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Letters

Research directions for an open unit manufacturing process repository: A collaborative vision

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ABSTRACT

The design of manufacturing systems can see dramatic improvements through the use of digital technologies for modeling and simulation prior to deployment. At the 2017 ASME International Manufacturing Science and Engineering Conference held jointly with the 45th SME North American Manufacturing Research Conference, researchers met within a workshop to discuss structuring and presenting research for modeling manufacturing processes to support life cycle assessment. Workshop participants explored a vision for using standard formats to represent manufacturing processes in a community-based repository and identified research opportunities and challenges. This paper places these resulting research directions into a plan for implementing the vision.

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1. Introduction

The convergence of digital components with advanced manufacturing technologies, or the paradigm of *smart manufacturing*, is fundamentally changing the way organizations design, control, and maintain production systems [1]. To support this trend, researchers at the National Institute of Standards and Technology (NIST) have proposed an open repository that stores unit manufacturing process (UMP) models to provide reference material to US manufacturers [2]. The objective of this *UMP Repository* is to facilitate collaboration among industry and researchers to take advantage of emerging digital technologies and to support innovative manufacturing-related research that will improve sustainability performance across the product life cycle.

Recently, ASTM International published a standard for formally characterizing manufacturing processes to enable the sharing and use of structured manufacturing-process information [3]. Implementing this standard can aid in optimizing process plans, minimizing energy consumption, or controlling material flow. When a group of manufacturers adopt compatible modeling methods, sharing information across organizations can result in new opportunities for industry-wide analysis.

The UMP Repository will provide an environment wherein industry and academia can share process-specific information, access formal representations of manufacturing processes, and reuse manufacturing information. One challenge is that traditional manufacturing systems lack unifying frameworks to enable seamless sharing and reproducibility of manufacturing-related data. Defining a data format that can be shared between manufacturing processes and system models will create information-reuse opportunities.

Understanding the issues with deploying a distributed, shared ecosystem is critical to support implementation of the UMP Repository. If fully realized, the development of a common, open repository for manufacturing information will influence ASTM International standards for characterizing manufacturing processes and could provide a baseline for identifying new

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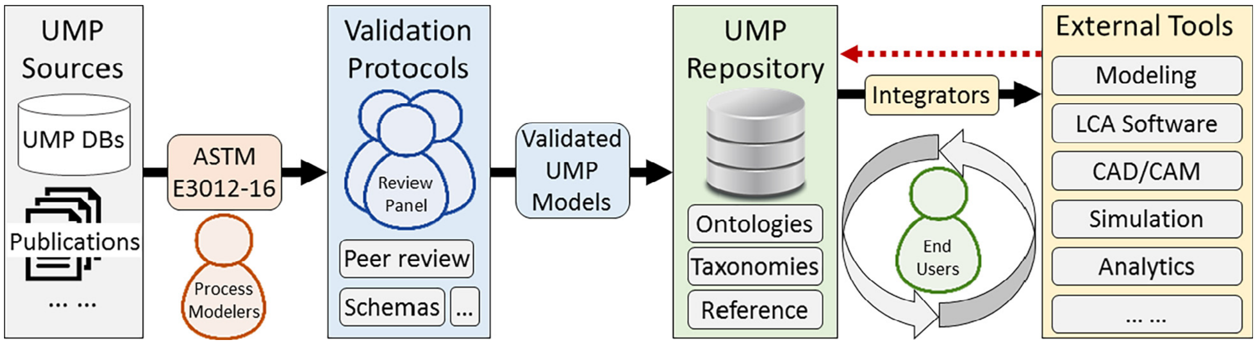

Fig. 1. Vision for the UMP Repository. Process modelers (in orange) use ASTM E3012-16 to submit to the repository, a review panel (in blue) validates the model, and end users (in green) link the models to external tools. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

manufacturing capabilities. Such a resource will be particularly impactful for smaller manufacturers, as this repository would provide ways of quantifying their own performance and distinguishing themselves from their competitors. However, providing guidelines for building robust infrastructures for such firms is required to help them support easier implementation.

This paper aims to scope the collaborative vision and define the requirements of an open UMP repository, as seen in Fig. 1. What form will the content take? How will content contributions be validated? These questions (and more) were the subject of a workshop at the 2017 ASME International Manufacturing Science and Engineering Conference (MSEC), held jointly with the 45th SME North American Manufacturing Research Conference (NAMRC 45), where researchers met to begin to develop a vision and research plan to answer these questions. The shared vision resulting from this workshop is presented through a list of research and development priorities, shown in Section 3, Fig. 4.

2. Backcasting the vision for an open UMP repository

The vision of an open UMP repository is grand. To help focus the work, NIST led a backcasting exercise to procure research priorities. Backcasting is a planning method that defines a desirable future and then works backwards to identify policies and programs that connect the future goal to the present state [4]. Fifty-six researchers representing 27 different organizations participated in the workshop.

2.1. The vision

The main driver of the backcasting exercise was to target an aggressive, optimistic vision of the technology in question [4]. Ideas that garnered consensus included

- open availability of models using technologies like Git,[1]
- integration with simulation and modeling technologies,
- Docker[2]-based encapsulation of linked tools,
- automated model validation protocol, and
- decision support for choosing the appropriate model for a specific manufacturing scenario.

2.2. The present: existing efforts

Workshop participants identified existing efforts for standardizing, storing, and sharing UMP models. The CO2PE![3] approach performs energy and materials balances on a UMP, accounting for process inputs and outputs that are either calculated based on known laws or collected from research studies [5]. Complementary to CO2PE!, the unit process life cycle inventory (UPLCI)[4] approach, hosts theoretical equations that provide life cycle assessment (LCA) practitioners guidance in estimating environmental impacts of manufacturing processes. Brodsky et al. [6] codified UPLCI models into computer-readable programs and demonstrated opportunities for decision support with respect to sustainable manufacturing. These publicly open datasets and models will aid in initializing the UMP Repository. Existing commercial LCI datasets, e.g., *ecoinvent*[5] and GaBi[6] databases, and government resources, e.g., the DARPA AVM Manufacturing Model Library from C2M2L,[7] are also useful information sources for integration with the repository.

Other researchers have focused on tool development leveraging existing data-modeling techniques [7–12]. Capable of providing sustainability impact estimates, the tools focus on augmenting LCA-based workflows by providing comparisons of alternative products or manufacturing process chains. Assessments performed using the tools are likely to vary, since the methods used for assessing individual UMPs are similar, but they lack formalization or are opaque. Furthermore, these methods (Fig. 2 left) lack continuity with the traditional LCA workflow (Fig. 2 right), as integration is often achieved through manual implementations.

Workshop participants also enumerated complementary efforts, including engineering-related ontologies [13–15], general analytical tools (e.g., scikit-learn[8]), PLM or manufacturing-focused standards (e.g., ISO 20140, ISO 14041, MTConnect, and ISO 10303), and available simulation-related technologies (e.g., SysML and Modelica).

2.3. Bridging the gap

After proposing desirable features for the repository, participants identified R&D processes that could coalesce existing technologies for realizing the repository. Participants classified these concepts into four research categories focusing on (1) domain models, (2) supporting infrastructure, (3) model validation and governance, and (4) engineering workflows and integration. Fig. 3 presents an overview of ideas and concepts raised at the workshop.

2.3.1. Domain models for manufacturing processes

Though ASTM E3012-16 provides guidelines for characterizing manufacturing processes, it is only a starting point towards the

[1] https://git-scm.com/.
[2] https://www.docker.com/.
[3] https://www.eeinstitute.org/.
[4] http://cratel.wichita.edu/uplci.
[5] http://www.ecoinvent.org/database/database.html.
[6] http://www.gabi-software.com/international/databases/gabi-databases/.
[7] https://cps-vo.org/group/avm/C2M2L-overview.
[8] http://scikit-learn.org/stable/.

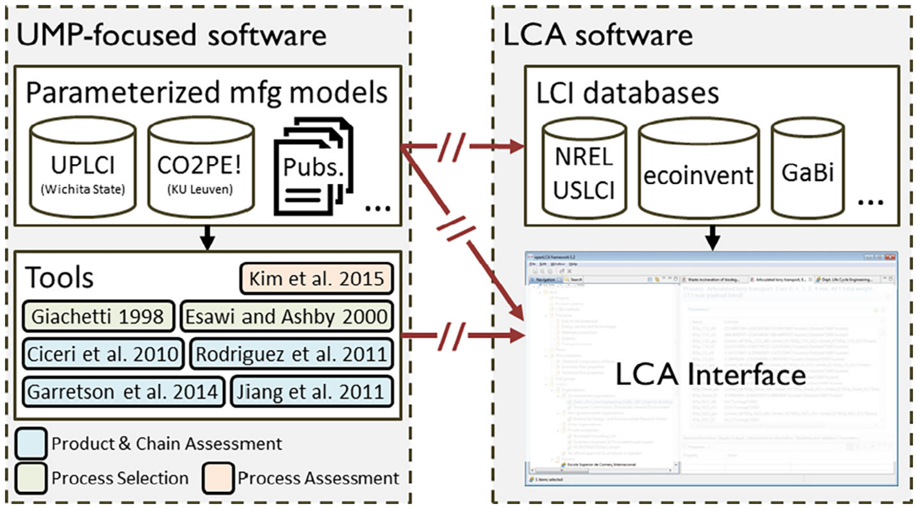

Fig. 2. LCI databases are designed to interface with LCA tools (right). Parameterized UMP models are used in custom tools for manufacturing-based decision scenarios (left). Red lines indicate gaps. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

grander vision. More descriptive incorporation and integration with different aspects of the characterizations will enrich the formal representation described in the ASTM standard and support automation and integration techniques. For example, product and process information, including geometric dimensioning and tolerancing (GD&T), bills of materials (BOMs), production flow, domain (either traditional or non-traditional), performance models, and ontologies and taxonomies, can be fully utilized and formally incorporated

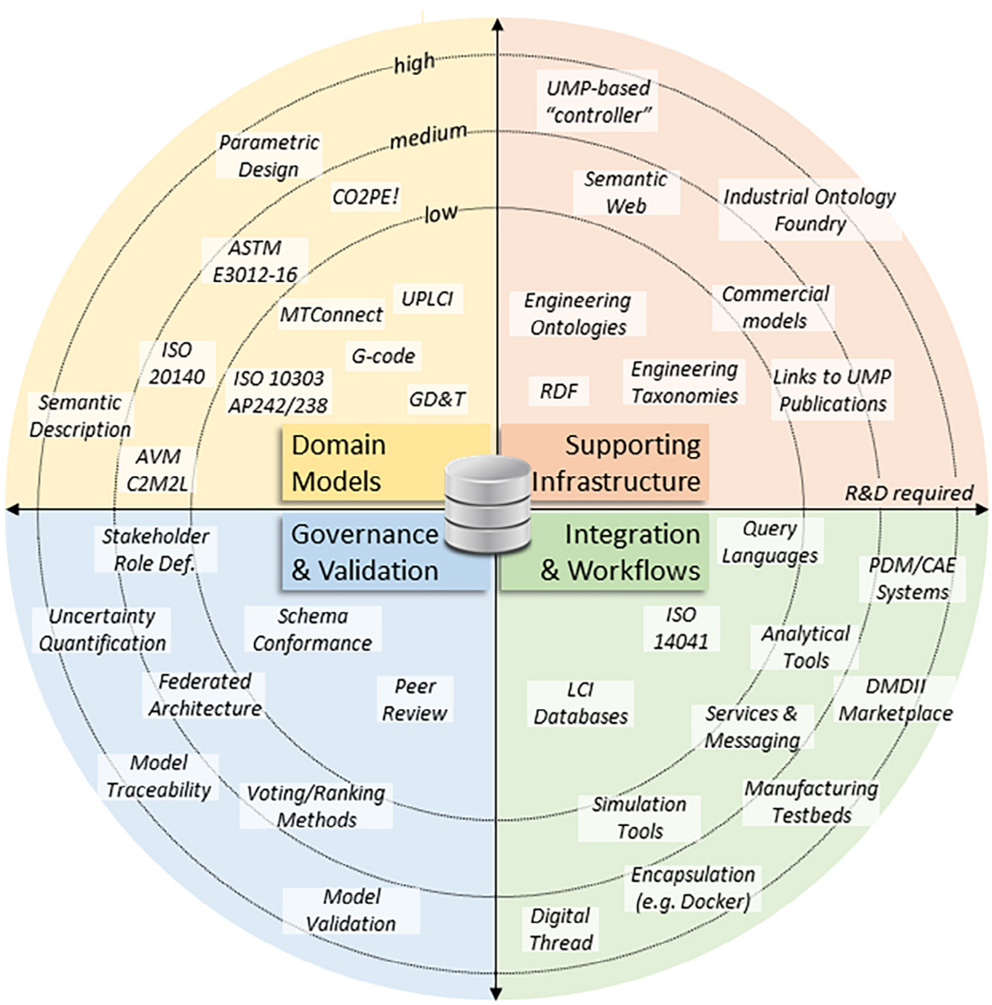

Fig. 3. Overview of ideas and concepts raised at the workshop. Concepts closer to the center require less R&D to implement, while those on the edge of the chart require further research.

		Class			
	Research & Development Priorities	**D**	**S**	**G**	**I**
1 YEAR	Augmenting standards to formally describe performance models for UMPs	●	●	●	
	Developing methods to facilitate new UMP models by generalizing or refining existing UMP models	●	●		
	Developing generic performance models to be used when physics-based models are unavailable	●	●		
	Formally describing composite process performance models for a network of UMPs	●	●		
~3 YEARS	Creating updateable (dynamic) models to ensure relevance over time for different users & settings	●		●	
	Designing a web-based system that would provide a platform for users to perform tasks		●		●
	Developing modeling formats to facilitate metric quantification, feeding key performance indicators	●	●		
	Implementing approaches to aid in modeling specialized, in-house developed processes	●			
	Implementing decision support tools that utilize UMP models within existing CAE workflows				●
	Integrating analytics functions, e.g. prediction, learning, optimization, & trade-off analysis		●		●
	Integrating models to facilitate the generation of refined STEP 238 instances and link to CAM tools		●		●
	Re-purposing models at various phases of the lifecycle in the style of the digital thread	●			●
	Visualizing environmental influence of production systems using UMP and value stream mapping				●
5+ YEARS	Converting native models into an open FEM model through adapters for commercial CAE software				●
	Enforcing metering of cloud platform usage if cloud computing is part of the repository			●	●
	Enforcing security for industry data and information that can be used to validate UMP models			●	
	Identifying, quantifying, and dealing with uncertainties in UMP models	●		●	
	Projecting sustainability and LCA data to the part features to inform detailed design		●		●

Fig. 4. Research priorities classified by a suggested deadline and their relation to domain models (D), supporting infrastructure (S), governance and validation (G), and integration and workflows (I).

into the standard specifications. However, developing a formal, generalized data model for manufacturing processes requires considerable effort, as every process has its own characteristics. Also, the formal data model developed should align with existing modeling standards, best practices, and paradigms.

2.3.2. Supporting infrastructure for the repository

Coupled with the underlying data models that characterize the repository's contents, the range of functionalities and uses it supports can turn it into a full-fledged knowledgebase. Workshop participants focused on specific affordances that could be provided to a user. For example, the repository should be structured formally enough to perform reasoning on a collection of models to aid in decision making. Such decision scenarios include identifying the appropriate model(s) for a given design/manufacturing case, composing a system-level model comprised of multiple UMP models, and optimizing performance balancing multiple criteria.

2.3.3. Model validation and governance

One challenge in coordinating an effort with multiple stakeholders (e.g., model contributors and repository users) is validating and governing the repository's contents. Governance focuses on who can make contributions, how those contributions will be accepted and vetted, and who may use the content of the repository. Validation addresses the conceptual structure and correctness of the UMPs in the repository. Thus, guidance in each model's use, such as standard methods to, at least, describe the bounds of each UMP's utility or the degree of certainty associated with a given model, will be needed.

2.3.4. Integration and workflows

The integration of a UMP model and repository into existing engineering workflows is a significant barrier to their adoption (and broad dissemination). Workshop participants proposed concepts broadly related to integration and workflows. Topics of discussion included coordinating the representation of UMPs with existing computer-aided engineering (CAE) software, modeling and simulation environments, and software deployment architectures. A common vision of the group was that the UMP representations could contribute to realizing the Digital Thread in manufacturing, closing the loop on design, manufacturing, and distribution practices.

3. R&D directions and priorities

Fig. 4 enumerates the R&D priorities for realizing the envisioned open UMP Repository. A salient theme across these directions is to functionalize UMP models into existing platforms to perform advanced data analytics (including methods for uncertainty quantification), to augment engineering and manufacturing decision-making, and to improve the precision of LCA.

4. Conclusions

Equipping stakeholders with integrated tools for smarter decision-making to support more sustainable manufacturing is key for the realization of smart manufacturing systems and Industry 4.0 [16]. The vision for an open UMP Repository addresses this need by providing a rich source of digitally-accessible reference material for industry to cull from for modeling and improving their operations.

Successfully achieving this vision presents its own research needs. Additional parameterized UMP models are greatly needed to demonstrate the tools and workflows suggested throughout this paper. Though many models have been reported in literature, extracting and functionalizing them into computer-readable formats holds a significant cost. Even with minimal functionality surrounding the repository, converting existing UMPs into a formal representation is a challenge. Emerging technologies, such as text-mining techniques, show promise in supporting this conversion, but not without the deep involvement of domain experts. Still the group agreed that even a minimally functional repository, such as a collection of relevant literature accessible through a taxonomy of manufacturing concepts, would be useful in and of itself in supporting community-wide efforts toward achieving smarter, more sustainable product manufacturing.

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