Designation: E3012 – 20

Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes[1]

This standard is issued under the fixed designation E3012; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide provides an approach to characterize any category of manufacturing process and to systematically capture and describe relevant environmental information.

1.2 This guide defines the conceptual model of a unit manufacturing process (UMP) from which a formal representation can be specified.

1.3 This guide defines the graphical representation of a UMP model that supports the systematic structuring and visualizing of manufacturing information.

1.4 This guide defines a process characterization methodology to construct UMP models that characterize the environmental aspects of the manufacturing processes under study.

1.5 This guide provides the necessary structure and formality for identifying and capturing key information needed to assess manufacturing performance, yet provides no details about an actual assessment of the process performance.

1.6 This guide provides the conceptual definition for a system composed of multiple UMPs to represent a production system.

1.7 This guide may be used to complement other standards that address sustainability and the product life cycle. This guide most closely relates to the inventory component as discussed in the ISO 14040 series (ISO 14044) standards, and resource management as discussed in the ISO 55000 series (ISO 55001) standards.

1.8 *This guide does not purport to address all of the security issues and the risks associated with manufacturing information. It is the responsibility of the user of this standard to follow practices and establish appropriate information technology related security measures.*

1.9 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.10 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E2114 Terminology for Sustainability Relative to the Performance of Buildings

E2986 Guide for Evaluation of Environmental Aspects of Sustainability of Manufacturing Processes

E3096 Guide for Definition, Selection, and Organization of Key Performance Indicators for Environmental Aspects of Manufacturing Processes

2.2 *ISO Standards:*[3]

ISO 14040 Environmental management—Life cycle assessment—Principles and framework

ISO 14044 Environmental management—Life cycle assessment—Requirements and guidelines

ISO 55000:2014 Asset management—Overview, principles and terminology

ISO 55001:2014 Asset management—Management systems—Requirements

2.3 *UL Standard:*[4]

ULE 880 Sustainability for Manufacturing Organizations

2.4 *UNECE Document:*[5]

Recommendation No. 20 Codes for Units of Measure Used in International Trade

[1] This guide is under the jurisdiction of ASTM Committee E60 on Sustainability and is the direct responsibility of Subcommittee E60.13 on Sustainable Manufacturing.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from International Organization for Standardization (ISO), ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, http://www.iso.org.

[4] Available from Underwriters Laboratories (UL), 2600 N.W. Lake Rd., Camas, WA 98607-8542, http://www.ul.com.

[5] Available from United Nations Economic Commission for Europe (UNECE), Palais des Nations CH-1211 Geneva 10 Switzerland, https://www.unece.org.

3. Terminology

3.1 Definitions of terms shall be in accordance with Terminology E2114.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *composite unit manufacturing process (UMP) model, n*—a structure representation of interactions between more than one UMP model.

3.2.1.1 *Discussion*—Similar to a UMP model, a composite UMP model is defined with distinct inputs, outputs, product and process information, transformations, and manufacturing resources.

3.2.2 *manufacturing resource, n*—an entity that enables a manufacturing process.

3.2.2.1 *Discussion*—Manufacturing resources include (but are not limited to) manufacturing assets, such as equipment, human operators, machinery, software, automation units, control devices, instrumentation, and tooling.

3.2.2.2 *Discussion*—Manufacturing resources do not include natural resources since natural resources such as iron ore do not directly facilitate the completion of a manufacturing process. For other uses of the term "resource," refer to the common definition of the term.

3.2.3 *model composition, n*—the act of linking individual unit manufacturing process (UMP) models together to create a composite of UMP models that can characterize the metrics of interest of a production system or product.

3.2.4 *unit manufacturing process (UMP), n*—the smallest element or subprocess in manufacturing that adds value through the modification or transformation of shape, structure, or property of input material or workpiece.

3.2.4.1 *Discussion*—A UMP is a clearly-scoped and well-defined manufacturing process that products a component, assembly, or product.

3.2.5 *unit manufacturing process (UMP) model, n*—structured reprsentation of the information associated with a UMP.

4. Significance and Use

4.1 This guide provides a systematic approach for characterizing the environmental aspects of manufacturing processes based on well-established formal languages.

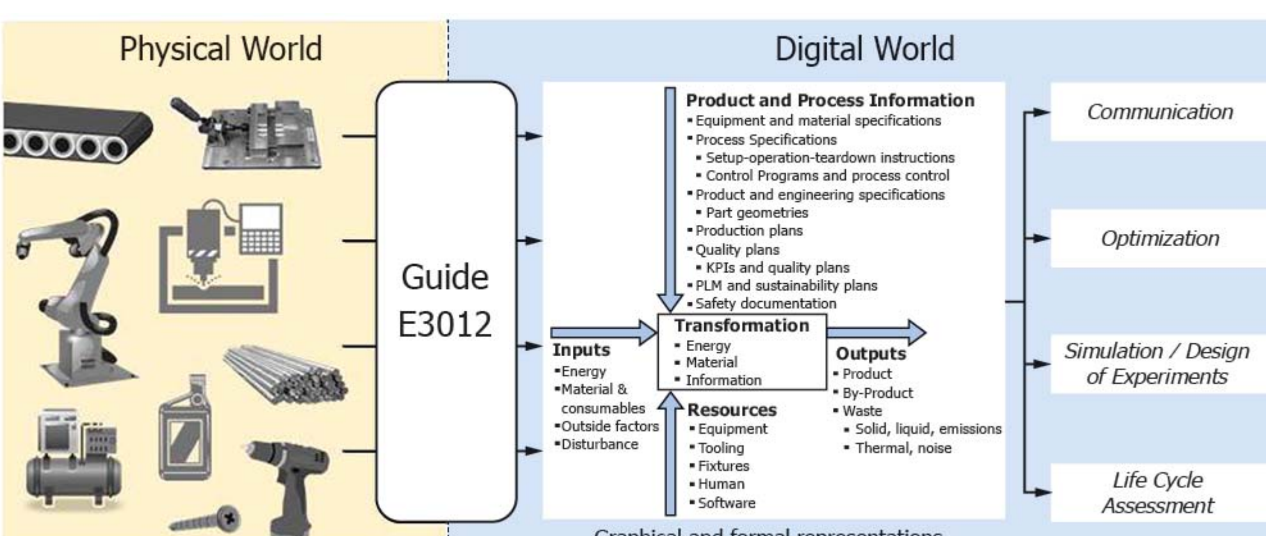
NOTE 1—In computer science, a formal language is a language designed for use in situations in which natural language is unsuitable as, for example, in mathematics, logic, or computer programming. The symbols and formulas of such languages stand in precisely specified syntactic and semantic relations to one another. Formal representations are derived from formal languages.

NOTE 2—A UMP model is defined using formal languages, such as eXtensible Markup Language (XML) (**1**),[6] Unified Modeling Language (UML) (**2**), or Systems Modeling Language (SysML) to facilitate data exchange, computability, and communication with other manufacturing and analysis applications. These capabilities support manufacturers in evaluating, documenting, and improving performance. This guide specifically incorporates UML and XML but does not limit implementations to these languages.

4.2 This guide provides the structure and formalism to ensure consistency in characterizing manufacturing processes in a computer-interpretable way, thus enabling effective communication, computational analytics, and exchange of performance information.

4.3 Fig. 1 shows how this guide is used to transition manufacturing resources, such as industrial robots, machine tools, and auxiliary devices, from the phycical world to the digital world through graphical and formal representations. In doing so, required information to perform engineering analysis,

[6] The boldface numbers in parentheses refer to a list of references at the end of this standard.



UMPs store digital representations of physical manufacturing assets and systems to enable engineering analysis, for example, optimization, simulation, and life cycle assessments.

FIG. 1 Overview of Significance and Use of this Guide

such as optimization, simulation, and life cycle assessment, is characterized in a manner that is complete, standardized, and efficient.

NOTE 3—This guide will promote new tool development that can link manufacturing information and analytics for calculating the desired environmental performance measures.

4.4 This guide also supports the development of tools to improve decision support capabilities while facilitating the development and extension of standardized data and information bases.

NOTE 4—Data collected within manufacturing enterprises can be used to build enterprise-or-sector-specific databases that complement or extend Life Cycle Inventory (LCI) databases (ULE 880). This approach will improve the relevancy and completeness of the data while retaining key links to Life Cycle Assessment (LCA) methods.

4.5 Fig. 2 presents a road map to this guide. Section 5 describes the graphical representation of the UMP. Section 6 presents a conceptual definition of the UMP concept. Section 7 presents a step-by-step guide on how to characterize a manufacturing process using the formal methods presented in

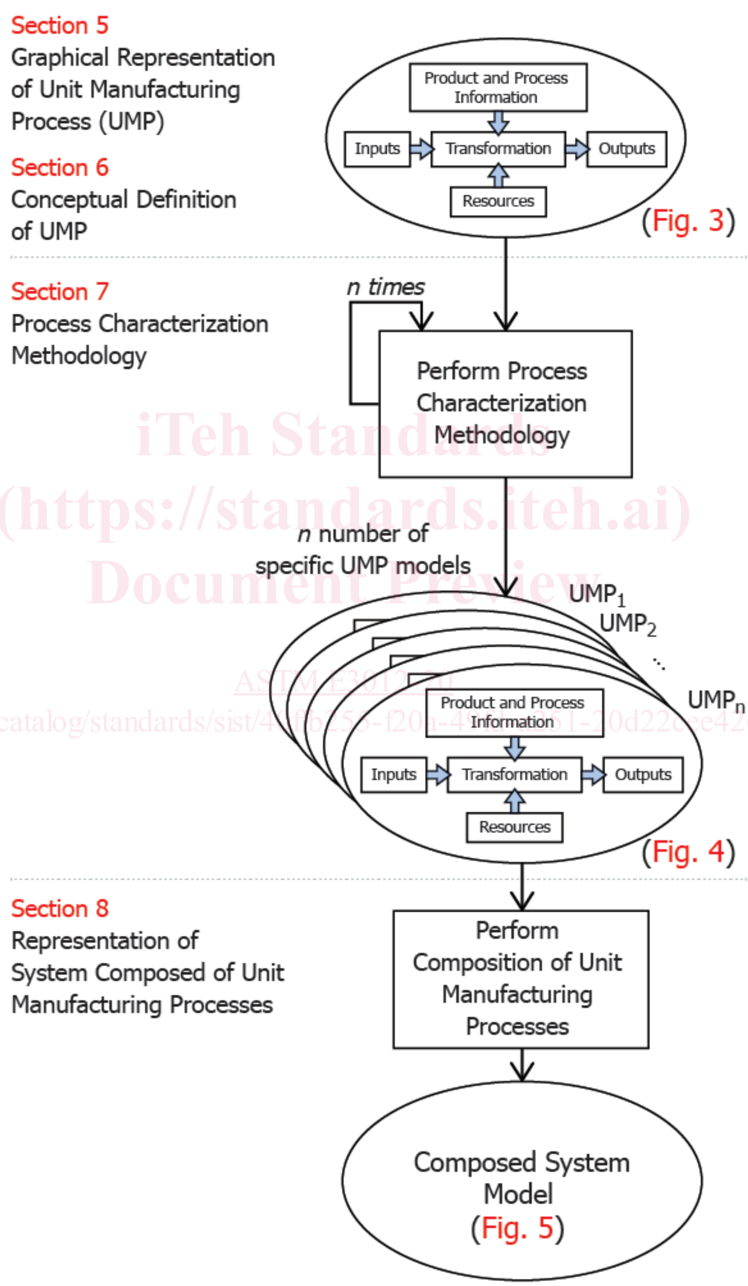


FIG. 2 Systematic Illustration of Use of UMP Representation and Process Characterization Methodology to Develop a Number of Specific UMP Models to Support Model Composition

Sections 5 and 6. Section 8 describes how to create a composed system model, or a network of UMPs.

5. Graphical Representation of Unit Manufacturing Process

5.1 The graphical representation (Fig. 3) facilitates communication of manufacturing process information. It is comprised of five blocks (inputs, outputs, product and process information, transformation, and manufacturing resources) to systematically structure and visualize manufacturing information. Structured information of manufacturing processes facilitates data exchange, sharing, and communication between people and other manufacturing applications such as modeling, simulation, and analysis tools.

5.2 The contents of each of the five blocks is defined in Section 6 using UML (the Unified Modeling Language) to define a conceptual representation. From the conceptual representation, a formal representation may be defined. An example of a formal representation of the UMP implemented as an XSD schema (eXtensible Modeling Language Schema Definition) (**3**) is presented in Appendix X1. An instantiated UMP model conforming to the example XSD schema is presented in Appendix X2 as an XML document.

6. Conceptual Definition of Unit Manufacturing Process

6.1 Fig. 4 presents the conceptual definition of a UMP as a UML class diagram. Starting with the *UnitManufacturingProcess* definition in the center, UMP concepts are described as UML classes in boxes in the figure. Concept attributes are described as UML attributes, and are shown inside the boxes. Relationships between concepts are described as UML aggregations and associations, and are depicted as connecting lines in the figure. In 6.2, each of the UMP concepts is defined. *Italics* are used to indicate the names of UML classes and attributes that represent that concept. Examples are given for the attributes of each concept.

NOTE 5—Information described in the conceptual definition of a UMP is purposefully written to provide flexibility in implementation. For guidance towards implementation strategies, see Appendix X1 and Appendix X2 for examples of implementation based on XML Schema. Other implementation forms may be defined.

NOTE 6—Subsections 6.2 and 6.2.1 – 6.2.5 provide examples and semantic explanation of concepts and attributes presented in the conceptual definition.

6.2 *Unit Manufacturing Process (UMP)*—A model of a physical process in a manufacturing setting that adds value through the modification or transformation of shape, structure, or property of input material or workpiece. A unit manufacturing process (defined as *UnitManufacturingProcess*) accepts inputs (defined as *InputOutput*), generates outputs (defined as *InputOutput*), uses product and process information (defined as *ProductProcessInformation*), uses manufacturing resources (defined as *Resource*), has a transformation (defined as *Transformation*), includes reviews (defined as *Review*), and has authors (defined as *Person*). Some examples of a *type* of a unit manufacturing process include milling, turning, die casting, injection molding, and laser powder bed fusion. An example of the *description* in a *UseBound* is "This model is only valid when assessing the process in the state of Ohio." An example of a *mathematicalExpression* of a *UseBoundEquation* is "15 °C < temperature_ambient < 40 °C" and an example of the associated *description* is "The model has only been validated under this range of temperature conditions."

6.2.1 *Input*—All physical inputs that enter the UMP, such as material (for example, raw materials or work-in-progress), consumables (for example, lubrication or forced air), energy, as well as external factors (such as temperature, humidity,

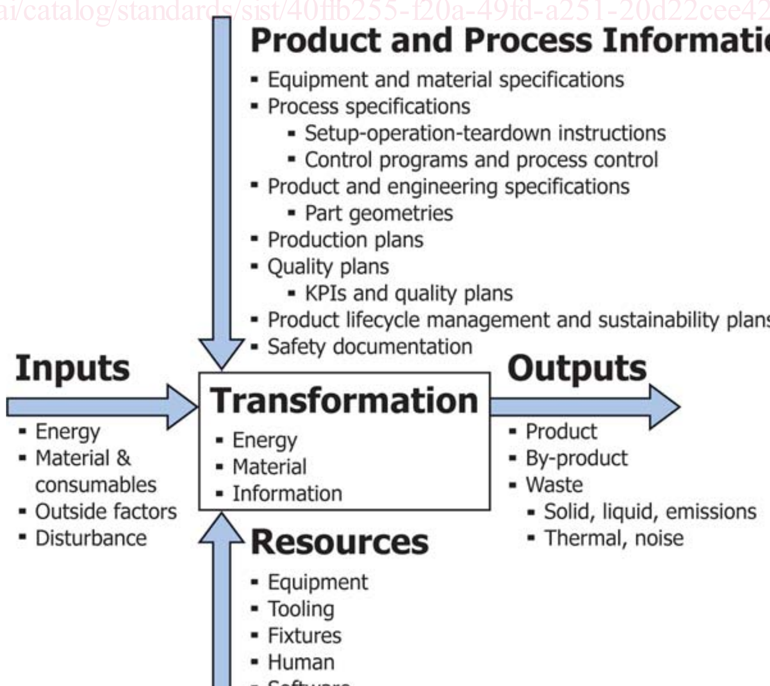


FIG. 3 Graphical Representation of UMP Information

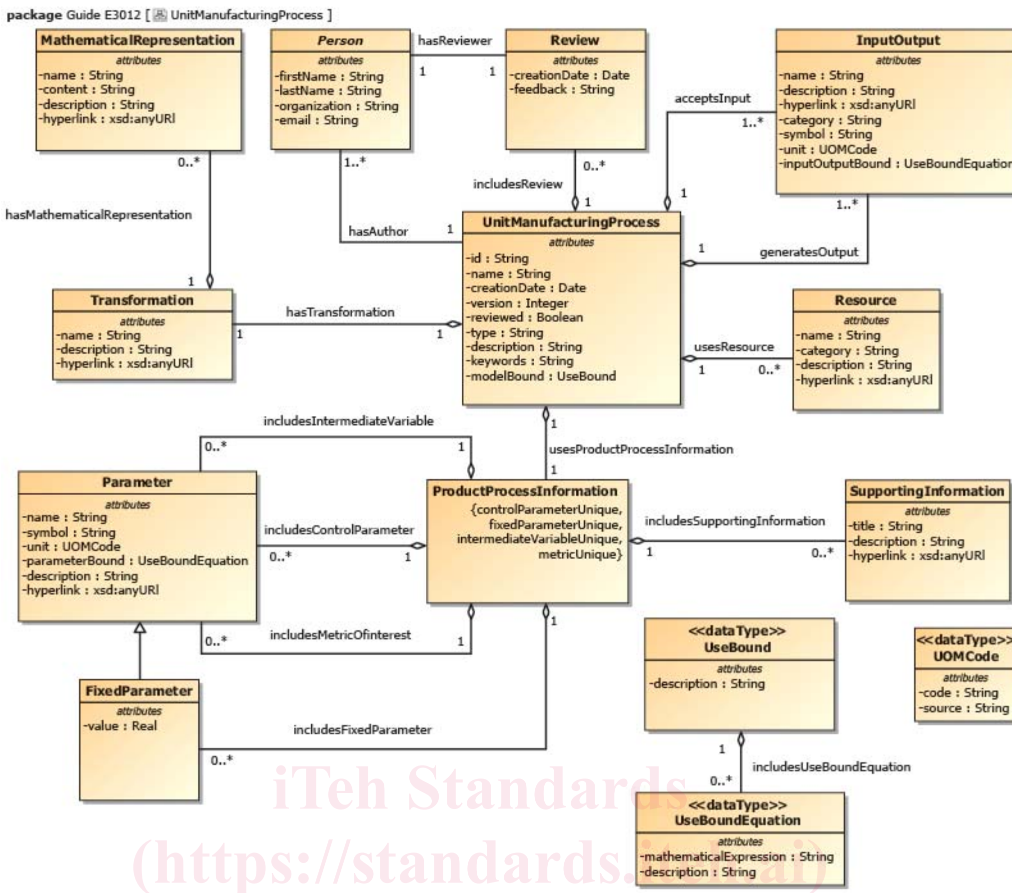


FIG. 4 Conceptual Definition of UMP

particulates, vibration, and shocks) that occur during the manufacture of a product. An example of a *category* of an input can be material, energy, or part-in-process. An example of the *symbol* is "electricity_used." An example of the *code* in a *UOMCode* is "KWH" with the *source* "UNECE Recommendation No. 20 - Units of Measure used in International Trade." An example of the *mathematicalExpression* of a *UseBoundEquation* is "electricity_used > 0" and an example of the associated *description* is "For this process to run, electricity is required."

6.2.2 *Output*—All physical outputs that exit the UMP model, such as products, by-products, waste, and emissions. Output of one UMP can be an input to another UMP. An example of the *symbol* is "waste_aluminum." An example of a *category* of an output can be waste, by-product, or product. An example of the *code* in a *UOMCode* is "KGM" with the *source* "UNECE Recommendation No. 20 - Units of Measure used in International Trade." An example of the *mathematicalExpression* of a *UseBound Equation* is "waste_aluminum ≥ 0" and an example of the associated *description* is "It is possible that the process does not produce any waste."

6.2.3 *Product and Process Information*—Relevant information to facilitate the evaluation of the transformation (6.2.5) calculations of material, energy, and information. This includes items such as part geometry, material properties, control programs, and process plans. Product and process information includes control parameters (defined as *Parameter*, intermediate variables (defined as *Parameter*), metrics of interest (defined as *Parameter*), fixed parameters (defined as *FixedParameter*), and supporting information (defined as *SupportingInformation*). *FixedParameter* extends the concept of *Parameter*. The process parameters are distinguished into the following four types. For each type of parameter, unit of measure codes, use bound equations, and descriptions are similar to the ones provided for input (6.2.1) and output (6.2.2). For specific examples, refer to the UMP example in Appendix X2.

6.2.3.1 *Control Parameter*—Tunable parameters that can be adjusted to evaluate different process settings. Examples of control parameters in machining processes include depth of cut, spindle speed, and feed rate.

6.2.3.2 *Fixed Parameter*—Parameters that are fixed through the evaluation of the transformation equations. Examples of fixed parameters in machining processes include specific cutting energy and density of the workpiece material.

6.2.3.3 *Intermediate Variable*—Calculated variables required to complete the evaluation of the metrics of interest (6.2.3.4). An example of an intermediate variable in a milling process is the milling time of a given surface area. Milling time must be calculated before assessing the machining power.

6.2.3.4 *Metric of Interest*—Performance metrics related to the process that the UMP model is used to evaluate. Examples of metrics of interest include cost per part and mass of CO_2 emissions per part.

6.2.3.5 *Supporting Information*—All other relevant links to information regarding the manufacturing process, including production plans, product and engineering specifications, and setup-operation-teardown instructions.

6.2.4 *Manufacturing Resource*—Information about process resources such as equipment, fixtures, tooling, and inspection gauges.

6.2.5 *Transformation*—The formal relations between inputs, outputs, and metrics of interest through the use of product and process information and information about the manufacturing resources. A transformation is represented as some form of mathematical representation (defined as *MathematicalRepresentation*).

6.2.5.1 *MathematicalRepresentation*—A description or a formal definition, or both, of components of a transformation. Examples for *content* of a mathematical representation include an equation described as a MathML expression, a data-driven model described as a PMML model, and an inequality constraint described as a MathML expression representing a feasibility space in a manufacturing model.

NOTE 7—MathML is a markup language (**4**) developed by the World Wide Web Consortium (W3C) to describe mathematical notations, capturing both its structure and content. PMML (5) is a standard developed by the Data Mining Group (DMG) to represent predictive models in an XML format, promoting the deployment of such models.

6.2.6 *Review*—An expert review of a UMP model. A review has a reviewer (defined as *Person*). Examples of ways in which a model can be reviewed include a peer-review procedure, a validation study using empirical data, and a cross-validation study using a subset of training data in the case of data-driven models.

6.3 Tables 1-14 describe the attributes and relationships of each concept in the conceptual definition. For each attribute, a data type and description are provided. For each relationship to the concept, the name of the related concept, the cardinality of the relationship, and a reference providing additional information are provided.

NOTE 8—These tables provide additional information to facilitate implementation of the conceptual definition.

7. Process Characterization Methodology

7.1 The process characterization methodology supports the derivation of specific UMP models for characterizing the environmental and other aspects of manufacturing processes. The process characterization methodology is comprised of the steps described in 7.2 through 7.4.

7.2 *Identify UMPs and KPIs:*

7.2.1 Select appropriate UMP(s) to be characterized (for example, the compacting process represented in Fig. 5).

7.2.2 Specify the boundary (see Guide E2986) that encompasses one or multiple UMPs to enable the identification and selection of UMP-specific information (6.2).

7.2.3 Product and process information can be common to a number of UMPs, such as material feed-rate, or unique to certain UMPs, such as injection molding material injection temperature. Further, additional process-unique information provides important guidance on selecting the appropriate equipment, tooling, and fixtures, such as part geometry, engineering specifications, number of mold cavities, and material selection, for injection molding.

7.2.4 Select the appropriate KPIs ensuring process control and product conformance (see Guide E3096).

7.3 *Identify UMP-Specific Information:*

7.3.1 Using the graphical and formal representations, one can identify and capture the essential information required to develop the specific UMP models. See Fig. 5 for an example of a compacting process. The information includes the specific inputs, manufacturing resources, product and process information, and outputs for the chosen UMP.

(a) Identify the Inputs—The inputs that enter the UMP can include intermediate products, works-in-progress (WIP), raw materials, lubrication, energy, and external factors (such as temperature, humidity, particulates, vibration, and shocks) that occur during the manufacture of a product. For the compacting process as represented in Fig. 5, the inputs include the electrical energy, the blended powder, the lubricant, and humidity.

TABLE 1 Description of UnitManufacturingProcess Concept

Attribute	Data Type	Description	
id	String	Unique descriptor to identify the model among a collection of UMP models	
name	String	Name to identify the UMP model	
creationDate	Date	Date of model creation	
version	Integer	Version number for the model	
reviewed	Boolean	Indication of whether the model has been reviewed	
type	String	Designation within a classification of manufacturing processes	
description	String	Textual description of the UMP model	
keywords	String	Textual descriptor to aid in model query	
modelBound	UseBound	Formal description of the valid bounds of use of the model	
Relationship	**Cardinality**	**Concept**	**Reference**
acceptsInput	1...*	InputOutput	See Table 2
generatesOutput	1...*	InputOutput	See Table 2
usesProductProcessInformation	1	ProductProcessInformation	See Table 3
usesResource	0...*	Resource	See Table 7
hasTransformation	1	Transformation	See Table 8
includesReview	0...*	Review	See Table 10
hasAuthor	1...*	Person	See Table 11