Reusable Models of Manufacturing Processes for Discrete, Batch, and Continuous Production

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Abstract

This article explores the new ASTM E3012-16 International Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes, its application and potential impact in the manufacturing industry. The standard provides guidance for industries to examine unit manufacturing processes, capture characteristics in terms of how they impact the environment, and explore opportunities to be efficient and sustainable in their operations. The standard further encourages formal representations for consistent and effective deployment of manufacturing tools and reuse of data and information models for automated analysis.

Introduction

TO REMAIN COMPETITIVE manufacturers today seek to improve productivity while maintaining quality and meeting sustainability objectives. With the manufacturing sector consuming a large percentage of our national resources, smart manufacturing and sustainable manufacturing implementations through process optimization hold tremendous potential for improvement[1,2,3,4]. Being cognizant of the production improvement opportunities is key to success. But where do we start? Starting at the process level poses an opportunity – an opportunity to improve process performance through the meticulous understanding of selected processes.

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[1] Mani, M., Madan, J., Lee, J. H., Lyons, K. W., & Gupta, S. K. (2013). Review on Sustainability Characterization for Manufacturing Processes. National Institute of Standards and Technology, Gaithersburg, MD, Report No. NISTIR, 7913

[2] Haapala, K.R., Zhao, F., Camelio, J., Sutherland, J.W., Skerlos, S.J., Dornfeld, D.A., Jawahir, I.S., Clarens, A.F. and Rickli, J.L., 2013. A review of engineering research in sustainable manufacturing. Journal of Manufacturing Science and Engineering, 135(4), p.041013

[3] Stephan Mohr, Ken Somers, Steven Swartz, and Helga Vanthournout, Manufacturing resource productivity, McKinsey Quarterly, June 2012.

[4] https://itif.org/publications/2018/11/28/innovation-agenda-deep-decarbonization-bridging-gaps-federal-energy-rdd

Eventually, these individual opportunities can be harnessed at a systems level where multiple manufacturing processes work in concert. Characterization of process-level activities can empower better engineering at higher levels of manufacturing automation and control. These control levels are described in the widely-acknowledged enterprise to control system hierarchy (ISA 95[5]). Besides this, the ISO 14000 family[6] of environmental management standards are useful towards developing a management approach to sustainability and retroactively comparing the impacts of different comparable products. But, specific guidance for manufacturers to characterize individual processes and identify opportunities for improvement can be an added advantage. To provide such guidance for industries to examine basic manufacturing processes (a.k.a. unit manufacturing processes) ASTM International[7] issued a set of standards, including E2979-18[8], E2986-18[9], E2987-18[10], E3012-16[11], and E3096-18[12]. These standard guidelines help manufacturers scrutinize and capture the characteristics of individual processes in terms of how they impact the environment, and look for opportunities to be more sustainable in their operations.

This article specifically explores the new ASTM *E3012-16* International *Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes*[13] and its consideration for use with discrete, batch, and continuous production. The standard provides guidance for industries to examine unit manufacturing processes, capture the

5 https://www.isa.org/isa95/
6 https://www.iso.org/iso-14001-environmental-management.html
7 https://www.astm.org/
8 ASTM International (2018). E2979-18: Standard Classification for Discarded Materials from Manufacturing Facility and Associated Support Facilities.
9 ASTM International (2018). E2986-18: Standard Guide for Evaluation of Environmental Aspects of Sustainability of Manufacturing Processes.
10 ASTM International (2018). E2987/E2987M-18: Standard Terminology for Sustainable Manufacturing.
11 ASTM International (2016). E3012-16 Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes.
12 ASTM International (2018). E3096-18 Standard Guide for Definition, Selection, and Organization of Key Performance Indicators for Environmental Aspects of Manufacturing Processes
13 https://www.astm.org/E3012-16.htm

characteristics of those processes in terms of how they impact the environment, and look for opportunities to be more sustainable in their operations and improve their efficiency. The standard also encourages standard representations for consistent and effective deployment of manufacturing tools and reuse of data and information models.

Current Gaps and Potential for Standards

Several workshops[14, 15] facilitated by the National Institute of Standards and Technology (NIST)[2] across the U.S. have reiterated the viewpoint that gaps exist in terms of measurement capabilities to connect sustainable manufacturing practices with the promotion of resource efficiency. Today's practices for sustainability-related analysis for products do not explicitly account for individual manufacturing processes. Current practices fall short in promoting a science-based understanding of individual processes critical for their performance improvement and decision making[16,17]. Formal methods for collection and consolidation of sustainability related information on manufacturing processes is lacking.

The measurement science—including methods for process description, performance metrics, and a corresponding information base for unit manufacturing processes—will allow for a more consistent evaluation of sustainability performance across manufacturing systems. Providing the science in the form of best practices is a goal for the ASTM International standard.

[14] M. M. Smullin; K. R. Haapala; M. Mani; K.C. Morris. 'Using industry focus groups review to identify Challenges in sustainable assessment theory and practice.' ASME International Design and Engineering Technical Conferences & Computers and Information in Engineering Conference, Charlotte 2016

[15] W.Z. Bernstein *et al.,* 2018. 'Research directions for an open unit manufacturing process repository: A collaborative vision,' Manufacturing Letters, 15 (B), pp.71-75

[16] M. Mani, Madan, J., Lee, J. H., Lyons, K. W., & Gupta, S. K. (2014). Sustainability characterization for manufacturing processes. International Journal of Production Research, 52(20), 5895-5912.

[17] Duflou, J.R., Sutherland, J.W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M. and Kellens, K., 2012. Towards energy and resource efficient manufacturing: A processes and systems approach. CIRP Annals-Manufacturing Technology, 61(2), pp.587-609

ASTM International Standards on Sustainability

ASTM International is a global leader in the development of voluntary consensus standards. ASTM International formed the E60.13 Subcommittee on Sustainable Manufacturing to guide industry in best practices to inform sustainability-related decisions. More information on the standards published through this committee can be accessed from the committee website [18]. The E60.13 E3012-16 standard defines a methodology to develop *unit manufacturing process* or *UMP* information models. The standard contributes to the measurement science needed to quantify sustainable manufacturing practices to the benefit industrial competitiveness. Standard methods for describing the environmental choices that a manufacturer makes allow them to improve their practices and to differentiate themselves from the competition.

Application of the standard benefits manufacturing practices in two ways. First, it raises consciousness about manufacturing processes, their environmental impacts, and opportunities for their improvement. The goal of applying the standard is to improve the environmental aspects of the process through the definition of key performance indicators specific to an individual process addressing potential enterprise level goals. Establishing that rigor sets the stage for better informed decision-making and production planning.

The new ASTM standard provides guidance to help manufacturers effectively understand processes, capture process characteristics in terms of decision making and, as a result, leads to more sustainable systems. Secondly, the use of standard practices and formal representation methods poises manufacturers for transition into scientific modeling environmental impact, and identify opportunities for improvement. Characteristics of a processes imply descriptions of what goes into and out of the process, how the process transforms its inputs to outputs, and what types of information is used in the transformation. The standard format defined in ASTM E3012-16 provides a basis for ensuring that a specific set of details are defined and that they are covered in a consistent manner. See Figure 1. In this way, the standard offers a method to generate reusable constructs (UMP information models) that provide a structured way of both understanding and specifying

[18] https://www.astm.org/COMMIT/SUBCOMMIT/E6013.htm

unit manufacturing processes. Such constructs presented in an abstract and precise manner can be parameterized and reused in different application contexts like information processing, simulation, and analysis. The standard makes for better comparisons, increased reuse, and, in the end, more reliable results.

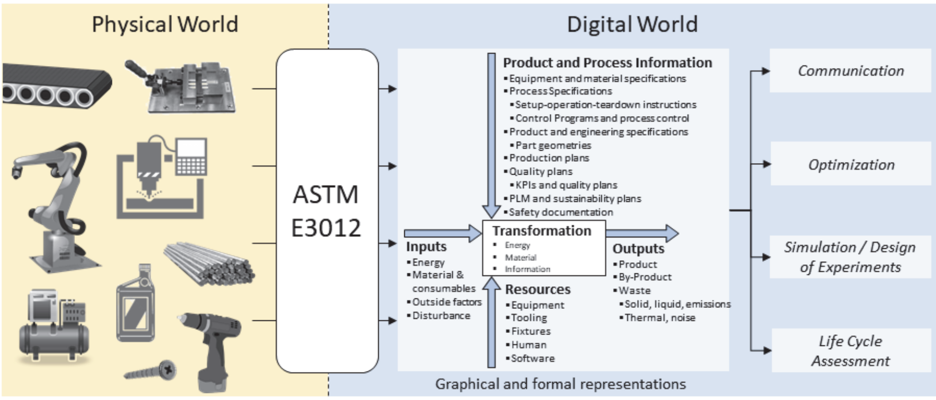

Figure. 1 Overview of the significance and use of this standard. UMPs store digital representations of physical manufacturing assets and systems to enable engineering analysis, *e.g.*, optimization, simulation, and life cycle assessments.

Potential Impact

ASTM E3012-16 is a good starting point for creating reusable descriptions of manufacturing processes that will ultimately realize process analytics and tool integration. In addition to systematic characterizations of processes, the formal representations for those characterizations support the direct use of the information within a variety of applications. The most basic application is to support effective communication by ensuring consistency and completeness. More advanced applications include computational analytics and comparison of performance information. The formal information model described in the guide facilitates new software tool development to link manufacturing information and analytics for calculating environmental performance measures. Further, the standard format paves the way for more specific software tools supporting the development and extension of standardized data and information bases such as Life Cycle Inventory (LCI). LCI data is extensively used in life cycle assessments (LCA), part of the 14000 family of standards. The top down approach of the ISO 14000 family and the bottom up measurements approach from ASTM standards are complimentary.

Formally defined UMP models can cater to different user information from a variety of perspectives. For example, using the standard,

- a variety of stakeholders, *e.g.*, plant managers, process engineers, technicians and operators, can better understand and communicate manufacturing processes through consistent and tailored views of the model;
- manufacturing engineers can develop system models from the unit manufacturing processes by linking them together to characterize specific production plans for discrete batch or continuous production;
- systems integrators can use models of manufacturing processes to understand material and information flows, and
- manufacturers can capture their own data for LCA-based environmental assessments by developing data sets representing the environmental impacts of their unit processes, complimenting and sharpening LCI data sets.

In a related work, the authors explored the use of the standard with three use cases in the pulp and paper industry. The case studies showed the utility of the draft standard as a guideline for composing data to characterize manufacturing processes. The data, besides being useful for descriptive purposes, was used in a simulation model to assess sustainability of the manufacturing system.[19,20]

Scope of the Current Standard and Beyond

Leveraging unit process models is by no means a new idea to continuous process industries, such as the Chemical Industry. For nearly a century, mathematical representations of "unit operations," such as

[19] Mani, M., Larborn, J., Johannson, B., Lyons, K., & Morris, KC. (2016). Standard representations for sustainability characterization of industrial processes. Journal of Manufacturing Science and Engineering

[20] Rebouillat, L., Barletta, I., Johansson, B., Mani, M., Bernstein, W.Z., Morris, K.C. and Lyons, K.W., 2016. Understanding sustainability data through unit manufacturing process representations: a case study on stone production. Procedia CIRP, 57, pp.686-691

filtration, evaporation, humidification and distillation, have been derived for controlling both small-scale plants and industrial installations.[21] Considering the longevity of the unit process-based approaches in Chemical Engineering[22], the authors envision its direct relevancy to the process industry and beyond. The hope will be that the formal characterization of UMPs across diverse industries would enhance existing analysis frameworks, such as improving the precision of life cycle assessment, a method that still is burdened with significant uncertainty.[23]ASTM E3012-16 is designed to be relevant across different production types, including discrete, batch, and continuous. The standard provides a fundamental representation to support unit manufacturing process in all of these production settings. Characterizing the bounds of each unit manufacturing process drives insight into each process's functional characteristics.

The current standard is a first step to facilitate studies of existing processes and to make those studies more accessible in the future. It can serve as the basis for the development of production system models to better understand process flows and interactions between and across different processes. A repository of UMP models can be used for planning both to retrofit existing facilities or for new facilities. Designs for new facilities are almost always based on prior experience with operating processes and realistic models should prove useful especially for verification and validation activities.

The perceived scientific benefits to manufacturers from application of the standard include reduced operational costs, improved prediction of product costs, improved schedule, maximization of manufacturing resources, improved control of product quality, and incorporation of best practices. Modeling individual manufacturing processes facilitates the generation of quantifiable evidence that improvements are being made. The standard provides a uniform and repeatable way for more practitioners to reap these benefits.

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[21] Walker, W.H., Lewis, W.K. and McAdams, W.H., 1923. Principles of chemical engineering. London: McGraw-Hill Publishing Co

[22] Turton, R., Bailie, R.C., Whiting, W.B. and Shaeiwitz, J.A., 2008. Analysis, synthesis and design of chemical processes. Pearson Education.

[23] Jacquemin, L., Pontalier, P.Y. and Sablayrolles, C., 2012. Life cycle assessment (LCA) applied to the process industry: a review. The International Journal of Life Cycle Assessment, 17(8), pp.1028-1041

The standard will be of interest to software providers across industries interested in providing analysis and modeling/simulation solutions to manufacturers. The standard format promotes information exchange and communication through digitalization of manufacturing assets for decision making purposes. Moving forward, with contribution from industries, future standards can encompass a broader set of processes and functionalities using ASTM E3012-16 as a platform on which to build. Further, the creation of a repository of models should reduce modeling time and improve model verification and validation activities. The creation of a repository of models also provides a forum for industries to come up with best practices and target sets of UMP models for common processes as reference data.[24]

Future Work and Conclusions

As a relatively new standard co-developed by supportive manufacturers, the ASTM task group is now seeking more participation from across industries, especially SMEs, to demonstrate and further improve the standards. The standard has already received some attention and efforts are underway to spread the word. Much of the vision for the work will require further research and future standards based on real world experience[25]. UMP-focused industrial case studies are of interest to the task group. NIST has already hosted two competitions, and will host a third, to apply the standard to existing process models.[26] This resulted in a diverse set of models and focused attention within the educational world. To realize the promise of reusing such models and automating analytics and system integration for manufacturing significant research challenges remain including advancements in the following areas

- **Knowledge and understanding of UMP modeling**. This includes novel formal representations and methodologies, more accurate or specialized metric, metric representations that support cascading to

[24] W. Z. Bernstein; M. Mani; K. W. Lyons; K.C. Morris; B. Johansson. 'An Open Web-Based Repository for Capturing Manufacturing Process Information.' ASME International and Design and Engineering Technical Conferences & Computers and Information in Engineering Conference, Charlotte 2016

[25] W.Z. Bernstein *et al*., 2018. 'Research directions for an open unit manufacturing process repository: A collaborative vision,' Manufacturing Letters, 15 (B), pp.71-75

[26] https://www.nist.gov/news-events/events/2018/01/ramp-reusable-abstractions-manufacturing-processes

higher production levels, or exploration of variations for families of UMP models.

- **Standards supporting models reuse**. This includes automated methods that allow linking of UMP models into systems, facilitating system composition through naming conventions or other methods, generalization that unifies a collection of processes, or standards-based methods for integration with applications.
- **Techniques for development and validation of UMP models**. This includes demonstration of validation techniques for the effectiveness and accuracy of the UMP models or techniques for producing useful derivatives of UMP models or creative methods for mining documentary model descriptions into formal representations.

As more groups apply the standard in their domains, the shared experience will provide a basis on which to further understand standardization needs and opportunities. Formal methods for acquiring and exchanging information about manufacturing processes will lead to consistent characterizations and help establish a collection for reusable models. Standardized methods will ensure effective communication of computational analytics and sharing of sustainability performance data. NIST is also looking for manufacturers to collaborate on pre-pilot projects to contribute to the collection of use cases for the standard. In conclusion, the use of a reusable standard format should result in models suitable for automated inclusion in a system analysis, such as a system simulation model or an optimization program

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Bios

Mahesh Mani is a Senior Technology Adviser with Allegheny Science and Technology supporting the Advanced Manufacturing Office of the Department of Energy. His research interests include smart, sustainable and additive manufacturing.

KC Morris leads a group at the National Institute of Standards and Technology focused on standards to infuse smart technologies into the manufacturing sector while ensuring that new practices lead to more competitive and sustainable manufacturing. Currently, KC is on detail to the US House of Representatives serving as an ASME Manufacturing Fellow.

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