Proceedings of the ASME 2018 13th International Manufacturing Science and Engineering Conference
MSEC2018
June 18-22, 2018, College Station, Texas, USA

MSEC2018-6707

TOWARDS A STANDARDS-BASED METHODOLOGY FOR EXTENDING MANUFACTURING PROCESS MODELS FOR SUSTAINABILITY ASSESSMENT

Arvind Shankar Raman
School of Mechanical, Industrial and Manufacturing Engineering
Oregon State University
Corvallis, Oregon 97331, USA
shankara@oregonstate.edu

Karl R. Haapala
School of Mechanical, Industrial and Manufacturing Engineering
Oregon State University
Corvallis, Oregon 97331, USA
Karl.Haapala@oregonstate.edu

KC Morris
Systems Integration Division
National Institute of Standards and Technology,
Gaithersburg, MD 20899, USA
kcm@nist.gov

ABSTRACT

Over the past decade, several efforts have characterized manufacturing processes from a sustainability perspective. In addition, frameworks, methodologies, and standards development for characterizing and linking unit manufacturing process (UMP) models to construct manufacturing system models for supporting sustainability assessment have been pursued. In this paper these research efforts are first briefly reviewed, and then, ASTM standards derived from this work are described and built upon. The contribution of this research is to demonstrate how more formalization of these prior efforts will facilitate systematic reuse of developed models by encapsulating different aspects of complex processes into reusable building blocks. The research proposes a methodology to define template UMP information models, which can further be abstracted and customized to represent an application-specific, upgraded manufacturing process. The methodology developed is based on the ASTM standards of characterizing manufacturing process for sustainability characterization. The approach is demonstrated for analyzing manual and computer numerically controlled (CNC) machining processes.

1. INTRODUCTION

While manufacturing has primarily focused on gaining profits and securing market share, manufacturing with a sustainability focus has gained traction [1]. Globally, a number of sustainable manufacturing efforts have been pursued in response to growing societal concerns over the non-monetized impacts of manufacturing [2,3]. In particular, green, or environmentally-responsible design and manufacturing philosophies have paved the way for assessment tools that promote sustainable manufacturing during the conceptual and early design stages of the product life cycle [4].

A variety of software tools are available to perform product life cycle assessment (LCA), such as SimaPro and GaBi [5,6]. LCA tools are able to guide manufacturers in making more informed decisions about the environmental impacts of their production processes and supply-chain activities [7,8]. These tools can sometimes also offer insight into product- and process-related economic and social impacts during design and, thus, aid manufacturers in developing and implementing sustainable product design and manufacturing modifications. One major drawback of LCA tools, however, has been the generic representation of manufacturing processes for analysis [8,9].

Manufacturing phase, or gate-to-gate, LCAs often do not address process-specific impacts, but rather utilize generalized process models, which are often not representative of the machine tool setup in the setting evaluated [9,10]. For example, a comparative LCA for machining a one-kilogram sphere and a one-kilogram cube would yield identical results, since the machining process model in the database reports impact based on the mass of the part processed. However, since the machine setups, cutting paths, and volume of material removed would all be different, the impacts also would vary significantly between the two parts. To overcome this limitation of manufacturing process models, efforts have been undertaken to improve manufacturing process characterization. One aim of these efforts is to enhance the ability of LCA tools to more accurately assess the environmental impacts of unit manufacturing processes

(UMPs) [8]. Further, more accurate process models will enhance manufacturing system evaluations for other metrics and indicators (e.g., cost and productivity).

UMPs have been defined as "the individual steps required to produce finished goods by transforming raw material and adding value to the workpiece as it becomes a finished product" [11]. A UMP has also been defined as "the smallest elementary manufacturing activity required for a specific taxonomological [referring to a taxonomy of manufacturing process types] transformation and composed of machines, devices, or equipment" [12]. As noted above, characterizing a UMP enables a deeper understanding of the process and improves process-level decision making. Further, being able to link characterized UMPs to form a manufacturing system model will enable system-level characterization and enhance sustainability assessment.

To demonstrate the operational application of these concepts, the research presented herein focuses on development of a methodology for constructing reusable abstractions of UMPs based on two ASTM standards (ASTM E2986-15 and ASTM E3012-16). First, related prior work is briefly introduced. Next, the methodology is presented and demonstrated for several abstractions of a machining process (manual and computer numerically controlled milling). Finally, several advantages of the methodology are presented.

2. BACKGROUND

Several efforts have addressed the development of methods for UMP characterization. One of the initial efforts was under the Unit Process Life Cycle Inventory (UPLCI) project [13]. The goal of the UPLCI project was to formalize a systematic framework for inventory analysis of the manufacturing phase of LCA. By dividing a manufacturing process into sub-processes, representative models are more reliable and precise. Thus, the UPLCI framework proposed the creation of a toolset that would help compile life cycle inventories (LCIs) for UMPs to support LCA. The framework could enable manufacturing system analyses by aggregating LCI data for individual manufacturing processes involved in the production of a part [5,6,14].

UPLCI framework development work was later undertaken in conjunction with the Cooperative Effort on Process Emissions (CO2PE!) in Manufacturing, an initiative undertaken by the International Academy for Production Engineering (CIRP) [8]. CO2PE! was launched to address the lack of precise and specific environmental impact data in LCI databases. The effort aimed to compile a repository of data from research labs and other organizations from various geographic locations. The focus was to emphasize the coordination of the various global efforts in consolidating and analyzing environmental impacts of UMPs toward sustainability characterization of manufacturing [10,14]. In merging these two initiatives, the UPLCI effort formed a screening method for building LCI databases, while the CO2PE! effort presented an in-depth approach for quantifying LCI data. No recent developments toward LCI data collection and sustainability characterization have been reported under this initiative.

In addition to these two relatively *ad hoc* efforts, the International Organization on Standardization (ISO) published the ISO 20140:2013 standard, titled "Automation systems and integration – Evaluating energy efficiency and other factors of manufacturing systems that influence the environment" [15]. This standard instituted a method for environmental performance evaluation (EPE) of individual manufacturing processes by assessing the energy efficiency and other factors of manufacturing systems. The standard helps in conducting EPEs of manufacturing systems by aggregating UMP EPE data.

Despite the fact that these methods and standards have helped in characterizing discrete manufacturing processes for sustainability evaluation, there has not been much recent development. Also, these prior methods have focused on developing distinct and specific information models of UMPs. Developing these information models from scratch requires a high level of expertise and knowledge in characterizing specialized manufacturing processes and, thereby, also requires significant time and effort. Having robust information models that can be reused and expanded upon to specify configurations of manufacturing processes would greatly benefit manufacturers and researchers alike. Prior methods of UMP model development have not focused on creating reusable abstractions for information models that can be instantiated for sustainability characterization in a variety of settings.

To overcome this inherent gap in existing methods, research collaborations with the ASTM International working group have engaged in standards development to support sustainable manufacturing. The collaboration contributed to the ASTM E2986-15 standard, titled "Standard Guide for Evaluation of Environmental Aspects of Sustainability of Manufacturing Processes," which provides a method for the evaluation of manufacturing process-related environmental impacts [16]. A second standard, ASTM E3012-16, titled "Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes," further develops ASTM E2986-15 [17]. This standard helps analysts and decision makers in the systematic characterization of the environmental impacts of a UMP. It provides a defined structure for representing a UMP, enabling industry practitioners and researchers to more easily share UMP models [18,19]. The structure is formalized in XML (eXtensible Markup Language) using XSD (XML Schema Definition). The standard also provides for the specification of variables for linking, or composing, multiple UMPs for sustainability characterization of manufacturing systems. However, the implementation of this concept is not fully developed in the standard. Composability is enabled by the use of linking variables defined for a UMP that are appropriate for a subsequent UMP.

The methodology presented below extends prior framework development efforts based on ASTM standards. For example, we previously reported a complementary framework which solely focused on composing UMPs to enable sustainability assessment of manufacturing systems [20,21]. However, the previous framework lacked aspects of model reusability and extensibility, which is being addressed in this research. Other efforts at NIST have explored the needs for creating a repository of UMP models [22–24]. The reuse of models in such a repository is an ongoing research challenge that this work addresses. Here, we posit that information models can be created for a specific manufacturing process and then abstracted to characterize variations of that manufacturing process. Using these abstractions of the UMPs, process model composability can be performed to evaluate systemic sustainability assessment.

3. METHODOLOGY

As noted above, the aim of the research presented here is to build on the existing ASTM E3012-16 standard to improve the reusability, extensibility, and composability of UMP models. The standard provides a graphical model structure to represent UMPs (Fig. 1). This standard structure defines five aspects: inputs, outputs, resources, product and process information, and transformation equations. Inputs indicate the types of energy, materials, and consumables flowing into the process. Outputs indicate the product and, when relevant, co-products and by-products, types of wastes/emissions, and process feedbacks (e.g., status of consumables and tools). Resources define information related to resources used by the process, such as tooling/fixtures, equipment, software, and people. Product and process information is the information needed to enable transformation functions (equations), which includes information related to the material, part, process plans, and control programs.

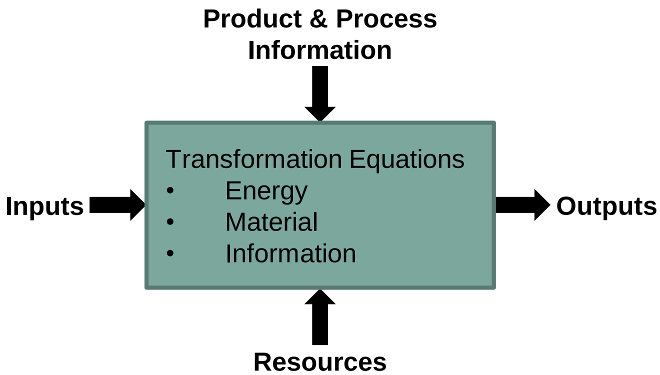


FIGURE 1. GRAPHICAL REPRESENTATION OF A UMP [14]

The model structure includes transformation equations. These equations describe the physical transformations that occur based on pertinent engineering information (for example, part dimensions and material properties) into information describing the physical outputs of the process, including information transferred to the subsequent UMP model. These equations maybe also used to calculate sustainability metrics and key performance indicators (KPIs), typically represented as product and process information for the manufacturing process. Thus, the transformation equations provide a physical basis for characterizing the sustainability performance of the UMP. The standard provides a formal representation of all five UMP aspects using an XML schema. Since these aspects are represented as element blocks in the standard model structure, they are easy to read, edit, and expand upon from a software programming perspective.

The research presented here contributes a methodology for abstracting an existing model and molding it into a specific model for a particular application (instantiation). We propose the development of template models that can be reused, extended, and composed. Figure 2 shows the activities comprising the methodology.

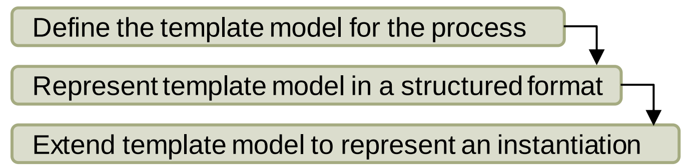


FIGURE 2. METHODOLOGY FOR ABSTRACTING UMP MODELS FOR EXTENSIBILITY AND COMPOSABILITY

This methodology defines what constitutes a template model, devises a method to develop and represent a template model, and presents an approach for abstracting models for extensibility. The remainder of this section discusses each of these activities in greater detail. The next section then demonstrates the activities using a case study for milling operations.

3.1 Define the template model for the process

The ASTM standard guides researchers and industry practitioners in developing process-specific UMP models. Here, we propose the concept of a template model to represent discrete manufacturing processes of a particular classification. We then evaluate the feasibility of extending these template models to use-specific models. First, template models will need to be established for each class of manufacturing process. A template model (abstraction) can be defined as a model that completely characterizes the most simplistic instantiation of a manufacturing process that has varying levels of machine configurations. Thus, a template model would be developed for the most basic machine form for a manufacturing process that utilizes multiple alternatives of machine types. The template model would be able to be expanded to accommodate models for similar machine configurations or higher complexity machine configurations. This can be explained using the example of a milling operation.

A UMP model for a process using a manual milling machine is considered as a template model for milling (multi-point material removal). A manual knee and column mill is understood to be the basic physical representation of most vertical milling machines [25]. While the spindle is electrically powered, all other capabilities of the machine are manually controlled (e.g., spindle speed, feed rate, and depth of cut). By adopting the manual milling machine to create the template model, any milling machine configurations with enhanced or upgraded capabilities would be considered as extensions of the template (manual milling) model.

While it is expected that these template models can be applied to the majority of upgraded machine configurations, there will be complex machine/process models that require further processing to facilitate abstraction from template models. Such cases would derive from machine configurations that are combinations of multiple manufacturing processes within a single machine configuration, e.g., five-axis milling or hybrid manufacturing. The methodology is generally applicable to these complex configurations, but requires a complete and thorough understanding of the machine and process to model accurately.

3.2 Represent template model in a structured format

Next, the identified template model must be represented in a structured manner to enable software tool implementation. The schema proposed in the standard is currently being applied in this research. Changes in the schema do not affect the proposed methodology, which is independent of the structure and can be applied to any XML schema definition. Software tools will facilitate adoption and use of manufacturing process and system modeling and analysis. We investigated how UMP models could be represented for software implementation using XML, since it is capable of handling functional modeling of manufacturing systems [26,27]. We found that XML schema can handle complex relationships, has a defined structure, which is beneficial for model development, and is amenable to extension for software programming [28].

In addition, XML models are capable of handling the research-specific needs for model reusability, extensibility, and composability due to their structured and compartmentalized way of representing data [29]. Also, by representing models as XML documents, parsing, analyzing, and processing data is not software platform dependent and can be handled by any language that can work with XML. In the current format, the transformation equations are in string, written as free form. The National Institute of Standards and Technology (NIST) has an ongoing effort to create a web tool, called the UMP Builder [30] to model and represent UMPs as a standardized XML document. The UMP Builder handles these transformation equations as MathML functions and can be processed through MathML interpreters to be read as executable computations. The language is relatively easy to learn for non-expert practitioners, supporting adoption of the standard. For industry practitioners and researchers to perform sustainability assessment, models must be represented as real-time operational standardized XML documents. By conforming to the standards, these models can be used by other researchers and practitioners by expanding them into application-specific process models.

3.3 Extend template model to represent an instantiation

The next step focuses on extending the template models to represent more complex, use-specific manufacturing systems. Complex variations could include extensions of physical inputs/outputs or instantiations of product and process information to reflect a specific physical piece of equipment and would require modification of the transformation equations. Instantiations of these template models to depict more complex variations of the processes studied are called extensions. Since the template models are created based on ASTM E3012-16, the model structure inherently allows for extensions of unit process models. For example, let model UMP A in Fig. 3 be the template model for all similar manufacturing processes, A. Let UMP A1 be a complex variation of UMP A. To develop a model for UMP A1, an instantiation of the template model of UMP A is generated. This model is then extended using information related to UMP A1 as a layer (Layer A1) of template model UMP A. We posit that extensibility can not only be done by building upon template models using such layers, but also by building upon already extended models using additional layers, which will develop higher order UMP models. This concept is illustrated for milling in the next section.

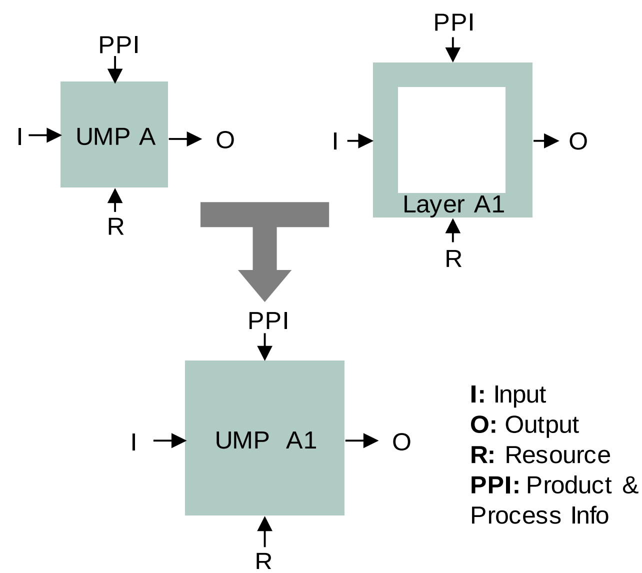


FIGURE 3. EXTENSIBILITY OF TEMPLATE MODEL UMP A TO FORM MODEL UMP A1 USING LAYER A1

Another important aspect of extensibility is that the layers that can be added to the template model are not just the higher order variants of the primary process. For example, auxiliary systems (e.g., exhaust gas pressure control systems, monitoring equipment, and electric boosting systems) that are essential to support the manufacturing process, but might not directly modify the workpiece, can be added as layers to create specific models of the equipment in use. To be amenable for reuse, the template models require certain information and characteristics to be instantiated and expanded. To establish these characteristics, template models have been developed under this research for a few manufacturing processes (i.e., milling, inertial welding, and heat treatment using a natural-gas fired furnace). These efforts (to be reported later) have aided in characterizing the processes and in developing a generic model structure for these processes.

4. DEMONSTRATION CASE: MILLING PROCESS

To demonstrate the application of the methodology, a template model for a manual milling machine was developed using the steps above. The template model was then extended to model a milling machine with computer numerical control (CNC) of its x-axis and y-axis movement (referred to here as a "two and a half axis milling machine"). It was further extended to consider use of a lubrication system. These extensions were created by instantiating the template model and adding information layers, representing a two and a half axis milling machine (Layer 1) and the lubrication system (Layer 2), as shown in Fig. 4.

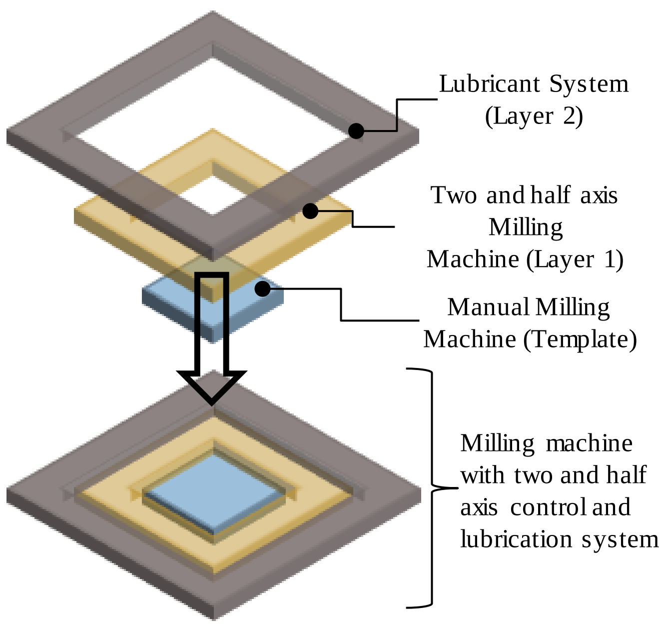


FIGURE 4. EXTENSIBILITY OF MANUAL MILLING FOR TWO AND HALF AXIS MILLING WITH LUBRICATION SYSTEM

A representative template model of manual milling machine is illustrated in Appendix A, as specified by the standard. The representative manual milling machine has just the spindle powered in this demonstration case. The model represented here primarily performs an energy characterization of the milling process. Energy characterization provides a detailed view to improve energy performance of the process. The development of the template model begins with capturing the physical inputs and outputs of the process. Inputs and outputs are a description of the physical inputs and outputs (e.g., bar stock, work in progress, electrical input, and type of waste) to the manufacturing process. Product and process information holds information related to the product data (e.g., length, width, thickness, and density), process data (e.g., speed, feed, and depth of cut), and sustainability metrics (e.g., energy consumption, total cost of energy, and mass of greenhouse gas emissions) and KPIs (e.g., energy consumption per kilogram of part). The transformation equations contain the mathematical functions required to quantify the desired metrics and KPIs. UMP model resources capture all the information pertaining to process resources (e.g., software, tools, fixtures, and workers). Resources do not have a direct effect on either the product or process, but are needed to aid in the functioning of the machine.

An equivalent information model representation is also developed based on the ASTM standard, and documents the five aspects of a UMP model (i.e., inputs, outputs, product/process information, resources, and transformation equations) as elements in the XML documents. Appendix B reports the representative information model for the manual milling case in XML format [31–34].

With the template model in place, it can be extended to create models of different milling processes based on the specific machine infrastructure. As noted above, for this case study, two and a half axis milling with lubrication is considered. The two and a half axis milling model can be created by extending the template model by adding a CNC table (Layer 1). Similarly, the lubrication system (Layer 2) is an auxiliary system to the milling machine. Thus, the extended model with Layers 1 and 2 added captures the information related to both the two and a half axis milling machine and the lubrication system, as shown in Appendix C. Information such as coolant flow rate, volume of coolant used during the milling operation, and the energy required to run the lubricant system represent some of the additional information pertaining to the lubricant system layer. Similarly, table motor power, basic power, and basic time represent some of the added information that is related to the two and half axis layer. Added information is indicated by bold blue text in the UMP representation of two and a half axis milling with lubrication. In addition to information being added to the product and process information, extension of the template models requires editing of the transformation functions to accommodate the addition of layers. For example, on-site energy in the manual milling model is the energy supplied to the motor, whereas, in the two and half axis milling model, it is the sum of basic energy (energy required for part setup and idle) and energy supplied to the table motors and lubricant system. Development of the models herein relied on prior research [35–38].

Similar to the template model, the extended UMP model is an energy-based model. XML representation of the template model can be updated by editing individual elements of the XML document reported in Appendix B to accommodate the two and a half axis milling machine layer and the lubricant system layer. This additional XML information is presented in Appendix D. Input and output elements remain unchanged as the information is the same in both the models. The product and process information for Layer 1 and Layer 2 is appended to the product and process information for the manual milling model. Similarly, new transformation equations for the extended layers are added as new elements. This XML representation captures the different aspects (inputs, outputs, product and process information, resources, and transformations) and adheres to the standard representation.

5. CONCLUSION

The methodology presented establishes a mechanism to create reusable abstractions (models) of unit manufacturing processes (UMPs) for characterizing the sustainability performance of a variety of manufacturing processes and systems. The methodology facilitates the creation of extensible and composable UMP models, and enables manufacturers and researchers to develop more accurate system models for sustainability characterization by tailoring existing validated models for their specific needs. This approach offers several advantages over current and prior practices:

- Straightforward development of basic and extended UMP models supported by a standardized model structure;
- Simplified tracking for evaluating a UMP model and validating modifications made to extend a model;
- Improved model reusability and extensibility through multi-layer buildup of an existing validated UMP model; and
- Maintained reusability, extensibility, and composability characteristics of the UMP model after extension.

The methodology proposed in this research is portable (UMP models can be incorporated into computer-aided engineering tools) and scalable (models can be developed for processes and systems of varying complexity from a variety of domains). To realize the vision of facilitated model creation, extensibility, and application to sustainable manufacturing characterization, future work will be needed to build a repository of template models and extension layers for a broad set of manufacturing processes [22]. This effort can be accelerated by creation of software capable of validating the models, as well as tools that can aid decision makers from various domains in composing the models for system analysis.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the National Institute of Standards and Technology (NIST Award No. 70NANB16H223) for their support of this research. We would especially like to thank William Bernstein, David Lechavalier, Swee Leong, and Kevin Lyons, for their generous inputs to the research.

REFERENCES

[1] Jovane, F., Westkämper, E., and Williams, D., 2009, The ManuFuture road: towards competitive and sustainable high-adding-value manufacturing, Springer, Berlin.

[2] Tilton, J. E., 1996, "Exhaustible resources and sustainable development: Two different paradigms," Resour. Policy, 22(1–2), pp. 91–97.

[3] Allouche, J., 2011, "The sustainability and resilience of global water and food systems: Political analysis of the interplay between security, resource scarcity, political systems and global trade," Food Policy, 36, pp. S3–S8.

[4] Dornfeld, D., and Wright, P., 2007, "'Technology Wedges' for Implementing Green Manufacturing," NAMRI/SME, 35(1), pp. 193–200.

[5] Overcash, M., and Twomey, J., 2012, "Unit Process Life Cycle Inventory (UPLCI) – A Structured Framework to Complete Product Life Cycle Studies," Leveraging Technology for a Sustainable World, D.A. Dornfeld, and B.S. Linke, eds., Springer Berlin Heidelberg, pp. 1–4.

[6] Overcash, M., Twomey, J., and Kalla, D., 2009, "Unit Process Life Cycle Inventory for Product Manufacturing Operations," ASME International Manufacturing Science and Engineering Conference, ASME, West Lafayette, IN, pp. 49–55.

[7] Reap, J., Roman, F., Duncan, S., and Bras, B., 2008, "A Survey of Unresolved Problems in Life Cycle Assessment: Part 2: Impact Assessment and Interpretation," Int. J. Life Cycle Assess., 13(5), pp. 374–388.

[8] Kellens, K., Dewulf, W., Duflou, J. R., and others, 2010, "The CO2PE!-initiative (cooperative effort on process emissions in manufacturing)," International framework for sustainable production., Netherlands, p. 13.

[9] Overcash, M., Duflou, J., Kellens, K., Looman, K., Dewulf, W., Sutherland, J., Twomey, J., and Isaacs, J., 2012, "Unit Process Life Cycle Inventories CO2PE! - UPLCI Workshop," CIRP Annals - Manufacturing Technology, Berkeley, CA.

[10] Duflou, J. R., Kellens, K., Renaldi, Guo, Y., and Dewulf, W., 2012, "Critical Comparison of Methods to Determine the Energy Input for Discrete Manufacturing Processes," CIRP Ann. - Manuf. Technol., 61(1), pp. 63–66.

[11] Mani, M., Madan, J., Lee, J. H., Lyons, K. W., and Gupta, S. K., 2014, "Sustainability Characterization for Manufacturing Processes," Int. J. Prod. Res., 52(20), pp. 1–18.

[12] Garretson, I. C., 2015, "A Unit Manufacturing Process Characterization Methodology and Supporting Terminology for Sustainable Manufacturing Assessment," Master of Science, Oregon State University.

[13] Luttikhuis, E. O., Toxopeus, M. E., and Overcash, M., 2013, "Applying Unit Process Life Cycle Inventory (UPLCI) Methodology in Product/Packaging Combinations," Re-engineering Manufacturing for Sustainability, A.Y.C. Nee, B. Song, and S.-K. Ong, eds., Springer Singapore, pp. 15–20.

[14] 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 Ann. - Manuf. Technol., 61(2), pp. 587–609.

[15] International Organization for Standardization [ISO], 2013, "Automation systems and integration -- Evaluating energy efficiency and other factors of manufacturing systems that influence the environment (ISO 20140)."

[16] ASTM, 2015, "Standard Guide for Evaluation of Environmental Aspects of Sustainability of Manufacturing Processes (ASTM E2986)."

[17] ASTM, 2016, “Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes (ASTM E3012).”
[18] Mani, M., Larborn, J., Johansson, B., Lyons, K. W., and Morris, K. C., 2016, “Standard Representations for Sustainability Characterization of Industrial Processes,” J. Manuf. Sci. Eng., 138(10), p. 101008.
[19] Rebouillat, L., Barletta, I., Johansson, B., Mani, M., Bernstein, W. Z., Morris, K. ., 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.
[20] Smullin, M. M., 2016, “An Information Framework for Composing Manufacturing Processes,” Master of Science, Oregon State University.
[21] Smullin, M. M., Iman, Z., and Haapala, K. R., 2017, “A Desktop Application for Sustainability Performance Assessment of Composed Unit-Based Manufacturing Systems,” Proceedings of the 12th International Manufacturing Science and Engineering Conference, ASME, Los Angeles, CA, p. V004T05A022; 11 pages.
[22] Bernstein, W. Z., Mani, M., Lyons, K. W., Morris, K. C., and Johansson, B., 2016, “An Open web-based repository for capturing manufacturing process information,” Proceedings of the International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, ASME, p. V004T05A028; 8 pages.
[23] Bernstein, W. Z., Bala Subramaniyan, A., Brodsky, A., Garretson, I. C., Haapala, K. R., Libes, D., Morris, K. C., Pan, R., Prabhu, V., Sarkar, A., Shankar Raman, A., and Wu, Z., 2017, “Research directions for an open unit manufacturing process repository: A collaborative vision,” Manuf. Lett.
[24] Brodsky, A., Krishnamoorthy, M., Nachawati, M. O., Bernstein, W. Z., and Menasce, D. A., 2017, “Manufacturing and contract service networks: Composition, optimization and tradeoff analysis based on a reusable repository of performance models,” IEEE, pp. 1716–1725.
[25] Groover, M. P., 2015, Fundamentals of Modern Manufacturing, Wiley, New York.
[26] Sung, R. C., Ritchie, J. M., Lim, T., and Kosmadoudi, Z., 2012, “Automated generation of engineering rationale, knowledge and intent representations during the product life cycle,” Virtual Real., 16(1), pp. 69–85.
[27] Meihua, Z., Aiping, L., and Liyun, X., 2008, “Integrated Modeling and Information Interaction Mechanism of Collaborative Production Information,” Proceeding of the International Conference on Information Management, Innovation Management and Industrial Engineering, IEEE, Taipei, Taiwan, pp. 67–70.
[28] Yadong, F., Ping, K., and Lei, Z., 2009, “Research and application of machine tools life-cycle management system based on web,” Proceedings of the ISECS International Colloquium on Computing, Communication, Control, and Management, IEEE, Sanya, China, pp. 117–120.
[29] Guha, R. V., Brickley, D., and Macbeth, S., 2016, “Schema.org: evolution of structured data on the web,” Commun. Assoc. Comput. Mach., 59(2), pp. 44–51.
[30] Bernstein, W. Z., Libes, D. E., and Lechevalier, D., 2018, “UMP Builder: capturing and exchanging manufacturing models for sustainability,” Proceedings of the 46th SME North American Manufacturing Research Conference (NAMRC) and the ASME Manufacturing Science and Engineering Conference (MSEC 2018), ASME, College Station, Texas.
[31] Kara, S., and Li, W., 2011, “Unit process energy consumption models for material removal processes,” CIRP Ann. - Manuf. Technol., 60(1), pp. 37–40.
[32] Avram, O. I., and Xirouchakis, P., 2011, “Evaluating the use phase energy requirements of a machine tool system,” J. Clean. Prod., 19(6–7), pp. 699–711.
[33] Kalla, D., Twomey, J., and Overcash, M., 2009, MR 3 Milling Process Unit Process Life Cycle Inventory.
[34] Branker, K., 2011, A study of energy, carbon dioxide emissions and economics in machining: milling and single point incremental forming, Queen’s University (Canada).
[35] He, Y., Liu, B., Zhang, X., Gao, H., and Liu, X., 2012, “A modeling method of task-oriented energy consumption for machining manufacturing system,” J. Clean. Prod., 23(1), pp. 167–174.
[36] Overcash, M., Twomey, J., Isaacs, J., Duflou, J., and Sutherland, J., 2010, “Energy efficiency improvements in manufacturing life cycle technology for analysis of machines and products,” Soc. Manuf. Eng. Tech. Pap. TP10PUB8 Dearborn MI, p. 5.
[37] Li, W., Zein, A., Kara, S., and Herrmann, C., 2011, “An investigation into fixed energy consumption of machine tools,” Glocalized Solut. Sustain. Manuf., pp. 268–273.
[38] Dahmus, J. B., and Gutowski, T. G., 2004, “An environmental analysis of machining,” Proceedings of the International Mechanical Engineering Congress and Exposition, ASME, Anaheim, CA, pp. 643–652.

APPENDIX A: MANUAL MILLING MACHINE MODEL REPRESENTED BASED ON ASTM STANDARD E3012-16

Product and Process Information

F_c – Cutting force
V_c – Cutting speed
f – Feed
d – Depth of cut
T_c – Cutting time
V_i – Initial volume
V_f – Final volume
η – Efficiency of motor

V_r – Volume removed
MRR – Material removal rate
W – Tool wear rate
P_{cut} – Cutting power
P_m – Power at motor/spindle
r_{CO2} – Generation rate of CO_2
r_{CH4} – Generation rate of CH_4
r_{NO2} – Generation rate of NO_2

E_c – Cutting energy
E_{on} – Onsite energy consumption
E_{off} – Offsite energy consumption
E_T – Total energy consumption (*)
c_e – Unit cost of energy
C_e – Total cost of energy (*)
GHG – Mass of greenhouse gas emission (*)

Inputs

Electrical energy
Workpiece (Raw material/WIP)

Transformation Equations

$V_r = V_i - V_f$
$MRR = v_c * f * d$
$P_{cut} = F_c * V_c$

$P_m = P_{cut} / \eta$
$E_c = P_{cut} * T_c$
$E_{on} = P_m * T_c$

$E_T = E_{on} + E_{off}$
$C_e = E_T * c_e$
$GHG = E_T * (r_{CO2} + r_{CH4} + r_{NO2})$

Outputs

Finished part
Waste

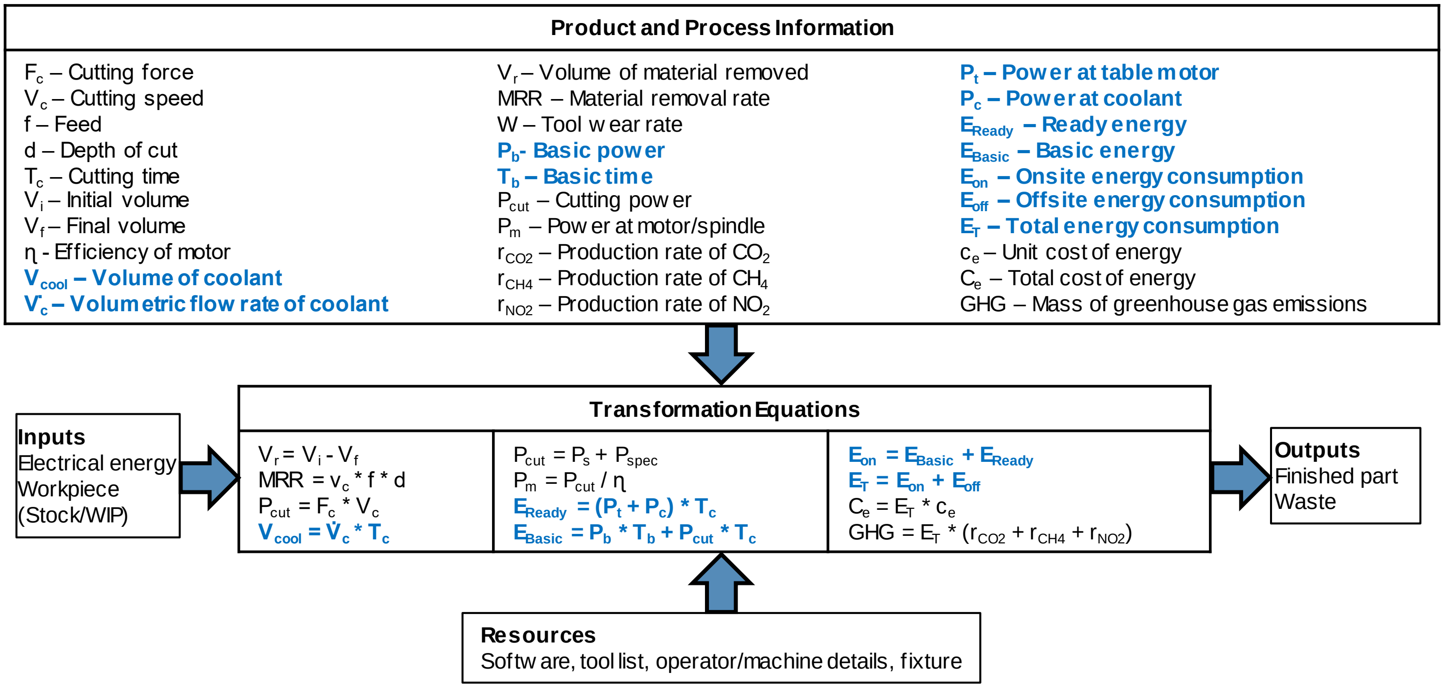
Resources

Software, tool list, operator/machine details, fixture

APPENDIX B: XML REPRESENTATION OF MANUAL MILLING INFORMATION MODEL

```
<UMP name="Manual Milling" type="Material Removal" description="Manual milling model">

//INPUT SECTION
<Input name="Bar stock" description= "Type of workpiece input to the process" category=""type="Workpiece" unit="" / >
<Input name="Electrical Energy" description="Input electrical energy to the process" category=""type="Energy" unit="kWh" / >

//PRODUCT AND PROCESS INFORMATION SECTION
<ProductProcessInformation name="Cutting force" description="Force on the cutting tool" category="Process"value="" unit="N" / >
<ProductProcessInformation name="Cutting speed" description="Speed of cut" category="Process"value="" unit="mm/sec" / >
<ProductProcessInformation name="Feed" description="Input feed of tool" category="Process"value="" unit="mm/s" / >
<ProductProcessInformation name="Depth of cut" description="Axial depth of cut per pass" category="Process" value="" unit="mm" / >
<ProductProcessInformation name="Cutting time" description="Total cutting time" category="Process"value="" unit="s" / >
<ProductProcessInformation name="Initial volume" description="Volume of workpiece before operation" category="Product"value="" unit="mm^3" / >
<ProductProcessInformation name="Final volume" description="Volume of workpiece after operation" category="Product"value="" unit="mm^3" / >
<ProductProcessInformation name="Efficiency of motor" description="Efficiency of motor" category="Process"value="" unit="" / >
<ProductProcessInformation name="Volume removed" description="Total volume of material removed" category="Product"value="" unit="mm^3" / >
<ProductProcessInformation name="Material removal rate" description="Rate of material removal" category="Product"value="" unit="mm^3/s" / >
<ProductProcessInformation name="Tool wear rate" description="Rate of tool wear" category="Process"value="" unit=" mm^3/s" / >
<ProductProcessInformation name="Cutting power" description="Power required to cut material" category="Process"value="" unit="kW" / >
<ProductProcessInformation name="Motor/Spindle power" description="Power at the motor/spindle" category="Process"value="" unit="kW" / >
<ProductProcessInformation name="Generation rate of CO2" description="Mass of CO2 produced for unit energy use" category="Process"value=""
unit="kg CO2/kWh" / >
<ProductProcessInformation name="Generation rate of CH4" description="CH4 produced in equivalent mass of CO2 for unit energy use"
category="Process"value="" unit="kg CO2e/kWh" / >
<ProductProcessInformation name="Generation rate of NO2" description="NO2 produced in equivalent mass of CO2 for unit energy use"
category="Process"value="" unit="kg CO2e/kWh" / >
<ProductProcessInformation name="Cutting energy" description="Energy required to cut the part" category="Process"value="" unit="kJ" / >
<ProductProcessInformation name="Energy onsite" description="Onsite energy consumption " category="Process"value="" unit="kJ" / >
<ProductProcessInformation name="Energy offsite" description="Offsite energy consumption" category="Process"value="" unit="kJ" / >
<ProductProcessInformation name="Total energy consumption" description="Total energy consumption" category="Process"value="" unit="kJ" / >
<ProductProcessInformation name="Unit cost of energy" description="Cost of 1kWh of energy" category="Process"value="" unit="$/kWh" / >
<ProductProcessInformation name="Total cost of energy" description="Cost of Energy" category="Process"value="" unit="$" / >
<ProductProcessInformation name="Mass of GHG emissions" description="Greenhouse gas emissions in equivalent mass of CO2"
category="Process"value=""unit="kg CO2e" / >

//TRANSFORMATION SECTION
<Transformation>
        <Equation description="Volume removed" set="">V_r = V_i - V_f</Equation>
        <Equation description="Material removal rate" set="">MRR = v_c * f * d</Equation>
        <Equation description="Specific power" set="">P_cut= F_c * V_c</Equation>
        <Equation description="Motor power" set="">P_m= P_cut / Eff</Equation>
        <Equation description="Cutting energy" set="">E_c = P_cut * T_c</Equation>
        <Equation description="Onsite energy" set="">E_on = P_m * T_c</Equation>
        <Equation description="Total energy consumption" set="">E_T = E_on + E_off</Equation>
        <Equation description="Total cost of energy" set="">C = E_T * C_e</Equation>
        <Equation description="GHG emission" set="">GHG = E_T * (rCO2 + rCH4 + rNO2)</Equation>
</Transformation>

//RESOURCE SECTION
<Resource name="Software" description="Software used for computer control" value="Linux CNC" / >
<Resource name="Machine ID" description="ID of the machine that is being used" value="MM01" / >
<Resource name="Operator" description="Name of operator" value="John Doe" / >

//OUTPUT SECTION
<Output name="Finished Part" description="Number of workpieces produced in an hour" category=""type="workpiece" unit="" / >
<Output name="Waste" description="Total waste of stock material" category="Waste"type="workpiece" unit="kg"/ >

</UMP>
```

APPENDIX C: MANUAL MILLING EXTENDED TO TWO AND A HALF AXIS MILLING WITH LUBRICATION SYSTEM



APPENDIX D: ADDITIONAL INFORMATION MODEL FOR EXTENDED LAYERS (TWO AND A HALF AXIS MILLING AND LUBRICATION SYSTEM)

```
<UMP name="Two-Axis Milling with Lubrication System" type="Material Removal" description="Two and a half axis milling with lubrication system">

//INPUT SECTION
      <Input> // This section is the same as the input section in Appendix B

//OUTPUT SECTION from Appendix B
      <Output> // This section is the same as the output section in Appendix B

//Additional product and process information specific to two and a half axis milling with lubrication system, appended to product and process information in Appendix B
      <ProductProcessInformation name="Coolant flow rate" description="Volumetric flow rate of coolant" category="Process" value="" unit="L/s" / >
      <ProductProcessInformation name="Volume of coolant" description="Volume of coolant used" category="Process" value="" unit="L" / >
      <ProductProcessInformation name="Basic power" description="Power to setup and idle" category="Process" value="" unit="kW" / >
      <ProductProcessInformation name="Basic time" description="Time to setup and idle" category="Process" value="" unit="s" / >
      <ProductProcessInformation name="Table motor power" description="Power to table motor" category="Process" value="" unit="kW" / >
      <ProductProcessInformation name="Coolant motor power" description="Power to coolant motor" category="Process" value="" unit="kW" / >
      <ProductProcessInformation name="Basic energy" description="Energy to setup and idle" category="Process" value="" unit="kJ" / >
      <ProductProcessInformation name="Ready energy" description="Energy for cutting" category="Process" value="" unit="kJ" / >

//Additional and updated transformation functions appended to transformation section in Appendix B
      <Transformation>
         <Equation description="Basic Energy" set="">E_Basic = P_b * T_b + P_cut * T_c</Equation>
         <Equation description="Ready Energy" set="">E_Ready = P_m * T_cutting </Equation>
         <Equation description="Onsite Energy Consumption" set="">E_on = E_Basic + E_Ready</Equation>
         <Equation description="Volume of Coolant" set="">V_cool = V̇_c * T_c</Equation>
         <Equation description="Onsite energy" set="">E_on = E_Basic + E_Ready</Equation>
      </Transformation>

//RESOURCE SECTION from Appendix B
      <Resource>

</UMP>
```