. Although the field of knowledge management is immature, promising techniques can improve this situation for the process industry. Many companies are taking steps to capture the knowledge of their experts, creating knowledge bases that reduce costs, help with globalization and develop younger workers faster.

Use of captured knowledge for maintenance and reliability has been successful in many companies. These areas are highly promising for intelligent systems with the ability to monitor, analyze and respond autonomously and proactively to maintain operational control. However, the challenge is to integrate these systems with other applications, both intelligent and traditional, to optimize operations.

As multiple sources of information are aligned and connected based on cross-industry standards and design definitions, improved information mining and analysis will be possible, and valuable shared information repositories will emerge as resources for intelligent operation. The models resulting from this increasingly rich environment will be based on first principles – an accurate scientific understanding of the materials and processes involved. The models will apply scientific principles, historical information, and knowledge derived from real-time experience to the extent that the models will become accurate predictors of consequences, trusted decision support tools, and controllers of all manufacturing processes.

The departure of so many highly experienced workers as the Baby Boom generation moves into retirement has created a shortage of qualified personnel. There is much greater competitiveness internationally (in both numbers and quality) for engineers and scientists, with fewer students going into engineering in the United States than in other countries. Of those students going into engineering, even fewer are going into systems and modeling areas. As a result, there are fewer U.S. graduates in engineering with the needed technical knowledge. In addition, U.S. graduates are typically not multilingual or knowledgeable about other cultures, making it more difficult for them to be successful in international companies.

Meanwhile, the skill requirements for operators, engineers and managers are constantly changing with increasing automation and globalization in the process industry. The smart plant is typically a continuous process of balancing humans and systems, requiring both a trained operator and a robust human-machine interface. A knowledgeable chemical process operator who can monitor operating conditions and put the proper responses in place is of far more value to a company than an operator whose training ends at the responsibility to make a phone call when the red light goes on. This contribution should be rewarded with higher pay and better job security.

Managing production operations in this knowledge- and technology-intensive environment presents significant challenges for workforce education and training. A number of studies have identified the need for changes in education, but there has been little action toward developing process systems engineering (PSE) programs that supply the needs of today's globalized, high-tech process manufacturing enterprises. The lack of continuing education programs in manufacturing must also be addressed, as the strategy of intensive training specifically targeted for a new environment is the most effective way to address the critical skills shortage that is now facing the nation and the process industries.

A final step in achieving an intelligent manufacturing capability will be maturing use of models transitioning – from localized use of analytic models, each sub-optimized based on their individual scope and perspective, to total value optimization across the enterprise. As this occurs, key performance indicators will change from metrics focused on awareness of performance to metrics based on totally integrated performance. Performance will be measured in terms of compliance with predictive models. Self-learning models, coupled with expert workforce knowledge, will yield unparalleled excellence in process performance and enterprise success. The models will understand the protocols of the various components of the enterprise systems and serve as translators to ensure that systems “talk” to each other in a plug-and-play environment.

Lane 5: Solution Plan for People, Knowledge, and Models to a Combined Key Performance Indicator	
Provide comprehensive knowledge capture and knowledge management solutions	
	Standards for knowledge capture/management
	Shared repositories
	Implementation of knowledge capture methods
	Dynamic knowledge management for assets
	Expert process advisors
	Knowledge capture to augment staff skills
On-the-job training for process manufacturing	
	Point-of-use training
	Visualization and simulation-based training regarding models
	Improved operator guidance tools
	Improved human/machine interface for models
	Operator shutdown/startup training
Enhance new employee development	
	Early career development programs
	Manufacturing career path enhancement
	Universal credentials for process manufacturing
	Mentor programs for critical skills
Reassess curricula and pedagogy, and provide life-long learning	
	Improved educational programs
	Improved delivery of education and training
	Masters degree in pse
	Required continuing education
	Promotion of co-op programs
	Industry participation in education

A. Provide comprehensive knowledge capture and knowledge management solutions

- 1) Standards for knowledge capture/management** – Establish cross-industry standards for knowledge capture and management.
- 2) Shared repositories** – Develop shared knowledge, information, data and model repositories that are compliant with existing standards and that support sharing within a collaborative business environment.

- 3) **Implementation of knowledge capture methods** – Broadly implement knowledge capture processes and practices.
- 4) **Dynamic knowledge management for assets** – Provide a knowledge management solution for asset management that allows operators, engineers and all stakeholders to collaboratively enrich the knowledge base and extract value from the collective knowledge set.
- 5) **Expert process advisors** – Create expert process advisors that capture the knowledge and scientific basis for process operations and provide real-time advice for best actions.
- 6) **Knowledge capture to augment staff skills** – Implement a knowledge capture program and use the captured knowledge to continually train the staff and preserve core competencies.

B. On-the-job training for process manufacturing

- 1) **Point-of-use training** – Provide real-time, point-of-use training on using emerging technologies.
- 2) **Visualization and simulation-based training regarding models** – Use visualization and simulation to train operators and engineers to understand the place of models in production operations and to use the models when and where needed.
- 3) **Improved operator guidance tools** – Develop operator guidance tools that incorporate better human factors into the engineering of the operator console.
- 4) **Improved human/machine interface for models** – Refine the human/machine interface to increase operator use of complex models.
- 5) **Operator shutdown/startup training** – Develop less expensive, flexible and adaptable operator training tools, with a focus on best shutdown and startup procedures.

C. Enhance new employee development

- 1) **Early career development programs** – Design early career development programs to accelerate a new employee’s understanding and capabilities.
- 2) **Manufacturing career path enhancement** – Improve the attractiveness of career paths in manufacturing to recruit more people.
- 3) **Universal credentials for process manufacturing** – Develop a “universal credential” system that enhances the process-manufacturing career options and allows high levels of mobility for smart process manufacturing technical personnel.
- 4) **Mentor programs for critical skills** – Develop mentor/protégé programs to preserve critical skills.

D. Reassess curricula and pedagogy, and provide life-long learning

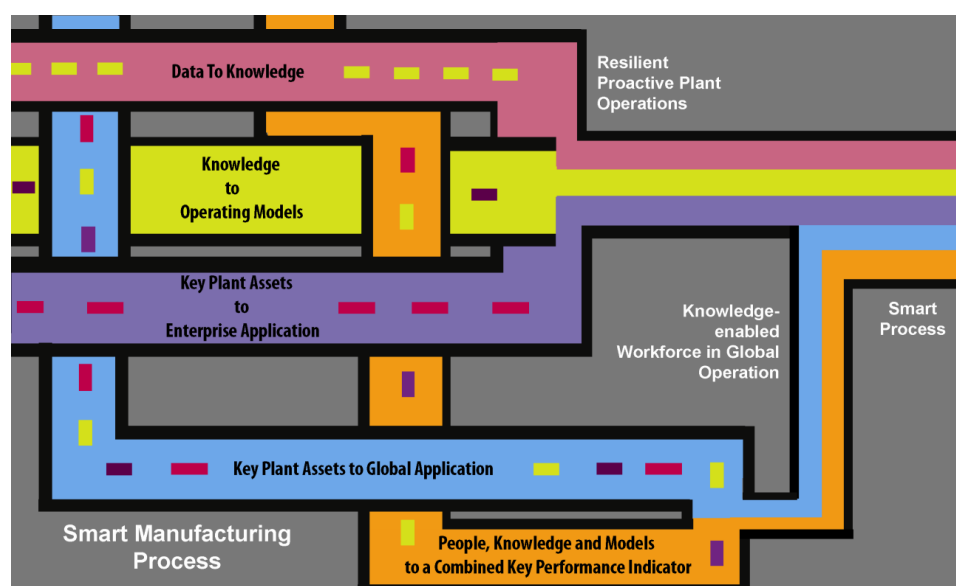
- 1) **Improved educational programs** – Reassess current approaches to teaching (what, how, where) and develop revised curricula, pedagogical approaches, and educational resources that reflect the needs of the global process manufacturing industry.

- 2) **Improved delivery of education and training** – Develop cohesive, vertically and horizontally integrated education and training programs, optimizing the balance between internal and external delivery.
- 3) **Masters degree in PSE** – Develop Masters of Process Systems Engineering programs for manufacturing in collaboration with industry.
- 4) **Required continuing education** – Promote the requirement of continuing education on industry-specific technologies as part of job profiles. Provide courses developed and supported by professional organizations (e.g., American Chemical Society and American Institute of Chemical Engineers) in collaboration with industry leaders and academia.
- 5) **Promotion of co-op programs** – Develop national and international academic-industry cooperative field programs.
- 6) **Industry participation in education** – Encourage industry to participate actively in academic advisory councils on research and curriculum development, advocating to academia on effective and beneficial technologies and manufacturing knowledge that industry needs, both for new graduate employees and for developing continuing education programs.

5.0 THE PATH FORWARD

This report represents the consensus of a national cross-section of industry leaders involved in planning the future of the process manufacturing industry, providers that supply technology solutions for manufacturing operations, and academic researchers engaged in a range of associated systems research. There is agreement that smart process manufacturing (SPM) should be defined as an integrated, knowledge-enabled, model-rich enterprise in which all operating actions are determined and executed proactively, applying the best possible information and a wide range of performance metrics.

The centerpiece of this report is an operating and technology roadmap for smart process manufacturing:



Key drivers for the roadmap include:

- Global competitiveness with existing assets
- An installed base of equipment that is fragile with respect to modern demands
- New plants with higher and more sustained value
- A large base of installed automation equipment that is nearing obsolescence
- A workforce whose members, many of whom are retiring, carry a great deal of knowledge
- The high value of workforce knowledge and capability for the future
- Changing workforce and resources
- Operations and the economics of change
- Regulatory compliance to regulatory performance
- Resilient, fault-tolerant operations
- Management of risk and uncertainty

- Energy and material supply chains
- Profitability while addressing environmental, health, and safety issues

As indicated in the graphic, the roadmap addresses several key areas of transition:

- Substantially increased use of data and information
- Substantially increased use of models
- Models as managed, lifecycle assets
- New operational management models
- Substantially increased operational attention to the economics of change
- Management of rapid change through operational resilience and fault tolerance

Foundational elements include:

- Workforce
- Sustainability
- Environmental Safety and Health
- Globalization
- Cyberinfrastructure

This report is intended to be a work-in-progress. As discussions and further development of the roadmap progress, the report and, in particular, the roadmap will be refined and updated. Latest versions will be continuously available at this website. Action areas, involvement, progress, and outcomes will be tracked. You are encouraged to share and discuss this report widely and to become involved. The report and the mechanisms for involvement, comment and interaction can be found at:

[HTTP://WWW.OIT.UCLA.EDU/SMART_PROCESS_MANUFACTURING/](http://www.oit.ucla.edu/smart_process_manufacturing/)