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MANUFACTURING PROCESS INFORMATION MODELS FOR SUSTAINABLE MANUFACTURING

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ABSTRACT
Sustainable manufacturing systems use processes, methodologies, and technologies that are energy efficient and environmentally friendly. To create and maintain such systems, well-defined measurement methodologies and corresponding manufacturing information models play a crucial role to consistently compute and evaluate sustainability performance indicators of manufacturing processes that will result in reliable decision support. However, when it comes to describing sustainability of product manufacturing, the presently available methods and tools do not account for manufacturing processes explicitly and hence result in inaccurate and ambiguous decisions between alternate systems. Furthermore, there are no formal methods for acquiring and exchanging sustainability-related information that help establish a consolidated sustainability information base for decision support. This paper presents a study on the scope of the currently available manufacturing information models to incorporate sustainability. Identifying the requirements for information models that cater to sustainable manufacturing was done utilizing an earlier developed Systems Integration for Manufacturing Applications (SIMA) reference architecture model. We propose an extension to the SIMA architecture considering sustainability and refer to it as a GreenSIMA architecture. We present injection-molding unit manufacturing process as an example.

Keywords: sustainable manufacturing; information models; systems integration; manufacturing processes; injection molding

INTRODUCTION
Sustainable manufacturing utilizes methodologies that minimize material and energy consumption and are safe for both people and the environment. Today, sustainability has become a crucial aspect of manufacturing. As reported by the U.S. Energy Information Administration, the U.S. industrial sector consumes over 30 quadrillion BTU of energy every year [1]. Furthermore, manufacturing accounts for 65% of that industrial energy usage [2]. Combined with today's health and environmental awareness and global competition, increasing energy costs signify that manufacturers must reduce their energy consumption and costs while maintaining or increasing quality, flexibility, and speed if they are to remain competitive in the global market.

To create and maintain those sustainable manufacturing systems, standard performance measurement methodologies and corresponding information models are essential for the consistent computation of sustainability performance indicators. However, there are no existing methods and tools available that enable consistent evaluation, and prediction of manufacturing process sustainability. Current ad-hoc methods result in inaccurate and ambiguous comparisons of processes. There is also no reliable, formal information base for decision support in sustainable manufacturing. Even the Life Cycle Assessment (LCA) tools that are available are limited to material production and use sustainability approximations for specific manufacturing process-related decisions [3]. To enable the measurement methodologies to consistently compute and evaluate sustainability performance indicators, information models for manufacturing, modeled against Unit Manufacturing Processes (UMPs), need to be developed. The building blocks of manufacturing, UMPs are the individual processes, e.g., injection molding, which add value to input material in producing a product. The identification of information requirements for UMP information models is a first step in the development of models for the standardized evaluation procedures of sustainable manufacturing processes.

This paper is organized as follows. The next section on related work presents a literature review of sustainable manufacturing and the standard tools and methodologies available to support such systems. Currently available manufacturing process information models are then discussed, and followed by an extension of the SIMA model reference architecture to create a corresponding sustainability GreenSIMA. Injection molding is used as an example in the new sustainability reference architecture to show how it can be implemented as a functional model. Finally, the paper concludes with the impact and the scope of future work.

RELATED WORK

Using a process based modeling for the cradle-to-gate energy and carbon footprint reduction in product design, Alsaffar [4] shows that environmental performance measures are often not accounted in the product development stage of manufacturing. He asserts the necessity of a cradle-to-gate approach and parametric models in order to support manufacturing decision-making in a way that minimizes energy consumption. He also notes that the current methodologies and tools suffer from several deficiencies and can lead to inaccurate and uncertain assessments as they are limited by variability, time intensity, and errors.

When presenting an overview for Manufacturing Engineers, Leahu-Aluas [5] defines sustainable manufacturing emphasizing its consideration of the entire product life cycle. The author details the fact that increasing natural resource prices, environmental and human health issues, and global economics all drive sustainable manufacturing. The author also asserts a positive link between company growth and sustainability. Furthermore, it was emphasized that for companies to adopt sustainable manufacturing practices, there needs to be standards and metrics for sustainable manufacturing.

In their work on information modeling for manufacturing system life cycle, Euler-Chelpin [6] specify what information models are and discusses the importance of those models as standards for the manufacturing system life cycle. The author notes the complexity of manufacturing system development and discusses the usefulness of existing models. The goals for manufacturing-specific information models are emphasized, as the information models must be communicable, reusable, accessible, composable, interpretable, and well-structured to address the problems that exist.

INFORMATION MODELS

To determine the information requirements for sustainability, it is necessary to look into the current information models and the existing tools available to support manufacturing processes. An information model is a formal representation of entities, their properties, and their relationships that enable understanding of complex and/or hypothetical systems. These models play a crucial role in creating and maintaining manufacturing systems because they map data to rules of interpretation in a manner that produces effective and consistent results. This enables an observer to create and use an information model representing the real world in order to answer questions about it. Figure 1 depicts this relationship.

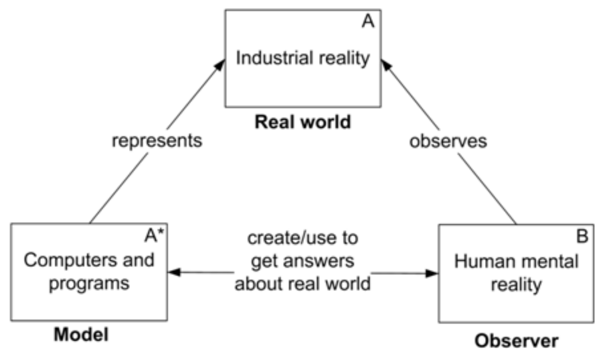

Figure 1 Model use and relationships [6]

There are many models and model architectures that have been developed for manufacturing processes. However, looking into these existing models reveals that they do not explicitly account for sustainability in a way that can be utilized to consistently compare and evaluate sustainable manufacturing processes. The typical performance indicators used in information models include production rate, cost, and quality while ignoring water consumption, toxicity, and other aspects of manufacturing sustainability. This leads to difficulties when trying to make decisions for sustainable manufacturing. At the same time, there are elements of existing models that involve such factors as energy use and emissions at some level; these elements can be utilized in the creation or expansion of information models to include sustainability. A summary of existing models and model architectures that include useful information for sustainability is shown in Table 1.

Table 1 Existing models and model architectures

TITLE	LANGUAGE	PHASE(S)	USEFUL INFORMATION
CMSD [7, 8]	Unified Modeling Language (UML), Extensible Markup Language (XML)	production	• Information Categories (e.g., Resource, Setup, Part, Bill-of-Materials, Process Plan) define information about parts, equipment, how long it takes to configure a resource, characteristics of materials, production activities, scheduling, etc. •Packages include Resource Information, Part Information, Production Operations, Production Planning, and Layout. • Intended to facilitate simulation.
SIMA [9]	Integrated DEFinition (IDEF0)	all	See Figure 3 for diagram. • Model architecture divides production process into five major activities: Define problem, Specify processes to produce product, Design production system, Simulation, Prepare plans and budgets. •Inputs: manufacturing resources, quality, time, and cost constraints, product specifications, production requirements. •Outputs: process specifications, simulations, performance analyses, system specifications, implementation plans, budgets.
CPM [10,11]	UML, Ontology Web Language – Description Logic (OWL-DL)	design	•Classes describing objects and relationships include Artifact, Feature, Port, Specification, Requirement, Function, Flow, Behavior, Form, Geometry, Material, Constraint, EntityAssociation, Usage, etc.
OAM [10]	UML	design	•Extension of Core Product Model (CPM) for part assembly. •Assembly model represents function, form, and behavior; defines system level model and associated relationships. •Allows for tolerance representation and propagation, kinematics representation, and engineering analysis at system level.
MOKA	(Moka Modelling Language) MML, UML	design	•Five distinct views of a product: Structure (parts, assembly, and features), Function, Behavior, Technology (materials and manufacturing process), and Representation (other user-defined technological information). • Product model described using class diagram in UML [10].
IDEF1/X models [12]	IDEF	production	•How information is used and managed; most useful after info requirements are known. Modular -eliminates inconsistencies. •Method for creating model is in five stages: Define model scope and state objectives, Define the Entity Classes, Define Relation Classes between entities, Identify Key Classes, Identify Non-Key Attribute Classes. •Note: Process-oriented, not product view. Cannot do sustainability performance analysis. [13]
STEP models (ISO 10303) [14]	EXPRESS [14]	all	•Describes product data. Different Application Protocols (APs) support specific product manufacturing process stages; Main groupings of APs are Design, Manufacturing and Life cycle support. •*STEP Application Handbook* contains descriptions of APs. Manufacturing APs include 219, 223, 224, 238, 240. Also 201-204, 239, 221, 241, 235. Part Design / Manufacturing: 203, 214, 224, 240, 238. Note: AP 221 model similar to ISO 15926-2 model.
ISA 95 models [15]	XML	production	•Focus on manufacturing business logistics/management and relation to processes. •Defines Manufacturing Operations Management (MOM) activities; Includes project schedule, definition, bill of materials, process optimization, maintenance, etc. •Note: Information can be inferred from production data collection and performance analysis. Does not include emissions.
MANDATE models (ISO 15531) [16]	EXPRESS	production	•Contains three management data categories: time, resources, and flows. •Standardized representations of manufacturing information other than product-related data. Management view, not product view.
OntoSTEP models [17]	OWL-DL	all	• Translation of STEP *(see above)*. • Enables application of mechanisms to check models and data validity, to check consistency of individual instances, and to infer new knowledge.

In Table 1, *Title* is the name of the manufacturing process model or model architecture. *Language* is the language the model is written in. *Phase(s)* describes which part(s) of the manufacturing process, i.e., design or production, are covered by the model. *Useful Information* details what aspects of that existing information model could be used in a sustainability model. For example, the SIMA (Systems Integration for Manufacturing Applications) architecture uses the IDEF0 modeling language. It covers both the design and production phases of manufacturing and contains several useful pieces of information such as manufacturing resource data and performance analyses. Exploring all of the models in depth was outside the scope of this study. However, the information requirements for the development of a standardized sustainability model were identified.

SIMA TO GREENSIMA

Determining the requirements for an information model catering to sustainable manufacturing was done utilizing the SIMA model reference architecture. SIMA was chosen for its clear depiction of process flow and the fact that it covers all phases of the manufacturing process, but a different model could have been used. Figure 2 shows the product realization activity model of the original SIMA reference architecture in IDEF0. This model consists of the activities involved in the manufacturing process along with the information flows required to support those activities. It is focused on the technical aspects of product realization, i.e., the process by which products are designed or produced [9]. The scope of this study involved finding the information necessary to develop an extension of the SIMA model that incorporates sustainability, using injection molding as a example.

First, the existing SIMA architecture was analyzed to determine specifically which aspects of the model contain sustainability-related information or can be modified to contain such information. Instances of useful information include data on materials, resources, and processes as well as calculations of how different properties and decisions affect energy use, waste volume, and other important factors. The key factors to be addressed in sustainable manufacturing are water and materials' consumption, energy use, emissions, and waste. To create a comprehensive model, it was also noted what new items would be necessary to address these different aspects of sustainability. This modified, extended SIMA architecture considering sustainability is referred to as a GreenSIMA model architecture.

Figure 3 is the main diagram of the GreenSIMA, showing what existing elements need to contain sustainability-related data or calculations as well as the new items that will allow for the creation of a consistent, accurate decision-making model. In the diagram, *blue* indicates an element that already existed and needs to contain sustainability-related information, *green* indicates an activity including sustainability calculations, and *red* indicates new sustainability information necessary to perform the calculations. This framework for a sustainability model can be used to develop a full GreenSIMA standardized process model based on the original SIMA model architecture. Note that the architecture can be further extended to include recyle/reuse depending on the manufacturing process.

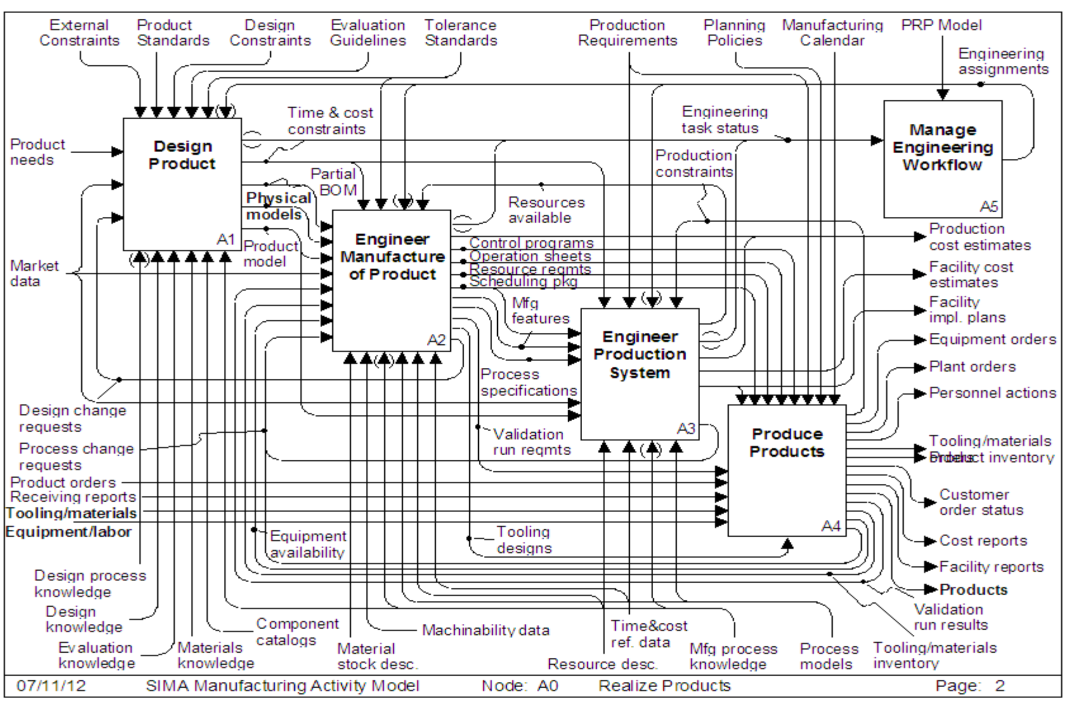

Figure 2 SIMA activity model

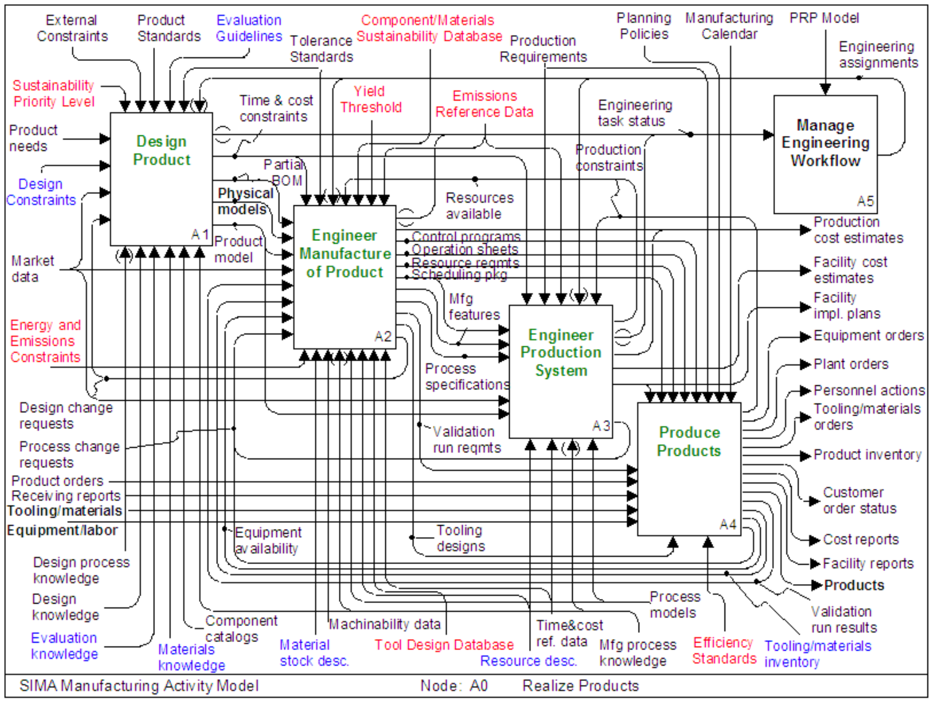

Figure 3 GreenSIMA overview

INJECTION MOLDING EXAMPLE

Once the basic requirements for a sustainable manufacturing information model were found and a GreenSIMA structure established, an example was created using the injection molding UMP. In the injection molding process, as seen in Figure 4, plastic pellets contained in a hopper are fed into the barrel of an injection unit. Within the barrel, heater bands melt the resin as the screw forces the plastic forward into a mold. Once the mold is filled, the injection unit maintains holding pressure as the injected part solidifies. These first steps are energy-intensive; melting the pellets consumes 50-60% of the entire process energy, while injection and follow-up pressure use another 15 percent [19]. When the part is cooled, the mold opens, the ejector pins push the part out of the mold, the mold is clamped shut again, and the entire process is repeated. Throughout this process, waste, emissions, energy use, and other sustainability indicators vary depending upon machine type, part geometry, material type, and many other process parameters.

In the example, parameters of the injection molding process were used to populate a table of information requirements for a sustainability model based on the general GreenSIMA architecture established above. Node A2 of the GreenSIMA model i.e., Engineer Manufacture of Product, is presented in Figure 5. Table 2 lists the modified elements of the original SIMA model along with the sustainability information that needs to be included to create a comprehensive GreenSIMA.

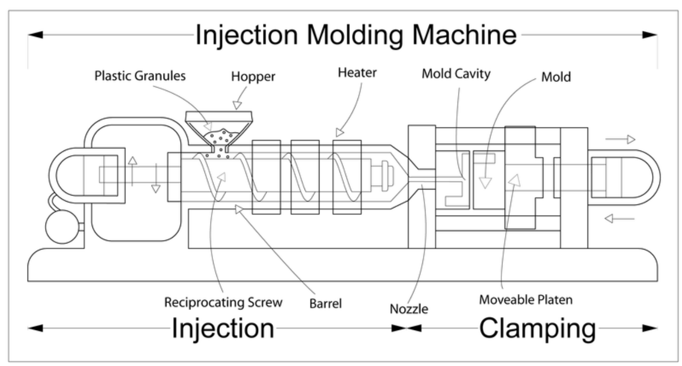

Figure 4 Injection molding process
(Source: wikipedia)

For example, Material Stock Description, a modified element, would include information on the material recyclability, the environmental impacts of the material extraction and creation, and the relative energy use associated with that material. Similarly, for activity node A21, calculations and two new items are necessary to determine and account for sustainability factors when selecting the manufacturing methods to be used.

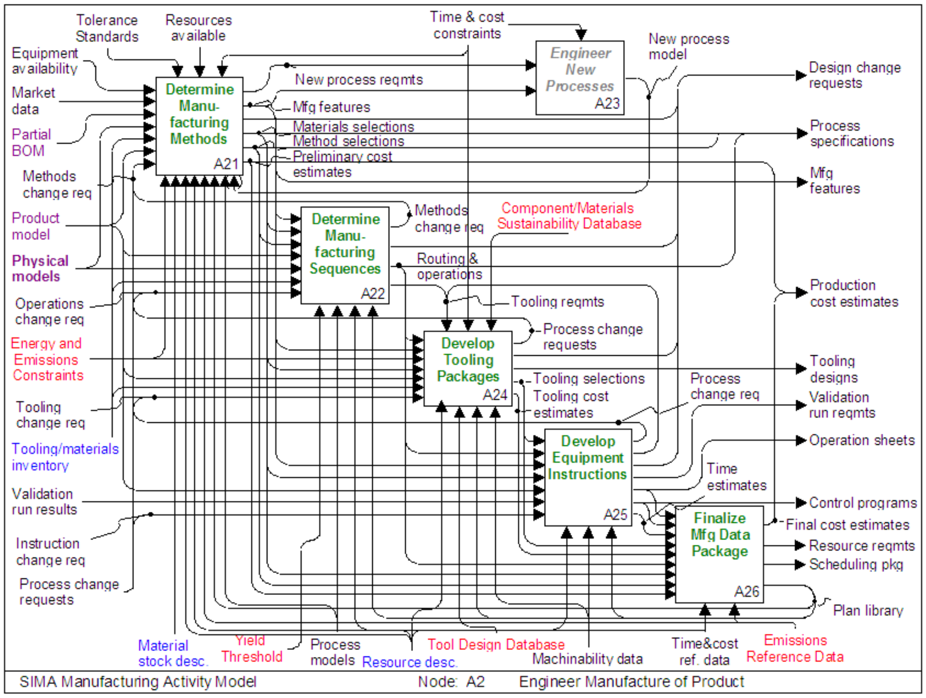

Figure 5: GreenSIMA activity A2

Table 2: Sustainability related information

Material Stock Description	Information from Materials Knowledge, plus reusability and/or recyclability, environmental damage of extraction and production (energy use, emissions, waste, toxins, water consumption), Energy Usage Indicator
Machine Description, Resource Description	Operating emissions, power profile, dry cycle time, average setup time, average number of setup parts, maximum capabilities (shot size, clamping force, and stroke length)
Tooling/Materials Inventory	Sustainability factors (e.g., carbon footprint, recyclability, lifetime) of tools and materials
Determine Manufacturing Methods (A21)	Select best process using material and geometry information unless two or more are comparable, then both considered until calculations determine which is most sustainable; Emissions Reference Data, see A26; Energy and Emissions Constraints, request design changes if exceed constraints; Estimate energy, time, and power based on machine selections
Determine Manufacturing Sequences (A22)	Minimize energy waste and emissions with machine idling time and transportation, Yield Threshold of necessary percentage of parts to survive quality control inspection
Develop Tooling Packages (A24)	Component/Materials Sustainability Database, minimize energy, emissions, and waste; Tool Design Database, calculations to optimize runner system, cooling channels, etc.
Finalize Manufacturing Data Package (A26)	Emissions Reference Data, consider emissions with/as cost

Now that the information requirements for a sustainability model have been identified and an injection molding example created using the GreenSIMA reference architecture, the next step towards standardization is to actually create a sustainability information model utilizing that reference architecture. This would include populating all of the information elements and capturing their relationships. With such an information model, design information, sustainability analysis, and compliance information becomes readily available thus enabling systems integration for manufacturing processes inherently more efficient and cost-effective. Further, analytical capabilities not possible in traditional methods are easily accessed through the information model. Although the creation of such a model was outside the scope of this study, a few example sources have been collected to demonstrate that such information is available.

For the Materials Knowledge and Materials Stock Description items, environmental information such as energy use, waste, atmospheric emissions, and waterborne emissions data for different plastics are available in the C*radle-To-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors* [18]. Furthermore, material properties such as density, specific heat, crystallinity, thermal conductivity, recommended injection rate and pressure, and recommended injection and ejection temperature for plastics can be calculated and/or obtained from the manufacturer, as evidenced by the *Injection Molding Processing Guide* [19]. Similarly, for activity node A21 Determine Manufacturing Methods, formulas for the calculation of energy consumption and to decide between hot and cold runner systems are available from Thiriez [20]. Along with other resources that are available, this information can be used to create a functional GreenSIMA model.

CONCLUSION

Overall, the goal of this work was to contribute towards requirements identification for the development of standardized information models to evaluate sustainability of manufacturing processes. More specifically, this paper looked into existing models and model reference architectures before identifying the requirements for a GreenSIMA architecture based on the existing SIMA reference architecture. This architecture will potentially aid in the creation of information models that will capture sustainability-related manufacturing process information explicitly to enable consistent computation and evaluation of sustainability performance indicators. Future work includes creating and implementing specific unit manufacturing process models based on the GreenSIMA reference architecture reported in this paper.

DISCLAIMER

Mention of commercial products or services in this paper does not imply approval or endorsement by NIST, nor does it imply that such products or services are necessarily the best available for the purpose.

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