Developing a Sustainability Manufacturing Maturity Model

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Abstract

Sustainable manufacturing (SM) broadly implies the development of innovative manufacturing sciences and technologies that span the life cycle of products and services to minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers, and are economically sound. The goal towards SM is multifaceted. SM is more than recycling materials and sourcing renewable energy as commonly perceived; it requires a holistic and life cycle thinking. Industry today falls short of a comprehensive, yet, amicable framework that will encompass all aspects of sustainable manufacturing (design practices, energy use, zero landfill, toxic materials, etc). Additionally there is a lack of support for quantifiable measurements to objectively evaluate and identify improvement areas for standards conformance. Further, industry needs appropriate tools to effectively plan for and evaluate sustainable manufacturing's maturity short-term, intermediate and long-term objectives. Such a maturity model's value will rely on a consistent set of performance indicators and test models that can be quantifiably measured with stated uncertainties. This paper discusses the concepts of, and efforts required to develop, a sustainable manufacturing maturity model (SMMM). Our SMMM recommendation is facilitated by life cycle management (LCM) tools, techniques and measurements through manufacturing unit process characterizations.

Keywords: *Sustainable Manufacturing, maturity models, unit process characterizations, best practices*

1. Introduction

Sustainability is most commonly accepted as a triple bottom line of economic profitability, respect for the environment, and social responsibility [1]. Recently, technology is being viewed as a fourth dimension for sustainability. Sustainable manufacturing (SM) has varying definitions [2, 3] depending on the context of discussion. SM broadly implies the development of innovative manufacturing sciences and technologies that span the life cycle of products and services to minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers, and are economically sound. Today, a move towards sustainability has more so become a norm and not a mere initiative or practice. There has been a recent trend where global companies are declaring their adherence to the principles of sustainable development. Green design, eco-friendly design or design for environment has been the catchphrases in the last decade in almost every field, especially in engineering. Reports suggest that design for environment (DfE), life cycle assessment (LCA) and extended producer responsibility (EPR) are clearly catching up and new awareness is being created in the mindset of both producers and consumers [4, 5]. SM has become a strategic move as industries begin to seek novel ways to make efficient use of resources, ensure compliance with regulations related to environment and health, and enhance the marketability of their products and services. Many of the manufacturing industries are investing in research towards reducing (resources, energy, and waste), reusing, and remanufacturing. Industries are actually challenged to proactively manage the entire life cycle of a product (life cycle thinking).

2. Life cycle thinking

Life cycle thinking is about going beyond the traditional focus on production sites and manufacturing processes so that the environmental, social, and economic impact of a product over its entire life cycle is taken into account, including the consumption and end of use phase, [6- 9]. The goal is to reduce a product's resource use and emissions to the environment as well as improve its socio-economic performance throughout the life cycle. Life cycle thinking, as depicted in Figure 1, enables product designers, service providers, government agents, and individuals to make choices for the longer term.

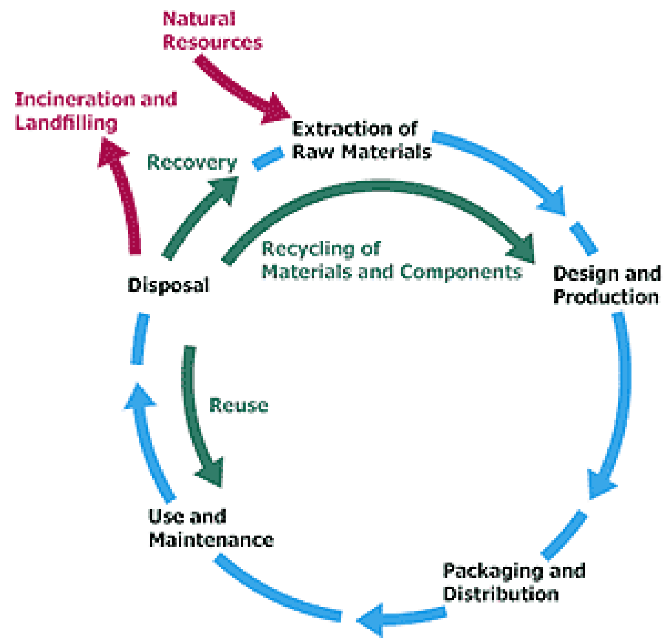

Figure 1 Life cycle thinking, Adopted from [9]

To be truly sustainable the entire life cycle of a product must be considered, because products may have totally different environmental impacts during different stages of their life cycle. Traditionally, environmental consciousness addresses pollution prevention or waste management, but these strategies only focus on avoiding or minimizing potential environmental impacts without considering the design of products. In [10] the authors use a medical metaphor, to convey that this traditional approach alleviates the symptoms without addressing the reasons for the illness. We need effective tools and measures that integrate the environmental and other impacts into the product development process. As rightly pointed out in [10], we actually begin to "design the environmental impacts out of the product and manufacturing processes."

Life Cycle Management (LCM) is the organizational dimension of the life cycle approaches. It is an integrated concept for managing the total life cycle of goods and services towards more sustainable production and consumption. In general, LCM is making life cycle thinking and product sustainability operational for businesses through the continuous improvements of product systems and processes [6, 7, 8, 11-13]. It must be noted that LCM is not a single tool or methodology but a management system for collecting, structuring and disseminating product-related information from the various programs, concepts and tools incorporating environmental, economic, and social aspects of products, across their life cycle. The LCM guide [6] articulates a series of key definitions and principles related to LCM, a description of the importance and scope of intervention that different areas have in the organizations, and a step-by-step guide, adaptable to enterprises of any size, to support the integration of LCM in the management process. Several different strategies have been used by companies to implement LCM in their operations for different applications and to integrate the triple bottom line aspects into an institutional context. Among these strategies and tools are design for environment (DfE), green procurement, LCA, Life Cycle Costing (LCC), eco- and energy labeling, environmental product declarations, ecological and carbon footprint analyses, environmental performance indicators, and social sustainability assessments and approaches, in addition to essential organizational strategies for actual implementation.

Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment. The LCA process also identifies and evaluates opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal [7, 14-16]. LCA can provide information for production and for consumption choices because it assesses the impacts of goods and services.

According to ISO 14040 [17, 18], LCA consists of four stages: 1) definition of the goal and scope; 2) life cycle inventory analysis; 3) life cycle impact assessment, and 4) life cycle interpretation. In the "goal and scope" stage, the problem and its boundaries are defined. In the "inventory" stage, the materials used, processes executed, and waste produced at each stage of the product's life cycle are quantified. In the "assessment" stage, values from the LCA are used to calculate, normalize, and weigh the impact of the product in one or more categories. In the final stage, "interpretation", the reviewer interprets the results of the assessment, draws conclusions, and makes recommendations. Environmental LCA and social LCA are two complementary techniques, each offering their perspective of the products' life cycle impacts. Both are methodologies of a wider sustainability toolbox that differ based on their scope (life cycle) and their product focus [6, 7, 19].

Life Cycle Costing (LCC) provides information on costs throughout the life cycle of a product. Traditional LCC is a method of calculating the total cost of a product (goods and services) generated throughout its life cycle from its acquisition to its disposal, including design, installation, operation, maintenance, recycling and disposal. Environmental LCC extends traditional LCC in a way that it assesses all costs associated with a product's life cycle that are covered by one or more of the actors in the product's life cycle. These actors include suppliers, manufacturers, customers, end-users or end-of-life actors [7, 20].

The subsequent organization of the paper is as follows. Section 3 presents a review of related efforts in life cycle thinking, LCM approaches and Maturity Models. Section 4 presents the motivation and a proposed approach followed by discussion and conclusions.

3. Related efforts

The European Commission has provided a comprehensive user guidance list of the currently available LCA tools [21]. A similar list of LCA resources is provided by the US Environmental protection agency [22]. Examples of the tools incorporating the LCA methodology include several commercial (SimaPro [23] and GaBi [24]) and academic environmental assessment tools (EioLCA [25], TRACI [26], BEES [27] and EcologiCAD [28]). More recent reports on the Design for Sustainability [29, 30], an extension of an early report on ecodesign [31], outlines the evolution of ecodesign to the concept of Design for Sustainability (D4S). Several other publications [32-36] also discuss ecodesign and design for environment in greater detail. Product design tools supported by LCA based information exist in various forms such as eco-design and design for sustainability [37]. Several publications [38-41] broadly discuss the design for environment at an enterprise level. Other publications have reportedly incorporated eco-design strategies along with LCA and other metrics for environmentally conscious design [42-55].

A number of point solution suppliers provide tools such as InSight [56] that incorporate standards, such as RoHS (Restriction of Hazardous Substances) [57], WEEE (Waste Electrical and Electronics Equipment) [58], ELV (End of Life of Vehicles) [59] and REACH (Registration, Evaluation, and Assessment of Chemicals) [60]. The SWEBOK (Software Engineering Body of Knowledge) [61] provides insight into the use of Software Engineering tools for other technology areas. However in all, we require a procedural approach to objectively assess, predict, or identify improvement areas for standards conformance in the manufacturing industries.

In 1979 Philip B. Crosby proposed the Quality Management Maturity Grid (QMMG), for use by a business or organization as a benchmark of how mature its processes are, and how well they are embedded in their culture, with respect to service or product quality management [62]. This was the earliest inspiration to develop maturity models.

A capability maturity model (CMM) can support companies in moving towards a next level of evolution in business management. CMM is a reference model of mature practices in a specified discipline, used to assess a group's capability to perform that discipline. The Capability Maturity Model Integration (CMMI) [63] from the Software Engineering Institute (SEI) [64] and the Organizational Project Management Maturity Model (OPM3) [65] from the Project Management Institute (PMI) [65] are examples of two maturity models that address sustainable performance improvements.

CMMI is a reference model with a collection of best practices from the disciplines of software and systems engineering, integrated supplier management and integrated product and process development. CMMI can be used to guide process improvement across a project, a division, or an entire organization. It helps to integrate inter-organizational functions, set process improvement goals and priorities, provide guidance for quality processes, and provide a point of reference for appraising current processes [66, 67]. OPM3 is the standard for organizations looking to improve their capability to deliver their strategies through projects. By treating all of the organization's projects as investments in an overall portfolio and applying best practices to manage those initiatives at multiple levels, organizations can achieve their objectives and align their resources to work on things that matter the most [68-69].

Maturity models in general, including CMMI and OPM3, provide mechanisms for organizations to assess themselves against best practices, identify gaps, and create improvement plans to close those gaps with continuous improvements. Organizations can achieve sustainable performance improvements by embracing either CMMI or OPM3 or both. With CMMI's in-depth coverage of systems, software engineering, supplier management, and OPM3's broad coverage of project, program and portfolio management, the two models provide a wealth of knowledge [69]. Each model also comes with assessment methods which provide different perspectives in order to reveal potentials and to identify the needs. CMMI provides a systems and software engineering, quality and supplier management best practices perspective, while OPM3 provides a perspective that describes best practices of organizations that achieve their strategic objectives through successful projects. Yet, as an organization moves from a compliant strategy toward sustainability, higher levels of maturity or capability are required for successful execution [6-7].

Besides the introduced models there also exists a PLM-CMM that defines the levels of Product Life cycle Management (PLM) capability and maturity. The model is intended to quantify the situation of PLM in a company and addresses eight components of PLM namely: product, processes, data and documents, human resources, organizational issues, techniques, equipment and applications. For each component, the level is assessed by examining hundreds of parameters indicative of capability and maturity, to quantify a company's PLM situation on an industry-standard, vendor-independent scale [70].

A more recent draft report by the US Department of Defense [71] discusses the Manufacturing Readiness Levels [72] elaborately in order to define the current level of manufacturing maturity, identify maturity shortfalls, associated costs and risks, and provide the basis for manufacturing maturation and risk management. The document also provides best practices for conducting assessments of manufacturing readiness. Although designed specifically for acquisition program managers, the document could potentially prove useful towards identifying and conducting the manufacturing assessments in general.

4. Motivation and Approach for SMMM

Manufacturing industries need appropriate and dedicated tools to effectively plan for and evaluate sustainable manufacturing's maturity life cycle objectives. A maturity model tailored specifically through LCM tools and techniques like LCA, LCC, checklists, manufacturing unit processes, performance indicators and standards, can help interest manufacturing industries to objectively evaluate their maturity and appropriately facilitate the benchmarking of their manufacturing processes. The proposed research idea is the development of a dedicated maturity model to gauge the progress of sustainability in manufacturing industries. The Sustainable Manufacturing Maturity Model (SMMM) could be used by manufacturing companies to objectively evaluate their initial and evolving states with regards to sustainability. For SMMM development we draw inspirations from the earlier developed and successfully implemented maturity models. SMMM will take a systems approach to integrate inter-organizational functions, set manufacturing process improvement goals and priorities, provide guidance for quality manufacturing processes, and provide a point of reference for appraising sustainability in current manufacturing processes.

The SMMM can help build awareness to reduce carbon dioxide and other greenhouse gas emissions economy-wide in a cost-effective manner, but also contribute to energy conservation and recycling. Through this paper we intend to present some initial thoughts and initial dialogue sessions on how a capability maturity model for sustainable manufacturing can be developed in conjunction with LCM tools to objectively evaluate the maturity levels of a manufacturing industry. Drawing inspirations from the previous maturity models, we propose to tailor the process areas [68], the related best practices [69], and the assessment techniques combining LCM tools like LCA and LCC with more fundamental manufacturing unit processes, performance indicators and standards for SMMM. The more difficult challenge is to identify levels of maturity with well defined indicators and metrics.

Figure 2 presents an initial schematic as a first step toward the development of SMMM. The levels from CMMI in Figure 2 are presented only for demonstration purposes. In the figure at Level 3 for example, process characterizations and definitions can be pursued in line with the concept of Unit Manufacturing processes [73]. Manufacturing a product or component usually requires the integration of a number of processes. “Unit processes,” are those individual operations (e.g., casting, machining, and surface treatment) required to produce finished goods by transforming raw material and adding value to the work piece as it becomes a finished product. Benchmarks and unit process templates can be developed to support process standardization and manufacturing best practices reflecting product, process and resources. The National Research Council has earlier identified five distinct unit process families:

- ***mass-change processes***, which remove or add material by mechanical, electrical or chemical means (included are the traditional processes of machining, grinding, shearing and plating, as well as such nontraditional processes as water jet, electro-discharge and electrochemical machining).
- ***phase-change processes***, which produce a solid part from material originally in the liquid or vapor phase (typical examples are the casting of metals, the manufacture of composites by infiltration and injection molding of polymers).
- ***structure-change processes***, which alter the microstructure of a work piece, either throughout its bulk or in a localized area such as its surface (shot peen stress relief, heat treatment and surface hardening are typical processes within this family; the family also encompasses phase changes in the solid state, such as precipitation hardening).
- ***deformation processes***, which alter the shape of a solid work piece without changing its mass or composition (classical bulk-forming metalworking processes of rolling and forging are in this category, shot-peen sheet-forming processes such as deep drawing and ironing).
- ***consolidation processes***, which combine materials such as particles, filaments or solid sections to form a solid part or component (powder metallurgy, ceramic molding and polymer-matrix composite pressing are examples, and permanent joining processes such as welding and brazing).

Similar taxonomies of manufacturing processes are also discussed in [74].

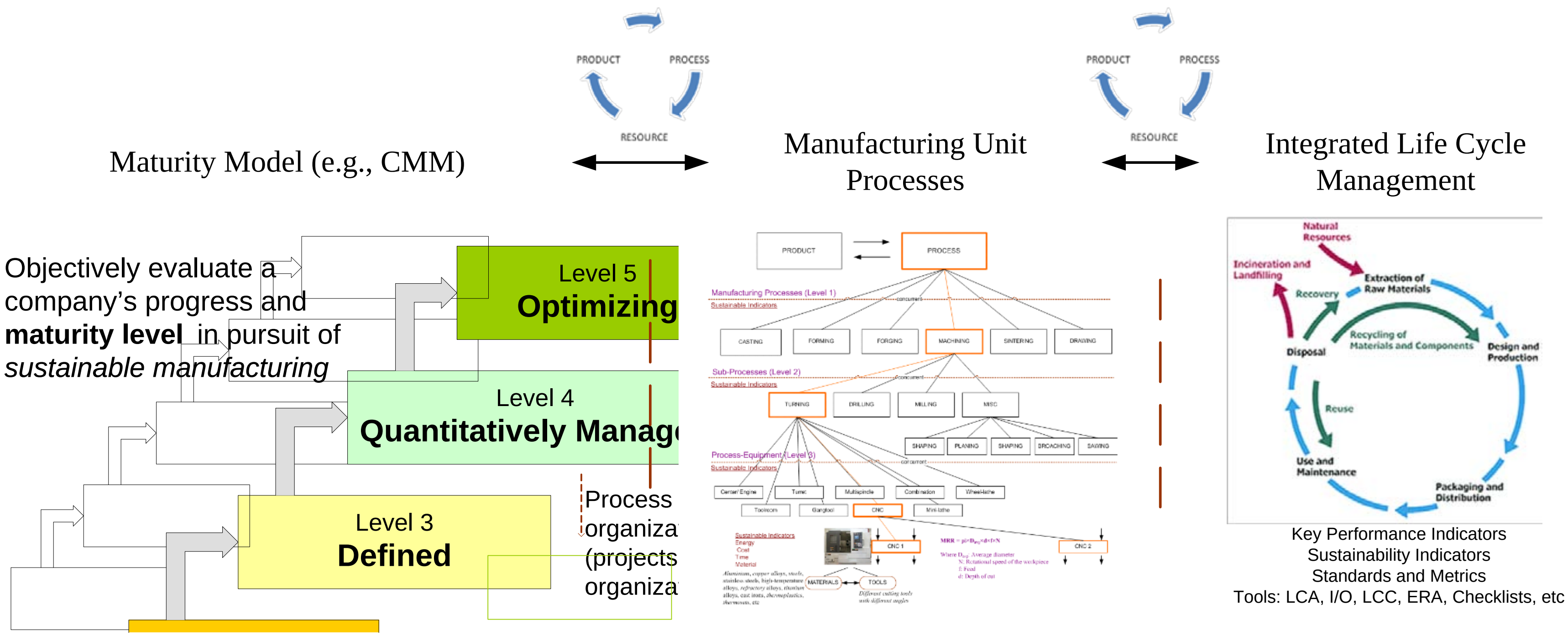

Figure 2 An initial schematic for SMMM

While developing the unit processes and characterizations, appropriate goals from the maturity model must be coupled with goals from the LCM tools and techniques. For example, LCA checklists [75], appropriate key performance and sustainability indicators [76-82] must be integrated at various levels of maturity reflecting the manufacturing goals.

If successful, the SMMM could have a direct economic impact on the manufacturing industries. The SMMM can also be used for objectively assessing the ability of a manufacturer's processes to produce products in a sustainable way. It will encompass all aspects of sustainable manufacturing such as design practices, energy use, zero landfill, toxic materials, etc., and it will support quantifiable measurements for objective evaluation. The SMMM, in conjunction with other metrics and as part of periodic reviews, will provide useful management insight and will:

- objectively evaluate initial and evolving states with regards to sustainable manufacturing
- help identify complex, intertwined issues
- allow use of statistical controls and methods
- use measurement principles to allow reporting and conformance to standards
- allow users to meet or control requirements thus supporting cost and schedule control
- support mutual understanding of requirements by product development and manufacturing team members
- support implementation of new technologies and processes with ability to evaluate performance
- promote continuous improvement culture

5. Discussion, Future work and Conclusions

This paper briefly proposed and discussed a Sustainability Manufacturing Maturity Model used to gauge the progress of sustainability in the manufacturing industries. The SMMM is envisioned to be used by manufacturing companies in objectively evaluating their initial and evolving states of sustainability. The plan of action is to first create awareness in the industry promoting the usefulness of such a manufacturing maturity model and its implications. Work of this focus and scale is beyond the capability of one company and requires strong coordination of an alliance of companies, standard development organizations and universities. The next step is to identify potential manufacturing collaborators. This should be through dialogue in workshops and manufacturing-related conferences or focused summer schools such as this. The effort should be initiated by meetings with collaborating partners; and a review of leading-edge assessment tools must be performed addressing sustainable manufacturing. This will potentially set the stage to identify the initial framework for an actual sustainability model and its essential elements. Then identification of appropriate questions at different levels and systematic integration of LCM tools and techniques will have to be completed. At this point, visits with industry should occur to get their views and inputs. This will lead to the final stages of study in identifying the maturity levels within the model and a final assessment of its information structure and completeness. The following steps summarize the proposed plan of action:

- substantial review on the state of art in manufacturing of those addressing sustainability
- identify initial framework for sustainability model
- identify the essential elements of the sustainability model
- identify the maturity levels in the model

- identify the right questions and checklists at different levels
- conduct industrial interactions and collect inputs
- assess and implement model

Today with the global drive towards sustainability further propelled by regulatory agencies, manufacturing industries do realize that improving the manufacturing processes can contribute to sustainable development. However, in practice it turns out to be hard to define what steps to take for improving and controlling the process, and in what order. The development of a SMMM will assist the manufacturing industries to take a proactive step, to be able to gauge and improve their current level and provide opportunities for maturity and progress.

DISCLAIMER

Mention of commercial products or services in this paper does not imply approval or endorsement by NIST, nor does it imply that such products or services are necessarily the best available for the purpose.

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