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USING INDUSTRY FOCUS GROUPS AND LITERATURE REVIEW TO IDENTIFY CHALLENGES IN SUSTAINABLE ASSESSMENT THEORY AND PRACTICE

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ABSTRACT

The bottom up demand from consumers for more sustainable products, and the top down need to comply with government regulations motivates manufacturers to adopt tools and methods to evaluate their operations for opportunities to reduce environmental impact and improve competitiveness. Manufacturers have actively improved the sustainability of their products through the use of such tools and methods. However recently, manufacturers are struggling to maintain the necessary gains in energy and material efficiency due to the assessment inaccuracies of current ad hoc methods and their inability to identify large sustainability improvement opportunities. Overcoming this barrier requires standardized methods and tools that are implementable and which contain accurate manufacturing process-level information. To aid in developing such methods and tools, this study contrasts the perspective of industry and academic research on the topics of sustainable manufacturing metrics and measurements, and process modeling to determine the deficits that exist in enacting academic theory to practice. Furthermore, this study highlights some of the industry responses to the development of related standards for sustainability assessment.

INTRODUCTION

Sustainable manufacturing is defined as the creation of manufactured products using processes that minimize negative environmental impacts, conserve energy and natural resources; are safe for employees communities and consumers; and are economically sound [1]. To that end, researchers have created methods to assess the environmental, social, and economic impacts of manufactured products or processes through a myriad of indicators and metrics [2–4].

Over the past two decades, studies have repeatedly emphasized a lack of accurate tools and methods to support sustainable manufacturing. A 2002 workshop on environmentally benign manufacturing [5] supported the consensus that better assessment tools and more accurate data are needed. Bunse et al. [6] reported on the implementation gap between academic theory and industrial practice. Through interviews they affirmed their initial hypothesis that standardized tools and methods could speed up the adoption of sustainable practices. Bhanot et al. [7] published a survey in 2015 concluding that one of the main barriers to sustainable manufacturing is the lack of standards. This was supported by Rachuri et al. in 2009 [8] in an analysis of sustainable manufacturing best practices.

The work reported herein documents existing barriers related to (1) manufacturing metrics and measurements and (2) manufacturing process modeling that can support sustainable manufacturing. Findings are based on an industry perspective (focus groups) and academic perspective (literature review). Strategies for overcoming the barriers, including standards development are presented from both perspectives.

The paper is organized as follows. First, the *Research Approach* section presents the design of industry focus groups (here, called roundtables), as well as supporting literature on methods for conducting qualitative research. The *Literature Perspective* section is presented as two subsections reviewing the literature on (1) manufacturing metrics and measurements and (2) manufacturing process modeling. Next, the *Industry Perspective* on the two focus areas is presented, based on the roundtables. The *Research Findings* section presents barriers and gaps identified by contrasting the industry and literature perspectives. Further, this section tabulates the identified barriers and recommended changes to foster standards development and adoption. Next, the *Relevant Standards Efforts* section presents current standards and their capabilities. Finally, the *Conclusions* section presents underlying trends identified from the research, as well as directions of future work.

RESEARCH APPROACH

To investigate the two focus topics of this research, i.e., metrics and measurement, and process modeling, from the perspective of the literature and industry, a literature review was conducted and three roundtables were hosted to gather a relevant body of key findings (Fig. 1). These findings were then compared to identify barriers and gaps and to support the introduction of academic theory to industry practice.

The literature review was organized and conducted as a traditional literature review. This type of review identified and summarized the literature on one or more chosen topics. The primary focus was to develop a comprehensive background illuminating current research findings [9,10]. The literature review investigated three subtopics due to their influence on the two overarching focus topics. Thus, to summarize the literature perspective of manufacturing metrics, measurements, and manufacturing process modeling required investigating root causes. The literature perspectives/findings were later compared to the findings of the industry roundtable group discussions.

The industry perspective was gathered by hosting three roundtables meetings from June 2015 to March 2016. The roundtables were distributed geographically to gather a diverse set of industry participants and information since companies tend to cluster to achieve greater competitiveness [11]. A small group of 8-12 representatives attended each roundtable. Represented companies spanned a range of industries and sizes, from small high tech startups to well established, large manufacturing companies.

Each roundtable meeting was organized into three dialogue sessions lasting about two hours each. Each dialogue session was conducted as a focus group, however, the term “roundtable” is used hereafter to imply that the research was more academic in purpose and not to be affiliated with the more political or commercial connotations of a typical “focus group.” Questions were designed to foster discussion in each area of interest, while also allowing time for note takers to document relevant information.The intent of the first dialogue session of each roundtable was to foster discussion about performance indicators, processes, process flow and plant/facility performance, and the communication of metrics.

The intent of the second dialogue was to foster discussion about capturing and describing sustainability information at the process level to support system level decision making. Topics included manufacturing process modeling and benefits of process characterization. The third dialogue centered on measurement science as a means to characterize manufacturing processes and to systematically capture and describe sustainability information to enable better decision making.

To determine how the dialogue sessions would be conducted, the authors investigated four well-known methods for soliciting opinions from subject matter experts (Fig. 2). The four methods included the Delphi, brainstorming, nominal group technique, and focus group techniques. References [12] and [13] were reviewed by the authors to gain a sense of the respective strengths and weaknesses of each group discussion method. From the investigated methods, the authors selected the focus group method for its strength in extracting the range and diversity of participants agreements and disagreements [14]. Focus groups are a research technique to collect data based on personal experience and opinion from a set of participants presented with a question from a researcher. Krueger and Casey [14] established some of the first guidelines for applying the focus group technique. The guidelines recommend that a focus group be conducted in three phases: conceptualization, interview, and analysis.

In the conceptualization phase, questions are designed to elicit specifics, but remain open ended. Following this guideline, a set of five key questions were formulated and discussed by the research team to ensure they remained specific, and logically sequenced.

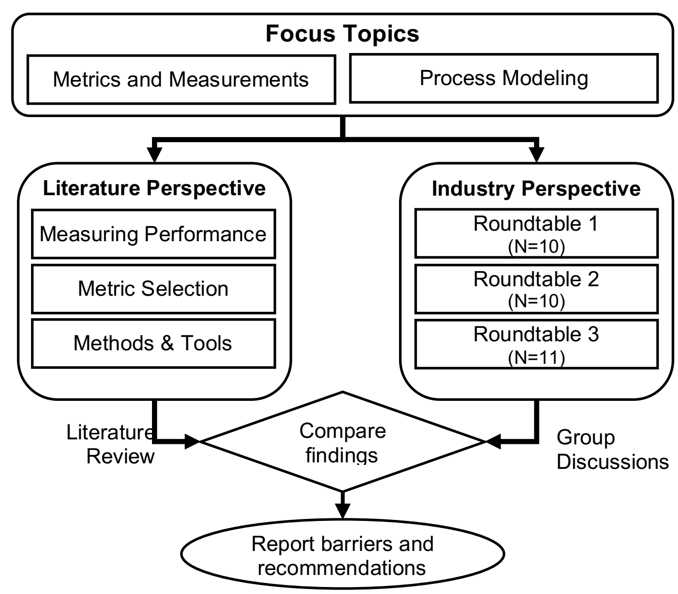

FIGURE 1: METHODOLOGY FOR IDENTIFYING DEFICITS IN THEORY AND PRACTICE FOR EACH FOCUS AREA

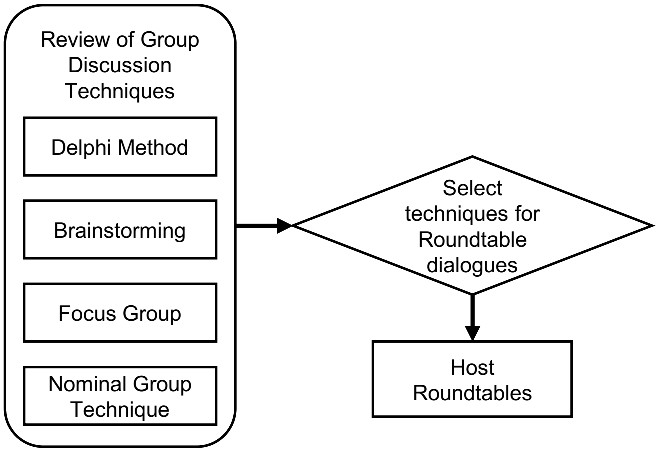

FIGURE 2: DESIGN OF THE ROUNDTABLE DIALOGUES

In the interview phase, the moderator, who is knowledgeable on the discussion topics, begins the discussion with a welcome, overview, and ground rules before asking the first question [14]. Time is allocated to allow participants to socialize prior to the discussion. In keeping with this guideline the authors designed the roundtables to allow informal greetings over a continental breakfast before formally welcoming and introducing the participants to the dialogue topics. Furthermore, focus groups are designed such that each participant individually responds to the moderator's question with their own opinions. To ensure this, the roundtable moderator walked within the perimeter of the open circle of participants and questioned each participant in round-robin style on each topic. When each participant had voiced their answer, the floor was opened for group discussion.

The guideline for the analysis phase instructs a research team to collect and collate all notes, analyze the notes either quantitatively or qualitatively, and distribute the results to participants. Following this guideline, the notes collected by the researchers were collated and compared. Raw data was qualitatively described and interpreted and reported out to participants and the research team observers to achieve consensus on the interpreted findings. The findings are described in the Industry Perspective section, below. The key ideas from each roundtable are reported. Where available, specifics are given to substantiate the claims in the form of quotes or mentioned tools and methods.

LITERATURE PERSPECTIVE

The literature perspective is presented on the two focus topics 1) Manufacturing Metrics and Measurements, and 2) Manufacturing Process Modeling. Each focus topic was approached by assessing the relevant literature in identifying how sustainable manufacturing performance is measured, how metrics are selected, and how methods and tools are applied in practice.

Manufacturing Metrics and Measurements

Over the last twenty years, studies have detailed the necessity for sustainable manufacturing metrics and indicators, the means for determining what metrics to use, and how they should be deployed. Indicators and metrics relate sustainability performance areas to each other and to the process in question (Fig. 3).

Each performance area can have one or more indicators. In turn, an indicator can be described by one or more metrics. Indicators provide a context to measure, analyze, and score sustainability aspects of manufacturing processes. For example, the social performance area might include an indicator for occupational health and safety (OH&S) and could be assessed on the performance of the related metrics, such as number of acute injuries. Indicators can be defined internally, or selected from various indicator repositories. Evaluation metrics associate the process(es) to be evaluated with the identified indicator [15] [16]. Some of the earliest proposed sustainability indicators and metrics were sourced from life cycle assessment (LCA) [17,18], and used to evaluate company performance [19]. These indicators were categorized by Joung et al. [3] who discovered that, while there is a large number of social indicators, there are few related social metrics. In part, the lack of social metrics is due to the inability to accurately quantify a number of qualitative indicators [27].

The most common indicators include material, energy, and waste [20] as they are tactile and easily measurable. Other authors noted that only recently have efforts incorporated system level indicators into the final sustainability decision making process [21]. Only recently has focus shifted towards extending indicators and measurement methods to cover factory, system, and unit process impacts. Linke et al. [22] developed process level metrics for use in grinding operations, noting that grinding require different metrics than other processes [23]. Further, only recently have methods been devised to account for factory overhead, such as HVAC systems, into the decision making process for production [24]. However, in an interesting dichotomy, as more metrics and measurement methods have been introduced and the process flows been made more complex [25], the number and scope of tools available to aid sustainability assessment for decision makers has multiplied to unmanageable levels [26,27].

The perceived deficit in metrics for the social performance area has not interrupted the profusion of unique tools and methods for assessing sustainability. From the perspective of industry, however, these tools tend to be limited in relevancy as a result of being either too narrow in focus, and thus myopic, or too broad in focus, and therefore inaccurate [28]. Furthermore, the tools often do not consider the technical or cultural maturity of the organization and thus contain no provisions for adaptability [29]. A need has arisen for simple, easy to use tools [26] that are standardized, well-rounded, and well-communicated to individual companies [30], as well as scalable to meet the maturity of companies' sustainability endeavors.

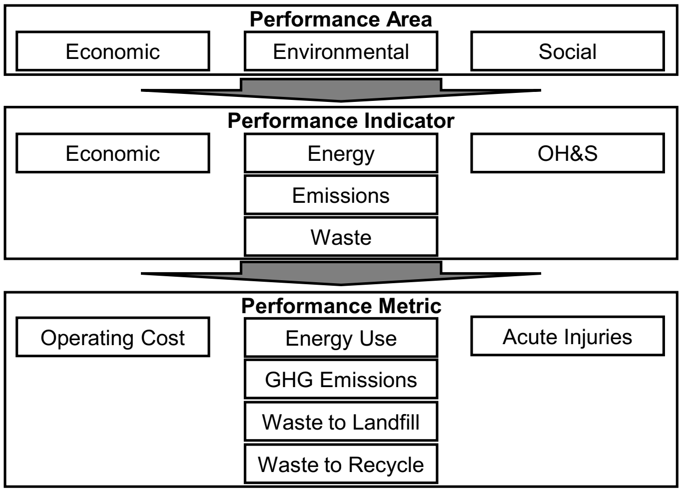

FIGURE 3: MANUFACTURING INDICATORS/METRICS [31]

In light of the findings of the literature review, the questions posed during the dialogue were designed to address these deficits and gather useful information for wider distribution to the research community.

1. What approaches do companies use to understand process-level issues and their effects on system-level performance?
2. How are manufacturing performance indicators selected?
3. What tools, methods, and systems are used to capture and track manufacturing-process level performance indicators?

Manufacturing Process Modeling

While the research into manufacturing process modeling has seen advancements (see [32,33]), the prevailing methods and tools employed by small and medium size enterprises (SMEs) to characterize and assess the sustainability performance of their processes are diverse and *ad hoc* [28]. This is the result of a deficit in standards development for modeling processes and conducting sustainable performance assessments. Standards for representing manufacturing processes and the collection of sustainability-related data would support sustainability analysis and facilitate reuse of that data in multiple types of analyses [16][15].

Central to a process model is the unit manufacturing process (UMP). UMPs have two inherent themes. The first considers that the UMP is the smallest element in manufacturing [1]. The second is that value is added through a specific shape, structure, or property transformation. UMP models are developed to explore process and material interactions, and can be used to quantify sustainability metrics [34]. The models, developed through mechanistic relationships or empirical observations [31] relate material and energy inputs to outputs and can account for variations in the process. A process model represents a process or set of processes by incorporating process and workpiece analytics. This allows reusability of the model in sustainable manufacturing evaluations. A process model links the internal transformation of inputs to outputs to the evaluation metrics selected for final performance evaluation [35] (Fig 4).

In the process model, the transformation of the workpiece requires a set of inputs, which are then converted into output form. In the figure, each input arrow is uniquely drawn to emphasize a special characteristic. Information relays the process and workpiece parameter settings, and can enable composing of UMP models. Consumables are expended through use and outputted as wastes or emissions. Energy is transformed, not consumed in the traditional sense. Labor is a necessary input that can result in labor hazards, or injuries imparted to the worker. For each set of inputs and outputs, a set of evaluation metrics connected to selected performance indicators that can be tracked to determine the system performance.

A brief review of the literature revealed what research has been conducted in the field and what deficits exist that could benefit from industry inputs. The first process models used theoretical physics to estimate the impact of the chosen environmental indicators [36]. Later process models were more empirically based, such as the energy models developed by Gutowski et al. [37] and Li and Kara [38]. More recently, the CO2PE! initiative developed models using a standard unit process life-cycle inventory approach (UPLCI) [39]. UPLCI was defined by Overcash and Twomey [40] to contain an overview of the process, literature data and references, a parameter selection of the process, life-cycle inventory (LCI) energy calculations, and LCI mass loss calculations. The intent of this method is to bridge the gap between UMP modeling and LCA and has been used to model the energy and material flows of laser sintering and stereolithography [41], and grinding [42] to more transparently and accurately determine the environmental impact of the respective processes.

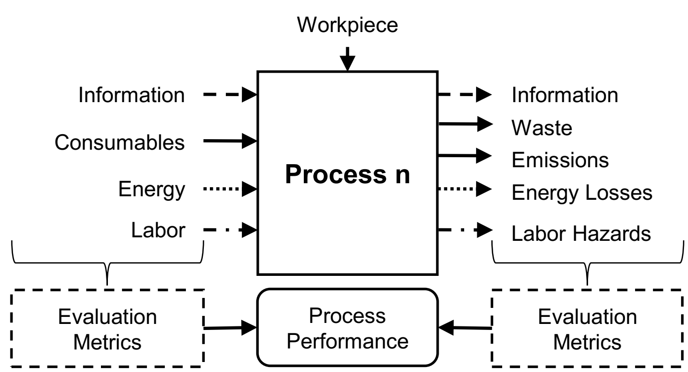

FIGURE 4: UMP MODEL SCHEMATIC WITH PLACEMENT OF SUSTAINABLE EVALUATION METRICS ADAPTED FROM GARRETSON [35]

Others have worked to aid decision making in UMP modeling through benchmarking [43], focusing only on waste, energy, and materials [20], or attending to the variability, information, and modeling uncertainty inherent in UMP models by incorporating Bayesian Networks [44]. Model uncertainty has been investigated using Monte Carlo simulation [45]. Extending the work of integrating sustainability into the supply chain, Kremer et al. [46] reasoned that supply chain methods and tools fail in industry applications for a number of reasons, e.g., exclusion of manufacturing process modeling from "what if" analysis when selecting suppliers.

The literature review identified several deficits related to manufacturing process modeling: First, there are challenges in determining the most accurate method for modeling a given process; second, there are challenges in allocation of system overhead to the process level; and third, there is a lack of simple tools to first model unit processes and subsequently link them together. The dialogue on manufacturing process modeling was designed around these central concerns. The questions asked were:

1. What is the value of modeling manufacturing processes?
2. How does your company characterize individual manufacturing processes?

INDUSTRY PERSPECTIVE

The following section reports on the findings from the industry roundtable dialogues related to manufacturing metrics and measurements. The second section reports on the findings from the dialogues on manufacturing process modeling.

Manufacturing Metrics and Measurements

When asked what approaches their companies had used to understand the effect of process-level issues on system-level performance, participants overwhelmingly identified using metric heavy approaches including such metrics as defect rate and labor cost. The companies represented at the roundtables used a variety of methods to assess the quality of their products (e.g., defect detection systems, flow analysis, data analysis, and on-line inspection). Standards for judging quality are typically set industry wide; however, no standard exists for how to measure quality. For example, a representative from the wood products industry mentioned their company built windows in two different facilities. The final quality grade was the same, however, the measurement method used to inspect build quality differed.

On the topic of sustainability performance, the consensus was that most sustainability assessments focus only on system level environmental and social indicators and metrics and are commonly conducted in consultation with LCA practitioners. The intent of these sustainability assessments is to identify areas for improvements, though these can become quickly exhausted if the focus is only system level indicators (e.g., factory energy consumption and total waste). To identify new improvement opportunities requires tracking and reporting process-level data and information.

Means for tracking the process-level issues include various types of control and monitoring devices. Historical data is used to identify root causes of process issues and map process responses to control parameters. For example, a carbon nanotube manufacturer required 2-3 years of data to understand process operation. Another common approach identified was the use of factory floor operator experience, go/no go gauges, and, generally, holding line managers accountable for process control. Identifying and selecting metrics for process-level tracking is often done based on the experience of managers and line operators and only in response to specific problems.

The result is that metrics and their related process equations are not standard and often are not documented in a standard manner, if at all, and many metrics rely on a controller's tacit knowledge of the process. This lack of standardization and reliance on expert knowledge leads some business units to be starved of data, while others are inundated. Standards (e.g., AS 9001) were discussed by a few participants as a means of addressing the data and metric disparity by centralizing a common core of measurements, metrics, and indicators.

When asked if currently utilized indicators and metrics originated and were communicated from top down or bottom up, participants identified waste generated and safety, alongside quality, as common top-down performance metrics. Common bottom-up metrics are those that are quantifiable, e.g., energy, water, and waste – with waste appearing to be the only commonality. In general, bottom-up metrics are reactively developed to meet the mandated top-down (often regulatory) indicators. Compliance is achieved by employing bottom-up metrics to improve modeling accuracy and system performance at the process level. Industry also proactively select indicators to improve quality or to reduce the risk of environmental accidents. Some are even selecting indicators to gain sustainability minded customers or benchmarking against other companies using indices (e.g., Dow Jones Sustainability Index).

However, industry continues to struggle with the organizational difficulties of reconciling bottom up with top down indicators and metrics. The same is true for communication of information and goals among different business units. This disconnect is due to business autonomy with the result that both bottom-up and top-down data and metrics often become siloed within a business unit.

Communication between engineering departments and shop floor operations was identified by managers as a continuing struggle. Oftentimes communication is one sided, with management sending work instructions to shop floor personnel with no intention of receiving feedback. This wall between management engineering and shop floor was widely agreed upon by participants as the largest contributor to system, process, and product issues. Furthermore, there was common agreement that it can be difficult to engage shop floor personal to enact top down initiatives. A few participants noted that in their experience, incentives such as cash handouts or dashboards can act as pushes to overcome these barriers.

In summary, most metrics and measurement methods are selected on the experience of the managers. Repeated on a large scale, this compartmentalization leads to a lack of uniform and formally-defined metrics and methods to capture manufacturing process data across an industry. This lack of standardization inhibits industry's ability to benchmark and collectively learn best practices. Furthermore, without standardized metrics and measurements, standardized process models cannot be successfully created. The topic of manufacturing process modeling is presented in the next section. Manufacturing process modeling was the focus of the third and final dialogue session.

Manufacturing Process Modeling

The first question asked of participants gathered high-level inputs on the perceived value of manufacturing process modeling and the use of tools for manufacturing process modeling. One of the more prominent values is the increased prediction accuracy compared to control or monitoring only. The literature review concluded that UMP modeling has the capability to increase the accuracy of sustainability assessments by quantifying resources in the form of labor and machine hours, equipment utilization, energy, and water use to produce a product or perform a process. Yet, due to the number of competing tools and methods advocated by the literature, industry is loath to adopt a new method or tool from a yet to be standardized field. For example, participants noted that other time-tested techniques (e.g., Six Sigma and lean techniques) or tools (e.g., ARENA) accomplish the desired quality and accuracy goals.

This reluctance extends to the adoption of new resources. Common resources dedicated to process modeling include software for computational fluid dynamics (CFD), input-output mass and energy balances and process flow analysis (e.g., Aspen), environmental impact (e.g., SolidWorks Sustainability), solid modeling (e.g., Pro/ENGINEER), and specialized tools in MS Excel. Process failure modes and effects analysis (P-FMEA) has been used, but does not have suitable off-the-shelf tools for sustainability analysis. In most cases these tools are not equipped to facilitate UMP modeling. Most software tools address sustainable design-for-manufacture but not the sustainability of the manufacturing processes themselves. Furthermore, these tools often lack accurate databases, forcing companies to construct unique internal databases.

From a mathematical standpoint, manufacturing process transformations are calculated using first principles. For activities requiring more accuracy, companies turn to empirical modeling. Model uncertainty is handled using Monte Carlo analysis, and some participants noted seeing Bayesian analysis used in practice. In both cases, these techniques are applied piece-wise to a single chosen process. Moving from the process to the facility, process flow diagrams and material flow analysis are sometimes used for modeling plant layout, plant replication, and plant improvement.

In summary, industry is hesitant to adopt UMP modeling for a number of reasons. First, the sustainability literature shows little cohesion or unison in advocating a common approach to UMP modeling. This makes industry wary to adopt methods and tools that run the risk of become obsolescent. Second, industry is aware that the benefits of UMP modeling may not be apparent until after the models have been developed, but the nascent state of UMP research reduces the industries willingness to invest the resources necessary to create these models. In the next section, the results of comparing the two perspectives are presented as a discussion on the perceived barriers to the adoption of standards and recommended changes to current practices.

RESEARCH FINDINGS

Based on a comparison of the literature review and the industry roundtables, a set of identified barriers and recommendations was developed. This set emerged by identifying deficits between theory and practice. They are presented below in tabular form (Table 1 and Table 2).

Comparing the findings from literature with the results of the roundtables illustrates several key findings where literature and industry diverge in theory and practice of UMP modeling. The summary conclusion from industry is that product quality remains the key process indicator. Supported by lean principles, the implicit understanding is that increasing quality at the process level reduces system level costs. Yet, the sustainable manufacturing literature on the topic of product quality as an indicator and metric is brief. Product surface quality has seen extensive research [23,47,48], however, this work is still in the minority from sustainability perspective. For example, in a recently proposed sustainable indicator framework to aid small manufacturers, only one indicator could be directly related to product quality, and the rest measure the costs related to manufacture of the product and not the product itself [49]. This also alludes to the discrepancy between sustainable metrics and accounting principles. That is, few metrics explicitly connect the sustainability performance of UMPs to cost competitiveness. Furthermore, while the literature details many bottom-up metrics, the consensus among larger, more mature industries is that top-down metrics dominate as dictated by government regulations. Recently, there has been a trend in the sustainability research field to respond by incorporating elements of public policy and governance into sustainability tools and methods [50]. The need is for bottom-up metrics that satisfy top-down compliance requirements. Industry and academia are working to address these issues, such as with the development of process metrics to aid tracking of social indicators, e.g., worker safety [35]. Even if all of the above situations were solved, industry participants adamantly noted that the final hurdle often encountered in conducting sustainable performance assessments is due to the breadth of the available specialized tools. The lack of standardization in sustainability assessment methods has led to a profusion of individual tools encapsulating different methods [51].

Proposed solutions to this and other identified barriers are presented in the following Relevant Standards Efforts section.

RELEVANT STANDARDS EFFORTS

This section presents the current standards capable of addressing the identified industry concerns. Existing manufacturing standards provide instructions for designers, engineers, builders, operators and decision makers to conduct activities within their fields. They also facilitate communication between stakeholders across different organizational borders. Furthermore, standards facilitate information transfer across borders of the manufacturing system hierarchy and between life cycle phases. Standards are fundamental to advanced manufacturing systems to facilitate the delivery of information to the right place at the right time. Standardization enables automating system responses and permits establishing repeatable processes all sharing common functional understanding. This reduces the cost of adopting new technology.

TABLE 1: IDENTIFIED BARRIERS TO THE ADOPTION OF STANDARDIZED SUSTAINABLE ASSESSMENT TOOLS AND METHODS

Manufacturing Metrics & Measurements	
• Current tools do not emphasize usability with their steep learning curves	• Standards cannot address the needed cultural change to address sustainability in a proactive manner
• No standard method exists for combining process and system level indicators in a holistic manner	• Sustainability R&D projects do not receive equal funding within companies
• Current tools and methods do not always show immediate practical change; a necessity for adoption by industry	• Standards do not address the potential for falsification of material or process data by companies
• Recertification of a manufacturing process after modification is a financial barrier to wider standards adoption	• Sustainability metrics included in standards do not explicitly address quality; a common measure of performance amongst companies and individuals
• Companies and suppliers hesitate to share sensitive process data or models for fear of losing trade secrets or competitive advantage	• Tools and methods will not be widely adopted if they require the upgrade or replacement of analogue, but still functional, machinery
• Incorporating new methods, tools, or standards requires large time investments before showing practical results	• Current research lacks a cohesive theory on how to evaluate and close the design-for-manufacturing gap
Manufacturing Process Modeling	
• Regulatory changes can antiquate currently used methods or tools	• Proposed process models risk sub-optimization occurring when only considering least cost manufacturing
• Commercial software packages are costly and fragmented impeding their wide-scale adoptions	• Standards cannot readily address the difficulty of sharing process models and linking them due to process setup variability and machine age

To this end, ASTM International has formed both a committee on Sustainability (E60) and a Subcommittee on Sustainable Manufacturing (E60.13) [52].

Of immediate relevance to this paper is the recently published *E3012-16 Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes*, provides guidance for the actual characterization of manufacturing processes [16]. This guide outlines a characterization methodology and proposes a generic representation from which manufacturers can derive specific UMP representations for meaningful sustainability performance analysis. Also, ASTM published two related standards namely, *E2986-15 Standard Guide for Evaluation of Environmental Aspects of Sustainability of Manufacturing Processes*, which provides guidance for manufacturers on how to conduct a sustainability study in order to improve their practices [15] and *E2987/E2987M-16 Standard Terminology for Sustainable Manufacturing*, includes terminology applicable to sustainable manufacturing [53]. Other relevant standards under development within the E60.13 Subcommittee include:

- Classification for Waste Generated at Manufacturing Facilities,
- Guide for Integration and Reporting of Environmental and Social Sustainability within the Manufacturing Supply Chains,
- Standard Specification for Net-Negative Landfill Waste Manufacturing Processes.

The vision of these standards is to provide manufacturers with a way to better describe their manufacturing processes with regards to sustainability. This will facilitate data exchange, sharing and communication with other manufacturing applications, such as LCA. The ease with which data can be exchanged and compared sets the stage for the development of decision-making tools capable of benchmarking sustainability process performances. These tools access standardized repositories of reusable UMP models.

CONCLUSIONS

With limited resources available and cultures that have yet to become proactive, companies have struggled to implement sustainability initiatives that extend deeply into their operations. In part, this is the result of research advocating the use of many indicators and metrics, without providing easy-to-learn, quality introductory tools or directly equating all metrics to cost values. On the other hand, industry is reluctant to collectively share, even if anonymously, information regarding processes and materials.

The findings from the roundtable meetings indicate a need for metrics that are simple and relate to core business practices, transparent data and information flows, process models that are accessible, accurate, and standardized, and incentives to speed the adoption of these methods. From the results of the roundtables, it is apparent that the development of standards for representing manufacturing processes and collecting relevant sustainability data is both needed and will support industry's ability and desire to collect more accurate data for sustainability assessment. Further, these standards will support the reuse of that data in multiple types of analyses.

TABLE 2: RECOMMENDED CHANGES TO CURRENT PRACTICES TO FACILITATE ADOPTION OF STANDARDS

Manufacturing Metrics & Measurements	
• Orient standard metrics to explicitly state cost value to appeal to high level management who are chiefly concerned with maintain cost competitiveness and market share	• Due to the high cost of creating full manufacturing process models, create a "light" version focusing only on primary process drivers to alleviate initial investment concerns
• Make metrics and indicators standard industry wide to facilitate friendly competition and increase supplier participation	• Develop a library of materials and UMPs to aid design-for-manufacture decision making and to be incorporated into the engineering toolbox
• Make tools with an easy entry version to highlight small improvements and aid in identifying low hanging fruit and to justify larger investments	• Engage shop floor personnel by showing real-time feedback on the sustainability performance metrics through visualizations, such as dashboards
• Any sustainable manufacturing tool should be usable on current equipment (e.g., machine tools) to demonstrate future usefulness	• Incorporate process modeling into the manufacturing step of LCA to increase total model accuracy and identify areas for improvements
• Incorporate traceability into sustainable manufacturing tools as it is frequently requested by manufacturers	• Plan for the introduction of new top-down regulations and their impact on product manufacturing
• Clearly and uniformly define tool boundaries and capabilities to reassure industry that they are purchasing and using the correct tool	• Demonstrate an allocation method for system-level indicators, such as how occupational health and safety information is directly relatable to product manufacture
• Identify environmental impact drivers using on-the-line data and not industry or facility averages	• Incorporate accountability of materials and consumables into assessments e.g., including impact of an alternative solvent within an LCA
Manufacturing Process Modeling	
• Consider regional location, access to resources, and laws when conducting LCAs and developing process models. No standard as of yet allows a large degree of localization freedom or adaptability	• Make models and data generated by a standard or government accessible to all e.g., integrate with the Digital Commons or the NREL U.S. Life Cycle Inventory Database
• Future standards development should integrate UMP models back into LCA methods and tools	• Standardize the composability of UMP models such that they do not require soliciting the individuals who created the process models to understand the underlying process models

Future work will involve the deployment of the proposed standards for sustainable manufacturing. Pilot projects in specific industries will serve to validate the standards and their usability, utility, and benefits. Projects will be designed to address a chosen problem within a company and apply the new standards to facilitate the problem definition and data collection. The standards [16][15] shall guide the user through selecting a goal, choosing relevant indicators, assigning process boundaries, identifying process metrics, and determining the input-output transformations. Experience gained from the completion of pilot projects will influence future editions of the standard. Further, the pilot projects will lay the foundation for exploring composability of UMP models.

Composability is an ongoing area of research into modeling how UMPs meaningfully interact and link together within manufacturing systems [35,54]. The suggestions and barriers identified in the dialogues support the reasoning that standards are needed to assist in the composition of the process models such that process-level issues can be holistically evaluated and mapped to the system-level decision making. Future work and standards development will involve developing tools and methods capable of assessing the sustainability of manufacturing systems. This system should be supported by information models that standardize the relationships between UMPs [55], which would further the goal of integrating sustainability into manufacturing system performance decisions [56].

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