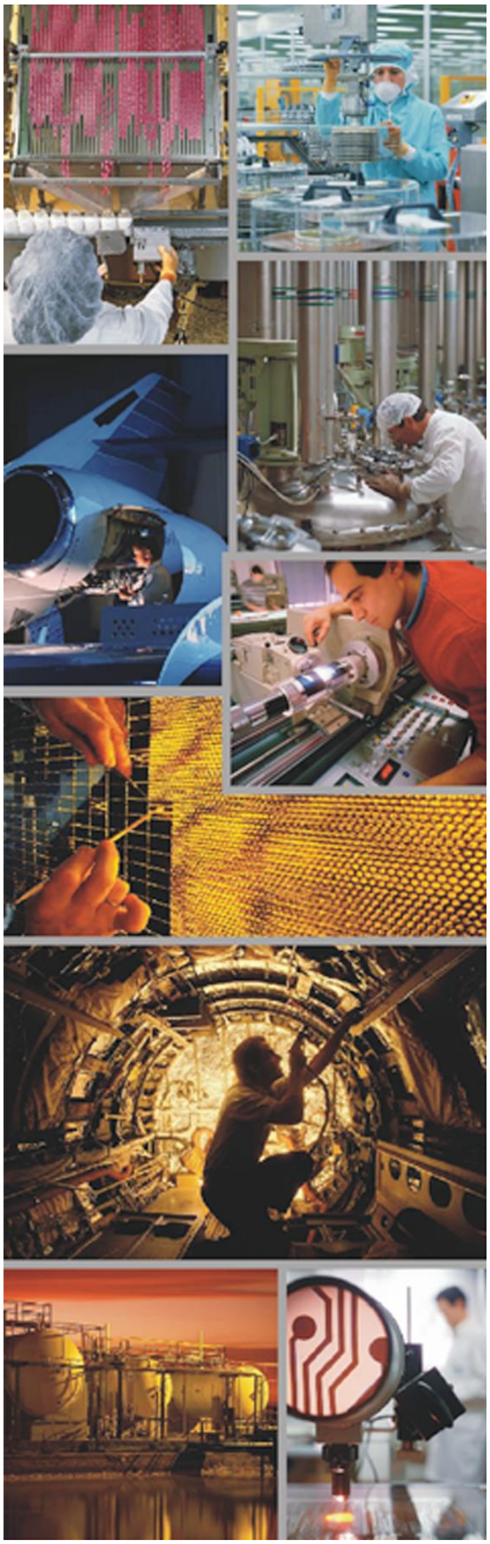


# Sustainable Manufacturing – A Business Perspective

## A Technology Roadmap

**February 25, 2015**

**Sponsored by the University of Kentucky, Institute for Sustainable Manufacturing**

**Funding Provided through the National Institute of Standards and Technology, Advanced Manufacturing Technology Consortia Program**

This Draft Report Captures the Results of a Workshop that was conducted on November 13 and 14, 2014 in Lexington Kentucky



Integrated Manufacturing Technology Initiative

## Table of Contents

# Preface

Advanced manufacturing is a systems approach to product and process optimization and is an important concept in the nation's drive for economic success and stability. This document explores why and how sustainable manufacturing should be addressed as an integral component of advanced design and manufacturing systems – well beyond a limited focus on energy efficiency and environmental responsibility. The current state assessments, the visions, and the solutions that are presented focus on the advanced manufacturing enterprise and emphasize the necessity of sustainable manufacturing as an important component of that enterprise.

The material for this roadmap was gathered at a workshop held in Lexington, Kentucky on November 13 and 14, 2014. The document does not seek to provide background materials to support a richer understanding of sustainable manufacturing and of the business case perspective. Providing this background information was the goal of the pre-read package that we distributed before the workshop. That pre-read package is available in the Institute for Sustainable Manufacturing website at http://www.ism.uky.edu/2014/11/21/sustainable-manufacturing-roadmap-workshop-documents/

The set is comprised of three documents, all of which are available on the website (above). The pre-read package provides background material. This document is the reference document. The first 32 pages present a summary of the work. The rest of the document presents deeper insight and is intended chiefly for the sustainable manufacturing professional. It is a living document that will be continually upgraded as the work progresses. A more abbreviated summary document is available for executive distribution. This is the beginning of a journey, the end of which will be the dynamic management of an industry focused R&D agenda.

# Workshop Participants

| First Name | Last Name | Organization |
|---|---|---|
| Rod | Amacher | US Army |
| Fazleena | Badurdeen | University of Kentucky |
| Bill | Barkman | Consolidated Nuclear Security, LLC |
| James | Blood | FP International |
| Ryan | Bradley | University of Kentucky |
| Adam | Brown | University of Kentucky |
| Blaine | Early | Stites & Harbison, PLLC |
| Anthony | Elam | University of Kentucky |
| Ahmed | Elsawy | Tennessee Technological University |
| Aldo | Ferreira | KDMK |
| John | Gershenson | Michigan Technology |
| Tom | Goldsby | Ohio State University |
| Bhaskaran | Gopalakrishnan | West Virginia University |
| Bridgid | Hogan | University of Kentucky |
| Craig | Hopkins | Kentucky Center of Excellence in Advanced Automotive Manufacturing |
| Greg | Hume | TechSolve, Inc. |
| I. S. | Jawahir | University of Kentucky |
| Sara | Jordan | IMTI |
| Cheyenne | Kemp | FP International |
| Kelley | Kline | General Electric, Appliances and Lighting |
| Scott | Ladd | Lexmark International |
| Thomas | Lester | University of Kentucky |
| Diane | Leveridge | KCTS |
| Wei | Li | University of Kentucky |
| Tao | Lu | University of Kentucky |
| Sam | McSpadden | IMTI |
| Manish | Mehta | National Center for Manufacturing Sciences (NCMS) |
| Ashish | Mundphan | University of Kentucky |
| Richard | Neal | IMTI |
| Charlie | Neal | IMTI |
| Michelle | Ramsey | GE Aviation |
| Hongjoo | Rhee | Center for Advanced Vehicular Systems (CAVS), Mississippi State University |
| Todd | Rockstroh | General Electric Aircraft Engines (GE) |
| Keith | Rouch | University of Kentucky |
| Chris | Saunders | Lexmark International |
| Dan | Seevers | Lexmark International |

| | | |
|---|---|---|
| Michael | Shesterkin | What's Next |
| Charlie | Smith | Move The Peak |
| John W. | Sutherland | Purdue University |
| Curtis | Toone | BAE Systems Platform & Solutions |
| Bill | Walch | NCDMM |

# Executive Summary

Presented herein are the proceedings, collated and sifted, of a workshop on ***Sustainable Manufacturing – A Business Perspective.*** Sustainable manufacturing, traditionally, deals with the development of products that are energy efficient and environmentally responsible across their lifecycle – using processes that value sustainability. We embrace that limited definition, and strongly emphasize that sustainable manufacturing must include all attributes of a continuously profitable business enterprise and will never be fully achieved if addressed as a singular objective. However, it can be achieved as part of a business equation that values all aspects of a triple bottom line of economic, social, and environmental optimization and assures long term success while maintaining uncompromising short term excellence. In emphasizing the business case, this document seeks to place sustainable manufacturing in a position as a major element of an environment for integrated product realization that optimizes every decision across the product lifecyle.

The work is sponsored by the University of Kentucky, Institute for Sustainable Manufacturing (ISM), and funded by a grant from the Advanced Manufacturing Technology Consortia (AMTech) program of the National Institute of Standards and Technology (NIST). Through this activity, the ISM is launching the Partnership for Research and Innovation in Sustainable Manufacturing (PRISM). PRISM will build on the foundation of this roadmap and the followon activities to create a continuous process of awareness, prioritization, selection, and execution of important R&D projects. These projects, led by industry, will deliver solutions that enhance the global competitiveness and sustainability of the U.S. manufacturing base.

The Sustainable Manufacturing Workshop addressed three elements: sustainable products, sustainable processes, and sustainable systems. Small groups were led through a methodology for defining the current state and compelling needs, the vision, and the solution set for all topics related to their element. The full body of work of the groups is included in sections 2 – 4 of this document. After the workshop, the results were analyzed to define the most compelling themes – "the imperatives." The 12 Imperatives include:

**Imperative 1: Sustainable Manufacturing Education and Workforce Development:** Comprehensive Academic and Industrial Curricula for Sustainable Manufacturing Integrated with Opportunities for Work Experience for Education and Training of the Next Generation Manufacturing Workforce

**Imperative 2: Next Generation Life Cycle Assessment (LCA) and Decision Support Toolset:** Toolset that Supports Interactive and Integrated Affordable, Accessible Applicable, Actionable, and Scalable Product Lifecycle analysis

**Imperative 3: Corporate Asset Management**: Management of Corporate Assets for Sustainability across the Enterprise, Including the Sustainability Footprint for Equipment and Facilities

**Imperative 4: Risk, Uncertainty, and Unintended Consequence Analysis for Supply Networks:** Comprehensive Risk Modeling and Mitigation Tool for Supply Network Management that also Addresses Uncertainty and Unintended Consequences

**Imperative 5: Product Lifecycle Management (PLM) Capability for Process Planning:** Enhanced COTS CAD/CAM Tools for Model Development and Product & Process Sustainability Analysis for Process Planning

**Imperative 6: Public-Private Partnership for Sustainable Manufacturing:** Public-Private Partnership For Data-Driven Sustainability Science In Manufacturing Supporting Holistic Product/Process/System Optimization For Best Economic, Social, And Environmental Value.

**Imperative 7: Lifecycle Cost Models:** Total Life-Cycle Process Cost Models that Reflects True Value and Support Total Value Optimization for Sustainable Value Creation

**Imperative 8: 6 R End-of-life Management:** Management of End-of-Life Products with a 6 R,[1] Emphasis and OEM Responsibility for Greater Economic Returns

**Imperative 9: Flexible and Scalable Manufacturing Alternatives:** Flexible and Scalable Manufacturing Alternatives Including Localized Manufacturing and Multiuse Systems with Customized/Personalized Manufacturing for Improved Sustainability

**Imperative 10: Sustainable Manufacturing Metrics:** Sustainable Manufacturing Metrics to Accurately Define and Reflect Sustainability Values

**Imperative 11: Information - to Knowledge - to Intelligent Sustainable Manufacturing:** Transforming Information to Knowledge and Application in Realizing Intelligent Design, Manufacturing, and Lifecycle Support

**Imperative 12: Secure Collaboration:** Protection Of Information To Assure That All Those For Whom Information Is Legitimately Intended Receive Exactly What Is Needed, And That The Possibility Of Unauthorized Access Is Eliminated

## Path Forward

The National Center for Manufacturing Sciences (NCMS), a key PRISM partner, will host a series of workshops in the spring of 2015 that will build on this roadmap to define specific projects and constituencies for PRISM. The workshops will seek sector specific consensus regarding needs and solutions, and will launch the methodology for continuous prioritization, project selection, and execution. Details of these workshops will be released in February, 2015.

[1] 6 R is an extension of the traditional concept of 3 R engineering (recycle, remanufacture, and reuse) to embrace a broader view that includes reduce, remanufacture, reuse, recover, recycle, and redesign.

# 1 Sustainable Manufacturing – A Business Perspective

## 1.1 Introduction

This is the preliminary roadmap for the Partnership for Research and Innovation in Sustainable Manufacturing (PRISM) – a newly formed sustainable manufacturing consortium. The development of the roadmap is supported by an award from the Advanced Manufacturing Technology Consortia (AMTech) program of the National Institute of Standards and Technology (NIST) to the University of Kentucky Institute for Sustainable Manufacturing (ISM). The purpose of the award is to establish the PRISM consortium and to produce a plan for its success in defining and executing a research and development agenda.

To gather information for the roadmap, a workshop entitled "Sustainable Manufacturing – A Business Perspective," was held on November 13 and 14, 2014. Workshop participants included 46 invited stakeholders from industry, government, and academia/research communities. Emphasis was placed on the necessity of industry leadership; nearly half the participants represented commercial manufacturing companies.

In preparing this report, the editors chose to write for an audience of design and manufacturing practitioners aware of the national advanced manufacturing movement and of the goals of sustainable manufacturing. For those who may find some background helpful, we suggest the pre-read package available from the ISM and to the many good works on the subject.

Our viewpoint builds on the wealth of knowledge that precedes us and emphasizes a common theme:

> ***To make the needed impact, sustainable manufacturing must become one of the key decision variables in achieving optimization of the total business equation by considering all three elements of the triple bottom line – economic, social, and environmental responsibility and the protection of sustained, profitable operation. By embracing this holistic approach to "lean and green" manufacturing, radical improvement can be realized.***

**Workshop Methodology:** To understand the material presented, it is important to understand the roadmapping methodology the workshop used. The Functional Model provided the foundation for the workshop and identifies the three small groups that addressed the elements of sustainable manufacturing – product, process, and systems sustainability. The functional model is presented in the next section. The small groups were led through an exploration process that included four major activities:

**Current state assessment** – The attributes of the current state were defined, including barriers, deficiencies, state of practice, emerging best practices and specific needs.

**Vision –** The assumption was made that all barriers were overcome and deficiencies were corrected. Participants were then asked to describe the ideal future state.

**Solutions –** Based on an understanding of both the current state and the vision, solutions were defined that would, if delivered, overcome the barriers and deficiencies and deliver the capabilities needed for the future state. Each small group was asked to prioritize to ten key solutions.

**Projects –** The solutions from the small groups were prioritized by the large group to define the most compelling topics. The small groups were then asked to provide information about those topic areas that could be useful in the creation of a project slate.

After the workshop, the PRISM facilitation and leadership team analyzed the work and defined the Imperatives from the workshop. Following the philosophy that most of the effort should be devoted to the most important and impactful topics, the initial PRISM technology roadmap is built around these Imperatives. It should not be forgotten that the content of the roadmaps is pulled directly from the rich content of the small group discussions. It is important that these deeper insights not be lost in the rollup to more pervasive key topics.

### 1.1.1 Functional Model

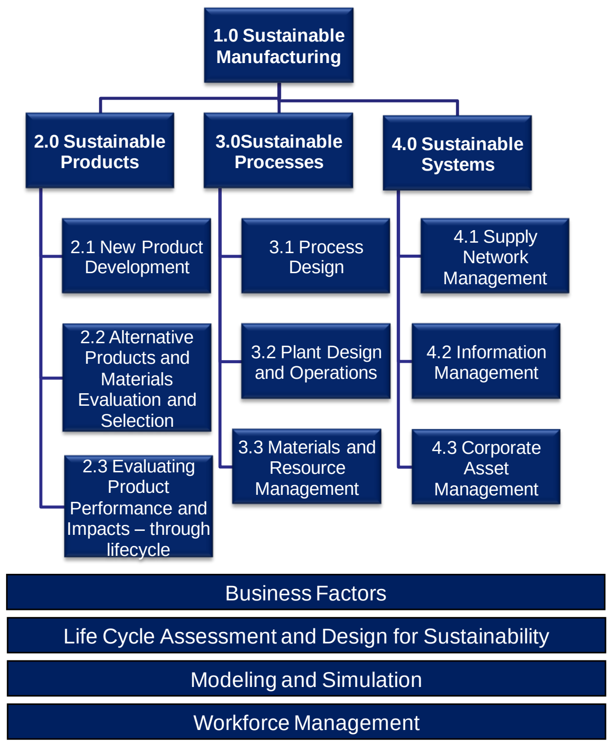



**Figure 2: The Functional Model provides a consistent structure throughout the technology roadmapping process. For the workshop, it provided a guide for gathering information.**

The Functional Model, shown in Figure 2, provides a consistent structure for the workshop, for this document, and for the technology roadmap and subsequent project activities. It proposes that sustainable manufacturing can be adequately addressed by considering three principal elements – Products, Processes, and Systems – and four crosscutting elements -- Business Factors, Life Cycle Assessment and Design for Sustainability, Modeling and Simulation, and Workforce Management.

### 1.1.2 Sustainable Manufacturing Imperatives

**Imperative 1: Sustainable Manufacturing Education and Workforce Development:** Comprehensive Academic and Industrial Curricula for Sustainable Manufacturing Integrated with Opportunities for Work Experience for Education and Training of the Next Generation Manufacturing Workforce

**Imperative 2: Next Generation LCA and Decision Support Toolset:** Toolset that Supports Interactive and Integrated Affordable, Accessible, Applicable, Actionable, and Scalable Product Lifecycle analysis

**Imperative 3: Corporate Asset Management**: Management of Corporate Assets for Sustainability across the Enterprise, Including the Sustainability Footprint for Equipment and Facilities

**Imperative 4: Risk, Uncertainty, and Unintended Consequence Analysis for Supply Networks:** Comprehensive Risk Modeling and Mitigation Tool for Supply Network Management that also Addresses Uncertainty and Unintended Consequences

**Imperative 5: Product Lifecycle Management (PLM) Capability for Process Planning:** Enhanced COTS CAD/CAM Tools for Model Development and Product & Process Sustainability Analysis for Process Planning

**Imperative 6: Public-Private Partnership for Sustainable Manufacturing:** Public-Private Partnership for Data-Driven Sustainability Science in Manufacturing supporting holistic product/process/system optimization for best economic, social, and environmental value.

**Imperative 7: Lifecycle Cost Models:** Total Life-Cycle Cost Models that Reflect True Value and Support Total Value Optimization for Sustainable Value Creation

**Imperative 8: 6 R End-of-life Management:** Management of End-of-Life Products with a 6 R Emphasis and OEM Responsibility for Greater Economic Returns

**Imperative 9: Flexible and Scalable Manufacturing Alternatives:** Flexible and Scalable Manufacturing Alternatives Including Localized Manufacturing and Multiuse Systems with Customized/Personalized Manufacturing for Improved Sustainability

**Imperative 10: Sustainable Manufacturing Metrics:** Sustainable Manufacturing Metrics to Accurately Define and Reflect Sustainability Values

**Imperative 11: Information - to Knowledge - to Intelligent Sustainable Manufacturing:** Transforming Information to Knowledge and Application in Realizing Intelligent Design, Manufacturing, and Lifecycle Support

**Imperative 12: Secure Information Exchange and Collaboration:** Protection Of Information To Assure That All Those For Whom Information Is Legitimately Intended Receive Exactly What Is Needed, And That The Possibility Of Unauthorized Access Is Eliminated

## 1.2 Summary of Workshop Results

This section presents summaries of the work of each small group. The summaries include the current state and vision for each element and the ten top solutions for each group. After the summaries by topic area, the document presents the Imperatives from the workshop in the form of one-page overviews. The more detailed roadmaps for each Imperative are included in Appendix A. The content on which these findings are based is found in sections 2-4 of this document. The reader is urged to examine this rich material to obtain an optimal understanding of the Imperatives and the roadmap.

### 1.2.1 Sustainable Products

#### *1.2.1.1 Sustainable Products Current State*

There is an explosion of new and innovative products. Product performance continues to improve. The importance that consumers place on sustainability in product selection is increasing, and companies are responding. However, there is great diversity in the degree to which this emphasis influences the corporate product decisions. There are many reasons for this diversity. One of those reasons is the inability to accurately assess the risks, costs, and performance in product decisions and to foresee and avoid unintended consequences, which limits the ability to quantitatively influence the product decision process.

**Product Development:** The explosion of new and innovative products presents a paradox for sustainable manufacturing. Prominent Business strategies in many sectors, perhaps symbolized by electronics and consumer products, dictate that products be designed for limited life and planned obsolescence, which creates a matching stream of end-of-life products. Most often, there is limited planning for 6R end-of-life management of these innovative products.

The product design and development toolkit has attained a new level of excellence over the last decade, and Lifecycle Analysis (LCA) has become an accepted requirement in systems engineering approaches to product development. Product Lifecycle Management (PLM) vendors have launched sustainable manufacturing modules that provide excellent foundations for moving toward a fully integrated design environment. The maturation of these tools, including access to needed data, information, and knowledge, is a key goal and need area. The integration of PLM with LCA to create a decision support engine for total value optimization offers exciting potential.

Studies show that the consuming public is becoming more attuned to sustainability issues in the products that they buy. Companies are branding their products for sustainability. For example, the EPA Design for the Environment (DfE) program offers the use of the DfE branding for qualified products. This trend will place more pressure on the product developers to move to a total systems view that values sustainability.

**Alternative Products and Materials Evaluation and Selection:**

New products tend to be incremental revisions and evolutions of existing products with tight limits and controls on the adoption of new technologies. There are several reasons for this. Probably the most important is risk aversion. In our litigious society, the risk of failure often negates the value of radical innovation. The consequence is that we often embrace the well understood and proven capabilities and lose the potential value of breakthrough improvement at the altar of risk version. A better informed risk and unintended consequences assessment capability, as a part of the design and development process, is needed to move the balance to harvest emerging capabilities.

Another important inhibitor to rapid and broad adoption of new technologies and capabilities is the inability to rapidly and cost effectively assess the performance of alternative solutions. High speed computing and improvements in modeling and simulation systems enable improved evaluation of alternative products and materials, but there is much to do before we can effectively assess alternatives in real time and quantify the impact of those selections. Such assessment can be done (often at great cost) for specific applications, but efficient, broad application is lacking. The limitation is most vividly noted in the simultaneous evaluation of multiple alternatives and performance factors. Ready access to needed data, information, and knowledge to support the analytical toolset is a key need as we seek total value optimization.

The selection of alternative products and materials must be driven by consideration of end-of-life issues. Europe is, arguably, taking the lead in this area with programs that negate or limit the use of certain materials and that mandate end-of-life responsibility lie with the original equipment manufacturer. Other countries, particularly in Asia, are following suit. It is noted that this is a controversial approach. The heavy handed adoption of such strategies without complete/balanced consideration of business consequences is problematic. In the U.S., there are multiple programs that address materials management issues, including multiple government agencies and sector advocacy organizations.

There is a major push across transportation-related sectors, including energy production and distribution, to move to lightweight materials. In many cases, the emphasis is on lightweight metals and composites. While primarily driven by energy efficiency goals, lightweighting priorities are opening new opportunities for the inclusion of broader sustainability factors in material substitution.

**Evaluating Product Performance and Impacts:** The balance between business success (often defined in the short term), human safety, societal well-being, and environmental responsibility is a delicate one. For products where human safety or the possibility of catastrophic consequences is present, process qualification, product certification, and attention to every detail cannot be compromised. At the other extreme, many consumer products are produced for rapid obsolescence and replacement driven by very effective marketing and sales strategies. Often there is little or no planning for second generation and beyond. The regulations vary, so the balance between social responsibility and business decisions is often left for the companies and the consuming public to sort out.

Cyber security has emerged as a major factor in managing potential impacts. Threats to products through intentional acts, attacks on the infrastructure, and the growing threat of the compromise of information -- all are in the forefront of our national consciousness and stand to receive increased attention over the next decade.

**Crosscuts:**

**Business Factors:** Short term financial goals are seen to conflict with a balanced emphasis on economic, social, and environmental factors. The result is that society is impacted by unsustainable practices. The trend is toward increased corporate emphasis on sustainability.

**Life Cycle Assessment and Design for Sustainability:** LCA is most often seen as a regulatory requirement instead of a product optimization opportunity. The present toolset does not adequately support improved sustainability in product development.

**Modeling and Simulation:** There is tremendous growth in the capabilities of PLM toolsets, and the toolsets are embracing the broader challenges of product and process development. The inclusion of sustainability tools in PLM is still in its early stages, and, in general, the integration is not mature enough to support decision processes.

**Workforce:** Product design and development education, including sustainability, is not adequately emphasized in the engineering curriculum. The “industrial commons” or shared knowledge gained from experience on which such education and practice should be based is limited – and declining with the retirement of a generation of skilled manufacturing professionals.

#### *1.2.1.2 Sustainable Products Vision*

In the future, a comprehensive set of computer-based tools will guide the Integrated Project Team (IPT) through an evaluation of requirements and product possibilities. The alternative materials, configurations, and features will all be evaluated for cost, performance, risk, potential impacts, and total lifecycle value/cost. The total cost will include all of the hidden costs that are not visible for consideration currently. All potential problems and risks that might not normally be visible in the data or in the final recommendations will be flagged for human evaluation and interaction. The result will be a recommendation for each important decision plus quantification of risk and uncertainty. The final deliverable will be a quantified, total value recommendation of all product attributes in the integrated product/system with a data file documenting the decision process.

**New Product Development:** In the future, new product development will be a virtual process from ideation to detailed product design and will include all necessary information to drive the product lifecycle. The highly analytical process will start with the needs, goals, and requirements of the customer and will move toward an optimized product design package. Sustainable design and manufacturing attributes will be integrated components/factors of the optimization process. A better understanding of the defined needs and desires of the customer, coupled with the innovative exploration of "what is possible" will result in products that satisfy the balanced set of criteria, goals, and expectations. This development environment will be data rich, but not data inhibited, because the complexity of big data access and management will be solved and the right data will support the analysis and decision process. The result will be the ability to evaluate alternatives and quantify the total lifecycle cost and performance – resulting in the best total value decisions.

**Alternative Products and Materials Evaluation and Selection:** Sustainability factors will be considered in all material and product selections. Knowledge rich advisory systems will guide the selection of best alternatives for all sub-products and materials that comprise a product. Access to all needed data will support a rich evaluation and optimization of cost, risks, impacts, and performance, enabled by a capable set of modeling and simulation tools. Knowledge rich decision support tools will evaluate all alternatives to select and quantify the alternatives, thus assuring that the best total solutions are selected. Every evaluation will address risks, uncertainties, and the potential for unintended consequences.

**Evaluating Product Performance and Impacts**:

Internationally accepted and uniformly applied standard metrics will be in place to accurately characterize the sustainability of products. Potential impacts will be quantified and visible. This visibility will create widespread awareness of total sustainability and life-cycle issues to aid consumers in purchasing decisions.

Corporate certification and participation in sustainability optimization – well beyond energy and environmental awareness – will be a necessary business strategy supporting a positive public image, improving working conditions, and perhaps mitigating the necessity of aggressive regulatory enforcement. The sustainability metrics and indices will create growing consideration and support of remanufactured products and modular reuse from the second to the $n^{th}$ generation.

**Crosscuts:**

**Business Factors:** The ubiquitous visibility of all product attributes and their impact on cost and performance will enable corporations and consumers to properly value sustainable products, to assure the best total value decisions.

**Life Cycle Assessment and Design for Sustainability:** Life Cycle Assessment systems will access all needed data and models to virtually evaluate the total value of the product, highlight deficiencies and points of failure, and support optimized decisions for best total product value.

**Modeling and Simulation:** Modeling and simulation systems will access a rich storehouse of materials data and performance knowledge to interactively evaluate various product attributes, alternatives and uncertainties, supporting the virtual development of the most advantageous products.

**Workforce:** A strong, flexible, and available workforce will be well schooled in the importance of sustainability in design and manufacturing. They will be equipped with the education and the toolsets to support the development and production of products that meet and exceed both requirements and expectations, and they will produce products that do no harm to the environment or to society.

#### *1.2.1.3 Top Solutions for Product Development (not listed in order of priority)*

**Reduce end-of-life impacts of products:** Develop methods and tools that include end-of-life optimization in the product design and development process, for example featuring the ability to dismantle and recycle components at the end of product life. Work with the technology supplier community e.g. PLM vendors, to include end-of-life management functionality in the product development toolset.

**Multi-Use Flexible/Shared Machining/Processing centers**: Create multi-use flexible product fulfillment centers for identified classes of products (e.g. after-market support parts). Establish regional centers equipped with additive manufacturing and other appropriate technologies and feedstock materials to provide customers with customized, on-demand parts. These centers will provide low risk, high benefit products built according to a library of specifications, with appropriate intellectual property protection. Sustainability will be incorporated in the equipment design and in the operational procedures that support their utilization.

**Cooperative Knowledge & Solutions:** Create shared repositories that provide access to needed data and information and support the "industrial commons" across the sustainable manufacturing community. This capability could begin with benchmarking of existing and emerging systems such as Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), International Material Data System (IMDS), Restriction of Hazardous Substances Directive (RoHS), and Materials and Processes Technical Information System (MAPTIS).

**Guidelines for Consistent LCA Tool Use:** Develop guidelines and standards for the consistent use of Life Cycle Assessment (LCA) Tools. Develop rules by product category for using LCA and extending its use to a more effective decision support framework, incorporating the triple bottom line of social, environmental, and financial responsibility in all products.

**Accessible LCA tools to enhance sustainability considerations:** Integrate LCA tools and methods into the existing product development toolset (PLM) and specifically target low cost, ease of use, and applicability/availability for small and medium manufacturers. Work with the PLM vendor community and others to clearly define the requirements and to assist in developing the plan for solution.

**Explore and Pilot Localized Manufacturing**: Explore alternative manufacturing methods and quantify the triple bottom line value of utilizing such alternatives. Localized manufacturing, point of use manufacturing, microfactories, "skunk works" and other ideas should be explored. Pilot activities should be conducted with their impact quantified and their outcomes widely reported.

**Sustainability Accountability across Supply Chain:** Develop and incorporate standards and regulatory authority for sustainability compliance across all tiers of the supply network including, in some cases, OEM responsibility for product disposition at the end of its lifecyle. Establish the business case and incentives, based on product value and consumer preference, for voluntary compliance and seek to avoid an additional imposed compliance burden placed on corporate America.

**Foreseeing Unintended Consequences:** Recognizing that many of the negative impacts are the result of events that were not considered beforehand, develop a system that supports the creative exploration of obscure possibilities and unintended consequences. The system could be modeled after a potential problem analysis methodology and the methodologies related to qualification of man-critical applications e.g. NASA, the aerospace industry, automotive, etc. It is envisioned that this system would pioneer new methods to engage humans in creative exploration beyond their usual considerations.

**National Awareness of Sustainability Education Imperatives:** Create and execute a national awareness campaign to make visible the need for the inclusion of sustainability education in the curricula of all institutes of higher education and across all educational disciplines – from engineering to all aspects of workforce education. Extend this emphasis to K-12 education including STEM. Follow the awareness campaign with the development of shared curriculum that addresses all levels of the educational system.

**Knowledge Supply Chain Including Sustainability Readiness:** Create a "knowledge supply chain" in which sustainability education is tied directly to defined needs and opportunities in the job market. Based on needs and opportunity assessments, create partnerships (including internships) between educational entities and corporations to provide exactly the needed training for immediate job placement.

**OEM Responsibility for Total Product Life-Cycle:** Define critical national priorities and establish regulatory authority that places 6R responsibility for end-of-life processing for some products (whether refurbishment, recycling, proper disposal, etc.) with the OEMs.

### 1.2.2 Sustainable Processes

#### *1.2.2.1 Sustainable Processes - Current State*

The last decade has brought great improvement in the integration of manufacturing process considerations in product design and development. IPTs are working together for best solutions and new virtual tools are being applied to optimize plants and processes before the design is completed – even in the conceptual and scenario stages. More attention is paid to materials impacts, and, hence, alternative materials and resources are important drivers for many manufacturing enterprises.

**Process Development:** The culture has changed. The advent of systems engineering, concurrent engineering, and IPTs has brought product and process development much closer together. The necessity of working as a team to utilize mature process technology and assure that manufacturing processes can support product requirements is a reality in most manufacturing enterprises. However, while the culture and business practices have improved, the toolset does not yet fully support the integrated product and process environment. Process selection and development should be an open exploration of the best alternatives to optimize total value. The delivery of this capability requires a toolset that accepts requirements, accesses needed data, and evaluates and quantifies alternatives. This capability, although emerging, has yet to be realized.

**Plant Design and Operation:** Plant design offers a great opportunity to add a process sustainability emphasis. Design for flexibility, scalability, and reconfigurability are key opportunity areas. There are examples of plant design in which all facilities, utilities, equipment, processes, and workflows were modeled and optimized as part of the conceptualization and design process. In some cases, these factories operate in virtual reality before final design to assure that potential problems are identified and resolved.

One of the greatest opportunities in plant and process operation is in reliability engineering. Companies have reported billions of dollars in savings as a result of a commitment to this discipline. Reliability engineering involves the analysis of a system to determine and categorize all parameters and operational elements. A "sense, analyze and control" scheme is put in place for every parameter that has a potential to significantly impact process or product performance. Control limits and response algorithms assure that each parameter is maintained within the safe operating envelope. The proper level of control is activated for each parameter, resulting in a system optimized for most efficient operation and for assured product quality. This trend toward protecting the sustained operation of important manufacturing processes and equipment, and delivering products with an assured ability to function as designed, is growing and will continue to grow.

**Materials and Resource Management:** The discussion of the current state for materials and resource management addresses three key issues: access to needed materials, the selection of materials, and the processing of waste materials.

Material access and materials replacement is important for companies as well as for nations. There are many examples of materials that had been commonly utilized until their hazards were fully revealed. There is a growing commitment to better understand the interactions and impacts of materials and to move proactively to eliminate or control questionable materials. The European Community has adopted REACH (which addresses chemicals) and RoHS (which restricts the use of certain hazardous materials and promotes recycling and reuse). The current state is characterized by a tension between business and social necessities and compliance with imposed regulations.

The supply of materials needed for manufacturing is subject to volatility. Rare earth elements provide an excellent example of the sustainability challenges that are faced in assuring an reliable and affordable supply of necessary materials.

The selection of the best materials, qualification of alternative materials, and match of materials to processes are important capabilities with strong sustainability implications. In the current state, the risks and uncertainties, the cost of materials and process development, and the complexity of material and process qualification all tend to reinforce continued use of existing and proven material/process combinations. The use of modeling and simulation systems to support more efficient evaluation is migrating toward a more systemic approach of Integrated Computational Materials Engineering (ICME) which combines advanced computational tools with systematic experimentation to accelerate the evaluation process, reducing cost, risk, and cycle time for new product and process development.

Business value and individual social responsibility are dominant factors in reuse and recycle. Aluminum cans, reused paper, etc. are commonly recycled for two reasons: responsible citizens believe that it makes a difference, and significant energy and cost savings accrue from recycling. However, the consumer decision in most recycling efforts is not driven by economic considerations. To achieve broader engagement in recycle, consumer incentives need to be increased. The European Union is taking a lead in the international community with programs like the End-of-life Vehicles Directive which places responsibility for end-of-life management with the original equipment manufacturer.

**Crosscuts:**

**Business Factors**: The biggest barrier for the business case approach to sustainable processes is the difficulty of establishing accurate cost baselines for comparison of alternatives.

**Life Cycle Assessment and Design for Sustainability:** There is a strong need for Life Cycle Assessment of the product-to-process, process-to-process, and materials-to-process interactions and impacts. A holistic picture that includes these interactions would promote better decisions regarding total costs, environmental impacts, and societal impact.

**Modeling and Simulation:** Process modeling has lacked clear targets and a shared focus. Currently the modeling and simulation community falls short of delivering an available toolset that can be adapted to specific applications, especially in creating integrated models across processes. Models proliferate, but often ***the models that I have are not what I need, and the models that I need are not available.***

**Workforce:** The rigors of process development and qualification in a cost conscious, risk aversive environment have increased the tendency to use proven processes, resulting in limited investment in process development. Hence, the knowledge and experience that comes from hands-on, trial and error solutions has become scarce, which in turn means the ability to sustain and grow our industrial commons and to nurture our critical innovation skills in process development is at risk.

#### *1.2.2.2 Vision for Sustainable Processes*

In the future, product requirements will drive a virtual evaluation of all manufacturing elements -- materials, facilities, processes, and other resources -- to produce the best alternatives for total value optimization, including sustainability. Knowledge-based systems will support best alternative selection and will automate/augment the creation of the information needed to drive an intelligent manufacturing environment. LCA systems will move from compliance tools to valued decision support systems that enable the optimization environment.

**Process Design and Development:** In the future, the definition of product requirements and opportunities will launch a quantitative evaluation of alternatives for best total lifecycle value.

Sustainability attributes will be core to the assessment, and the impact of choices will be visible to the Integrated Product Teams. The process design and development environment will be supported by a rich modeling and simulation capability – for individual processes and integrated across processes - and captured knowledge will guide the evaluation process. All needed data will be available to assure that the evaluation is accurate and that uncertainties and risks have been included and mitigated.

**Plant Design and Operations:** In the future, the corporate mindset will embrace optimum sustainability in plant design and operations and total lifecycle value as "business-as-usual." Plants will be designed in a rich virtual world with optimization of process operation "designed-in," with a strong emphasis on realizing the most sustainable operations as an attribute of total business success. Plant operations will be supported by all needed data, information, and knowledge. Processes, systems, and facilities will apply triple bottom line principles to optimize energy utilization and waste generation with zero net impact as the norm. The full processing stream, both upstream and downstream, will be visible; any deviations will be immediately flagged and addressed. The knowledge garnered from the operation will be continuously processed, the knowledge-base will be enhanced, and operational improvement will be performed in real-time.

**Materials and Resource Management:** Materials/process interactions will be fully characterized based on scientific first principles. This foundational understanding will support a full analysis of the operational results for all alternatives, including energy and environmental impacts and the impact of product attributes. The full business analysis of material selection and process interaction, including cost, time, and impacts will be available. The status of materials, resources, wastes, and emissions will be continually visible, in-process.

**Crosscuts:**

**Business Factors:** The analysis, design, and development systems for manufacturing processes will assign realistic and accepted values for all parameters, including externalities[2]. This accurate valuation will enable realistic true cost projection and process optimization.

**Life Cycle Assessment and Design for Sustainability:** LCA will be integrated with a growing PLM capability to extend its applicability from product lifecycle evaluation toolset to integrated toolset with capability to evaluate product and process options, quantify the expected results of all possible selections, and optimize for best total lifecycle value. All required data, information, and knowledge will be accessible in useful form.

**Modeling and Simulation:** Modeling and simulation activities will be focused and coordinated to provide classes of open-systems models, by sector and domain, that offer generalized process modeling functionality that can easily be adapted to specific applications and products. These

---

[2] Externalities is a concept in economics, frequently criticized by the sustainability community, that describes a cost or benefit that affects a party that did not choose to incur the cost or receive the benefit. When used in sustainable manufacturing, the term refers to the associated costs that are not or cannot be charged with the product.

models will support the evaluation and quantification of the relative value and tradeoffs of various process alternatives and, because of their interoperability, combinations of processes.

**Workforce:** Sustainability Engineering will be valued as a premium career path and as an integral component of all engineering disciplines. All areas of educational and career pursuit will include knowledge of the attributes of sustainability and a broad view of the importance of sustainability from a business perspective.

#### *1.2.2.3 Top Solutions for Sustainable Processes*

**Clear Definition, Scope, and Metrics for Sustainable Processes:** Establish a framework for Sustainable Processes that enables the realization of a process evaluation and optimization system with due consideration of sustainability issues. Develop a pilot project that identifies two processes that crosscut industrial sectors and populate the framework.

**Additive Materials and Processes Sustainability Data Access and Planning Modules:** Maximize the advantages of additive processes by providing data and planning systems that optimize the sustainability of the processes. The timing is right to enhance this technology value by creating standard sustainability driven data and planning systems that address the best use of both the materials and the additive processes.

**Inclusion of Sustainability in PLM Toolset:** Enhance the existing COTS PLM toolsets with the needed modules to achieve sustainability optimization in the definition/development of processes to meet product requirements. Provide process and operations planning capability to optimize process operation across multiple processes.

**Lifecycle Management of Equipment:** Establish regulations, methods, and tools to support the delivery of a lifecycle sustainability package with each new equipment purchase. The sustainability package will include operational models, assistance in sustaining and efficient operation, and end-of-life management.

**Design and Process Planning Data/Tools for Continued Life Decision Support:** Establish sustainability driven process standards for each of the 6R pathways for the 2nd to $n^{th}$ use cycle and include these factors in an overall evaluation process. The standards should address: material flow & processing parameters, materials/components valuation data for balanced total value prediction and valuation models, materials/resource consumption optimization, and waste reduction/creation/management considerations.

**Establish Monitoring and Management Practices for Incoming & Outgoing Resources and Waste:** Develop practices, protocols, and standards for monitoring and measuring both incoming & outgoing resources and wastes. The result will be transparent flow of materials through the processing environment, including inside the factory and across the supply network where appropriate. This visibility will assist in minimizing impacts and spotting deviations, and will supply data and knowledge for continued materials and resource optimization.

**Cost Baselines for Materials and Process Evaluation:** Establish cost models that respond to product features and requirements and enable accurate evaluation and comparison of material and process alternatives. The cost baselines should be built on a consistent structure (a consensus framework or architecture moving to standards) to the point that evaluations are comparable regardless of the application or the person performing the evaluation.

**Interactive Product/Process/Systems LCA capability:** Develop an efficient, "lean" LCA framework/system that enables the full evaluation of the lifecycle performance and sustainability impact of products, processes, and systems. "Lean" is used to stress a key point: the value and operation of the system must be based primarily on a business assessment and not on satisfying externally imposed requirements; all data and complexity must directly support the efficient delivery of useful business information.

**Cooperative Public/Private Partnership for Compliance Cost Reduction:** Establish an industry-led, public/private partnership (possibly an appropriate role/mission for PRISM) to inform policy decisions that will assure the protection of the environment while reducing the bureaucracy and associated costs of regulatory compliance. The partnership should include industry, regulatory bodies, and subject matter experts.

**Joint Development of Academic and Industrial Sustainability Curricula:** Establish a working group composed of representatives from industry, government, and academia charged with creating and managing a continuing needs assessment for academic curricula, related to sustainability, for all levels of education. Include in the mission/scope of this group a mandate to range from general education to meeting specific needs of sectors and companies in establishing a "knowledge supply chain" for specific job skills. This program should emphasize the elimination of all gaps in the ability of graduates to move directly into workplace assignment without the necessity of remedial training.

### 1.2.3 Sustainable Systems

#### *1.2.3.1 Sustainable Systems Current State*

Systems engineering and related themes have raised awareness of the necessity of addressing challenges from a holistic view, which includes an awareness of the value of a sustainable approach to design and manufacturing. Companies are investing in supply networks that minimize risks and provide long term stability of supply. Progress is being achieved in making information available to all who need it across a supply network. A more holistic view of corporate asset management is being embraced by some major companies and sectors. However, a tension still exists between short term financial gain and prolonged sustainable investments. Cyber security issues threaten the supply base and must be addressed. The aging workforce coupled with the lack of an appropriately trained emerging workforce that understands the importance of sustainability are crucial current state concerns.

**Supply Network:** Awareness of the value of a supply partnership is growing, especially for high value manufacturing. Driven by concerns about risks and uncertainty, proactive companies are investing in establishing relationships with trusted partners and engaging with those partners in an integrated, collaborative environment. The cost and quality of products is monitored at the various levels of the supply network, and, although the trend is not universal, more companies are investing in sustainable practices across their supply base.

This positive assessment of improved awareness and response is not to say that pressures to drive down costs are any less important, or that all companies are following a more sustainable approach. Indeed, the pressures to establish the lowest cost of supply, without regard for other factors, remain strong and are especially visible in the sourcing of low end commodity products through offshoring, pervasive in some sectors.

The protection of the supply base is paramount for sustained success. Supply partnerships must consider unintended consequences and protect critical supply. For example, natural or manmade disasters that impact a critical supplier may hamper or shut down production across multiple suppliers. Cyber security is a huge and growing issue, underlining the necessity of protecting products, infrastructure and information.

**Information Management:** The increasing partnership across the supply network makes securely sharing information and interoperability more necessary than ever. PLM, modeling and simulation, and Enterprise Resource Management (ERP) systems need to seamlessly and securely exchange data and information. This is a long standing challenge, generally addressed with translators and Applications Programming Interfaces (APIs). The real solution -- interoperable systems that adhere to protocol standards and support defined data and information requirements -- has yet to be realized.

Lifecycle product support demands access to all data and information required to maintain a product through its useful life, including end-of-life disposition. With the broad adoption of three dimensional computer aided design systems to create product models, and the use of analysis systems to support product and process maturation, comes the opportunity to move from drawings and documents to electronic technical data packages. These technical data packages capture the development of the product and can be extended to capture the as-required, as-designed, as-planned, as-built, and as-operated and supported data-files. This information makes sustainability options and decisions more visible in the product lifecycle and offers tremendous opportunity for improvement in operations management, reliability engineering, and leading to intelligent control.

As mentioned in the supply network discussion, the protection of corporate information is a national priority and necessity. The integrity of design and manufacturing information is imperative. Many recent examples of unauthorized capture of complete designs of important systems, both for industrial products and for critical defense applications illustrate this national crisis. The protection from both external and internal threats is a growing problem that will receive increasing attention over the next decade.

**Corporate Asset Management:** Human resources are critical corporate assets. In a time of reduced manufacturing employment, there is a critical shortage of manufacturing professionals and skilled trades. This is driven by retirement of the aging workforce and the shifts in career choice toward other professions. A vital education and training program, coupled with direct pathways to the workplace, is needed.

In terms of capability, performance, and utilization of manufacturing equipment, the trend is toward improved technologies, higher speeds and throughput, and improved performance. The new generation of manufacturing equipment, and the tooling that supports it, is designed for greater processing efficiency, improved reliability, enhanced energy efficiency, and more sustainable operation.

Brand management, a corporate asset, is receiving increased attention. The opportunity to enhance brand equity through an emphasis on sustainability has not been missed, especially in the consumer products industry. On the other hand, the loss of brand equity through product safety failure or adverse environmental impact is a major factor in raising sustainability awareness and emphasis.

**Crosscuts:**

**Business Factors:** Often business metrics do not include sustainability factors and therefore do not support a complete evaluation pointing to the best decisions. The business rewards and incentives structures (across all aspects of the business) may also not support the total, balanced optimization that enables sustainable selections. Emphasis on innovation and aggressive product development is often weighed against risks and uncertainty factors, including technology maturity and risks. It is noted that this give and take between aggressive technology deployment and entrenchment in present methods can be a positive tension that must be well managed.

**Lifecycle Analysis and Design for Sustainability:** LCA is widely accepted as a methodology and toolset for confirming that products will not adversely affect the environment. An alternative view sees LCA as a system with the potential for assessing and optimizing the total sustainability of a product and proactively supporting product and process optimization. In the main, this alternative view has yet to be realized. Specifically, LCA does not well address either the societal or economic considerations of the triple bottom line (and was not originally intended to do so). In addition, LCA is expensive; both the software and the expertise to run it are costly, especially when ISO standards compliance is included.

**Modeling and Simulation:** Modeling and simulation (M&S) systems have made great strides in modeling individual pieces, but modeling integrated systems is still a challenge. Effective use of M&S in a comprehensive, systems-based advanced manufacturing optimization product and process development system requires the ability to consider all factors, including product performance, costs, environmental impact, and social responsibility.

**Workforce:** The workforce needs to understand that design and manufacturing is a system, sustainability is a part of that system, and total optimization is the goal. Adequate emphasis is not being placed on this systems-based perspective.

#### *1.2.3.2 Vision for Sustainable Systems*

A holistic, systems-based approach to design, manufacturing, and lifecycle support will be the norm. The product team will define system requirements and will interactively examine various product scenarios with real-time, accurate assessment of the cost, performance, and sustainability impact of all options. The evaluation will include sourcing options and supply network design. All needed information will be available to the product team and the enterprise in an as-needed, yet secure environment. Corporate assets, including human assets, will be proactively managed, assuring that all needs, now and at any future time, are fully met. LCA will move from a tool that assures environmental responsibility to a system that interacts with other systems to optimize the triple bottom line for the product lifecycle.

**Supply Network Management:** A virtual environment will enable the user to easily evaluate all factors in an equation that balances cost, performance, sustainability, and risks for all supply options, conduct tradeoffs, and select the most advantageous alternatives, based on defined performance metrics. The models that support the environment will interoperate so the user can see the cost and performance of individual operations, components, subsystems, and systems. The visible factors will include social, environmental, and economic considerations. They will enable total optimization based on the best integrated solutions. The evaluations will consider all factors that influence supplier selection. The virtual environment will be a learning environment in which actual costs are fed back to the models to enable upgrading of the knowledge base and the decision processes.

**Information Management:** Needed information will be available at any place and at any time to support the design, manufacture, operation, or repair of any product. All needed information for which the recipient is approved flows to any user at any tier of the supply network. Alternatively, no information is made available or is accessible through any means to those who are not fully qualified, authorized, and authenticated for such receipt. There is no interruption of capability or function across information system versions or updates.

**Corporate Asset Management:** The inclusion of sustainability factors in all decisions regarding corporate assets will be the norm. All assets will be managed for individual best performance and collective business value delivery with monetized social/human value placed on sustainability factors. Systems methodologies will be applied in managing and optimizing assets. Equipment, facilities, and human resources will be viewed as systems with a balance of localized optimization and total system performance. Physical assets will be designed and managed through the application of reliability engineering, assuring peak performance of all systems and subsystems.

Corporations and enterprises will be resilient. Definition of threats - and protection against those threats - to assure sustainable prosperity will be routinely included in the design and operation of all systems.

**Crosscuts:**

**Business Factors:** All needed measures and metrics that enable the inclusion of sustainability in a systems approach to design and manufacturing will be in place. A hierarchy of definition will exist, starting at a high level of shared categories of measures and metrics that support all manufacturing enterprises. These high level measures will break down to the needed level of specificity, while maintaining the linkage to the triple bottom line responsibility mandated for all enterprises.

**Life Cycle Assessment and Design for Sustainability:** LCA tools will be accessible, affordable, and robust. They will be optimized and harmonized to enable consistency in application and in interpretation. All aspects of the product lifecycle will be well understood, and LCA will mature to the point that its application will drive business decisions for total best value.

**Modeling and Simulation:** User friendly, high resolution, and scalable modeling and simulation systems will populate a virtual product and process development environment that makes the attributes visible and supports a trade-off environment in which best business decisions are made without physical prototype production.

**Workforce:** A well trained and technically savvy workforce will embrace design and manufacturing as a system with sustainability as a major component in an optimization equation. A systems-based toolset will support the total optimization environment and the continuous skills development of the workforce.

#### *1.2.3.3 Top Solutions for Sustainable Systems*

**Comprehensive Risk Modeling Tool for Supply Network Management:** Develop an intuitive risk modeling tool for supply network management with a flexible and adaptable dashboard to identify and quantify business decisions. The tool should accommodate analysis of risk interdependencies, sustainability tradeoffs, and catastrophic failures within the supply network with a specific focus on unintended consequences and technology changes.

**Business Decisions Based on True Cost:** Develop a user-friendly interface and a model that enables business decisions based on the true cost of alternative actions. The systems should address all stakeholder perspectives and should include social, environmental, and economic factors.

**Collaborative and Secure Supply Network Management Platform:** Create a collaborative and *secure* web-based supply network management platform for handling data and communicating with partners. The system should be user friendly, with no specialized knowledge or local IT support required. The platform will include a taxonomy and protocol that addresses both traceability and visibility into social and environmental aspects of the supply network.

**Big-Data Based Knowledge Discovery to Support Optimized Product Development:** Develop a knowledge discovery and management system that addresses the search and retrieval of relevant information from multiple data sources, the extraction of data and information needed for product and process optimization, and the application of analytics, one that supports the discovery of the information and knowledge needed to support improved product and process development decisions. This capability should include, but not be limited to, sustainability issues.

**Monetization of Societal and Environmental Attributes:** Develop methods to quantify value for elements not normally monetized, including societal and environmental value and the impact of externalities.

**Corporate Asset Advisory and Management System:** Develop and broadly disseminate a managed services system that supports corporate asset optimization, starting from the definition of requirements, through design, including operation, and end-of-life disposition. The system should address the social, environmental, and economic factors and support an "open exploration and evaluation" of all alternatives (including contracting services not normally considered candidates for outsourcing) and decision support in realizing optimized asset management.

**Sourcing Advisory Systems:** Develop knowledge-based advisory systems that accept requirements input, support the collection of sourcing alternatives, access the needed data, information and knowledge needed for evaluation of sourcing options, and offer quantitative advice on best sourcing alternatives. This kind of system will assist in assigning value from a triple bottom line approach in decision support.

**Metrics and Measures of Performance for Sustainable Manufacturing:** Develop a set of metrics and measures of performance for all aspects of sustainable manufacturing. The metrics should accurately define and reflect sustainable values and drive corporate behavior and performance through appropriate incentives. The metrics should start with commonly shared, harmonized measures for all sectors and move to specificity as necessary for meaningful quantification.

**Next Generation LCA Toolset:** Develop LCA tools that are easier to use and broader in their scope. The goal: a next generation toolset that is accessible, affordable, and robust. Recognizing the diversity of sectors, domains, and applications, it is generally recognized that a single standard toolset is not possible. The toolsets should be harmonized to enable consistency in application and in interpretation, and should be tuned to the business environment to drive best value decisions.

**Curricula for Systems-Focused Education and Training:** Develop curricula at appropriate levels of the education and workforce training hierarchy to equip the existing and future manufacturing workforce with a systems mindset.

## 1.3 Exploring the Imperatives

The following twelve pages contain brief overviews of the Imperatives. Each one-pager contains:

- A definition of the opportunity
- A highlight of the business case
- An overview of gaps and challenges
- An abbreviated roadmap for realizing the goals defined in the Imperative.

A more extensive technology roadmap for each Imperative is included in Appendix A. These roadmaps compile all of the work related to that theme across all of the elements of the functional model. The roadmaps provide a beginning point for project planning and execution. Modifications and enhancements will be essential as PRISM moves to R&D investments

Naturally, the timelines of the abbreviated roadmaps and the more comprehensive roadmaps of Appendix A will differ. The timelines in the one-pagers consider macro-scale R&D activities required to enable success in the key topic area. The richer roadmaps contemplate a more detailed plan and support deployment.

### 1.3.1 Imperative 1: Sustainable Manufacturing Education and Workforce Development

**The Opportunity:**

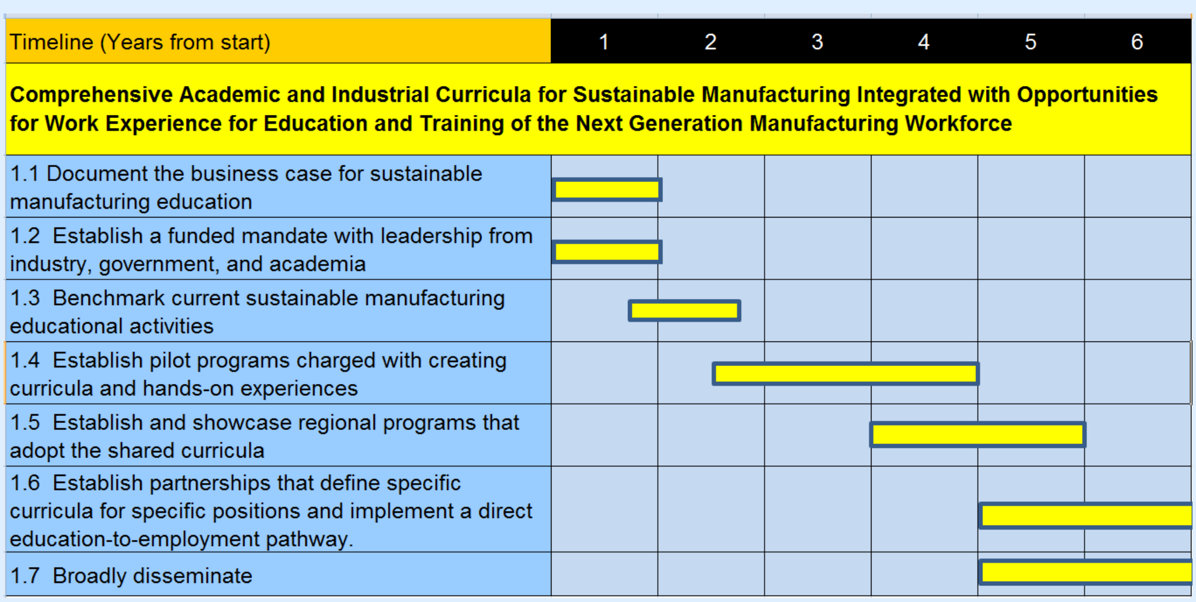
The emergence of advanced manufacturing as a technology enabled pathway to efficiency opens the door for sustainable manufacturing to take its place as an important factor in the optimization equation. First, a clear business case and plan for sustainable manufacturing education is required. Then, education across all levels of the academic and workforce spectrum will enable sustainable manufacturing to be broadly embraced as an important factor in lifecycle product management.

**Business Case:**

- An educated, sustainability aware workforce:
  - Enhances corporate knowledge and supports innovation
  - Enhances top-line brand equity
  - Delivers triple bottom line positive impact on the competitive position
  - Reduces the cost of compliance and risk of lack of compliance

**Gaps and Challenges:**

- The business case for sustainable manufacturing is not clearly established
- Sustainable manufacturing is not seen as an education priority. Leadership in industry and academia must be convinced that there is a compelling need
- The curriculum must be developed and broadly disseminated



### 1.3.2 Imperative 2: Next Generation LCA and Decision Support Toolset

**The Opportunity:**

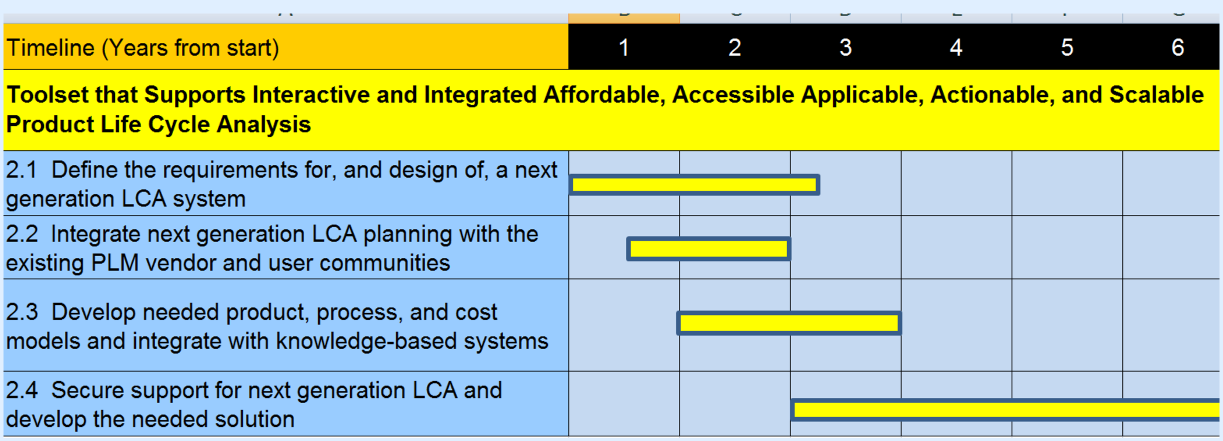
LCA delivers value when assessing the potential environmental and energy impacts, but it is often an isolated activity, not integrated with product and process development or providing decision support. There is a great opportunity to move sustainable manufacturing and LCA from a peripheral activity to a mainstream and integral component of a total value optimization environment.

Business Case:

- Most of the costs are locked in during the early phases of product development. Including sustainability in a total lifecycle value assessment, early in the development cycle, can lead to significant cost savings.
- The risks of product and process failure are great, and the consequences can be catastrophic. Early assessment and risk mitigation will protect corporate viability.

Gaps and Challenges:

- Sustainability lacks equal status with affordability and producibility in an optimization equation
- LCA is not integrated with the product lifecycle management toolset
- Effective outcome prediction requires the integration of LCA with M&S tools and knowledge-based systems



### 1.3.3 Imperative 3: Corporate Asset Management

**The Opportunity:**

Corporate asset management is a broad topic ranging from management of a specific piece of equipment to design and operation of a plant or a corporation - including human resources and sourcing decisions. Corporate asset management is often viewed as a tactical process with of separate individual decisions. Embracing corporate assets as a system offers the opportunity for optimization, stability in operations, and sustainability of the enterprise.

**Business Case:**

A holistic view of asset management assures that all needed resources will be available when needed, enabling

- Cost savings through reliability engineering
- More confident business development
- Risk mitigation and protection against disruption
- Improved corporate image and business position

**Gaps and Challenges:**

Corporate assets are distributed among siloed functional organizations; an awareness of the need for a systems approach is rare. The first challenge is to create a clear awareness and business case for integrated asset management – breaking organizational walls. The second challenge is to build and deploy a toolset that manages these assets for best total corporate value.

| Timeline (Years from start) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Management of Corporate Assets for Sustainability across the Enterprise, Including the Sustainability Footprint for Equipment and Facilities** | | | | | | |
| 3.1 Develop and disseminate an improved model to identify and optimize **all** corporate assets | | | | | | |
| 3.2 Develop corporate asset systems that strategically manage resources from the definition of requirements, through design, through operation, and including end of life disposition | | | | | | |
| 3.3 Develop knowledge-based advisory systems that optimize the decision process related to all resource and asset utilization decisions, including sourcing | | | | | | |
| 3.4 Create a culture in which reliability engineering and resilient systems are mainstream, and implement self-operating and self maintaining manufacturing systems | | | | | | |
| 3.5 Establish regulations, methods, and tools to support the delivery of a lifecycle sustainability package with each new equipment purchase. | | | | | | |

### 1.3.4 Imperative 4: Risk, Uncertainty, and Unintended Consequence Analysis for Supply Networks

**The Opportunity:**

The increasing complexity of the global supply networks and the consequences of interruption of supply present an opportunity and a demand for improved risk assessment, avoidance, and mitigation capabilities. The ability to establish safe operating envelopes, well within the bounds of acceptable performance, and to operate within those boundaries, assures safe, energy efficient, environmentally responsible, and sustained operation.

**Business Case:**

- Protection of the company from loss or supply disruption
- Confidence in the ability to produce product and meet requirements
- Aggressive and informed engagement
- Customer confidence, demonstrated in preferential selection

**Gaps and Challenges:**

The present risk models do not address all factors or the aggregation of factors and are particularly deficient in addressing uncertainty and unintended consequences. Better management of uncertainly and more extensive evaluation of obscure modes of supply network failure are critical need areas. Better and more intuitive user interfaces that facilitate innovative exploration of failure modes are needed. Real-time monitoring and dynamic model updating are areas of challenge.

| Timeline (Years from start) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Comprehensive Risk Modeling Tool for Supply Network Management that also Addresses Uncertainty and Unintended Consequences** | | | | | | |
| 4.1 Develop interactive systems that support the real-time evaluation of the ability of process alternatives to satisfy product needs within acceptable risk envelopes | ■ | ■ | ■ | ■ | | |
| 4.2 Provide a comprehensive, dynamic software-based risk advisory system that informs the user concerning materials-availability and utilization risks. | ■ | ■ | ■ | | | |
| 4.3 Develop a modeling and evaluation toolset that supports the innovative testing of the extreme boundaries of emerging products | | | ■ | ■ | ■ | |
| 4.4 Develop an intuitive risk modeling toolset with adjustable dashboard to identify and quantify risks in business decisions. The tool must accommodate analysis of risk interdependencies, sustainability tradeoffs, and catastrophic failures within the supply network. | | ■ | ■ | ■ | ■ | ■ |

### 1.3.5 Imperative 5: Product Lifecycle Management (PLM) Capability for Process Planning

**The Opportunity:**

The chance to shift from process planning driven by the need for specific product outcomes to the selection of optimized processes integrated with the product design for best total value. This approach provides a way to explore alternatives for holistic optimization, including a sustainability focus in all processes and optimized planning for each of the 6-r end-of-life processes.

**Business Case:**

- Saves money and time by reducing iterative process development
- Provides insight into the true costs
- Eliminates unintended consequences from optimization of single processes and parameters
- Supports new value streams by optimizing 6R value
- Enables confident application of better process alternatives

**Gaps and Challenges:**

Open exploration of process alternatives requires the full characterization of materials and processes and access to data and models – provision of which is a major challenge.

Process planning is caught in between PLM, Manufacturing Execution Systems and Enterprise Resource Planning. "As planned" has never been given the importance of "as designed" or "as built."

Advanced process planning is knowledge intensive. Knowledge capture and application is weak across most manufacturing systems.

| Timeline (Years from start) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Enhanced COTS CAD/CAM Tools for Model Development and Product & Process Sustainability Analysis for Process Planning** | | | | | | |
| 5.1 Develop material and resource characterization methods and apply in creating shared access | | | | | | |
| 5.2 Develop planning modules for sustainability analysis and optimization | | | | | | |
| 5.3 Integrate sustainability optimization in product-to-process decisions. Enhance commercial PLM | | | | | | |
| 5.4 Develop needed standards to support 6r planning. Develop and deploy systems to support all 6r alternatives | | | | | | |

### 1.3.6 Imperative 6: Public-Private Partnership for Sustainable Manufacturing

**The Opportunity:**

Effective definition of goals and focused collaboration can move sustainable manufacturing from an isolated topic of interest to a strong component within an integrated, holistic pursuit of total lifecycle product value. Present mechanisms for collaboration in sustainable manufacturing are limited, and the current stress on advanced manufacturing has not yet embraced sustainable manufacturing as a key topic. By coming together with a common purpose in an industry driven alliance, instilling a methodology for business-focused project selection, and working together to deliver value, the sustainable manufacturing community can contribute to the resurgence of manufacturing in the United States.

**Business Case:**

- Assures a strong "voice of industry"
- Provides a link from validated industry need to government funding sources
- Provides a methodology to assure that investments are focused
- Provides awareness of related activities, eliminating wasteful duplication

**Gaps and Challenges:**

- Determining roles and establishing governance in a broad alliance
- Gaining broad acceptance of the necessity for triple bottom line responsibility
- Effectively partnering with industry; avoiding competition for the same funding sources
- Providing shared access to needed data, information, models, and knowledge

| Timeline (Years from start) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Public-Private Partnership for Data-Driven Sustainability Science in Manufacturing supporting holistic product/process/system optimization for best economic, social, and environmental value.** | | | | | | |
| 6.1 Establish a neutral broker organization to facilitate the partnership | | | | | | |
| 6.2 Develop a business plan that includes the sustained operation and revenue generation | | | | | | |
| 6.3 Produce and manage a living technology roadmap and utilize the roadmap as a foundation for | | | | | | |
| 6.4 Put in place a collaborative model wherein projects are executed and results are shared. Include the indexing and management of the capabilities and activities of the partnership | | | | | | |

### 1.3.7 Imperative 7: Lifecycle Cost Models

**The Opportunity:**

*Better products can be delivered at lower cost by accurately predicting costs and optimizing product and process attributes for total lifecycle value.* The ability to evaluate alternatives and determine the best total product and process value requires the detailed understanding of cost factors – early in the development process. The conventional pathway to accurate cost knowledge is by analysis of historical data. This approach limits exploration to what we currently understand and discourages innovation. A rich understanding of the foundational cost elements is needed, based on requirements, from which accurate cost models can be constructed. Cost analysis should include all of the components of sustainable manufacturing.

**Business Case:**

Accurate cost assessment early in the development process:

- Reduces product cost
- Reduces the risk of unanticipated cost escalation
- Enables cost optimization based on an accurate evaluation of all options
- Supports a full evaluation of total lifecycle costs and includes sustainability

**Gaps and Challenges:**

The ultimate achievement of true cost analysis early in the development process requires access to data, information, and knowledge from which mathematical relationships can be developed. To support broad applicability of the cost models, the captured knowledge and relationships must cross the boundaries of domains to support multiple applications. Establishing a common framework for cost modeling, capturing the required knowledge, and building true lifecycle cost analysis into the product development toolset is a formidable challenge.

| Timeline (Years from start) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Total Life-Cycle Cost Models that Reflect True Value and Support Total Value Optimization for Sustainable Value Creation** | | | | | | |
| 7.1 Cost Modeling framework and user interface for consistent application | | | | | | |
| 7.2 Cost models for specific product and process families | | | | | | |
| 7.3 Shared access to cost models, data, and knowledge to support true cost analysis | | | | | | |
| 7.4 Adaptive, learning cost models | | | | | | |
| 7.5 Integrated lifecycle cost modeling as a component of early stage product development | | | | | | |

### 1.3.8 Imperative 8: 6 R focused End-of-Life Management

**The Opportunity:**

Improved and pervasive end-of-life planning offers the opportunity to reduce environmental impact, save energy, and maximize the total lifecycle value of the product. Including end-of-life considerations in the conceptualization and design process means the best disposition plans can be built into the products and conveyed in the accompanying product information. The 6 R concept offers an excellent foundation for instilling end-of-life planning in the development process.

**Business Case:**

- Triple bottom line responsibility enhances brand value and wins market share
- End-of-life management creates new revenue streams and new jobs
- Recycling saves energy and lowers the cost of new products
- Lifecycle management avoids costly environmental damage and brand damage
- The evaluation/utilization of all 6R alternatives optimizes total product value

**Gaps and Challenges:**

Gaps exist in the culture, the businesses processes, and the technology toolsets. The most stringent end-of-life activities are enforced by regulatory statues. While they may be effective, a compelling business case is preferable as a driver. Business processes need to be changed to embrace end-of-life responsibility. Tools are needed to support the full evaluation (including true cost) of 6R alternatives and the selection of and planning for the most effective end-of-life alternatives.

| Timeline (Years from start) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Management of End-of-Life Products with a 6 R Emphasis and OEM Responsibility for Greater Economic Returns** | | | | | | |
| 8.1 Establish a business case and support a culture in which end-of-life responsibility is accepted as a necessary product design/development function | | | | | | |
| 8.2 Working within the structure of 8.1, establish business processes, as part of a systems engineering methodology, to optimize end-of-life management following 6 R principles | | | | | | |
| 8.3 Work with the PLM and systems engineering communities to enhance the existing toolsets to support the requirments of 8.2. Emphasize knowledge-based decision support in development and implementation. | | | | | | |
| 8.4 Put in place management strategies to guide end-of use decisions and practices to disposition. | | | | | | |

### 1.3.9 Imperative 9: Flexible and Scalable Manufacturing Alternatives

**The Opportunity:**

Current developments in manufacturing present the opportunity to rethink basic concepts about manufacturing plants and equipment. Stand-alone manufacturing plants have become components of integrated supply networks. Manufacturing companies have become systems integrators. The next evolution envisions flexible and scalable systems that produce products at the most beneficial location, utilizing the best available resources, and applying best methods and equipment that offer dramatic cost, productivity, and sustainability advantages.

**Business Case:**

- Spare parts inventories and warehousing costs are slashed
- Alternative processes produce better products with reduced negative impacts
- Risk and quality issues related to supply networks are mitigated
- Transportation costs are reduced through point-of-use manufacturing
- Multi-purpose manufacturing equipment consolidates processes, reducing cost

**Gaps and Challenges:**

- The concepts are postulated – not proven – evidence must be presented
- Entrenched infrastructures and methods support continuation of the norm
- Building a reliable clientele for shared facilities may be difficult
- Alternative manufacturing processes and equipment are expensive, and the processes are often slow, relegating their use to high value custom products
- Standardization enabling operation from standard data packages is essential

| Timeline (Years from start) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Flexible and Scalable Manufacturing Alternatives Including Localized Manufacturing and Multiuse Systems with Customized/Personalized Manufacturing for Improved Sustainability** | | | | | | |
| 9.1 Conduct a benchmarking study to evaluate and quantify the impacts of alternative business methodologies, equipment, and processes | | | | | | |
| 9.2 Apply existing visualization and analysis tools to support the optimized design and development of plants, equipment, processes and supply networks | | | | | | |
| 9.3 Pilot shared product development facilities, dedicated to highly efficient, flexible, and sustainable production - from single parts to first production | | | | | | |
| 9.4 Identify specific sustainable manufacturing targets of opportunity. Develop processes and equipment to satisfy specific product requirements | | | | | | |

### 1.3.10 Imperative 10: Sustainable Manufacturing Metrics

**The Opportunity:**

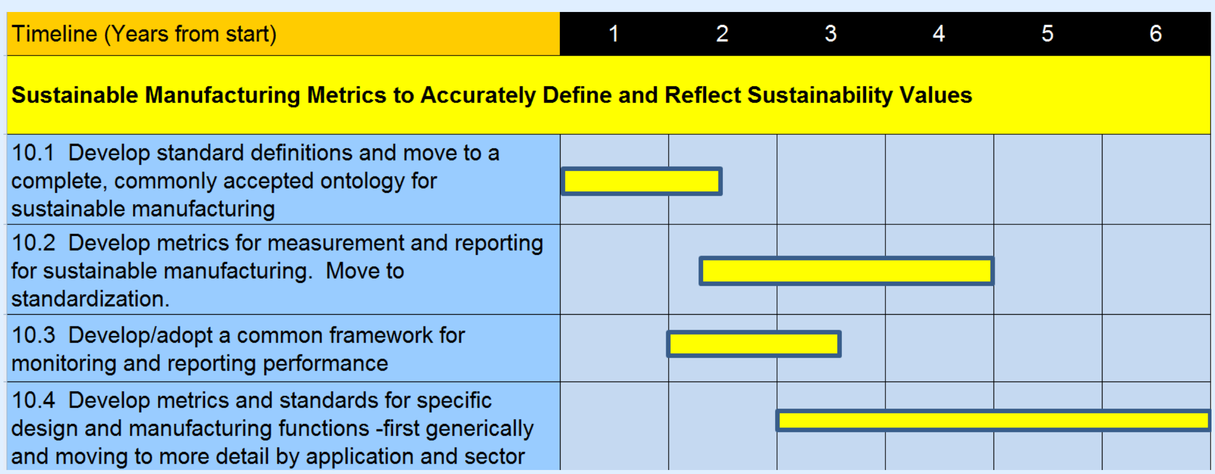
No standard method for measuring achievement of the triple bottom line currently exists. The provision of such a method would enable performance evaluation of strategies and companies. It would support goal setting and enable accurate determination of progress toward the goals. It would provide a measure of sustainability in products and processes across international boundaries and cultures. Standard metrics would support the determination of rewards and incentives that would lead to optimized lifecycle performance

**Business Case:**

- Improved and better informed purchasing decisions
- Definitive assessment of competitive position and need areas
- Improved contracting methods, including incentives
- More confidence in purchasing
- Enhanced brand value

**Gaps and Challenges:**

- Much of the work on standardization in sustainability has been led by/done in Europe (e.g. the Global Reporting Initiative). Using this work as a baseline, U.S. cultural and business practice differences need to be addressed
- There is limited international consensus for sustainable manufacturing metrics (present focus is on the broader qualitative view of sustainability)
- Securing effective industry engagement in such activities is difficult



### 1.3.11 Imperative 11: Information - to Knowledge – to Intelligent Sustainable Manufacturing

**The Opportunity:**

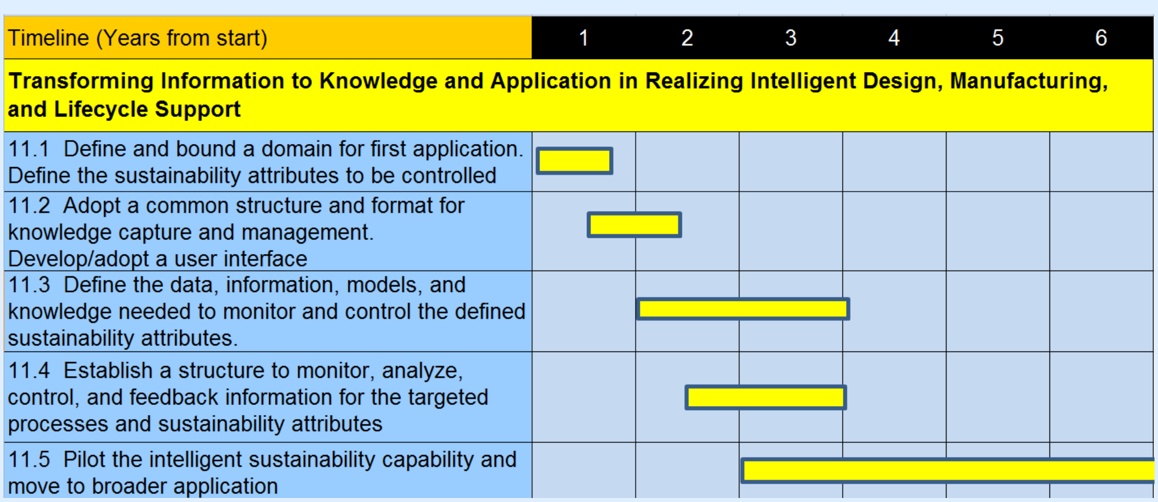
Smart or intelligent manufacturing is an opportunity to integrate data, information and analytical tools with **knowledge** to assure that the best decisions are made and that manufacturing processes are correctly executed. In an intelligent environment, products and processes designs are optimized and processes are monitored and controlled for 100% compliance within acceptable operating envelopes, yielding product quality assurance in real time. Further, the lifecycle performance of the product can be monitored and managed for best total value. Sustainable manufacturing provides an ideal basis for developing intelligent modules and piloting intelligent design and manufacturing.

**Business Case:**

- Slashes the cost associated with product, process, and equipment failure
- Protects against unintended consequences and mitigates risk
- Eliminates wasteful and inefficient operations
- Assures reliable operation and provides 100% assurance of quality product

**Gaps and Challenges:**

- Decision support requires a rich knowledge set, usually captured by domain
- Standardized methods for knowledge capture and application are lacking
- Intelligence across the product realization spectrum is required for complete intelligent design and manufacturing – a formidable task
- Fully characterizing and establishing intelligent control for complex equipment and processes is a challenging task
- Full achievement demands model-based development and control



### 1.3.12 Imperative 12: Secure Information Exchange and Collaboration

**The Opportunity:**

Cyber attacks cause harm globally every day, and the risk of US supply networks suffering catastrophic damage is significant. The threat of cyber intrusions impacts every aspect of the U.S. economy, including the nation's manufacturing infrastructure. While protection from attack is imperative, it is equally important that the supply network be able to confidently exchange needed information without fear and within acceptable risk boundaries. Providing an open, shared secure environment is the motivation for this imperative.

**Business Case:**

- The cost of lost proprietary data and information, intellectual property, and technical design data is estimated to exceed $300B annually
- Secure collaboration enables confident sharing of needed information across the supply network
- A risk of compromise, sabotage, or failure is unacceptable

**Gaps and Challenges:**

- Prevailing practice is for each organization to be responsible for its own information security, with little harmonization or standardization between firms
- Specific vendors are introducing collaboration management systems with proprietary practices and protocols, making common standards difficult
- There is a delicate balance in establishing a framework for open collaboration while assuring the security of the content
- Establishing agreement on shared/standard structures will be difficult

| Timeline (Years from start) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Secure Collaboration Platform to Assure That the Information That Is Critical to Enterprise Success Is Provided to All Who Have Need and Authorization and Denied to All Others** | | | | | | |
| 12.1 Capture best practices and develop design | | | | | | |
| 12.2 Develop and pilot a knowledge-based Secure Collaboration Platform (SCP) | | | | | | |
| 12.3 Establish need-to-know management strategies as an extension to the SCP | | | | | | |
| 12.4 Demonstrate the population and operation of the SCP for a specific program and application | | | | | | |

# 2 Sustainable Products

## 2.1 Functional Model and Definitions

**Sustainable Products** addresses all activities associating with conceiving, designing, and optimizing a product for lifecycle performance and is addressed in three sub-elements. Note that all definitions are in the context of sustainable manufacturing.

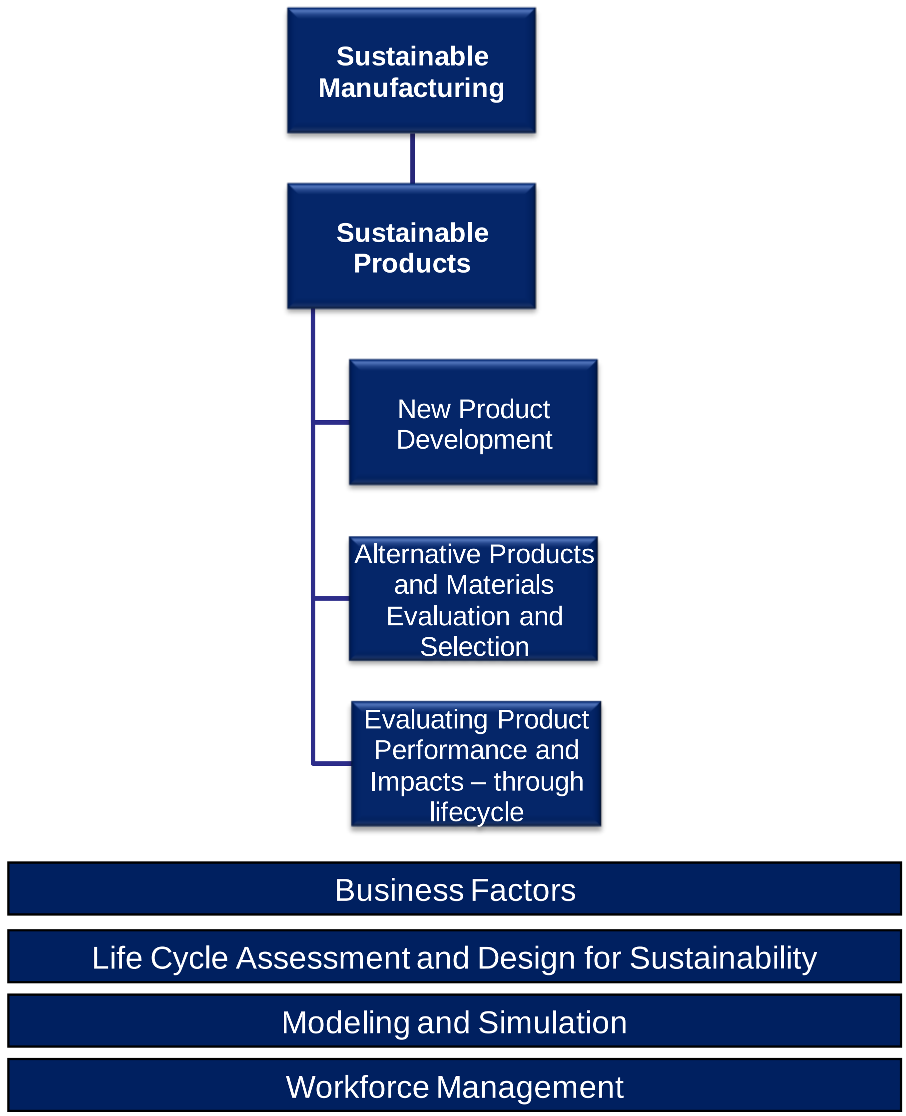



**Figure 2.1: The Functional Model for Sustainable Products includes three sub-elements and four crosscutting themes; the model addresses all aspects of product conceptualization, design, and lifecycle support.**

| | |
|---|---|
| **New Product Development** | Includes all activities associated with fully defining a new product. From ideation or requirements definition, to conceptualization, to capturing all requirements (full lifecycle planning) in a design package. |
| **Alternative Products and Materials Evaluation and Selection** | Addresses the requirements of and methods for the evaluation and selection of alternative feedstocks, materials, and product configurations including the evaluation of design alternatives and the selection processes for best alternatives. Design for process (designing products to optimize process options and efficiencies) is also included. |
| **Evaluating Product Performance and Impacts throughout the lifecycle** | Includes all activities associated with plans and actions to monitor and respond to the performance of products throughout their lifecycle |

**Crosscutting Enablers –** The crosscutting enablers are not specific to any of the three elements of the functional model, but are important to all of them. Each small group is asked to address the four crosscuts in the context of their functional element.

| | |
|---|---|
| **Business Factors** | Includes the factors that are required to sustain effective business operations, including but not limited to: lower cost, improved quality, more rapid development, compatibility with long-term enterprise strategic direction, and compliance with ethical and legal requirements. |
| **Life Cycle Assessment and Design for Sustainability** | Addresses the relationship of the specific element with Life Cycle Assessment, both in the concept of LCA and in the accepted practice and toolset for LCA (Note that in theory, Life Cycle Assessment is a full assessment of all impacts associated with a product. In practice, it may fall short of informing better decisions). Includes the requirements that design for sustainability places on the specific functional element |
| **Modeling and Simulation** | Addresses the modeling and simulation interfaces and needs related to product sustainability |
| **Workforce Management** | Includes all issues that support a sustainable manufacturing knowledgeable and enabled workforce. |

## 2.2 Current state

### 2.2.1 New Product Development

Products are getting better and better and they work well longer. The development cycles are shorter. The trend is to more emphasis on a continuous string of new products to the market, often at the expense of a longer term lifecycle strategy.

Improvement is obvious and fast. Even in a short window of 5 to 10 years, there is dramatic improvement in the new products being developed and in the process by which they are developed.

Companies are including sustainability in their product development and marketing strategies. Many major corporations now have sustainability organizations who participate in product conceptualization and development.

The trend is clearly toward higher performance with shorter development cycles. Consumer electronics, automotive, and energy solutions sectors provide great examples of the current direction. Cell phones and computers are barely broken in before they are no longer current. Both the quality and the product development time for automobiles have undergone a revolution. Even the longer lead time, higher risk sectors like aerospace and defense have seen revolutionary improvement in new product development. The full exploration of the improvement and the trends are beyond the scope of this document.

While great progress is being made, there is much room for improvement. The following paragraphs briefly highlight some of the target areas identified in the workshop.

The expected, or desired, life of the product drives the product development mindset. It is a business focused world, and the goal is to sell new products. Often this goal is in conflict with a longer view of a sustainable product with consideration of secondary markets and lifecycle optimization. For example, even though there are efforts at promoting reuse and recycle, most of us have a drawer full of cell phones or a stack of outdated computers. The concept of a continuous flow of products with iterative improvement that drives demand is a successful business strategy. However, the sustainability challenges that this business strategy presents are not being well met.

Iterative and risk averse introduction of new technologies is the norm. There is strong resistance to major, widespread technology upgrades both in new product development and in technology insertion for existing products. Hence, technologies are matured before introduction, and a strategy of iterative change is often followed. A new product offering is usually a minor progression from the previous offering, and the technology upgrades are limited in scope and number to respond to the risks. This conservative strategy is closely related to the fact that the product development toolset, which has achieved excellence in many ways, still needs improvement to minimize risk and support more aggressive technology insertion.

The product development toolset is deficient in its ability to assess total lifecycle impacts, and the tools that do support lifecycle analysis are often the domain of the experts and are not well understood by the IPTs that make the decisions. The simulation toolset lacks the ability to adequately support lifecycle performance evaluation. This deficiency means that expensive physical testing must be performed. This necessity is exacerbated by the fact that insufficient emphasis is placed on manufacturing process considerations in product development.

The provision of data packages for complex systems is often still in the form of 2-D drawings. In the aerospace and defense sector, the demand for the provision of complete technical data packages is driving an improvement in the inclusion of lifecycle issues and in the amount of knowledge provided to support lifecycle performance. The Defense Engineering Drawing and Modeling Working Group is providing a strong voice with industry and across all of government in developing standards for 3-D technical data packages.

To create change in product development and to accelerate lifecycle awareness, the culture must demand sustainability as a desired and demanded product attribute. In the perception of the sustainable products group at this workshop, corporations are perceived as more dedicated to product lifecycle responsibility and the public good than are consumers, and some surveys bear this out. Companies may be willing to embrace sustainable manufacturing, but the realities of the marketplace negate the possibility. Product sustainability could be improved if consumers were educated and culture evolved to accept and value refurbishment and reuse of products (such as biomedical equipment or electric vehicle batteries) and sustainable practices in new products. The rise of the millennials is gradually changing this balance and will have impact.

### 2.2.2 Alternative Products and Materials Evaluation and Selection

In the evaluation of alternative products and materials, the major issue is a lack of data, information and shared knowledge to support informed decisions. Analysis, including modeling and simulation and consistent characterization and interpretation of expected results, are keys to achieving an environment in which alternatives are compared and evaluated, impacts are assessed, and balanced, totally optimized decisions are achieved. Adding to this challenge is the complexity of LCA tools, which provide so many parameters and degrees of freedom that meaningful comparison of results between different assessments is problematic. Improvements in lifecycle analysis tools and standard methods for applying them would deliver improved selection of alternatives and better decision support.

The lack of a common understanding of alternatives and their impacts on all aspects to the product lifecyle is a key barrier. No common nomenclature or metrics set exists for evaluating product alternatives. This void is understandable due to competitive issues (both in manufactured products and in the technology toolset), but there should be more common ground for collaboration. Data repositories are available, and government programs (like the Defense Advanced Research Projects Agency (DARPA) Open Manufacturing Program) are placing great emphasis on shared data access. The NASA Materials and Processes Technical Information System (MAPTIS) provides a single-point source for materials properties for NASA and its associated contractors and organizations.[3] The automotive industry shares the International Materials Database System. These examples represent progress.

[3] http://maptis.nasa.gov/

Product evaluation improvements are needed. As discussed in the product development section, risk aversion limits aggressive changes in materials selection and is a forcing function for the status quo. In our litigious society, over-engineering is driven by public policy and risk assessment. Each company must make a strong investment in testing for reliability, durability, etc. Closing the gap between the virtual product development and physical testing and evaluation is critical for slashing product development costs, reducing the risk and increasing confidence – enabling more open selection of alternative products and materials.

There is a major push across transportation and energy related sectors to move to lightweight materials. In most cases, the emphasis is on lightweight metals and composites. The lightweighting priorities are opening new opportunities for alternative/new materials and for more sustainable options.

The selection of products and materials must include end-of-life considerations, which vary with industry sector and company. Perhaps the most notable example is the European automobile industry mandating materials that can and cannot be utilized and requiring manufacturer responsibility for end-of-life processing. Reprocessing facilities exist that are specifically engineered for sorting the automotive materials, in-process, providing targets for other sectors to emulate.

Diversity of materials creates barriers for end-of-life processing. There are issues beyond the ability to sort and separate material streams. Some materials, such as plastics and composites, cannot be effectively reused because some, perhaps minor, component would negate use or degrade performance in any secondary product, and even recycling is problematic. Composites are increasingly important in many products and sectors, and their recycle and reuse challenge remains to be addressed.

Cultural norms present barriers to improvement. The power of a single entrenched designer to dictate products and materials is lessened by the move to IPTs, but the tendency to use what has been used and do what has been done remains powerful. Education in the means of evaluation, better access to data, and improved decision processes for better alternatives are all needed across the design and manufacturing community.

### 2.2.3 Evaluating Product Performance and Impacts

The emphasis on product performance is closely tied to the application and the business strategies of particular companies and competition within the sectors. In some applications, product performance cannot be compromised. Recent well-publicized recalls in the automotive industry point to increasing emphasis on product safety and the elimination of the risk of failure. In the automotive sector, competition is causing a longer term commitment to the operational performance of vehicles. The aviation industry provides another excellent example of paramount focus on product performance and safety. At the other extreme, many products that lack a human safety factor are designed and produced for limited life performance.

While product performance in the first operational life is a key driver in product development, subsequent generations of use and end-of-life considerations tend to be ignored. The lack of a clear business case for - and limited understanding of - the importance of, including end-of-life planning in product development deters efforts to create appropriate priorities. The diversity of brands and the multiple generations of products add complexity and thwart unity in planning and in end-of-life processing.

The diversity of regulatory requirements in both domestic and international production hinders an equitable business assessment of economic, social, and environmental factors. After-market components and products are not as closely regulated, often resulting in impaired performance compared to the original equipment. Different nations and states have different regulatory policies. Some states like California drive product innovation by strict enforcement of regulatory statutes. The growth of consumer societies in some emerging countries creates pressure toward lessening the impact of regulatory diversity.

It is imperative to note that cyber security is a major product sustainability issue and the impact of failure can be disastrous. Product development must include protection of the product from tampering or counterfeiting, protection of the information with which the product is produced and supported, and, in many cases, protection in the use of the product. This concern is vital across many products and sectors. The pharmaceutical industry provides a vivid example of the security imperative.

### 2.2.4 Crosscuts

- **Business Factors**

The corporate emphasis on quarterly sales and profits may be incompatible with a broader analysis, including full lifecycle sustainability and the "triple bottom line" (financial, environmental, societal), but the analysis can be changed by consumer choices. Two out of three consumers believe that they can change how companies behave by their purchasing decisions but only just over 36% believe that they have a responsibility to purchase products that are good for the environment.[4] These facts must be balanced against the corporate realities of a very short corporate window with the average tenure of corporate CEO being 2.97 years,[5] and quarterly sales and profits reports that force short term decisions.

The trend is toward placing more value on sustainability. In a survey conducted in 2012, the number of responding corporations showing profit from sustainable practices went up from a 14% baseline established in 2011 to 37% – an increase of 23% in one year. In 2013, more than 50% of responding companies reported that they have changed their business models to support more emphasis on sustainability – a 20% jump over 2012.[6] Continued emphasis on consumer education

---

[4] BBMG, *" From Obligation to Desire: More than 2 Million Aspirational Consumers Mark Shift in Sustainable Consumption," 20013*

[5] Durakan, Banu, et al., "*CEO Turnover and Corporate Performance Relationship to Pre- and Post- IFRS Period," Journal of Business Economics and Management, Vol. 13, No 3, June 2012*

[6] MIT Sloan Management Review and The Boston Consulting Group, "The Innovation Bottom Line," Findings from the 2012 Sustainability and Innovation Global Executive Study and Research Report, Winter 2013.

to support product selection is important in shifting the sustainability profile of products developed and marketed.

- **Life Cycle Assessment and Design for Sustainability**

Lifecycle assessment methodologies and toolsets are important enablers for the sustainable manufacturing community. The present state of capability is not adequate to assure the consideration of sustainability issues in product development. The LCA process is time consuming and costly. There are many approaches and toolsets but limited standardization. Hence, it is not possible to compare results from multiple analyses or to properly draw conclusions from a specific analysis. The tools are focused on compliance and not, in the main, on decision support. Uncertainly is not properly considered. Hence, the results do not adequately support optimization in product development.

- **Modeling and Simulation**

There is broad agreement that a mature sustainability modeling and simulation toolset that integrates with the Product Lifecycle Management (PLM) system is critical for sustainable product development. PLM vendors are adding/have added sustainable manufacturing modules to their product lines, and the frameworks are impressive. The full and cost effective population of those systems with needed data, information, knowledge, and models that support broad applicability offers great potential benefit. The modeling systems that support sustainability analysis and would integrate with the PLM systems are often not sufficiently mature to provide effective decision support. Licenses for the existing and emerging M&S toolset are expensive. The utilization of modeling and simulation for sustainable product development is limited by the fact that the education system does not adequately support the learning of sustainable manufacturing and the inclusion of sustainability in product design and development courses.

- **Workforce**

Both the workforce and the knowledge base that should support the inclusion of sustainability attributes in product development are inadequate. Several factors contribute to this inadequacy. Product development instruction, including sustainability, is not adequately emphasized in the engineering curriculum. The “industrial commons” or shared knowledge on which such education and practice should be based has eroded. There is consensus among the Sustainable Products group that the strong emphasis being placed by the entire education system on computing skills and tools, although important, limits the depth and breadth of understanding of the graduates and the workforce. This lack of understanding of basic, practical principles inhibits the ability of the workforce to solve problems and to upgrade existing practices through innovation. A combination of technical and practical skills in all levels of workforce education, including “sustainability engineering” is needed across all industry sectors.

On the positive side, a growing portion of the emerging workforce (including the “millennials”) place more importance on sustainability issues and are more committed to a sustainable future.

## 2.3 Vision

### 2.3.1 New Product Development

In the future, new product development will be a virtual process from ideation to detailed product design and will include all of the information to drive all downstream applications. The highly analytical process will start with the needs, goals, and requirements of the customer and will move toward an optimized product design. Sustainable design and manufacturing attributes will be integral components of the optimization process. A better understanding of the defined needs and desires of the customer, coupled with the innovative exploration of "what is possible" will result in products that satisfy a balanced set of criteria, goals, and expectations. This development environment will be data rich, but not data inhibited, because the complexity of big data access and management will have been solved: the right data will support the analysis and decision process. The result will be the ability to evaluate alternatives and quantify the total lifecycle cost and performance – resulting in the best total value decisions. The clear value of sustainable products will drive better consumer acceptance and investment. The high visibility of sustainability factors, their influence on lifecycle value, the comparison with less sustainable alternatives, and the total cost differentials will influence consumer decisions toward sustainable selection.

A virtual development environment will support the visibility of product performance throughout the product lifecycle. In the design and development process, simulation systems will identify failure modes, uncertainties, and risks. Decision support systems will enable the selection of the best preventative action. These same virtual systems will follow the product through lifecycle operation supporting corrective action, potential secondary markets after product replacement, and end-of-life processing.

Product development will include lifecycle operation and end-of-life disposition. Design decisions will consider reliability engineering, including embedded sensors and control systems, modular design for ease of diagnosis and repair, redundancy, and other capabilities that assure reliable operation and "smart" interaction with other products in the use environment. The embedded systems will support performance monitoring during operation, and the monitored data will support knowledge extraction to enhance future products.

In the future, transportation costs will be a much smaller piece of the cost and environmental impact of many or most products. Immediate access to technical data, anywhere and at any time, data standards to enable universal languages and protocols, increased use of localized or regionalized supply chains, and technologies such as additive manufacturing (for example in after-market support products) will enable on-demand fulfillment of customer needs with products that are custom made and locally manufactured. The improved understanding and quantification of the full lifecycle cost and sustainability impact of a product will enable analysis and an optimized decision regarding global resource suppliers and logistics.

### 2.3.2 Alternative Products and Materials Evaluation and Selection

Product decisions will be made based on full access to and awareness of the attributes of the sub-products and materials that comprise the desired product. This decision process will be supported through shared access to data from the characterization of the alternative materials and will be conducted in a knowledge rich environment that is enabled by access to accurate plug-and-play modeling and simulation tools, allowing full evaluation and best decisions. Products and materials that do not support sustainability will be replaced by better alternatives. Documentation supporting all decisions will be available and will be archived as part of the product development process.

Low cost and plentiful natural gas will dominate the utilities industry in the short term, and new and improved systems and applications will make energy production and application more sustainable. Increasingly efficient solar applications will be available as low cost commodity products for low power, specific applications. There will also be increased availability and use of alternative fuels, especially highly efficient batteries that operate within safe envelopes, resulting in widespread replacement of petroleum-based fuels in specific products and processes.

Broad access to all needed data sources and modeling systems will enable full visibility of the available alternatives and their impact on lifecycle product performance and total product value. The risk of utilizing alternative materials will be mitigated by the full understanding of the tradeoffs and uncertainties. This understanding will lead to increased utilization of advanced materials like bio-based materials and shape memory alloys. The rigors of this improved understanding will be extended as far as is necessary into the supply base – including raw materials to subassemblies. The problem of product failure based on deficiencies in the constituent parts will be mitigated through this deep knowledge penetration. Higher performing materials will emerge that can meet the enhanced standards for safety and reliability.

### 2.3.3 Evaluating Product Performance and Impacts

Internationally accepted and uniformly applied standard metrics will be in place to accurately characterize the sustainability of products, and the impacts will be visible. This visibility will create widespread awareness of total sustainability and lifecycle issues for consumers to aid them in purchasing decisions.

Corporate certification and participation in sustainability optimization – well beyond energy – will be a necessary business strategy supporting a positive public image, improving working conditions, and mitigating the necessity of international regulatory enforcement. The sustainability metrics and indices will create growing consideration and support of remanufactured products and modular reuse from the second to the $n^{th}$ generation.

### 2.3.4 Crosscuts

- **Business Factors**

The ubiquitous visibility of all product attributes and their impact on cost and performance will enable corporations and consumers to properly value sustainable products. The resulting long-term view will support a total value assessment in making product decisions including societal, environmental, and economic impacts.

- **Life Cycle Assessment and Design for Sustainability**

Life Cycle Assessment systems will be fully integrated with design systems and will access all needed data and models to virtually evaluate the total value of the product, highlight deficiencies and points of failure, and support optimized decisions for best total product value. These LCA tools will be standardized, cheaper, and easier to use, making them available even to small companies. The accessibility of better data will allow correlation of sustainability factors to material characteristics and quicker characterization of new materials for lifecycle impact.

- **Modeling and Simulation**

Modeling and simulation systems will access a rich storehouse of materials data and performance knowledge to interactively evaluate various product attributes, alternatives, and uncertainties, supporting the virtual development of the most advantageous products. New material development and characterization will be done prior to, or concurrently with, product development and lifecycle analysis, to recognize potential problems earlier. This capability will support a trade-off environment against established product performance requirements and metrics, realizing a product optimized for total value over the lifecycle.

- **Workforce**

There will be a growing job market for people with an integrated engineering, business and sustainability skill-set. A strong, flexible, and available workforce will be well schooled in the importance of sustainability in design and manufacturing and will be equipped with the education and the toolsets to support the development and production of products that meet and exceed both requirements and expectations.

## 2.4 Solutions

### 2.4.1 New Product Development

#### *2.4.1.1 Modular Components for Multiple Applications:*

Embrace modular product development to provide the needed toolsets and methods to create components that support multiple applications and are optimized for best total value. Each module will possess well defined performance attributes and interfaces (both to users and other systems), and will include full lifecycle management plans.

#### *2.4.1.2 Product Development Platforms for Integrated Total Value Optimization:*

Provide product development platforms that balance affordability and performance factors with sustainability attributes for total lifecycle value optimization.

#### *2.4.1.3 Sustainability Standards for Procured Products:*

Develop industry accepted sustainability requirements and standards (both broadly shared and sector/domain specific) for procured products and systematically implement these standards in acquisition strategies across industry.

#### *2.4.1.4 Reduce end-of-life Impacts of Products:*

Develop methods and tools that include end-of-life optimization in the product design and development process, for example featuring the ability to dismantle and recycle components at the end of product life. Work with the technology supplier community, e.g., PLM vendors, to include/extend end-of-life management functionality in the product development toolset.

#### *2.4.1.5 OEM Responsibility for Total Product Lifecycle:*

Establish regulatory authority that places responsibility for end-of-life processing for some products (whether refurbishment, recycling or proper disposal) with the OEMs.

#### *2.4.1.6 Operational Data to Product Support Knowledge:*

Establish/extend product monitoring systems to support the collection of operational data from products in service and convert that data to knowledge that allows corrective actions in the field and impacts the product design and development process. Note that the capability to collect operational data for real-time product diagnostics and correction is prevalent today. The extension is the capture of knowledge that impacts systemic correction in existing products and design modifications in new products.

#### *2.4.1.7 Intelligent Product Adaptation for Optimized Response:*

Integrate intelligence into products to enable the collection and processing of data in real-time, and the adaptation of the product for the optimized response to the existing operational requirements. An obvious and active example is the adaptation of airplane wings to optimize fuel efficiency in flight. This same mindset should be extended to many products and applications.

#### *2.4.1.8 LCA Response to Operational Data:*

Upgrade the existing LCA models and capabilities to include response to operational data. Establish intelligent/knowledge applications that collect data from existing operations and processes and determine the proper adaptations of LCA models to improve the overall performance of the product.

#### *2.4.1.9 Visible Product Information for Consumers:*

Create product information and packaging that makes sustainability characteristics and alternative choices visible to consumers. This information should make it possible to compare the sustainability of different products and make appropriate purchasing choices.

#### *2.4.1.10 Visible Choices and Impacts for Sustainability for Product Development:*

Create a product development environment in which the parameters that respond to product requirements are visible and in which the response to alternative choices is also visible. This system should emphasize the value choices related to sustainability as equal drivers to other attributes.

#### *2.4.1.11 Multi-Use Flexible/Shared Machining/Processing Centers:*

Create multi-use flexible product fulfillment centers for identified classes of products (e.g. after-market support parts). Establish regional centers equipped with additive manufacturing and other appropriate technologies and feedstock materials to provide customers with customized, on-demand components and subsystems. These centers will provide low risk, high benefit products that are built according to a library of specifications, with appropriate intellectual property protection, and will be dedicated to showcasing sustainable manufacturing practices.

### 2.4.2 Alternative Products and Materials Evaluation and Selection

#### *2.4.2.1 Materials Advisory System for Product Performance Evaluation:*

Develop a materials advisory system that evaluates and quantifies the ability of products to meet performance as well as sustainability requirements when alternative materials are utilized. This system should be coupled with a modeling and simulation capability that evaluates the response of a product to the range of environmental, mechanical, chemical, and other factors. Lightweighting should be a major consideration in providing this solution.

#### *2.4.2.2 Foreseeing Unintended Consequences:*

Recognizing that many of negative impacts are the result of events that are not considered, develop a system that supports the creative exploration of obscure possibilities and unintended consequences. The system could be modeled after a potential problem analysis methodology and methodologies related to qualification of man-critical applications e.g. NASA, the aerospace industry, automotive, etc. It is envisioned that this system would pioneer methods to engage humans in exploration beyond their usual considerations.

#### *2.4.2.3 Sustainability Collaborative Organization/Consortium:*

Create an effective Sustainable Manufacturing collaborative organization that supports the development of a common understanding of the drivers, metrics, and solutions related to the evaluation, understanding, and selection of product alternatives.

#### *2.4.2.4 Cooperative Knowledge & Solutions:*

Create shared repositories that provide access to needed data and information and support the "industrial commons" – sharing of knowledge – across the sustainable manufacturing community. This capability could begin with benchmarking of existing and emerging systems such as Reach (chemicals aerospace), IMDS (automotive), ROHS (management of hazardous substances), and MAPTIS (NASA). The emerging Digital Manufacturing Commons activity of the Digital Manufacturing and Design Innovation Institute (DMDI) offers a potential opportunity for collaboration.

#### *2.4.2.5 Guidelines for Consistent LCA Tool Use:*

Develop guidelines and standards for the consistent use of Life Cycle Assessment Tools. Develop rules by product category for using LCA and extending its use to a more effective decision support framework, incorporating the triple bottom line of social, environmental, and financial responsibility in all products.

### 2.4.3 Evaluating Product Performance and Impacts

#### *2.4.3.1 Accessible LCA tools to enhance sustainability considerations:*

Integrate LCA tools and methods into the existing product development toolset (PLM) and specifically target low cost, ease of use, and applicability/availability for small and medium manufacturers. Work with the PLM vendor community and others to clearly define the requirements and to assist in developing the plan for solution. Success in this approach will depend on strong pull from the major corporation user base that has significant leverage with PLM vendors. This solution is similar to 2.4.1.4 and should be worked together.

*2.4.3.2 U.S. Adaptation of Existing Databases and Toolsets for Sustainability:*
Augment existing databases and toolsets being successfully used in Europe to better serve the U.S. manufacturing environment as well, with the addition of certain metrics, regulations, etc.

*2.4.3.3 Influencing the Consumer toward Sustainable Selections:*
Provide visibility of sustainability issues and ratings, including costs and impacts, to the consumer in an unbiased way to enable the consumer to make better informed purchasing decisions.

*2.4.3.4 Product Reuse:*
Develop an awareness and leadership in promoting the reuse of products in the $2^{nd}$ through $n^{th}$ generations. This activity could be combined with the collaborative efforts of 2.4.2.3.

### 2.4.4 Crosscuts

- **Business Factors**

*2.4.4.1 Sustainability Factors in Product Development:*
Incorporate sustainability requirements in the product development process. This is related to 2.4.1.2.

*2.4.4.2 Sustainability Requirements Flow to and from the Supply Network:*
Establish mechanisms to flow sustainable manufacturing requirements and solutions to and from the supply chain in establishing and maintaining the product supply network and ensure that these requirements are included in the business agreements and contracts. The desired result is the assurance that sustainability is appropriately addressed at every level in establishing the supply network and that the sustainability requirements are met during product production.

*2.4.4.3 Visible Sustainability Performance Indicators:*
Incorporate metrics and management strategies that value the sustainability emphasis in the supply network. Utilize these indicators for the evaluation of both the prime contractor and the members of the supply base. Leverage this value in business relationships. It should be noted that reporting and rating activities are underway e.g. Global Reporting Initiative (GRI).

*2.4.4.4 Establish Chief Sustainability Officer as a Corporate Norm:*
Create and widely adopt the position of Chief Sustainability Officer (CSO) as a standard corporate officer. The major role of the CSO will be to assure that sustainability issues are addressed and properly valued in business decisions.

#### *2.4.4.5 Explore and Pilot Localized Manufacturing:*

Explore alternative manufacturing methods; quantify the sustainability value and the business value of utilizing such alternatives. Localized manufacturing, point of use manufacturing, micro-factories, "skunk works" and other ideas should be explored. Pilot activities should be conducted with the impact quantified and widely reported.

#### *2.4.4.6 Expand Sustainability Accountability Across Supply Chain:*

Develop and incorporate standards and regulatory authority for sustainability compliance across all tiers of the supply network including, in some cases, OEM responsibility for product disposition at the end of its lifecycle. Establish the business case (based on product value and consumer preference) for voluntary compliance and seek to avoid an additional compliance burden placed on corporate America.

- **Life Cycle Assessment and Design for Sustainability**

#### *2.4.4.7 Next Generation LCA System:*

Building on existing methodologies and platforms, define the requirements for a next generation LCA system that offers a turnkey solution for LCA. The evolving system should be user friendly, computer enabled, and consistent for all applications (not identical but consistent in its structure and use), enabling the delivery of comparable and understandable results.

- **Modeling and Simulation**

#### *2.4.4.8 Define Needs and Requirements for Modeling and Simulation for Sustainability:*

Define the needs for modeling and simulation for product sustainability, document existing capabilities, and conduct a gap analysis to identify and prioritize voids. Include the capability to model risk, uncertainty, and unintended consequences in the requirements.

#### *2.4.4.9 Benchmarking Deep Exploration of Unintended Consequences and Risks:*

Conduct a study and produce a resulting document that addresses the state of practice, the emerging best practices and the potential for using advanced computing systems and knowledge discovery systems to explore the extreme edges of the possible impacts of new materials, processes, product attributes, and technologies, including unintended responses, uncertainties, and risks. The system should be capable of combining knowledge gained from past instances with scientific knowledge and behavioral science to define and rank possible outcomes and quantify the risk.

- **Workforce**

#### *2.4.4.10 National Awareness of Sustainability Education Imperatives:*

Create a national awareness campaign to make visible the need for the inclusion of sustainability education in the curricula of all institutes of higher education and across all educational disciplines – from engineering to workforce education. Extend this emphasis to K-12 education including Science, Technology, Engineering and Math (STEM). Follow the awareness campaign with the development of shared curriculum that addresses all levels.

##### *2.4.4.11 Virtual Environment for Product Development Knowledge Enhancement:*

Create a virtual environment for product development that guides the workforce through an evaluation process. The environment should support methods for accessing needed information and making decisions. The system should allow the user to make mistakes and should educate regarding correction.

##### *2.4.4.12 Knowledge Supply Chain Including Sustainability Readiness:*

Create a "knowledge supply chain" in which sustainability education is tied directly to defined needs and opportunities in the job market. Create partnerships (including internships) between educational entities and corporations to provide exactly the needed training for immediate job placement.

##### *2.4.4.13 Corporate Training in Sustainable Manufacturing:*

Develop a comprehensive training program that can be utilized by internal corporate training groups or offered externally as professional training across organizations. The training should emphasize a basic and applied knowledge of sustainability factors in product development, and should include the use of the emerging toolset for assurance of consideration of sustainability attributes.

## 2.5 Top Solutions for Sustainable Products

### 2.5.1 Reduce end-of-life impacts of products:

Develop methods and tools that include end-of-life optimization in the product design and development process, for example featuring the ability to dismantle and recycle components at the end of product life. Work with the technology supplier community e.g. PLM vendors, to include end-of-life management functionality in the product development toolset.

### 2.5.2 Multi-Use Flexible/Shared Machining/Processing centers:

Create multi-use flexible product fulfillment centers for identified classes of products (e.g. after-market support parts). Establish regional centers equipped with additive manufacturing and other appropriate technologies and feedstock materials to provide customers with customized, on-demand parts. These centers will provide low risk, high benefit products that are built according to a library of specifications, with appropriate intellectual property protection. Sustainability will be incorporated in the equipment design and in the operational procedures that support their utilization.

### 2.5.3 Cooperative Knowledge & Solutions:

Create shared repositories that provide access to needed data and information and support the "industrial commons" across the sustainable manufacturing community. This capability could begin with benchmarking of existing and emerging systems such as Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), International Material Data System (IMDS), Restriction of Hazardous

Substances Directive (ROHS), and Materials and Processes Technical Information System (MAPTIS).

#### 2.5.4 Guidelines for Consistent LCA Tool Use:

Develop guidelines and standards for the consistent use of Life Cycle Assessment (LCA) Tools. Develop rules by product category for using LCA and extending its use to a more effective decision support framework, incorporating the triple bottom line of social, environmental, and financial responsibility in all products.

#### 2.5.5 Accessible LCA tools to enhance sustainability considerations:

Integrate LCA tools and methods into the existing product development toolset (PLM) and specifically target low cost, ease of use, and applicability/availability for small and medium manufacturers. Work with the PLM vendor community and others to clearly define the requirements and to assist in developing the plan for solution.

#### 2.5.6 Explore and Pilot Localized Manufacturing:

Explore alternative manufacturing methods and quantify the triple bottom line value of utilizing such alternatives. Localized manufacturing, point of use manufacturing, microfactories, “skunk works” and other ideas should be explored. Pilot activities should be conducted with the impact quantified and widely reported.

#### 2.5.7 Sustainability Accountability across Supply Chain:

Develop and incorporate standards and regulatory authority for sustainability compliance across all tiers of the supply network including, in some cases, OEM responsibility for product disposition at the end of its lifecyle. Establish the business case and incentives, based on product value and consumer preference, for voluntary compliance and seek to avoid an additional imposed compliance burden placed on corporate America.

#### 2.5.8 Foreseeing Unintended Consequences:

Recognizing that many negative impacts are the result of events that were not considered, develop a system that supports the creative exploration of obscure and non-obvious possibilities as well as unintended consequences. The system could be modeled after a potential problem analysis methodology and the methodologies related to qualification of man-critical applications e.g. NASA, the aerospace industry, automotive, etc. It is envisioned that this system would pioneer new methods to engage humans in creative exploration beyond their usual considerations.

#### 2.5.9 National Awareness of Sustainability Education Imperatives:

Create and execute a national awareness campaign to make visible the need for the inclusion of sustainability education in the curricula of all institutes of higher education and across all educational disciplines – from engineering to all aspects of workforce education. Extend this emphasis to K-12 education, including STEM. Follow the awareness campaign with the development of shared curriculum that addresses all levels of the educational system.

### 2.5.10 Knowledge Supply Chain Including Sustainability Readiness:

Create a "knowledge supply chain" in which sustainability education is tied directly to defined needs and opportunities in the job market. Based on needs and opportunity assessments, create partnerships (including internships) between educational entities and corporations to provide precisely the training needed for immediate job placement.

### 2.5.11 OEM Responsibility for Total Product Life-Cycle:

Define critical national priorities and establish regulatory authority that places 6R responsibility for end-of-life processing for some products (whether refurbishment, recycling, proper disposal, etc.) with the OEMs.

## 2.6 Projects

The top ten solutions from each small group were presented to the large group for a vote to determine the project candidates. The project input was used extensively in producing the one-pagers and roadmaps for the Imperatives. The topics assigned to the products group included:

### AP1: Map and Quantify the Recovery and Recycling of High-Value and High Negative Impact Products

**Goal Statement:** Develop an understanding of the end-of-life characteristics of two products (High value, high control vs. High negative impact, low control) to influence future design choices, product architecture, and supply chain decisions

### AP2: Lifecycle Sustainability Impact of Sourcing Location Decisions

**Goal Statement:** Identify and understand the differences of the complete sustainability cost of local vs. wide sourcing network. Determine outliers from traditionally expected approach, why they are outliers and what they do differently.

### AP3: Training and Certification in Sustainability

**Goal Statement:** Design and sponsor a variety of educational offerings in sustainability (technical degree programs, online courses) to provide needed expertise in sustainability. Develop certification programs based on this training leading to job opportunities for low-skilled/entry-level workers.

# 3 Sustainable Processes

## 3.1 Functional Model and Definitions

**Sustainable Processes** includes all activities associated with the evaluation and selection of process alternatives and the execution of those processes. All definitions are in the context of sustainable manufacturing. The Functional Model for Sustainable Processes includes three sub-elements – Process Design, Plant Design and Operations, and Materials and Resource Management. Sustainable Processes also addresses four crosscutting themes which include Business Factors, Life Cycle Assessment and Design for Sustainability, Modeling and Simulation, and Workforce Management. The Functional Model for Sustainable Processes in presented in Figure 3.1.

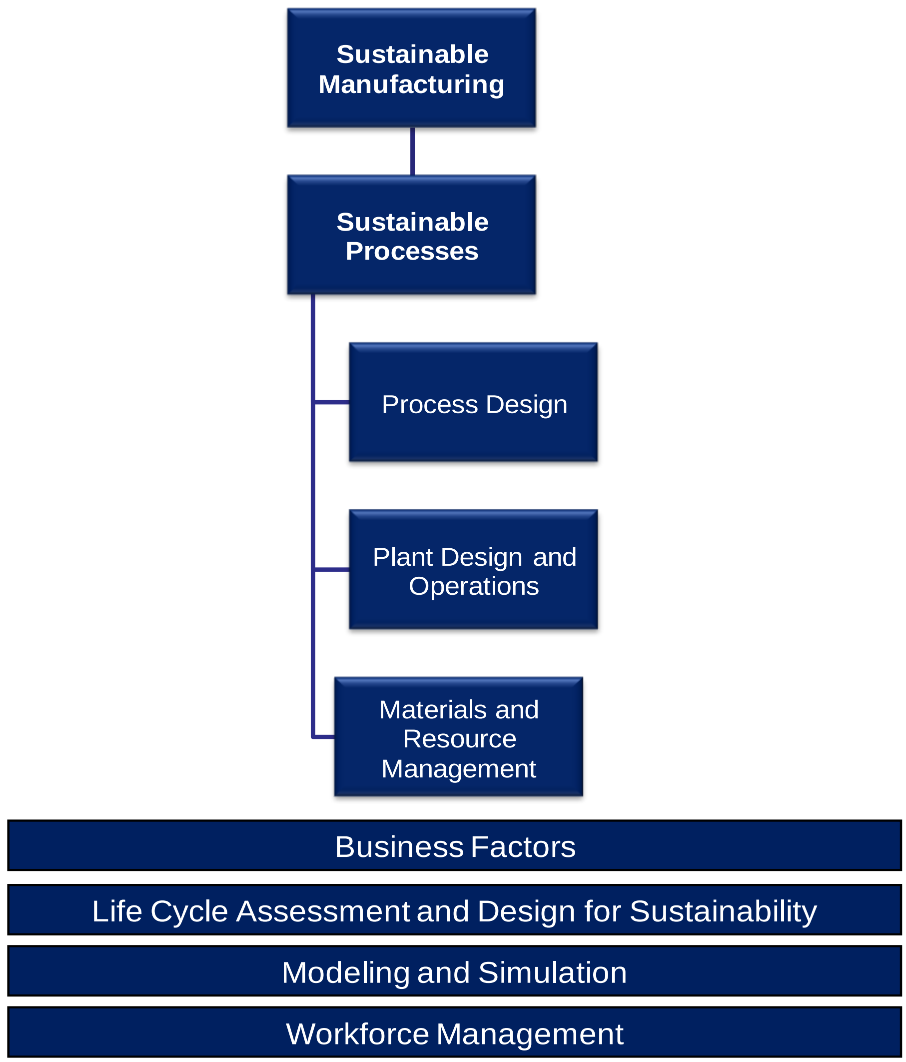



**Figure 3.1: The Functional Model for Sustainable Processes includes three sub-elements and addresses four crosscutting themes.**

**Process Design and Development** — Addresses all activities required to produce a process design, develop and mature the process technologies, and produce the needed plans and documentation to meet the requirements of the product and satisfy the necessity of sustainability from all standpoints including business and environmental issues.

**Plant Design and Operations** — Includes the design and operation of the processing infrastructure. Addresses all functions that must be executed to create and operate a physical facility in which processes are executed and products are produced. Includes the integration of process optimization in asset design and adaptation.

**Materials and Resource Management** — Addresses the management of all resources required to support process execution including the selection and management of primary (those directly used in transformative processes) and secondary materials (those that support processes). Also includes the management of all process waste.

**Crosscutting Enablers –** The crosscutting enablers are not specific to any of the three elements of the functional model, but are important to all of them. Each small group is asked to address the four crosscuts in the context of their functional element.

**Business Factors** — Includes the factors required to sustain effective business operations, including but not limited to: lower cost, improved quality, more rapid development, compatibility with long-term enterprise strategic direction, and compliance with ethical and legal requirements.

**Life Cycle Assessment and Design for Sustainability** — Addresses the relationship of the specific element with Life Cycle Assessment, both in the concept of LCA and in the accepted practice and toolset for LCA (Note that in theory, Life Cycle Assessment is a full assessment of all impacts associated with a product. In practice, it may fall short of informing better decisions). Includes the requirements that design for sustainability places on sustainable processes.

**Modeling and Simulation** — Addresses the modeling and simulation interfaces and needs for the sustainable processes.

**Workforce Management** — Includes all issues that support a knowledgeable and enabled sustainable manufacturing workforce.

## 3.2 Current State of Sustainable Processes

### 3.2.1 Process Development

Process design and development and product design are moving toward unity. Much progress has been made in integrating product and process development, but the same challenges that spawned concurrent engineering, systems engineering, and IPTs are not universally resolved. It is still generally felt that there is inadequate engagement of all stakeholders in the design process and that inadequate emphasis is placed on assuring sustainability. The knowledge available for product and process selection is inadequate to support the best process decisions. A major contributor to this problem is the fact that the requirements are often not well defined, leading to changes and design creep. In many cases, the product design requirements are seen as the one and only driver for process definition; proper knowledge of and appreciation for process requirements and capabilities is lacking. This lack of integration is often related to the lack of useful process knowledge. Current and updated process and equipment capabilities are often not available to, or used by, the product designers. The lack of a complete and stable product definition, the incompleteness of product data, and the lack of a clear linkage between product requirements and process selection limits the ability to create optimum process designs and to assure the inclusion of sustainability factors in the selection process.

Process selection and development should be an exploration of the alternatives that will best optimize total value. This mindset of open evaluation deviates from the norm. Cultural entrenchment, risk aversion, and other factors are strong influences that sometimes undermine a full evaluation of process alternatives. The opportunity for open exploration is becoming more compelling with the maturation of alternative processes - the most visible example being additive manufacturing. Additive manufacturing is not the answer for all products, but for some applications, it offers great advantages in cost, performance, and sustainability. For example, additive processes do not recognize geometric complexity as a barrier because of the full control of 3-D space: blind pockets and other challenging features are easily produced. It is important to note that additive is one example; there are other emerging processes that also offer great advantages in cost, performance, and sustainability.

Open alternative evaluation demands rich process characterization and knowledge capture (which includes access to data and information) to evaluate and quantify process alternatives and select the most advantageous ones. In the current state of practice, process selection is human dependent. However, emerging knowledge systems have demonstrated the ability to quantify the cost, risk, and performance of products from various processes, supporting improved decision making. Knowledge-based process optimization is a complex challenge because of the scope of the various options and the interaction of parameters, but early evidence points to success in well defined domains.

The development of processes for optimization of all factors, including sustainability, is limited by inadequate data access and a deficiency in the characterization of processes. There is an inseparable link between process optimization and full access to process data, models, and knowledge. All of these resources must be accessible, accurate, and in the correct formats to support tradeoffs and determine the best results. Shared repositories and licensed access databases can provide some of the needed data, but open access to the rich information that is needed is presently lacking. There are promising signs. For example, the Defense Advanced Research Projects Agency (DARPA) open manufacturing program seeks to establish shared repositories for materials and process data and process models.

### 3.2.2 Plant Design and Operations

In 2009, the DoD chartered a benchmarking study of American industry to evaluate the product realization process. Four major corporations were evaluated. One of the most striking findings was that, across the board, major emphasis is placed on "as-designed" and "as-built" with inadequate emphasis on "as-planned."[7] Much emphasis is placed on both the product and process design, but process planning, production planning and scheduling, and the operation of the processes receives less than adequate attention.

Plant design offers a great opportunity to maximize process sustainability. Design for flexibility, scalability, and reconfigurability are key opportunity areas. A few years ago, Proctor and Gamble built a new production facility in Utah. They modeled every aspect of the processes, the equipment, and the facility, and they operated the facility in virtual reality as part of the conceptualization and design process. Many challenges were addressed and optimization opportunities exploited. This is now the trend in plant design.

Reliability engineering is of the greatest challenge areas and greatest opportunities for improving overall operational performance, including sustainability. In current operations, the usual procedures include statistical process control (including both product and operational/equipment indicators), preventative maintenance, and repair before failure (and with minimum operational interruption). Backup and duplication is also used for critical operations. Reliability engineering and intelligent processing systems are an emerging trend. First, the equipment and processes are carefully engineered for optimum performance, including sustainable operation. Second, in an environment rich in sensors and control systems, the equipment and processes are honed for optimum performance. In parallel, a rich modeling environment is developed that matches the real-time optimal performance of the equipment; control limits and action triggers for deviations are built into the models, which then become the operational controllers. In more rudimentary applications, the indications may trigger annunciation to which humans respond. In the more advanced applications, intelligent control systems determine and command appropriate response. As these intelligent operations become the norm, it is important that sustainability factors such as energy, utilities, and waste streams be included in the control schemes.

### 3.2.3 Materials and Resource Management

The discussion of the current state for materials and resource management addresses three key issues: access to needed materials, the selection of materials, and the processing of waste materials.

---

[7] Integrated Manufacturing Technology Initiative (IMTI), Inc., "*Benchmarking New Technology Applications,*" *February 8, 2010*

**Material Access:** Access to needed materials and material replacement are major sustainability issues. The control of materials and their use have become global challenges. The Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) was put in place in 2007 by the European Commission to protect human health and the environment from the risks posed by the use of chemicals.[8] The Restriction of Hazardous Substances Directive (RoHS) restricts the use of certain hazardous materials[9] and promotes recycling and reuse. RoHS lists certain materials and calls for the replacement of those materials in manufactured products. RoHS is regularly refined and amended – a detailed discussion beyond the scope of this document.

These regulations are benchmarks in many ways. First, they represent a trend toward increased public control over the use of materials and protection of the environment. Second, while these regulations are specific to Europe, they apply to companies that do business in Europe and suppliers that support global products. Hence, their regulatory power is global. Thus, nations outside Europe have adopted similar regulations, and California has adopted a statute that essentially places that state under the RoHS restrictions.

Europe and Asia presents a highly visible, integrated approach to materials management and environmental regulations. The management strategies in the US tend to be spread across more regulatory authorities and managed by many statutes. The trend toward more aggressive regulatory enforcement is evidenced by the fact that the EPA created a watch list of environmental violators in 2004, which was maintained proprietary until 2011 at which time it was made public and is strong link in environmental enforcement.

Restrictions on material usage are certainly not limited to any country or region. Limitations on the use of chromium, galvanization, and lead offer striking examples of impactful regulatory actions. Lead-free solder -- including the catastrophe of tin whiskers - and the questionable dangers of limited use of lead in solder - offers a great case study in materials regulation and unexpected consequences.

Access to materials needed for manufacturing is a national concern – especially when the intentional disruption of supply is a foreign policy tool. The supply is volatile. We have become accustomed to fluctuations in the supply and cost of petroleum products and in the prices of gold and silver, but other materials have the potential to hit just as hard at the ability to produce and sustain products. The production of and access to rare earth materials is an outstanding example. The mining and processing of these materials has strong environmental and energy implications. Perhaps mostly by choice, the production is left to other countries – chiefly China – that consequently use access to the limited supplies as a bargaining tool. This topic is too deep to adequately explore in this document beyond noting that maintaining access is critical to the success of the nation's manufacturing sector.

---

[8] European Commission, Enterprise and Industry, http://ec.europa.eu/enterprise/sectors/chemicals/reach/index_en.htm

[9] European Commission, Enterprise and Industry, http://ec.europa.eu/environment/waste/rohs_eee/index_en.htm

**Material Selection:** The selection of materials is a huge opportunity for the sustainable manufacturing community to influence the direction of future manufacturing. In the current state, there are multiple pressures. Risk aversion and cultural norms tend to force the continued use of qualified materials for which the material/process interactions are well known. Other factors such as the necessity of lighter weight products and higher performance systems are forcing functions for the evaluation and selection of alternative materials. Some key examples are the use of composites, advanced high strength steel, and aluminum in automobiles and the increasing use of titanium and composites in aerospace. The dream of materials genomics for materials engineered to requirements sets the bar for success very high. However, the same research, perhaps short of a magic mathematical formula, may lead to an environment in which the interactions of materials and processes and the end result (predictable product performance) can be accurately modeled. The more immediate approach -- a rich modeling environment accessing big data to rapidly evaluate materials alternatives, called Integrated Computational Materials Engineering (ICME), is making inroads, not just in R&D, but in commercial applications. The American Lightweight Materials Manufacturing Innovation Institute in Michigan is focused on maturing and applying ICME.

Major current challenges in materials selection include access to data and the availability of models that accurately predict the interaction of material/process systems. As was noted for process design and development, the characterization of materials and processes also lacks a systematic approach, with results catalogued and access to them shared.

The complexity and cost of process qualification, especially in applications that involve human safety, e.g. automobiles, aerospace, etc., limits the exploration and adoption of new material systems. The government and the industrial communities are working on more rigorous methodologies and the use of modeling and simulation systems for rapid qualification, and the early results are encouraging.

**Reuse and Recycle:** The management of materials and products for reuse and recycle seeks equilibrium, based on business value. The pulp and paper industry offers an interesting example. Trees are a renewable resource, and forests were planted based on predicted demand. That prediction exceeded the actual need, so harvesting of timber across the nation is lagging the models by about 5 years. The business case for recycling paper can't be made on the availability of trees, but it is made on energy utilization with 40% less energy required to process recycled paper. Other materials have sought their balance. For example, the U.S. recycling rate for aluminum cans exceeds 55% over the last couple of years.[10]

The European Union's End-of-Life Vehicles (ELV) Directive, a strong benchmark for the more aggressive reuse and recycling mandates, seeks to reduce pollution and increase the percentage of material recycled. In so doing, certain important materials are forbidden. Japan and South Korea have also implemented end-of-life laws.

---

[10] Keep America Beautiful, "Recycling Facts and Stats,", http://www.kab.org/site/PageServer?pagename=recycling_facts_and_stats

One of the most innovative concepts for reuse is industrial symbiosis. By establishing and managing waste streams from one process as raw material for another process or processes, a symbiotic chain can be created. There are examples of effective symbiotic industrial parks in operation.

### 3.2.4 Crosscuts

➢ **Business Factors**

The biggest barrier to a definitive business case for sustainable processes is the difficulty of establishing cost baselines for comparison. To compare alternatives and select the best requires an accurate evaluation of the cost of meeting product requirements with each alternative process. This capability must also be available for attributes of the processes. Most of the cost models that evaluate process costs either operate by historical comparison or by parametric/predictive costing. Historical systems are limited to similar data for comparison; parametric systems demand broad availability of data, information, and knowledge to feed the models and algorithms. As a result, costing systems are expensive and are developed for applicability within a narrow domain. The ability to start with a tabulation of product requirements and then create accurate cost estimates for a broad range of applicable processes – including both initial costs and total lifecycle value is, in the main, a challenge yet to be met but worth pursuing..

The cost of process qualification and requalification is a key business factor. In aviation, medical, automotive components, consumer products, electrical systems . . . human safety factors dictate that caution and risk aversion dominate the change process. The result: the barrier for alternative materials and processes, and for market entry, is very high.

➢ **Life Cycle Assessment and Design for Sustainability**

LCA is chiefly a product focused analysis. There is a strong need for a Life Cycle Assessment of the product-to-process, process-to-process, and materials-to-process interactions and impacts. A holistic picture that includes these interactions would enable better decisions regarding total costs, environmental impacts, and societal impact.

While process evaluation in LCA is desirable, the pathway to such inclusion is limited by the lack of access to needed data (a recurring theme in this current state assessment). In some cases, LCA now mandates the collection of data not needed for the design and manufacturing process. The business value and wisdom of investment in this collection is questionable. However, data needed for process understanding and optimization and also required for LCA represents a useful investment.

➢ **Modeling and Simulation**

Product modeling and the development of PLM systems has matured relatively rapidly to a rich and capable toolset (yet still needing improvement). On the other hand, process modeling has lacked clear targets and a shared focus and seems to fall short in delivering an available general toolset that can be adapted to specific applications. Although models proliferate, it's often the case that the models we have are not what we need, and the models we need are not available. Existing models tend to be very specific and lack value beyond a narrow domain, or are overly general, lacking the capability to be customized for specific applications or the specificity needed to deliver real value. A critical void exists in the ability to create models by process family with well defined inputs, transfer functions, and outputs adaptable, at the needed fidelity, for specific data sets and applications. There have been and are several activities that seek to create shared model repositories. These efforts are important in moving to open access to needed capabilities.

Much emphasis in modeling and simulation of the processing environment is placed on discrete event simulation. The opportunity to embrace knowledge capture in modeling as a way to improve operations and preserve knowledge and skills is seldom a focus.

- **Workforce**

Manufacturing engineering is highly risk aversive. This means hands-on experimentation and process development is limited by the rigors of process qualification so that innovation in sustainable solutions suffers. Some of the more progressive companies recognize the importance of stimulating innovation in sustainable processes and have implemented innovation stimulation and recognition programs. One example is 3M's Pollution Prevention Pays (3P) which has saved the company more than $ 1.4 B while preventing more than 3 billion pounds of pollutants. The employees who have participated in this program have completed over 8,100 projects.[11] The program includes product reformulation, process modification, equipment redesign, and recycling and reuse of waste materials.

## 3.3 Vision

### 3.3.1 Process Design and Development

In the future, a clear definition of product requirements and opportunities will drive a rich evaluation of processing options, including the quantitative evaluation of alternatives for best total lifecycle value. Sustainability attributes will be core to the assessment, and the impact of choices will be visible to the IPTs. The environment will be supported by a strong modeling and simulation capability and captured knowledge which will guide the evaluation process. All needed data will be available to assure that the evaluation is accurate and that uncertainties and risks have been included and mitigated.

### 3.3.2 Plant Design and Operations

In the future, the corporate culture will embrace optimum sustainability in plant operations and total lifecycle value as "business-as-usual." The plants will be designed first in a rich virtual world with optimization of process operation designed-in and a strong emphasis on realizing the most sustainable operations as an established measure of total business success.

The plant operations will be visible and will be supported by all needed data, information, and knowledge. Processes, systems, and facilities will use minimum amounts of energy and create minimum amounts of waste, with zero net impact as the norm. The full processing stream, both upstream and downstream, will be visible, and any deviations will be immediately known at the point of knowledge and action. The information flow will be filtered to provide the needed level of information to each node in the enterprise, avoiding data and information overload. The knowledge

[11] "3P - Pollution Prevention Pays" 3M, http://solutions.3m.com/wps/portal/3M/en_US/3M-Sustainability/Global/Environment/3P/

obtained from the operation will be continuously processed, and operational improvement will be made in real-time. The continuous feedback will enable continuous update of the rule base. Quality assurance will be a continuous process with data streams to product design, process design, process operations, and forward to next processing steps. For extremely tight tolerance products, the capability will be in place to evaluate each individual part while in-process and adapt process parameters for custom optimization.

### 3.3.3 Materials and Resource Management

The vision of integrated evaluation and optimization of materials and process interactions will be broadly realized. Based on requirements, the applicability of all materials for an application will be quantified and areas of possible risk will be highlighted. Materials/process interactions will be characterized based on scientific first principles, and the characterizations will be indexed in repositories for shared access. This foundational understanding will support a full analysis of operational results, including energy and environmental impacts and the impact of product attributes. The full business analysis, including cost, time, and impacts will be provided.

The materials, resources, wastes, and emissions will be continually visible, in-process. This visibility will support best management practices including minimal environmental footprint and net-zero waste release.

### 3.3.4 Crosscuts

- **Business Factors**

The analysis, design, and development systems for manufacturing processes will assign realistic and accepted values for all parameters, including sustainability factors and externalities. This includes the attributes that are difficult to monetize. For example, the value of the reduction of natural resources and the environmental impact of mining and extraction processes will be tabulated with product and process costs and included in material and process selection. This accurate valuation will enable realistic true cost projection and process optimization.

- **Life Cycle Assessment and Design for Sustainability**

LCA will be extended from product evaluation to include all materials, processes, and systems that are engaged across the enterprise in producing and managing a product throughout its lifecycle. All data, information, and knowledge that are required will be accessible, in useful form.

- **Modeling and Simulation**

Modeling and simulation activities will be focused and coordinated to provide classes of open-systems models, by sector and domain, that offer general process modeling functionality easily adaptable to specific applications and products. These models will support the evaluation and quantification of the relative value and tradeoffs of various process alternatives and will include sustainability factors.

A rich modeling environment, coupled with captured knowledge, will support the process planning, scheduling, and operations functions, enabling intelligent, model-based control of the production planning and operations environments.

➢ **Workforce**

Sustainability Engineering will be valued by society as a premium career path and as an integral component of all engineering disciplines. Further, all areas of educational and career paths will include sustainability in their curricula. This inclusion will embrace the broad view of the importance of sustainability from a business perspective – not just placing value on environmental responsibility and energy conservation. The combination of sustainability engineers, broadly knowledgeable graduates from other disciples, and specifically trained graduates from technology programs (from community colleges, trade schools, etc.) will provide a robust pipeline of talent ready to meet the needs of the American manufacturing enterprises with a full working knowledge of the importance of sustainability. The workplace, in all enterprises, will become a learning platform for both the learning and the practice of sustainable manufacturing.

## 3.4 Solutions

### 3.4.1 Process Design and Development

#### *3.4.1.1 Clear Definition, Scope, and Metrics for Sustainable Processes:*

Establish a framework for Sustainable Processes that enables the realization of a process evaluation and optimization system with a sustainability emphasis. Develop a pilot project that identifies two processes that crosscut industrial sectors and uses them to populate the framework. The framework should:

- Define process performance metrics
- Define the knowledge linkages (rules, algorithms, requirements) that tie process alternative to product requirements. This should include product performance requirements.
- Utilize standard data protocols for collecting, storing, and accessing data.

#### *3.4.1.2 Additive Materials and Processes Sustainability Data Access and Planning Modules:*

Maximize the advantages of additive processes by providing data and planning systems to optimize their sustainability. The timing is right to enhance the value from this capability by creating standard sustainability driven data and planning systems that address the optimized use of both materials and additive processes. The solutions should include expert advisory systems for:

- Process energy utilization
- Materials savings in consumption
- Waste reduction factors
- Best materials and additive techniques for key products and features

#### *3.4.1.3 Data, Information, and Knowledge Availability for Process Optimization:*

Create shared data repositories that comply with the protocols of 3.4.1.1 and enable the cataloging of process data, information and knowledge that supports optimization of individual processes and of integrated process streams with the inclusion of sustainability attributes. Selectively populate the repository by determining the information that will enable delivery of the highest business value.

#### *3.4.1.4 Characterization of Processes:*

Define and prioritize target domains and applications; create model-based characterizations of both traditional and emerging processes. Make these characterizations available through the shared repository of 3.4.1.2.

#### *3.4.1.5 Open Evaluation and Optimization of Process Alternatives:*

Develop interactive systems that support real-time evaluation of the ability of process alternatives, and of parameters for those alternatives, to satisfy the product requirements. Present the evaluation results in terms of costs, sustainability indices, risks of failure, and production time.

#### *3.4.1.6 Inclusion of Sustainability in PLM Toolset:*

Enhance the existing COTS PLM toolsets with the needed modules to include sustainability in product to process data, rules, and models. Provide process and operations planning with the capability to optimize process operation across multiple processes.

### 3.4.2 Plant Design and Operations

#### *3.4.2.1 Lifecycle Management of Equipment:*

Establish regulations, methods, and tools to support delivery of a lifecycle sustainability package with each new equipment purchase. The sustainability package should include:

- The operations modeling and simulation code for the machine and for specific materials and resources.
- Energy consumption data and control parameters for management of compliant operation
- A standard data package that includes equipment capabilities and sustainability factors
- End-of-life disposition instructions – including any OEM take-back programs
- Applicable governmental and industrial standards for sustainable operation

#### *3.4.2.2 Planning Tools that Embrace Sustainability at the Plant Level:*

Provide discrete event simulation tools for manufacturing processes that include sustainability factors in the simulations:

- The operations modeling and simulation code for the machine and for specific materials and resources
- Energy consumption data and control parameters for management of compliant operation
- A standard data package that includes the capabilities and sustainability factors
- End-of-life disposition instructions – including any OEM take-back programs
- Applicable federal and industrial standards for sustainable operation

#### *3.4.2.3 Virtual Plant Development:*

Apply existing visualization and analysis tools and develop additional tools as needed to support the virtual design and development of plant facilities, equipment, and processes.

Utilize these tools to create highly sustainable, flexible, scalable, reconfigurable processing facilities.

#### *3.4.2.4 Reliability Engineering:*

Mature and apply the concept of intelligent operations to critical equipment and processes. Provide an environment wherein all process and equipment interactions are modeled to the point that expected performance, acceptable envelopes, and action levels are defined. Instrument the processes and equipment to provide all needed inputs to accurately determine the state of operation. Integrate the sensing and control environment with the models to create intelligent operation wherein any deviation from expected performance is immediately detected and optimally addressed.

### 3.4.3 Materials and Resource Management

#### *3.4.3.1 Material and Resource Characterization for Process Planning:*

Establish information structures to provide materials requirements and characterization data that define the condition of the materials and all resource requirements to the process planning function.

#### *3.4.3.2 Materials Risk Advisory and Selection System:*

Provide a comprehensive, software-based risk advisory system that informs the user concerning materials-availability risk. The materials-availability risk advisory system will provide expert, knowledge-based assistance in performing a risk assessment prior to the selection of a constituent material used in an assembled product. Extend the capability of the tool to provide expert advice in alternative materials selection.

#### *3.4.3.3 Rapid Qualification of Material/Process Systems:*

Develop methodologies and toolsets that utilize validated modeling and simulation systems to expedite the qualification of materials and material/process systems.

#### *3.4.3.4 Design and Process Planning Data/Tools for Continued Life Decision Support:*

Establish sustainability driven process standards for each of the 6R pathways for $2^{nd}$ to nth use cycle.

- Defining and measuring material flow & processing parameters
- Materials/components valuation data for best economic and sustainability decisions – including cost and ROI prediction and valuation models
- Energy and other materials consumption optimization
- Waste reduction/creation considerations

#### *3.4.3.5 Establish Monitoring and Management Practices for Incoming & Outgoing Resources and Waste:*

Develop practices, protocols, and standards for monitoring and measuring both incoming & outgoing resources and waste. The result will be visibility of the flow of materials through the processing environment, including inside the factory and across the supply network where appropriate. This visibility will support minimization of impacts and visibility of deviations, and will supply data and knowledge for continued materials and resource optimization. These practices and standards should support operations at any level:

- Discrete processes (ability to isolate individual processes for analysis)
- Across all processing operations – end-to-end product processing
- Across the factory and extending to the supply network

### 3.4.4 Crosscuts

- **Business Factors**

#### *3.4.4.1 `Cost Baselines for Materials and Process Evaluation:*

Establish cost models that respond to product features and requirements and enable accurate evaluation and comparison of material and process alternatives.

#### *3.4.4.2 Cooperative Public/Private Partnership for Compliance Cost Reduction:*

Establish an industry-led, public/private partnership (possibly a consortium and thus possibly an obvious mission for PRISM) to inform policy decisions that will assure the protection of the environment while reducing the bureaucracy and associated costs of regulatory compliance. The partnership should include industry, regulatory bodies, and academia/subject matter experts.

- **Life Cycle Assessment and Design for Sustainability**

#### *3.4.4.3 Interactive Product/Process/Systems LCA capability:*

Develop an efficient, "lean" LCA framework/system that enables the full evaluation of the lifecycle performance and sustainability impact of products, processes, and systems. "Lean" is used to stress the need to base the value and operation of the system on a complete and balanced business assessment and also to stress that all complexity must directly support the efficient delivery of useful business information. The first step should be to establish the framework and communications protocols for open systems addition of modular functionality.

- **Modeling and Simulation**

#### *3.4.4.4 Inclusion of Model-Based Sustainability in Design and Manufacturing Toolsets:*

Working with the existing design and manufacturing technology providers e.g. PLM vendors, modeling and simulation companies, etc., develop priorities for extending sustainability analysis and optimization in the design and manufacturing toolset. This should be a collaborative effort in which compelling needs are defined, R&D is supported to develop the needed solutions, and partnerships are created to deploy the emerging solutions.

#### *3.4.4.5 Proactive Evaluation of Potential Sustainability Impacts:*

Establish a culture and methodology for proactive evaluation and response to potential, and often unanticipated, sustainability impacts. For example, the health implications of, and possible protection needed, for working with materials like beryllium, asbestos, and uranium were not fully understood until many people had already been impacted. Nanomaterials are now at the same threshold. Establish and support continuing analysis and detection of potential problems and create a channel for broad communication of concerns from workers and the community at large.

*3.4.4.6 Model- and Knowledge-Based Planning for Closed Loop Production Operations:* Develop model- and knowledge-based comprehensive planning and decision support systems that scale from a science-based analysis of material/process interactions to planning systems for plant facility design, production planning, process planning, operations planning, and financial/business planning. Move beyond discrete event simulation of individual processes to the ability to evaluate the total processing environment. Create systems that not only perform forward looking planning, but also collect operations data for feedback to the planning systems and models for a continuous learning environment. The end result will be an augmented/automated environment that evaluates alternatives and produces optimized plans.

- **Workforce**

*3.4.4.7 Joint Development of Academic and Industrial Sustainability Curricula:* Establish, as a function of PRISM, a working group composed of representatives from industry, government, and academia to create and manage a continuing needs assessment for academic curricula related to sustainability, for all levels of education. Include in the group's mission a mandate to range widely, from general education needs to specific needs of sectors and companies by establishing a "knowledge supply chain" for specific job skills. This program should target the elimination of all gaps that limit the ability of graduates to move directly into workplace assignment without remedial training.

## 3.5 Top Solutions for Sustainable Processes

### 3.5.1 Clear Definition, Scope, and Metrics for Sustainable Processes:

Establish a framework for Sustainable Processes that enables the realization of a process evaluation and optimization system with due consideration of sustainability issues. Develop a pilot project that identifies two processes that crosscut industrial sectors to populate the framework.

### 3.5.2 Additive Materials and Processes Sustainability Data Access and Planning Modules:

Maximize the advantages of additive processes by providing data and planning systems that optimize their sustainability. The timing is right to enhance this technology value by creating standard sustainability driven data and planning systems that address the best use of both the materials and the additive processes.

### 3.5.3 Inclusion of Sustainability in PLM Toolset:

Enhance the existing COTS PLM toolsets with the needed modules to achieve sustainability optimization in the definition/development of processes to meet product requirements. Provide process and operations planning capability to optimize process operation across multiple processes.

### 3.5.4 Lifecycle Management of Equipment:

Establish regulations, methods, and tools to support the delivery of a lifecycle sustainability package with each new equipment purchase. The sustainability package will include operational models, assistance in sustaining efficient operation, and end-of-life management.

### 3.5.5 Design and Process Planning Data/Tools for Continued Life Decision Support:

Establish sustainability driven process standards for each of the 6R pathways for the 2nd to $n^{th}$ use cycle and include these factors in an overall evaluation process. The standards should address material flow & processing parameters, materials/components valuation data for balanced total value prediction and valuation models, materials/resource consumption optimization, and waste reduction/creation/management considerations.

### 3.5.6 Establish Monitoring and Management Practices for Incoming & Outgoing Resources and Waste:

Develop practices, protocols, and standards for monitoring and measuring both incoming & outgoing resources and wastes. The result will be visibility of materials flow through the processing environment, including flows inside the factory and across the supply network where appropriate. This visibility will help efforts to minimize impacts and make deviations visible, and will supply data and knowledge for continued materials and resource optimization.

### 3.5.7 Cost Baselines for Materials and Process Evaluation:

Establish cost models that respond to product features and requirements and enable accurate evaluation and comparison of materials and process alternatives. The cost baselines should be built on a consistent structure (a consensus framework or architecture moving to standards) such that evaluations are comparable regardless of the application or the person performing the evaluation.

### 3.5.8 Interactive Product/Process/Systems LCA capability:

Develop an efficient, "lean" LCA framework/system that enables full evaluation of the lifecycle performance and sustainability impact of products, processes, and systems. "Lean" is used to stress the need to base the value and operation of the system primarily on a business assessment, not on satisfying requirements imposed from without. "Lean" also indicates that all data and complexity must directly support the efficient delivery of useful business information.

### 3.5.9 Cooperative Public/Private Partnership for Compliance Cost Reduction:

Establish an industry-led, public/private partnership (a likely mission for PRISM) to inform policy decisions that will assure the protection of the environment while reducing the bureaucracy and associated costs of regulatory compliance. The partnership should include industry, regulatory bodies, and subject matter experts.

### 3.5.10 Joint Development of Academic and Industrial Sustainability Curricula:

Establish a working group composed of representatives from industry, government, and academia to create and manage a continuing needs assessment for academic curricula related to sustainability for all levels of education. Include in the mission/scope of this group a mandate to range from meeting general education needs to meeting specific needs of sectors and companies by establishing a "knowledge supply chain" for specific job skills. This program should emphasize eliminating all gaps that hinder graduates from moving directly into workplace assignment, removing the necessity of remedial training.

## 3.6 Projects

The top ten solutions from each small group were presented to the large group for a vote to determine the project candidates. The small groups did foundational work on the projects which provided strong input for the one-page write-ups of the Imperatives. Further work is anticipated as we seek a comprehensive project slate for PRISM and for others to use. The topics assigned to the process group, and the goal statements they developed, included:

### BP1: Sustainable Manufacturing Curriculum

**Goal Statement:** Create a curriculum that will enable leadership, management, and workforce to conceive, develop, and implement sustainable manufacturing practices. Include both general sustainable manufacturing and sector-specific foci.

### BP2: Public-Private Partnership for Sustainable Manufacturing

**Goal Statement:** Establish a public-private partnership to inform policy decisions about the benefits of sustainable manufacturing practices.

- Focus on data-driven sustainable manufacturing science.
- Cultivate a long-term, regional Technopolis focused on providing industry with sustainable manufacturing talent and tools.

### BP3: Sustainability Footprint for Manufacturing Machines and Equipment

**Goal Statement:** To create and implement a methodology/program through which machines and equipment come with standard data package that includes capabilities, materials, consumables and sustainability factors based on Federal and industrial standards.

### BP4: Sustainability Practices for 6R Process Planning

**Goal Statement:** Establish sustainability driven process practices for each of the 6R pathways.

# 4 Sustainable Systems

## 4.1 Functional Model and Definitions

**Sustainable Systems** focuses on all activities required to address sustainability holistically. These include using a systems mindset in addressing sustainable manufacturing across the enterprise with the objective of assuring total efficiency enterprise-wide. All factors involved in end-to-end product development and disposition are considered.

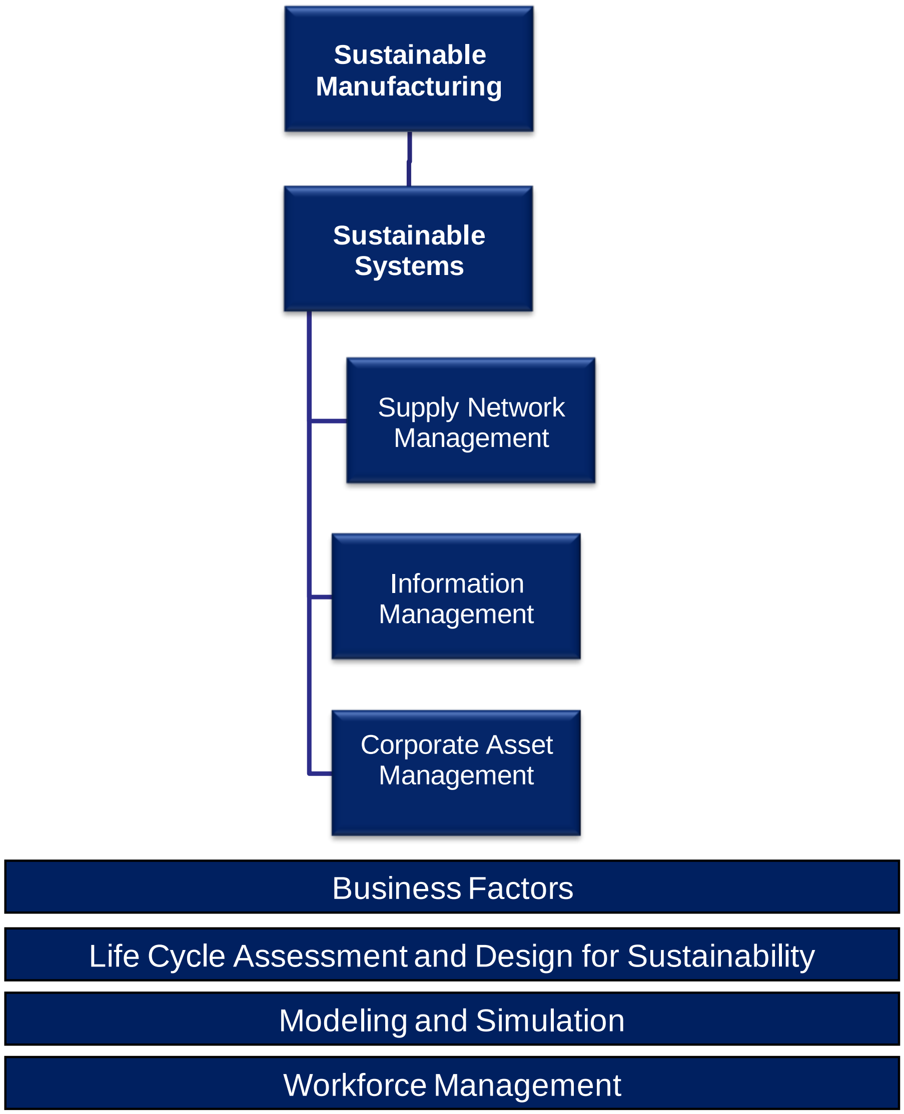



Figure 4.1 The Functional Model provides the guide and structure for the Sustainable Systems chapter of the Sustainable Manufacturing Technology Roadmap.

| | | |
|---|---|---|
| **Supply Network Management** | ➡ | Includes all activities involved in assuring that the sustainable manufacturing requirements, goals, and strategies important to the total value package of the product and the enterprise are consistently pursued by every member of the value chain. |
| **Information Management** | ➡ | Includes all activities associated with assuring the information that enables, assures, and verifies sustainable manufacturing practice within the context of enterprise mission is provided at the right place, at the right time, and in the correct format |
| **Corporate Asset Management** | ➡ | Addresses the inclusion of sustainable manufacturing considerations in the management of corporate assets. This includes the management of all corporate assets, including physical and human assets. |

**Crosscutting Enablers –** The crosscutting enablers are not specific to any of the three elements of the functional model, but are important to all of them. Each small group is asked to address the four crosscuts in the context of their functional element.

| | | |
|---|---|---|
| **Business Factors** | ➡ | Includes the factors required to sustain effective business operations, including but not limited to lower cost, improved quality, more rapid development, and compatibility with long-term enterprise strategic direction, compliance with ethical and legal requirements. |
| **Life Cycle Assessment and Design for Sustainability** | ➡ | Addresses the relationship of the specific element with Life Cycle Assessment, both in the theory and in the accepted practice and toolset for LCA. Note that in theory, Life Cycle Assessment is a full assessment of all impacts associated with a product. In practice, it may fall short of informing better decisions. Includes all systems requirements that result from a commitment to design for sustainability. |
| **Modeling and Simulation** | ➡ | Addresses the modeling and simulation interfaces and needs for sustainable systems. |
| **Workforce Management** | ➡ | Includes all issues that support a knowledgeable and enabled sustainable manufacturing workforce. |

## 4.2 Current State

### 4.2.1 Supply Network

There are two basic philosophical extremes in supply management. The one most detrimental for sustainable manufacturing emphasizes cost as the only compelling metric. Companies that follow this philosophy usually lack a strategic view of supply management; they seek to drive down cost in the supply network without considering any other factors important. The other philosophy -- one that has gained much traction over the last decade -- addresses the supply network from a systems approach and thereby places balanced value on all factors that impact corporate sustainability including cost, performance, quality, long term relationships, stability, energy efficiency, environmental responsibility, and others. Such companies are likely to strategically manage a network of valued partners, treating them as key stakeholders in the common goal: success of the product. They invest in management of the supply network, often having monitoring and evaluation systems in place and assisting suppliers that encounter problems. These companies are also most likely to manage their supply network according to the triple bottom line. This strategic approach to supply management does not deny that costs are often the most important metric. Rather, it offers a more inclusive view of cost, going beyond the immediate cost per unit.

Illustrative examples are not hard to find. In managing damaged vehicles, insurance companies place great value on speed and "disengagement." Hence, their single objective in managing a damaged vehicle is to sell it fast to minimize costs, with little regard for what happens to the vehicle afterwards. The scale of the food supply is a different example. It is very hard for small farms to compete with mega-farms on cost. However, an emerging trend is placing value on good will and consumer confidence by valuing what the consumers value: freshness, known sources, organic choices. . . More and more relatively large food chains are building and highlighting relationships with local small producers as a marketing strategy. These rather generic examples illustrate the point that can also be well illuminated by specific examples in large scale manufacturing. The U.S. automobile makers in the 1990's adopted a philosophy of driving down component costs at the expense of the supply base – often ruthlessly so. More enlightened companies took a different approach, one which eventually became pervasive across the industry.

Risk, uncertainty, and unintended consequences are major issues in supply network management. The complexity and the degree of engagement of the supply network impacts risks and confidence. The Boeing experience is an apt case study. Boeing is certainly a leader in supply management, having gone from tens of thousands of suppliers to a much smaller group of qualified partners who are mutually invested in success. In the 777 development, Boeing successfully pioneered an all digital design, distributed across the supply network. For the 787, in order to build and sell a global airplane, they engaged the suppliers in the conceptual design phase and gave both design and production responsibility to the various partners and stakeholders (with oversight and engagement in place). The risks were amplified by this partnering strategy. The assignment of mission, and the acceptance of risk in such assignment, is a complex issue without easy answers. In the 787 case, hindsight would indicate that the risks of great responsibility given to suppliers created problems that could have been avoided by tighter control of the requirements management and design functions.

Uncertainty and unintended consequences go hand in hand at all levels of the supply network, and these factors are most often not adequately addressed. When the operational parameters approach the edges of the safe operating envelope, unintended consequences become more likely.

Scaling is an area of concern in manufacturing processes; scale up or down is often not linear, and problems with scale-up often impact supply networks. While a process may work well in the laboratory or at testbed scale, it may present problems at production scale or it may not flawlessly transfer across organizations. Creating both models and physical environments that can test the robustness of systems at full scale is an important area for future investment.

Secure collaborative information sharing across all levels of the supply chain is a national imperative. For supply networks to be effective, rich information must be transferred and products and materials must be exchanged to every tier and with every supply partner without danger of loss or modification, either through accident or malicious act. Within the U.S., the value of the loss of proprietary data and information, intellectual property, and technical design data to enemies and adversaries is estimated to exceed $300 B annually.[12] Effectively addressing this issue is a national imperative. On February 12, 2013, President Obama signed Executive Order 13636, “Improving Critical Infrastructure Cybersecurity,” which calls for a national public/private Cybersecurity Framework. NIST is leading the development of this framework. However, as important as the framework is, it only provides the foundation for solution – leaving the creation of the actual solutions yet to be accomplished. A number of companies including Amazon, Google, and others are developing and providing secure collaboration systems. PLM vendors offer secure collaboration toolsets. However, these solutions inhabit proprietary structures and require proprietary protocols. An open framework for embracing best practices in a neutral environment, specifically focused on supply chain secure collaboration, is in order. GE is partnered with the Digital Manufacturing and Design Innovation Institute to create an open systems deployment for its members. Called the Digital Manufacturing Commons, this project has potential as a pilot for secure collaboration.

Traceability and visibility throughout the supply network is essential to the management of costs, performance and sustainability. Often the top tiers of the supply network actively engage with the systems integrators, but visibility and engagement drop off in the lower tiers. Yet lower tier suppliers often struggle with quality performance and financial stability and are most impacted by changes. Issues such as performance to requirements, cost management, environmental compliance and material management should be addressed at all levels of the supply network.

Regulatory requirements and their management is a supply management challenge. A striking example of business impact is found in the following:

*“In 2001, Sony exports of PlayStation consoles to Europe were blocked because the product’s cables contained unacceptable levels of cadmium. Replacing the cables led to delays over the Christmas sales season and cost the company more than $130 million in sales. It also forced Sony to conduct an extensive review of its supply chain and create a new system for managing suppliers.”*[13]

---

[12] The Commission on the Theft of American Intellectual Property by the National Bureau of Asian Research, 2013.

[13] Daniel C. Esty , “*Riding the Green Wave,”* The Washington Post.

The materials that comprise a product, or are used in manufacturing a product, should be visible at all levels of the supply network. Proprietary materials or formulations that may be embedded in the supply network cloud this visibility. There are differences in regulatory requirements at both the international and state levels that also come into play. For example, Genetically Modified Organisms are more highly regulated in Europe than in the U.S.

### 4.2.2 Information Management

A major challenge in information management is interoperable exchange of information. Getting the right information, in the right format, to the right place without loss of fidelity or cost of translation is an entrenched obstacle. The exchange of product data through CAD/PLM systems and the hundreds of millions of dollars invested in neutral translators is the most visible example. However, the challenge is broader and deeper than just product data management. Modeling and simulation systems are not compatible in their formats, so models can't be effectively linked. Because of variances in systems and in their application, it is difficult to impossible to compare LCA data, even within companies. Current practices that address interoperability issues involve translation and corporate selection of single vendor products. In supply networks, the imposition of selected systems and conventions by multiple primes is a large burden for the small and medium enterprises that make up the supply network.

Providing the information needed to manage a product throughout its lifecycle is a major challenge. For the consumer, the internet and search engines have created a revolution over just the last few years. For many products, a simple online search will reveal detailed schematics, troubleshooting instructions, immediate access to replacement parts, and even repair videos. The solution is not that simple for complex, special purpose products, both in the private and government sectors.

The Department of Defense faces a great challenge in system sustainment, and is being proactive in addressing it. There is a long standing debate between the government and the supply base about who owns the technical data for government procured product. The result has been that the government has gone to great expense to create and manage data to support system sustainment. Recently, the DoD convened the DoD Engineering Drawing and Modeling Working Group (DEDMWG) and charged them with updating the standards and related documentation to make complete technical data available for all forward procurements. That work is progressing nicely and it provides a good model to consider regarding the right of the purchaser, including the forward looking supply network, for access to information that supports the components and subsystems that comprise an assembly.

As was discussed in 4.2.1, cyber security is a huge information technology challenge. Protection against hacking from the outside and accidental or malicious acts by insiders is essential for corporate business success and is a major component in a sustainability strategy. The move to cloud-based computing brings both opportunities and concerns. The ability to move information around on multiple servers is seen as a method for making it virtually impossible to locate and compromise data, but the complexity of cloud operations, the detachment from the sphere of corporate control, and the fact that the human factor is still engaged introduces new concerns and risks.

Information overload is a challenge for Sustainable Systems. The ability to collect or access huge amounts of information makes the challenge of processing that data much larger. For example, Integrated Computational Materials Engineering (ICME) models can take hours to run, even with high performance computing. "Big Data" methods are being developed to expedite these applications and to assist in the extraction of the needed data, information, and knowledge.

Effective, sustainable operation demands that the right data, information, and knowledge be placed in the hands of the user, in the form in which it is useful. Filtering from the mass of data and information to get exactly what is needed is the first challenge. The second challenge is converting that data and information to knowledge that supports action – and capturing knowledge to support future decisions.

Keeping current is difficult. Hardware and software is being upgraded at an unprecedented rate. Maintenance of compatibility and preserving critical operations is problematic.

Information management for sustainability requires the ability to collect and report performance information. Such reporting is of value for assured compliance, but it also offers a great opportunity for corporations to make sustainability more visible and support continuous improvement. The visibility is important in gaining consumer confidence, attracting investments, and securing and maintaining needed staff. Systems are emerging that allow companies to report and measure their sustainability performance against established metrics. The Global Reporting Initiative is an international organization dedicated to promoting sustainability reporting. The Dow Jones Sustainability Indices showcases companies that are evaluated to be best-in-class and documents their sustainability performance. The companies that are indexed are viewed as more attractive to investors. The Index of Sustainable Economic Welfare (ISEW) is proposed to replace Gross Domestic Product as an indicator of the welfare of a nation. The ISEW considers many factors, with a strong emphasis on quality of life and sustainability issues, to measure the wellbeing of the people.

### 4.2.3 Corporate Asset Management

The topics related to corporate asset management are numerous, and space does not allow a detailed description. A short introduction to the factors comprising the current state is included.

In most cases, the emphasis in asset management is on sub-optimization of the different types of assets for specific circumstances. This siloed approach blocks the opportunity to strategically manage corporate assets, both physical and human, for the sustained health of the organization.

The human assets picture in manufacturing is full of contradictions. Unemployment is a problem; yet skilled worker supply does not meet demand. Valuable older workers are being lost yet old entrenched ways need to be discarded. New workers are needed but don't bring with them either the industrial commons on which the U.S. manufacturing success is built or new education in advanced and sustainable manufacturing. In a time of declining employment in manufacturing, caused by productivity shifts and global repositioning, there is a shortage of both professional and skilled workers. The retirement of the experienced leaders who have supported the manufacturing enterprises causes disruption, and the education and training functions are not effectively filling those voids. Further, new knowledge that reflects the importance of and commitment to sustainable manufacturing is not being effectively instilled in the new workforce. Breaking the mold of tribal knowledge and entrenched practices with new awareness and educational programs, including succession preparation, is imperative in addressing better utilization of human assets.

Industrial capacity utilization statistics tell a strong story of the recovery and increased health of the manufacturing sector. In the 1990's the capacity utilization was in the 80% plus range, with highs (1995-1997) in the range of 84%. In 2009, utilization for the year fell to the high 60s. In 2014, the numbers are consistently in the high 70s, showing a trend toward recovery in the manufacturing sector. While these numbers are encouraging and positive, they must be weighed in the context of decline and expansion in industrial capacity.[14] Higher and more efficient utilization generally enables more efficient operations and supports sustainability.

The trend in capability, performance, and utilization of manufacturing equipment is toward improved technologies, higher speeds and throughput, and improved performance. The improving health of the manufacturing equipment sector, with machine tool vendors seeing significant backlogs, points to a willingness to invest in needed improved performance when it is justified by the business case. The necessity of performance improvement is driven by increased global competition and the necessity for easier use and less reliance on the human factor, driven in turn by the decline in availability of skilled craftspersons. More productive equipment e.g. composite placement heads with 36 tows and 12 inch tape, improved energy efficiency, dramatic performance improvements in disposables, e.g. high performance cutting tools and improved sustainability practices, are part of this move to higher productivity capability.

The same pressures that are driving improved equipment and better operations are also driving awareness for good maintenance practices. Keeping equipment operational is an accepted imperative, which has led to more awareness of monitoring and intelligent control, reliability engineering, and proactive maintenance. However, there are still pockets where the tendency to operate until it breaks and short term band-aid approaches prevail.

Decisions regarding insourcing, outsourcing, and supply network utilization are key elements in asset management. There is a trend, particularly with the systems integrators, to utilize the supply network as a corporate asset, and to manage as such. In several industry sectors, examples can be cited of competition for key suppliers and jealous management of the relationships with those suppliers, including increased visibility for the prime into the supply network and for the suppliers into the larger picture. Also, there are examples of systems integrators who are including sustainability optimization in their supplier management strategies.

One of the lessons to be learned from the last decade is that sourcing decisions must be made with a strategic view of all factors, including sustainability vulnerabilities and risks. In the 1990s there was a rush to change roles, from manufacturer to systems integrator, in many cases abandoning core competencies and creating vulnerabilities in consequence. The marketplace has proven to be unforgiving about product failure and quick to blame the corporation, whether the manufacturing was outsourced or not, so more enlightened corporations are now taking a careful look at sourcing decisions and corporate responsibilities for enterprise sustainability.

---

[14] http://www.federalreserve.gov/releases/g17/current/table12.htm

Attention to sustainability has also assumed greater importance in the management of brand equity as a corporate asset. There are two aspects to managing brand equity. On the positive side, a good corporate image for sustainability awareness (some companies excel in this) is important for consumer relations. On the negative side, the brand can be destroyed by an accident or environmental insult caused by the product. The awareness of this opportunity/threat has created a new sensitivity about the importance of sustainability.

In certain sectors, a shift in the definition of the corporate product places -- or attempts to place -- sustainability responsibility on the manufacturer. That trend is associated with offering provision of a service instead of product ownership. Leasing automobiles and heavy trucks from the manufacturer, maintenance and operations contracts for engine and aircraft manufacturers, "sales" of earth moving and transportation equipment by the yard:  all these and many others that could be cited are examples of this growing trend where manufacturing corporations redefine themselves as service providers.

### 4.2.4 Crosscuts

- **Business factors**

When building the business case for sustainable manufacturing, quantification and management of motives and incentives is a critical issue. Systems engineering seeks to define requirements, weight the decision factors, and evaluate the ability of alternatives to satisfy the decision factors. This methodology only works to its potential when clear requirements and goals are defined and metrics are in place. In many cases, the metrics do not support the degree of selection rigor needed, and do not properly include sustainability factors.  In addition, the rewards and incentives may not support the total, balanced optimization that enables sustainable selections. When rewards for innovation and aggressive product development are weighed against risks and uncertainty factors, the latter can often outweigh the apparent payoffs for innovation and product improvement.

Instead of being welcomed as an enabler for assured compliant performance, regulatory compliance is often viewed as an albatross around the neck of U.S. companies in the global competitiveness race; therefore, there is often an adversarial relationship between business leaders and regulators. This adversarial relationship may be intensified by communications shortcomings and the unhelpful attitudes of the regulators. The public use of the EPA Watch List and the directions that this may lead is a present concern.  The challenges of regulatory compliance are more onerous for small businesses who must often comply at levels similar to large corporations but with neither the clout nor the staff to work through the roadblocks. Scaling down of the bureaucracy in meeting requirements and assistance to small businesses in assured compliance are both needed. The culture of regulatory compliance needs to change from being seen as a roadblock to being seen as an opportunity for reasoned and rational compliance as satisfying an obligation to the community and as providing a unique marketing tool. An example was shared in which one small business seized the opportunity to become a visible model of compliance, won the confidence of the regulators, and became an ally helping other businesses establish the same kind of positive relationship with regulators and auditors.

- **Life Cycle Assessment and Design for Sustainability**

LCA is a tool for assuring that products will not damage the environment. However, there is potential for LCA to become a system for assessing and optimizing the total sustainability of a product or, better still, of optimizing the total value of the product over its lifecycle. Currently, LCA does not address either the societal or economic considerations of the triple bottom line. LCA is also expensive, both in the costs of the software and of the expertise to run it, especially when ISO standards compliance is included.

Access to data and availability of expertise are key challenges for LCA. The data is often not available, and a process must be devised to collect it (adding a cost). Often the data collected has little or no value beyond satisfying LCA requirements. Also, certain materials and processes have little relevant history to support delivery of meaningful data.

There is currently a shortage of knowledgeable personnel to properly perform LCA. The root cause for the shortage is the limited education of both professional and skilled workers in the goals and requirements of sustainability, beyond the ability to satisfy the LCA requirements.

- **Modeling and Simulation**

Modeling and simulation systems have made great strides in modeling the individual components, but modeling of systems is still a challenge. Effective use of M&S in a comprehensive, systems-based advanced manufacturing optimization product and process development system requires the ability to consider all factors, including product performance, costs, environmental impact, and social responsibility. Further, the system must be capable of conducting trades to optimize all factors, based on defendable rules, priorities, and algorithms. The system must include consideration of uncertainties and risks. While the challenge is complex, the tools must be user friendly, transparent, and readily available for all sizes of enterprise and application.

- **Workforce**

Several characteristics of the current state impact the ability to systematically manage and maintain an effective workforce. The workforce needs to universally embrace the concepts that design and manufacturing is a system, sustainability is a part of that system, and total optimization is the goal. Current design tools are not sufficiently mature to support total optimization that includes sustainability. Design tools linked to the educational process to support the delivery of the next generation sustainability workforce are also needed.

A key issue for sustainable systems is where the system boundary is set and who sets it. Too often, the environmental impacts and benefits are pushed outside -- made into externalities -- of the manufacturing system's boundaries . . . for political and/or operational reasons. For example, decisions regarding fracking, clean coal, natural gas production and distribution, etc., may be artificially localized or made to focus on small details and thus not adequately consider the impacts of those activities on the nation’s economic and physical security and on the manufacturing sector. Political and economic pressures can make setting a system boundary more than just a simple decision based on the science. These pressures may bias a decision and not always for the common good.

The most relevant workforce issue related to sustainable systems might be the silo approach of the educational system. The academic world (from K-12 through higher education) is comfortable operating in defined disciplines, departments, and majors. However, systems thinking embraces a broad and crosscutting viewpoint. Instilling an ability to work in multiple disciplines, like the need for a cooperative environment across disciplines and organizational boundaries, is essential for systems thinking, the basic perspective for considering sustainability.

## 4.3 Vision

### 4.3.1 Supply Network Management

A virtual product development environment will enable the user to evaluate all factors related to material, component, and subsystem supply in an equation that balances cost, performance, sustainability, and risks for all options. It will also support tradeoffs, and select the most advantageous alternatives, based on defined performance metrics. The models that support the virtual environment will interoperate so the user can see the cost and performance of individual operations, components, subsystems, and systems. The visible factors will include social, environmental, and economic considerations and this visibility will enable total optimization based on the best integrated solutions. The evaluations will consider all factors that influence supplier selection including the long-term, uninterrupted continuation of supply, the avoidance of risk, the minimization and management of uncertainty, and other important factors. The virtual environment will be a learning environment in which actual true costs are fed back to the models to enable upgrading of the knowledge base and the decision processes.

The supply management systems and models will be robust, resilient, and responsive to unforeseen changes. Risks and uncertainties will be identified and protected. Information and physical security, including assurance of product integrity, will be built into the systems that manage the supply network. Visibility and traceability in the network will support early identification of deviations, management of impacts, and appropriate corrective actions. Collaboration and communication will enable unity of the enterprise, enabling seamless operation no less efficient than if all members were co-located.

### 4.3.2 Information Management

The Internet of **T**hings (Io**T**) will be a pervasive capability with complete cyber security, enabling the ability to manufacturing anything, anywhere, and at any time.

All needed information will flow to every tier and every function when needed, in the form in which it is needed, to enable the most efficient execution of the assigned functions. Those who are authorized and authenticated to receive the information will receive exactly what they need and nothing else. Those who are not approved will receive nothing in an environment that is absolute – no possibility of information compromise.

The pathway from data to information to knowledge and wisdom will be captured in a systematic structure. The rules, algorithms, and behaviors that enable the progression from data to the ability to make and command the right decisions, without format and protocol complexities, will be mature and commonly applied.

There is no interruption of functionality, data access, or usability across technology generations. New generations of systems maintain data integrity and functionality while enhancing capabilities. Training for systems upgrade will have no requirement for review of existing operations, but will only address new capabilities and changes essential to supporting that new capability.

### 4.3.3 Corporate Asset Management

An inclusive view of corporate assets will be the norm. Sustainability factors like consumer good will, employee capabilities and morale, brand equity, good environmental and energy citizenship and other sustainability attributes will be considered as part of the corporate value equation. These and other corporate assets will be managed for individual best performance and collective business value delivery with both monetized and social/human value placed on sustainability factors.

Systems methodologies will be applied when managing and optimizing assets. Equipment and facilities will be viewed as systems. Each piece or equipment or facility will be managed for best operation and value for individual optimization and for optimized total system operation. Reliability engineering will be routinely applied in the design and operation of equipment, resulting in an environment in which every parameter is monitored and controlled at the level required – based on the criticality of the operation and the contribution of that function. A monitoring and control environment will determine the best response to indicators and deviations, including the launch of intelligent diagnostics and self-maintaining systems, minimizing or eliminating the need for shutdowns and preventative maintenance.

Flexible, agile, resilient and adaptable systems will be quickly configured to meet corporate needs. The state of equipment, facilities, and operations will be visible; visibility will extend into the supply chain. Proactive contingency plans will protect critical supply and critical assets to assure a lack of interruption. A deep awareness of unlikely events and unintended consequences will feed an awareness and response system that minimizes the impact of unintended events.

### 4.3.4 Crosscuts

- **Business Factors**

A technology rich virtual environment will support holistic innovation across product, process and systems. Sustainable design and manufacturing applications will support faster and more secure economic returns. The measures and metrics that enable the inclusion of sustainability in a systems approach to design and manufacturing will all be in place. A hierarchy of definition will exist, starting at a high level of shared categories of measures and metrics that support all manufacturing enterprises. These high level measures will be able to be broken down to the needed level of specificity, while maintaining the linkage to triple bottom line responsibility mandated for all enterprises. Adversarial relationships to regulatory compliance that inhibit a responsible partnership for triple bottom line success will all be resolved.

- **Life Cycle Assessment and Design for Sustainability**

LCA tools will be accessible, affordable, and robust. They will be harmonized to enable consistency in application and in interpretation. All aspects of the product lifecycle will be well understood, and

LCA will have matured to the point that its application will drive business decisions for total best value.

- **Modeling and Simulation**

User friendly, high resolution, and scalable modeling and simulation systems will populate a virtual product and process development environment that will make the design product and process attributes visible and will support a trade-off environment in which best business decisions will be made without physical prototype production.

- **Workforce**

A well trained and technically savvy workforce will embrace design and manufacturing as a system with sustainability as a major component in the optimization equation. A rich set of tools will support the total optimization environment and the continuous skills development of the workforce.

## 4.4 Solutions

### 4.4.1 Supply Network Management

#### *4.4.1.1 Comprehensive Risk Modeling Toolset for Supply Network Management:*

Develop an intuitive risk modeling toolset with adjustable dashboard to identify and quantify business decisions. The tool must accommodate analysis of risk interdependencies, sustainability tradeoffs, and catastrophic failures within the supply network. Special attention should be paid to unintentional consequences and potential technology change.

#### *4.4.1.2 Business Decisions Based on True Cost:*

Develop a user-friendly interface and a model that allows users to base business decisions on the true cost of business actions among all stakeholders for social, environmental, and economic sectors. This model will enable the inclusion of stakeholder perspectives.

#### *4.4.1.3 Collaborative and Secure Supply Network Management Platform:*

Create a collaborative and secure web-based platform for handling data and communicating with partners that assures absolute security in data sharing and exchange. Other than adhering to the established protocol, the end user should not need specialized knowledge or extensive local IT support to take advantage of all features of the collaborative platform.

#### *4.4.1.4 Comprehensive Supply Management Systems:*

Develop a comprehensive system that incorporates the functionality of the three preceding solutions (4.4.1.1 - 4.4.1.3) into a single system that enables the visible and interactive evaluation of all alternatives for supply management, provides a quantitative assessment of the true lifecycle value of each alternative and combination of alternatives, and supports decision making for delivery of optimized supply networks – at every tier and as an integrated system. Create a supply management model through this virtual interaction, and utilize that model to manage the supply network.

### 4.4.2 Information Management

#### *4.4.2.1 Big-Data Based Knowledge Discovery to Support Optimized Product Development:*

Develop a knowledge discovery and management system that addresses the search and retrieval of relevant information from multiple data sources, the extraction of data and information that is needed for product and process optimization from those data sources. This capability should include, but not be limited to, sustainability issues.

#### *4.4.2.2 Monetization of Societal and Environmental Attributes:*

Develop methods to quantify value for elements not normally monetized, for example, societal or environmental value and the impact of externalities.

#### *4.4.2.3 Ubiquitous, Secure Access to Data, Information, and Knowledge:*

Create a system, based on workflow and information models and templates for classes of components and products that define the data, information, and knowledge requirements, for the product process and supply network development. Assure secure access to all needed information resources. Utilize the same approach to systematically populate the technical data packages as the product development matures and throughout lifecycle operation.

### 4.4.3 Corporate Asset Management

#### *4.4.3.1 Optimization of Corporate Assets:*

Develop and disseminate an improved model to identify and optimize the value of **all** corporate assets including workforce, supply base, brand reputation, intellectual property, expert (tribal) knowledge, surrounding community, and sustainable practices.

#### *4.4.3.2 Corporate Asset Advisory and Management System:*

Develop and broadly disseminate a managed services model that supports corporate asset optimization from the definition of requirements, through design, operation, and end-of-life disposition. The system should address the social, environmental, and economic factors and support an "open exploration and evaluation" of all alternatives (including contracting services that are not normally considered candidates for outsourcing) and should supply decision support for realizing optimized asset management.

#### *4.4.3.3 Sourcing Advisory Systems:*

Develop knowledge-based advisory systems that accept requirements input, support the collection of sourcing alternatives, access the needed data, information and knowledge needed for evaluation of sourcing options, and offer quantitative advice on best sourcing alternatives. This kind of system would place value on the triple bottom line.

#### *4.4.3.4 Systemic Reliability and Resilient Engineering:*

Create a culture in which reliability engineering permeates the design and development of manufacturing equipment, processes, and facilities. Create self-operating and maintaining manufacturing systems. Develop resilient systems that assure the sustainability of the corporation and the enterprise against any known or unknown threats, either intentional or unintentional.

### 4.4.4 Crosscuts

- **Business Factors**

#### *4.4.4.1 Innovation Across Product, Process and Systems:*

A technology rich virtual environment will support holistic innovation across product, process and systems leading to faster and more secure value delivery with economic, societal, and environmental factors collectively optimized.

#### *4.4.4.2 Metrics and Measures of Performance for Sustainable Manufacturing:*

Develop a hierarchical set of metrics and measures of performance for all aspects of sustainable manufacturing to accurately define and reflect sustainable values and drive corporate behavior and performance through appropriate incentives. The metrics should start with commonly shared, harmonized measures for all sectors and move to specificity as necessary for meaningful quantification.

- **Life Cycle Assessment and Design for Sustainability**

#### *4.4.4.3 Next Generation LCA Toolset:*

Develop LCA tools that are easier to use and broaden in their scope to produce a new generation toolset that is accessible, affordable, and robust. Recognizing the diversity of sectors, domains and applications it is recognized that a single standard toolset is not reasonable. However, the toolsets should be harmonized to enable consistency in application and in interpretation, and should be tuned to the business environment to drive best value decisions.

- **Modeling and Simulation**

#### *4.4.4.4 Modeling and Simulation for Virtual Product Development:*

Develop a user friendly, high resolution, scalable modeling and simulation system to populate a virtual product and process development environment that makes attributes visible and supports a trade-off environment in which best business decisions are made without physical prototype production. Develop and adopt a standard framework for the M&S system and populate that framework for specific sectors and applications to grow from initial deployment to broad application.

- **Workforce**

#### *4.4.4.5 Curricula for Systems-Focused Education and Training:*

Develop curricula at all levels of the education and workforce training hierarchy that cultivate a systems mindset in the existing and future manufacturing workforce.

## 4.5 Top Solutions for Systems Sustainability

### 4.5.1 Comprehensive Risk Modeling Tool for Supply Network Management:

Develop an intuitive risk modeling tool for supply network management with a flexible and adaptable dashboard to identify and quantify business decisions. The tool should accommodate analysis of risk interdependencies, sustainability tradeoffs, and catastrophic failures within the supply network with a specific focus on unintended consequences and technology changes.

### 4.5.2 Business Decisions Based on True Cost:

Develop a user-friendly interface and a model that enables business decisions based on the true cost of alternative actions. The systems should address all stakeholder perspectives and should include social, environmental, and economic factors.

### 4.5.3 Collaborative and Secure Supply Network Management Platform:

Create a collaborative and *secure* web-based supply network management platform for handling data and communicating with partners. The system should be user friendly with no specialized knowledge or local IT support required. The platform will include a taxonomy and protocol that addresses both traceability and visibility into social and environmental aspects of the supply network.

### 4.5.4 Big-Data Based Knowledge Discovery to Support Optimized Product Development:

Develop a knowledge discovery and management system that addresses the search and retrieval of relevant information from multiple data sources, the extraction of data and information that is needed for product and process optimization, and the application of analytics that supports the discovery of the information and knowledge that is needed to support improved product and process development decisions. This capability should include, but not be limited to, sustainability issues.

### 4.5.5 Monetization of Societal and Environmental Attributes:

Develop methods to quantify value for elements not normally monetized, including societal and environmental value and the impact of externalities.

### 4.5.6 Corporate Asset Advisory and Management System:

Develop and broadly disseminate a managed services system that supports corporate asset optimization from the definition of requirements, through design, operation, and end-of-life disposition. The system should address the social, environmental, and economic factors and support an "open exploration and evaluation" of all alternatives (including contracting services that are not normally considered candidates for outsourcing) and provide decision support for realizing optimized asset management.

### 4.5.7 Sourcing Advisory Systems:

Develop knowledge-based advisory systems that accept requirements input, support the collection of sourcing alternatives, access the needed data, information and knowledge needed for evaluation of sourcing options, and offer quantitative advice on best sourcing alternatives. These systems will place value on the triple bottom line in decision support.

### 4.5.8 Metrics and Measures of Performance for Sustainable Manufacturing:

Develop a set of metrics and measures of performance for all aspects of sustainable manufacturing. The metrics should accurately define and reflect sustainable values and drive corporate behavior and performance through appropriate incentives. The metrics should start with commonly shared, harmonized measures for all sectors and move to specificity as necessary for meaningful quantification.

### 4.5.9 Next Generation LCA Toolset:

Develop LCA tools that are easier to use and broader in scope to produce a next generation toolset that is accessible, affordable, and robust. Recognizing the diversity of sectors, domains, and applications, it is understood that a single standard toolset is not a reasonable goal. Toolsets should be harmonized to enable consistency in application and in interpretation, and should be tuned to the business environment to drive best value decisions.

### 4.5.10 Curricula for Systems-Focused Education and Training:

Develop curricula at appropriate levels of the education and workforce training hierarchy that cultivates a systems mindset in the existing and future manufacturing workforce.

## 4.6 Projects

The top ten solutions from each small group were presented to the large group; voting determined the project candidates. The project input was used extensively in producing the one-pagers for the Imperatives. The topics assigned to the Systems group included:

### CP1: Sustainable Manufacturing Metrics Accurately Define and Reflect Sustainable Values

**Goal Statement:** Develop metrics that accurately define and reflect sustainable values for all aspects of sustainable manufacturing.

### CP2: Comprehensive Risk Modeling Tool for Supply Network Management

**Goal Statement:** Develop an intuitive risk modeling tool for supply network management with adjustable dashboard to identify and quantify business decisions.

### CP3: Develop an Affordable Applicable, Actionable, and Scalable Life-Cycle Analysis

**Goal Statement:** Simplify the use and broaden the scope of the life-cycle assessment process to include economic, environmental, geographic, and societal aspects. The end result is a solution that is affordable, applicable, actionable, and scalable (available to companies of all sizes). The LCA will include the 6R concept and can be applied to products, processes, and systems.

### CP4: Develop and deploy a decision support system that incorporates risk and Triple Bottom Line value

**Goal Statement:** Develop a user-friendly interface and a model that allows us to base business decisions on the true cost of business actions

- Applies to all stakeholders
- Allows inclusion of stakeholder perspectives
- Includes social, environmental, and economic sectors
- Provides research methods to quantify value for elements not normally monetized, such as societal or environmental aspects

# Appendix A

The following pages contain the technology roadmaps for the 12 Imperatives. It is noted that these roadmaps were produced through an analysis and compilation of all of the materials across all three groups in the Sustainable Manufacturing workshop, with minimal filling of gaps by the editors. This process adds validity to the content. However, it should be noted that the roadmaps present a high level view of what needs to be done and when. As project planning gets underway, the roadmaps will evolve to match a higher fidelity planning process.

## Imperative 1: Sustainable Manufacturing Education and Workforce Development

| Timeline (Years from start) | 1 2 3 4 5 6 |
|---|---|
| **Key Theme 1: Comprehensive Academic and Industrial Curricula for Sustainable Manufacturing Integrated with Opportunities for Work Experience for Education and Training of the Next Generation Manufacturing Workforce** | |
| **1.1 Document the business case for sustainable manufacturing education** | Compile related works and publish a study qualifying the value of sustainable manufacturing education |
| **1.2 Establish a Funded Mandate With Leadership from Industry, Government, and Academia and Document the Mission and the Plan** | Establish a core team for leadership, and secure funding for the program<br>Establish an industry-led organization for management<br>Create a charter and program plan to guide the activities |
| **1.3 Benchmark Current Sustainable Manufacturing Activities - Aligned with the Goals of the Advanced Manufacturing Enterprise** | Identify leading national and international programs at all levels<br>Evaluate selected programs and define the best attributes<br>Integrate advanced manufacturing methods with sustainability benchmarks and define program attributes |
| **1.4 Establish Pilot Programs (That May Be Extensions of Existing Activities) Charged with Creating Curricula and Hands-on Experience for the Hierarchy of Sustainability Education and Training** | From benchmarking knowledge, develop pilot programs that support mission<br>Implement pilot programs that touch multiple geographic regions and demographics. Include education from community colleges to graduate degrees and training from skilled crafts to basic operations. Include existing workforce. |
| **1.5 Establish and Showcase Regional Programs that Adopt the Shared Curricula and Broadly Disseminate** | Grow the pilots through regional hubs to major cooperative programs. Utilize state and regional organizations as launch platforms |
| **1.6 Establish Industrial Partnerships that Define Specific Curricula for Specific Positions and Implement a Direct Education and Training to Employment Pathway. Include Coop Programs, Apprentice Programs, and Internships** | Expand the program by developing rich partnerships with industry. Implement a "knowledge supply chain" from education to the workplace |
| **1.7 Broadly Disseminate** | Showcase results and implement a spiral growth program for broadened impact |

# Imperative 2: Next Generation LCA and Decision Support Toolset

| Timeline (Years from start) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Key Theme 2: Toolset that Supports Interactive and Integrated Affordable, Accessible Applicable, Actionable, and Scalable Product Life Cycle Analysis** | | | | | | |
| **1.1 Define the Requirements for, and Design of, a Next Generation LCA System** | Convene a small group of experts to define the attributes of a needed LCA capability. Fund this working group<br>Produce a requirements document that captures the needed functionality<br>Create a modular systems design that assures migration from existing capabilities to the future system<br>Engage stakeholders and build a roadmap for development and deployment - including the commercialization plan | | | | | |
| **1.2 Integrate Next Generation LCA Planning with the Existing PLM Vendor and User Communities** | Engage the LCA and PLM Vendor communities in defining the requirements for LCA integration, including decision support, In existing and emerging PLM systems<br>Educate the corporate/user community in the importance of LCA/PLM integration. Engage this community to leverage vendor support | | | | | |
| **1.3 Develop Needed product, process, and cost models and integrate with knowledge-based systems (strong integration with deliverables from other activities)** | Based on the requirements and design of 1.1, benchmark existing solutions and projects to exploit leveraging opportunities<br>Build a prioritized, time-based plan to assimilate and integrate the needed models and knowledge systems<br>Develop a continuing pilot program and showcase in which the needed functionality is inserted into the emerging next generation LCA system - integrate with PLM and LCA communities | | | | | |
| **1.4 Secure Support for Next Generation LCA and Develop the Needed Solution** | Using the system design and plan, educate government and industry regarding the importance of the next gen LCA toolset<br>Secure needed support for a call for proposals (through any appropriate channel) for LCA development<br>Develop and deploy the need LCA solution | | | | | |

# Imperative 3: Corporate Asset Management

| Timeline (Years from start) | 1 2 3 4 5 6 |
|---|---|
| **Management of Corporate Assets for Sustainability across the Enterprise, Including the Sustainability Footprint for Equipment and Facilities** | |
| **3.1 Develop and disseminate an enterprise model to identify and optimize <u>all</u> corporate assets** | Document the elements that should be addressed in the enterprise model and their relationships (an ontology for enterprise assets)<br>Develop/adopt a shared structure for the individual models that will comprise the asset model.<br>Prioritize needs and develop modular models that populate the defined structure<br>Develop and deploy models |
| **3.2 Develop corporate asset management systems that strategically manage resources from the definition of requirements, through design, through operation, and including end of life disposition** | Integrate the ontology of 3.1, define the decision processes and requirements for asset management<br>Develop a structure (cockpit) that enables the interactive evaluation of alternatives<br>Populate the asset management system with rules, data, and models as they are made available |
| **3.3 Develop knowledge-based advisory systems that optimize the decision process related to all resource and asset utilization decisions, including sourcing** | Develop a framework - compatible with 3.2 - to incorporate the efficient creation and deployment of knowledge-based advisory systems as modules of the asset management system<br>Develop and deploy decision support/advisory systems |
| **3.4 Create a culture in which reliability engineering and resilient systems are mainstream, and implement self-operating and self maintaining manufacturing systems** | Build a business case for reliability engineering and resilient systems based on examples from industry e.g. P&G<br>Create supportive materials - publish and present<br>"Systematize" the concepts of reliable and resilient systems, build a roadmap, and coordinate focused R&D to deliver and deploy |
| **3.5 Establish regulations, methods, and tools to support the delivery of a lifecycle sustainability package with each new equipment purchase.** | Build a coalition of industry, government, academia - with an emphasis on the users and manufacturers of equipment - to define and prioritize the needs and define requirements.<br>Adopt, extend, and develop standards by manufacturing process to harmonize the models that support lifecycle operation<br>Work with industry associations (like AMT) to reach agreement on the inclusion of needed information for all equipment. |

## Imperative 4: Risk, Uncertainty, and Unintended Consequence Analysis for Supply Networks

| Timeline (Years from start) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Comprehensive Risk Modeling Tool for Supply Network Management that also Addresses Uncertainty and Unintended Consequences** | | | | | | |
| **4.1 Develop interactive systems that support the real-time evaluation of the ability of process alternatives to satisfy product needs within acceptable risk envelopes** | Develop an evaluation framework, including an intuitive user interface, that supports process alternative evaluation and quantification<br>By process family, document the process parameters and establish risk factors associated it processes and parameters<br>Define the acceptable operating envelopes for critical process parameters and associate risk assessment with each process envelop | | | | | |
| **4.2 Provide a comprehensive, dynamic software-based risk advisory system that informs the user concerning materials-availability and utilization risks.** | As a first deployment of the framework of 4.1, develop and deploy an advisory system for materials | | | | | |
| **4.3 Develop a modeling and evaluation toolset that supports the innovative testing of the extreme boundaries of emerging products** | Develop a methodology that supports the evaluation of the unlikely consequences that have a possibility of occurrence at the extreme boundaries of product specifications, including combinations of improbably circumstances.<br>Develop an evaluation toolset that supports the methodology | | | | | |
| **4.4 Develop an intuitive risk modeling toolset with adjustable dashboard to identify and quantify risks in business decisions. The tool must accommodate analysis of risk interdependencies, sustainability tradeoffs, and catastrophic failures within the supply network.** | Integrate the process evaluation system of 4.1. the materials evaluation system of 4.2, and the extreme boundaries system of 4.3 into a comprehensive risk assessment and quantification system that supports business decisions | | | | | |

# Imperative 5: Product Lifecycle Management (PLM) Capability for Process Planning

| Timeline (Years from start) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Enhanced COTS CAD/CAM Tools for Model Development and Product & Process Sustainability Analysis for Process Planning** | | | | | | |
| **5.1 Develop material and resource characterization methods and apply in creating shared access.** | Survey existing characterization activities and align<br>Develop/adopt a framework for characterization data and models<br>Define priority materials and processes and characterize material/process interactions including the impact of specific attributes on process performance and product results<br>Extend to multiple product families and manufacturing processes, and provide broad access to data, models, and analysis | | | | | |
| **5.2 Develop planning modules for sustainability analysis and optimization** | Define the sustainable design and manufacturing attributes that should be considered in process planning<br>Provide material flow planning capability for primary materials, consumables, and waste materials<br>Provide an interoperable, integrated set of planning modules | | | | | |
| **5.3 Integrate sustainability optimization in product-to-process decisions. Enhance commercial PLM systems to support the needed functionality.** | Provide a dashboard/cockpit framework wherein all process attributes can be quantitatively evaluated for sustainability optimization<br>Integrate the planning framework with PLM systems | | | | | |
| **5.4 Develop needed standards to support 6r planning. Develop and deploy systems to support all 6r alternatives** | Document the needed standards to support planning for each of the 6r options<br>Establish consensus protocols and lexicons to support 6r planning. Apply these common practices and move to standardization<br>Develop and deploy planning modules for the 6r alternatives | | | | | |

# Imperative 6: Public-Private Partnership for Sustainable Manufacturing

| Timeline (Years from start) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Public-Private Partnership for Data-Driven Sustainability Science in Manufacturing supporting holistic product/process/system optimization for best economic, social, and environmental value.** | | | | | | |
| **6.1 Establish a neutral broker organization to facilitate the partnership** | Build a coalition of stakeholders with industry leadership<br>Develop an organizational charter and strategic plan | | | | | |
| **6.2 Develop a business plan that includes the sustained operation and revenue generation** | Develop a business plan including a plan for securing and sustaining needed funding and support | | | | | |
| **6.3 Produce and manage a living technology roadmap and utilize the roadmap as a foundation for project selection and funding allocation** | Refine and adopt this roadmap as the foundational document<br>Establish a methodology and organization structure to continuously prioritize and queue projects for | | | | | |
| **6.4 Put in place a collaborative model wherein projects are executed and results are shared. Include the indexing and management of the capabilities and activities of the partnership** | Develop an automated indexing system wherein the activities and capabilities of the partnership (and outside the partnership) are readily accessible | Continuously prioritize needs and launch projects. Manage projects for success | | | | |

# Imperative 7: Lifecycle Cost Models

| Timeline (Years from start) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Total Life-Cycle Cost Models that Reflects True Value and Support Total Value Optimization for Sustainable Value Creation** | | | | | | |
| **7.1 Cost Modeling framework and user interface for consistent application** | Develop or adopt a common cost modeling structure that supports model use and reuse across applications<br>Provide a user-friendly interface that supports true cost evaluation of business decisions and embraces sustainability factors | | | | | |
| **7.2 Cost models for specific product and process families** | Develop and validate a set of cost modeling template that identify the major cost elements for common product families and manufacturing processes - emphasizing sustainability attributes<br>Develop suites of generic, PDM system-compatible production cost models for common product and process types - adaptable for specific applications | | | | | |
| **7.3 Shared access to cost models, data, and knowledge to support true cost analysis** | Align with or create shared repositories that enable a growing storehouse of data, models, and knowledge that supports cost analysis (aligns with characterization of 5.1)<br>Continually populate the repositories and facilitate secure, shared access | | | | | |
| **7.4 Adaptive, learning cost models** | Provide a closed-loop learning environment in which actual cost is captured for all costs and fed back to a knowledge discovery engine for model upgrade | | | | | |
| **7.5 Integrated lifecycle cost modeling as a component of early stage product development** | Develop methods to include lifecycle considerations in the cost analysis. Elements include maintenance, repair, sparing, recycling, disposal - all 6 r alternatives<br>Include supply network considerations and uncertainties in the cost analysis | | | | | |

# Imperative 8: 6 R End-of-life Management

| Timeline (Years from start) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Management of End-of-Life Products with a 6 R Emphasis and OEM Responsibility for Greater Economic Returns** | | | | | | |
| **8.1 Establish a business case and support a culture in which end-of-life responsibility is accepted as a necessary product design/development function** | Working with existing advocate organizations, establish sector specific forums regarding end-of-life responsibility<br>Document the business case for OEMs to voluntarily embrace end-of-life responsibility | | Conduct a 6 R awareness campaign | | | |
| **8.2 Working within the structure of 8.1, establish business processes, as part of a systems engineering methodology, to optimize end-of-life management following 6 R principles** | Working within the systems engineering discipline, develop a methodology for assuring 6 R evaluation in product development<br>Document the requirements for implementing the 6 R evaluation methodology | | | | | |
| **8.3 Work with the PLM and systems engineering communities to enhance the existing toolsets to support the requirements of 8.2. Emphasize knowledge-based decision support in the development and implementation.** | | Produce a roadmap/requirements document that defines the technology needs for supporting end-of-life planning | Define two challenge areas from different sectors and develop an end-of-life toolset | Showcase the toolset in phases, building a constituency for broad adoption | | |
| **8.4 Put in place management strategies to guide end-of use decisions and practices to disposition.** | | Define the requirements for enterprise-wide, end-of-use implementation | Work with ERP and other execution systems to implement enterprise-wide end-of-life management | | | |

# Imperative 9: Flexible and Scalable Manufacturing Alternatives

| Timeline (Years from start) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Flexible and Scalable Manufacturing Alternatives Including Localized Manufacturing and Multiuse Systems with Customized/Personalized Manufacturing for Improved Sustainability** | | | | | | |
| **9.1 Conduct a benchmarking study to evaluate and quantify the impacts of alternative business methodologies, equipment, and processes** | Build a constituency of stakeholders to define the desired outcomes and strategies for success<br>Broadly survey the manufacturing community to identify best practices and emerging technologies<br>Identify leading organizations and applications - beyond additive manufacturing - and analyze activities<br>Publish the results of the study which should include specific recommendations | | | | | |
| **9.2 Apply existing visualization and analysis tools to support the optimized design and development of plants, equipment, processes and supply networks supporting alternative evaluation and optimization** | | From the results of 9.1, identify best practices in the use of emerging technologies for design and development enhancement<br>Showcase the best toolset in addressing specific development challenges. Address plants, equipment, processes and supply networks in the showcase | | | | |
| **9.3 Pilot shared product development facilities, dedicated to highly efficient, flexible, and sustainable production - from single parts to first production** | Establish a constituency across sectors based on common needs. Define target processes and equipment. Establish organization and governance, including a plan for sustained financial resources<br>Repurpose or share existing facilities - renovate as required<br>Work with technology suppliers to populate the facilities with emerging technology solutions for mutual benefit<br>Related to the public/private partnership of key theme 6, provide services that support both the private good while adding to the industrial commons of the U.S. manufacturing base. Focus on providing services for small businesses. | | | | | |
| **9.4 Identify specific sustainable manufacturing targets of opportunity. Develop processes and equipment to satisfy specific product requirements** | | Utilizing the results from 9.1, identify specific technology R&D needs and coordinate the delivery of solutions | | | | |

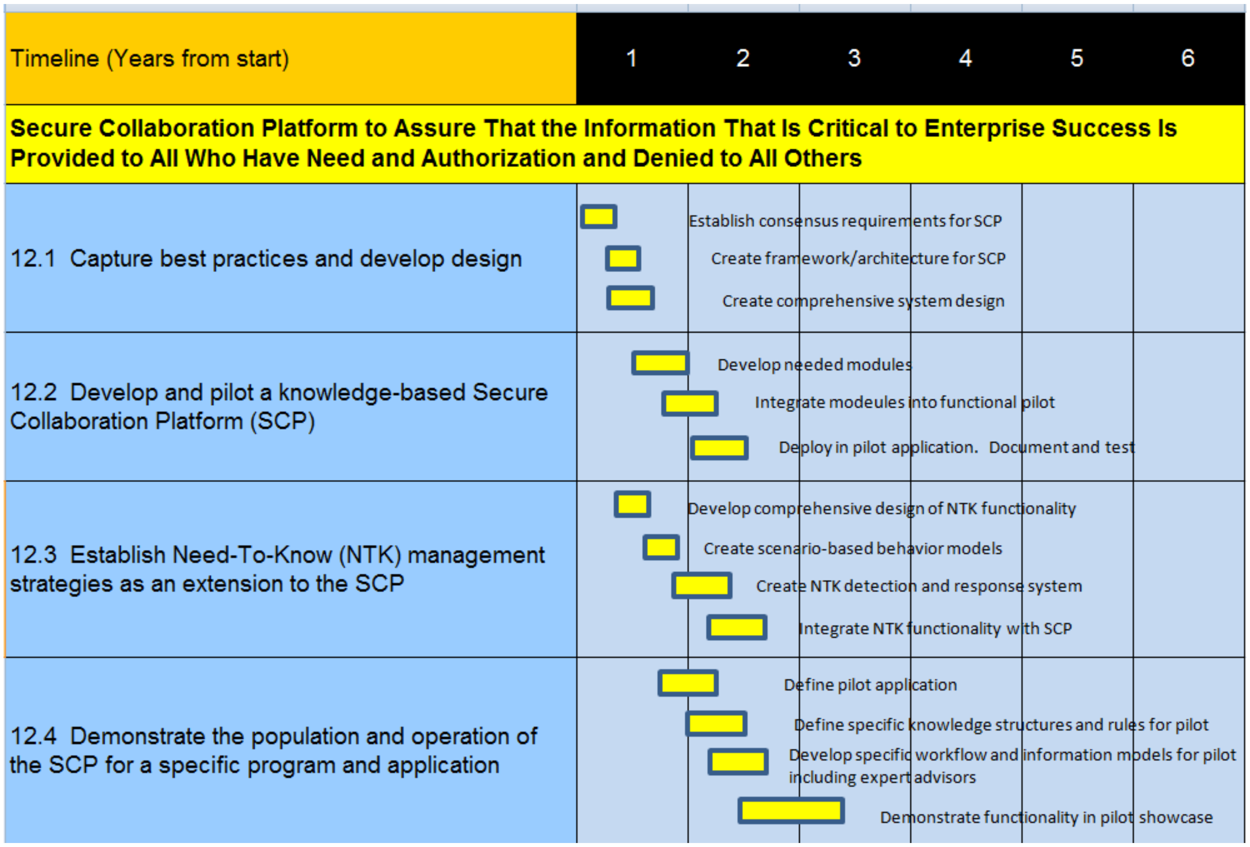
## Imperative 10: Sustainable Manufacturing Metrics

| Timeline (Years from start) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Sustainable Manufacturing Metrics to Accurately Define and Reflect Sustainability Values** | | | | | | |
| **10.1 Develop standard definitions and move to a complete, commonly accepted ontology for sustainable manufacturing** | Develop a consensus definition and lexicon of sustainable manufacturing<br>Produce and document a taxonomy for sustainable manufacturing | Extend to a complete, widely accepted, ontology | | | | |
| **10.2 Develop metrics for measurement and reporting for sustainable manufacturing. Move to standardization.** | | Utilizing the ontology, define the metrics general metrics for the high level elements<br>Define needed standards and initiate the standardization process | | | | |
| **10.3 Develop/adopt a common framework for monitoring and reporting performance** | | Survey existing structures and protocols and define a unification/harmonization strategy to enable common understanding<br>Develop/adopt protocols for uniform reporting and measurement against metrics | | | | |
| **10.4 Develop metrics and standards for specific design and manufacturing functions -first generically and moving to more detail by application and sector** | | | Consistent with the general metrics of 10.2, extend metrics to specific sectors and applications, moving to higher fidelity analysis and reporting | | | |

# Imperative 11: Information - to Knowledge - to Intelligent Sustainable Manufacturing

| Timeline (Years from start) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Transforming Information to Knowledge and Application in Realizing Intelligent Design, Manufacturing, and Lifecycle Support** | | | | | | |
| **11.1 Define and bound a domain for first application. Define the sustainability attributes to be controlled** | Working with industry, define a sector, domain, and specific product<br>Define the sustainability attributes to be controlled | | | | | |
| **11.2 Adopt a common structure and format for knowledge capture and management. Develop/adopt a user interface** | Develop the structure for a knowledge repository, applicable for a bounded application and scalable for broader applicability<br>Develop/adopt a dashboard for user interaction | | | | | |
| **11.3 Define the data, information, models, and knowledge needed to monitor and control the define sustainability attributes. Develop the rule sets, algorithms, models, and other required resources to support the defined decision set** | | Document the data, information, and knowledge requirements<br>Develop the pathways to all needed resources for achieving intelligent control<br>Develop the master control model for the defined application | | | | |
| **11.4 Establish a structure to monitor, analyze, control, and feedback information for the targeted processes and sustainability attributes** | | Establish the control algorithms for critical process parameters<br>Implement the monitoring capability necessary to establish control of targeted parameters<br>Establish feedback and "learning" capabilities | | | | |
| **11.5 Pilot the intelligent sustainability capability and more to broader application** | | Pilot the intelligent manufacturing system for a defined product family<br>Showcase and publish results supporting broader implementation | | | | |

## Imperative 12: Information - to Knowledge - to Intelligent Sustainable Manufacturing



# Appendix B

## List of Acronyms

| | |
|---|---|
| 2-D | Two Dimensional |
| 3-D | Three Dimensional |
| 6 R | Reduce, Remanufacture, Reuse, Recover, Recycle, and Redesign |
| AMTech | Advanced Manufacturing Technology Consortia |
| API | Applications Programming Interface |
| CAD/CAM | Computer Aided Design/Computer Aided Manufacturing |
| COTS | Commercial Off The Shelf |
| CSO | Chief Sustainability Officer |
| DARPA | Defense Advanced Research Projects Agency |
| DfE | Design for the Environment |
| DMDI | Digital Manufacturing and Design Innovation Institute |
| ELV | End-of-Life Vehicles |
| EPA | Environmental Protection Agency |
| ERP | Enterprise Resource Management |
| GRI | Global Reporting Initiative |
| ICME | Integrated Computational Materials Engineering |
| IMDS | International Material Data System |
| IMTI | Integrated Manufacturing Technologies Initiative |
| IoT | Internet of Things |
| IPT | Integrated Product Team |
| ISEW | Index of Sustainable Economic Welfare |
| ISM | Institute for Sustainable Manufacturing |
| IT | Information Technology |
| LCA | Life Cycle Assessment |
| M&S | Modeling and Simulation |
| MAPTIS | Materials and Processes Technical Information System |
| NASA | National Aeronautics and Space Administration |
| NCMS | National Center for Manufacturing Sciences |
| NIST | National Institute of Standards and Technology |
| OEM | Original Equipment Manufacturer |
| PLM | Product Lifecycle Management |
| PRISM | Partnership for Research and Innovation in Sustainable Manufacturing |
| REACH | Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals |
| RoHS | Restriction of Hazardous Substances Directive |
| STEM | Science, Technology, Engineering and Math |
| UK | University of Kentucky |