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A FRAMEWORK FOR INTEROPERABLE SUSTAINABLE MANUFACTURING PROCESS ANALYSIS APPLICATIONS DEVELOPMENT

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ABSTRACT

Sustainable manufacturing (SM) continues to grow in importance. However, analysis tools to assess the sustainability performance of SM processes are difficult to verify and validate. Additionally, the ability to share and reuse SM information is hampered by a lack of (1) standards to represent that information, (2) interoperability among the engineering applications that use that information, and (3) consistency across the current approaches for modeling that information. This paper focuses on an integrated approach required to address these limitations, proposing a framework that will enable sustainable manufacturing process analysis applications to be developed by manufacturers. The framework will facilitate the developing of analysis platforms and sustainable manufacturing information models by enabling the integration of simulation and optimization model components to analyze processes at different operational levels. An example is provided to illustrate the framework.

1 INTRODUCTION

The goal of sustainable manufacturing (SM), as defined by the U.S. Department of Commerce, is the "creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound" (DOC 2010). An increasing number of companies are looking into practices to improve the sustainability performance of their operations and processes (Fujitsu 2011, GM 2010, Rockwell Automation 2010). To succeed, these companies need the ability to assess accurately their current performance and determine how far they have to go to meet their SM goal. Currently, companies use assessment methodologies that are mainly stand-alone, provide problem-specific solutions, and are hard to reuse. They need a comprehensive framework that will support development of an integrated suite of tools to enable science-based performance assessment, analysis, and optimization.

As part of a larger SM Program, the National Institute of Standards and Technology (NIST) is developing the measurement science and standards that will provide a foundation for such a framework. The focus of the Program is energy and material efficiency, with a goal to provide the methodologies, tools, and infrastructure to enable industry to assess and analyze the sustainability performance of individual processes and to aggregate individual performances up to the plant floor and supplier network levels (NIST 2012). To achieve this goal, the Program is developing sustainability metrics, measurement methods, assessment methodologies, information models, simulations, and uncertainty quantifications

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(UQ). This paper proposes a framework that defines: (1) common concepts and models that facilitate the description and exchange of sustainability information; (2) reusable tools that enable the development of integrated modeling and simulation platforms that aid SM performance assessment, analysis, and decision-making; and, (3) common verification and validation (V&V) methods to ensure accurate modeling and analysis.

The proposed framework is called the Sustainable Process Analysis Framework (SPAF). This paper describes the current vision for SPAF that may evolve with program and industry input. SPAF will enable the integration of independent assessment methodologies, techniques, and tools with each other and with engineering and sustainability information systems, optimization and decision guidance applications, and uncertainty quantification tools. This integration will be realized through mapping and sharing of information using standardized data models that facilitate:

- Interoperability needed for assessment and aggregation of sustainability metrics.
- Efficient definition/storage/exchange of manufacturing process sustainability information.
- Modular definition with support for information composition, decomposition, and reuse.
- Direct analysis of manufacturing process sustainability issues at different levels of granularity.
- Translation/transformation of process information into computation-friendly forms for optimization and other analyses.
- The application of quantified uncertainty analyses as a part of model and application V&V.

The rest of this paper is organized as follows. The next section discusses industrial needs for SM analysis and the proposed framework. Section 3 presents an overview of the proposed framework. Section 4 demonstrates an application of the framework using an illustrative example. Finally, in Section 5, a summary is provided and future work is discussed.

2 THE NEED FOR THE PROPOSED FRAMEWORK

A SM workshop held at NIST showed that industry has strong "data" needs for (1) better sustainability data that are more accurate; (2) better data measurement and collection methods; and (3) better data standards for SM (NIST 2010). The workshop also identified three related challenges. First, new engineering information systems that manage that data must be developed. Second, new modeling and analysis tools, which use that data, must be developed to improve the evaluations, assessment, and decision support for continuous improvement of manufacturing operations. Third, common modeling methods and tools for that data must be developed to enable more efficient information exchange.

The SPAF is the first step towards solving these challenges. The following features of SPAF will increase the effectiveness of SM modeling and analysis:

Interoperability of systems: Companies use different methods and tools to assess sustainability performance at the process, plant, and network levels. Information exchange across these levels occurs through customized interfaces. These interfaces involve a variety of data formats, structures, and semantics. Translating among these interfaces is time consuming. For example, (Skoogh 2009) showed that more than 30% of the total time to develop simulation models is spent on gathering, extracting, and processing data. To facilitate application interoperability, SPAF will provide a common method for describing and encoding SM process information.

Aggregation of metrics: Metrics associated with different levels – process, plant, and network – must be assessed and aggregated to understand the total sustainability performance of a company (Kibira et. al. 2010). Methods and models to describe the sustainability information associated with these assessments and aggregations must be developed. SPAF will provide tools necessary to support those methods and models.

Reusability of metrics: To simplify aggregation, the metrics with the exact same definition should be used at every level. For example, if carbon footprint is the metric used to assess energy efficiency at the unit process level, it should also be the metric used to assess energy efficiency at the plant and network levels. A common representation and terminology for these metrics is essential to their successful reuse. The SPAF will provide such a methodology and terminology.

Modular Approach: When dealing with a large, complex problem, such as the description and analysis of a large number of interrelated SM processes, researchers often use a modular approach in developing models. This approach partitions the problem along a logical boundary into a collection of smaller, semi-independent but interrelated problem components or modules. This approach has several benefits. First, it can foster greater understanding of both the complete problem and its constituent parts. Second, it allows a team of analysts to concurrently develop solutions for the individual modules that can be later synthesized in a complete problem solution. Third, the same methods and tools can often be reused on different modules. SPAF will use this modular approach.

Accuracy of models: The accuracy of our sustainability assessments greatly depends upon the accuracy and completeness of the models and the data used to make those assessments. Asserting accuracy and completeness will not be easy because multiple kinds of uncertainties can exist in both the models and the data. New verification, validation, and uncertainty quantification methodologies and tools are needed across the SM process hierarchy to reduce uncertainty. SPAF will provide these methodologies and tools.

3 SUSTAINABLE PROCESS ANALYSIS FRAMEWORK

A high-level view of our framework is shown in Figure 1. It contains a methodology for describing sustainable manufacturing processes, reusable tools to support integration and analysis, and guidelines for verification, validation, and uncertainty quantification. A brief description of each is provided below.

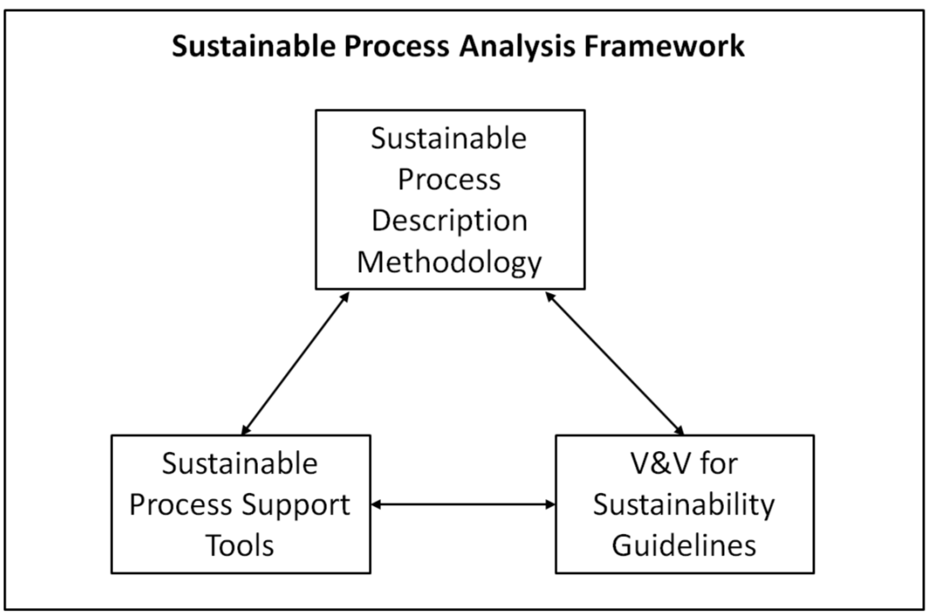

Figure 1: The sustainable process analysis framework

3.1 Sustainable Process Description Methodology

The Sustainable Process Description Methodology (SPDM) can be used to describe the sustainability aspects of manufacturing processes. The main component of SPDM is an information model that defines the structure, semantics, and formats of the key elements of the process, their relationships to one another, and the roles they play in the sustainability assessment of the process. In addition, SPDM employs the modular approach by enabling higher-level processes to be decomposed into a network of lower-level sub-processes and operations. The sustainability assessment of the process then is an aggregation of the sustainability assessments of the components of this network.

A detailed presentation of the SPDM information model is beyond the scope of this paper. Figure 2, however, shows a high-level model of the SPDM. Descriptions of the key elements in Figure 2 are provided below.

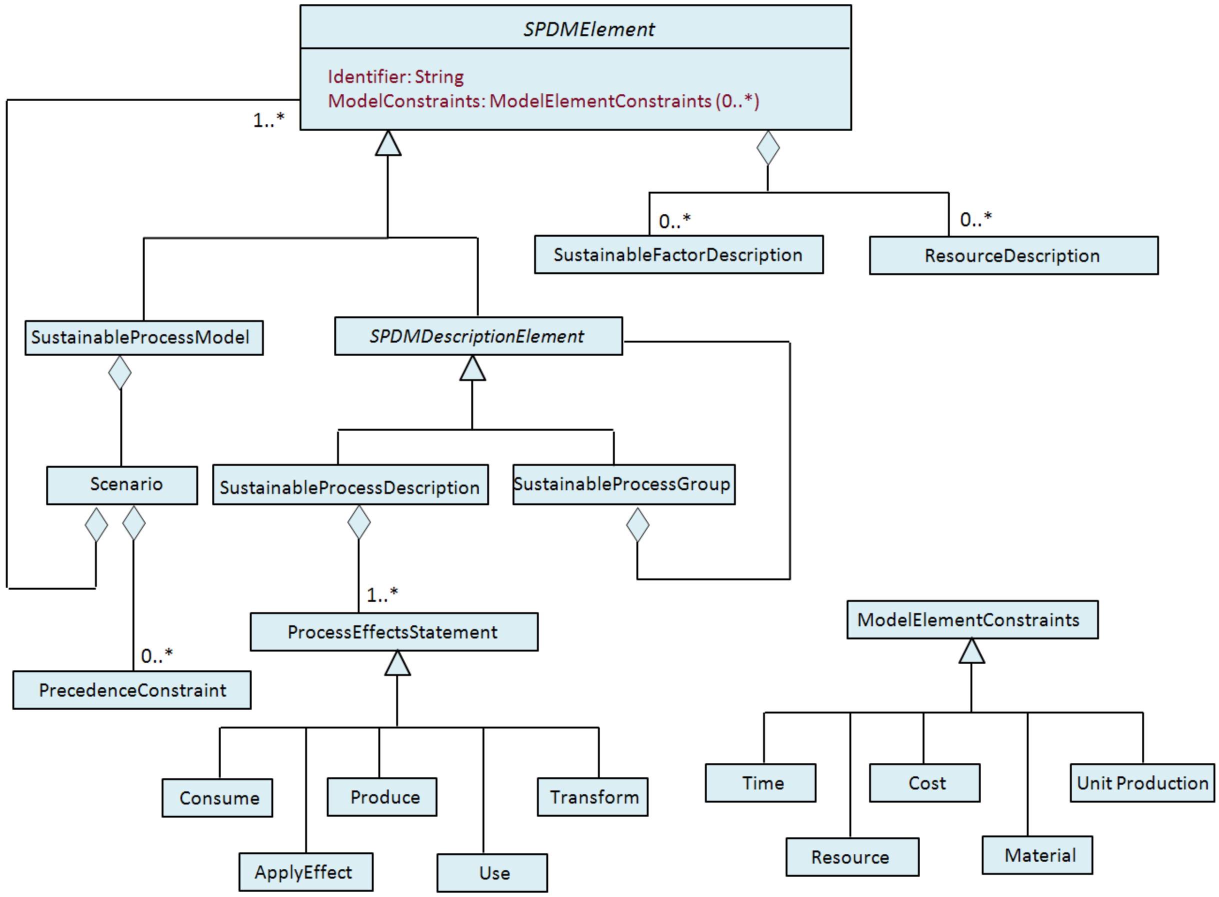

Figure 2: Sustainable process description information model

- Sustainable Process Description (SPD) – This is top-level element in the model. It provides a means to describe the sustainability effects of a manufacturing process. Examples of those effects include energy usage, raw material consumption, waste generated, resources used, and costs incurred.
- Sustainable Process Group (SPG) – This element relates a process's effects in terms its component sub-processes. The sub-processes can be structured as a group of processes where: (1) only one of the sub-processes' effects will take place; (2) the effects of each sub-process will occur in a predetermined sequence; or (3) the effects of the sub-processes will occur all at once.
- Resource Description (RD) – This element provides a means to designate a name for, and to define the characteristics of, the tools, equipment, and people involved in the execution of a process. SPDs use RDs to indicate which resources are used in a given process. The characteristics of those resources are used to help determine the effects of executing the process.
- Sustainable Factor Description (SFD) – This element provides a means to designate a name for, and to define the characteristics of, substances, part components, and types of energy sources that are involved in the execution of a process. SPDs use SFDs to indicate which substances/raw materials/part components are consumed or produced by the given process. The characteristics of the sustainable factors are used to help determine the effects of executing the process.

- Sustainable Process Model (SPM) – This element acts as a container for related SPDs, SPGs, RDs, and SFDs. It provides a means for process information (RDs, SFDs, or SPDs) defined in one SPM to be referenced in another SPM. Its most important feature is that it provides a means to specify precedence relationships between SPDs, SPGs, and externally defined SPMs so that they can be used to a complex processes as a precedence network of related sub-processes.

3.2 Sustainable Process Support Tools

The SPAF is a description of common concepts, tools, and methods from which different, interoperable, analysis platforms could be created. Platform interoperability is enabled by (1) common concepts and models as described by the SPDM and (2) common tools created based on the SPDM to support integration and analysis. Platform composition will depend on the type of analysis required. Below is a description of several kinds of tools that will be included or provided for in the SPAF.

Common metrics computation tools: Since SPDM provides a common representation for sustainable process information, tools that compute common or standard metrics need to be created and used in different platform implementations. Some tools will provide a simple computation such as determining the total power usage. Other tools will calculate the metrics for material intensity or energy consumption as defined in Tanzil and Beloff (2006) and National Research Council (1999).

Information transformation/translation utilities: SPDM is intended to provide a foundation for standardization. Sustainability assessments will be carried out using analysis and optimization tools that may not implement those standards. It may be necessary to transform the information from the standards format to the format required by analysis tool inputs and the results from the proprietary outputs to the standard. Therefore, the framework will provide translation/transformation utilities.

Sustainable process information repository: As the amount of sustainable process information increases, the need for storing, retrieving, and managing that information also increases. The framework will provide a design of a sustainable process information repository for manufacturers to manage their storage, retrieval, classification, and indexing of sustainable process information and provide a basis for a virtual testbed to showcase real industrial scenarios.

User interface tools: An analysis platform can be built using only command-line interface-based tools. However, productivity and efficiency in the analysis process can be improved if the platform is built using a graphical user interface (GUI). The framework will support a number of existing application development platforms to develop GUIs for use by manufacturing personnel.

SPDM information editors: Information described in SPDM can be instantiated in many different forms including relational databases and XML files. The framework will provide tools for creating those forms, modifying those forms, and translating from one form to another.

3.3 Verification and Validation for Sustainability Guidelines

Since models are representations of reality only, they are not capable of analyzing the present or predicting the future accurately. Given this, how can we ensure that the model's results are accurate enough for its intended purpose? We validate and verify the syntax and semantics of the model. To ensure that a model provides sufficiently accurate analyses and predictions, V&V of the model (including the supporting data) must be employed throughout the modeling life cycle (Balci 1997; Sargent 2007).

The V&V techniques discussed in Balci (1997) are separated into four categories: informal, static, dynamic, and formal. Formal V&V techniques are the most thorough since they based on formal mathematical proofs of model correctness. Key considerations in the development and application of formal V&V methods depend upon a model being (1) deterministic or stochastic, (2) analytical or simulated, and (3) computationally efficient or computationally expensive. In the SPAF, Uncertainty Quantification (UQ) guidelines are being developed to better achieve the goals of correctness and appropriateness using formal V&V (Roy 2011). Both epistemic and aleatoric uncertainties will be considered. Epistemic uncertainties arise from ignorance about the involved processes; aleatory uncertainties arise from inherent variability in processes. Knowing the type of uncertainty is important for interpreting uncertainty analysis results, sensitivity analysis may reveal only a small subset of aleatory and/or epistemic uncertainties that dominate.

When sustainability metrics are computed without the possibility of validation against direct measurements, UQ increases the creditability of sustainability performance assessments and confidence in the resulting decisions (National Research Council 2012). For process models/measurements, fidelity/data availability typically vary greatly across a given system process hierarchy. This issue complicates both the computation of metrics that describe a process' sustainability and decision-making based upon those metrics. For example, electricity usage data for a factory may only be available as a highly aggregated utility bill, and this usage must be accurately allocated among the factory's processes to recognize and rank opportunities to improve efficiency. On the other hand, higher-level sustainability data may be inaccurate due to measurement uncertainty in the measurements taken at lower-levels of the model. The guidelines are intended to provide direction on UQ for hierarchical process models and on data collection, processing, and reporting.

4 ILLUSTRATIVE EXAMPLE

In this section, we provide an illustrative example to demonstrate how to apply the framework. Performing this example involves (1) identifying and collecting input data, (2) implementing SPDM for that data, (3) implementing a sustainable process support tool to transform the SPDM data into a Delmia QUEST simulation model, (4) executing the simulation, and (5) analyzing the results.

4.1 Input Data Analysis

The product examined in this illustrative example is a steel case box. It has one top cover and one bottom sub-component. The expected production schedule for the part is four weeks per month, five days per week, two shifts per day, and eight hours per shift. The basic processes for the top cover and bottom part are similar; but, each process has specific production constraints. The processes for both the top cover and bottom part include press, inspect, and clean. The bottom part has an additional print/dry process after its clean process. After their initial independent processing sequences, both parts are simultaneously processed by packing and shipping processes. Table 1 and 2 summarize the inputs, outputs, constraints, and additional information about the processes for a top cover.

4.2 Applying the Framework

The next two steps involve implementing SPDM for structuring input data and then transforming the SPDM data into a format suitable for the chosen simulation software. First, using the process, resource, and sustainability factor data specified in Section 4.1, we created an SPD, an RD, and an SFD based on the SPDM definition. Figure 3 shows these models in XML file format (XML 2012). The SPD is for the press process of the top cover. This process consumes electricity as energy, steel as a material, and lubricant as a substance used by a press machine. The top cover is the product of the process and scrap (steel) is a by-product. Information related to the press machine is defined in the RD, which is connected with resource taxonomy and property files created using the Web Ontology Language (OWL) (W3C 2012). These files contain the pre-defined resource classification, types, and properties for this case. The SFD file contains energy, substance, and discrete part information and is connected with a sustainability factor taxonomy and property OWL files. That is, the SFD file contains the subset of allowable sustainability properties (for electricity, lubricant, scrap, material, and parts) that are relevant for the process being analyzed. The sustainable process, resource, and sustainability factor descriptions are collectively referred to as a sustainable process model (SPM) instance document.

Next, we created a transformation function to generate a simulation model from the input data. First, a general simulation model structure is created. Then mapping rules are defined to describe how SPM structures should be transformed into QUEST simulation model elements. Figure 4 shows the process through which sustainable processes information for the model is converted and merged into the simulation model. The simulation model is generated from the concept model of the example by transforming the SPM representation of the model using mapping rules. For example, if the required resource is a ‘machine’, the instruction needed is ‘CREATE MACHINE CLASS’. Other BCL instructions enable the creation of other simulation model elements, such as parts or part attributes.

Table 1: Process specifications for a top cover

<table>
<tr><th rowspan="2">Process</th><th rowspan="2">Resource</th><th colspan="3">Inputs</th><th colspan="3">Outputs</th><th colspan="2">Constraints</th></tr>
<tr><th>Item</th><th>Type</th><th>Unit</th><th>Item</th><th>Type</th><th>Unit</th><th>Item</th><th>Unit</th></tr>
<tr><td rowspan="3">Press[1]</td><td rowspan="3">Press Machine</td><td>Steel</td><td>Material</td><td>kg</td><td>Top Cover</td><td>Part</td><td>kg</td><td>Cycle Time</td><td>sec</td></tr>
<tr><td>Electricity</td><td>Energy</td><td>kWh</td><td rowspan="2">Scrap</td><td rowspan="2">Substance</td><td rowspan="2">kg</td><td rowspan="2">Cost</td><td rowspan="2">$</td></tr>
<tr><td>Lubricant</td><td>Substance</td><td>L</td></tr>
<tr><td rowspan="2">Inspect[1]</td><td rowspan="2">Worker</td><td rowspan="2">Top Cover</td><td rowspan="2">Part</td><td rowspan="2">kg</td><td>Top Cover</td><td>Part</td><td>kg</td><td>Cycle Time</td><td>sec</td></tr>
<tr><td>Defective Product</td><td>Substance</td><td>kg</td><td>Cost</td><td>$</td></tr>
<tr><td rowspan="3">Clean[1]</td><td rowspan="3">Clean Machine</td><td>Top Cover</td><td>Part</td><td>kg</td><td>Top Cover</td><td>Part</td><td>kg</td><td>Cycle Time</td><td>sec</td></tr>
<tr><td>Abstergent</td><td>Substance</td><td>L</td><td>Lubricant</td><td>Substance</td><td>L</td><td rowspan="2">Cost</td><td rowspan="2">$</td></tr>
<tr><td>Electricity</td><td>Energy</td><td>kWh</td><td>Abstergent</td><td>Substance</td><td>L</td></tr>
<tr><td colspan="10">Additional Information</td></tr>
<tr><td colspan="5">▪ <u>Press Machine</u>
- Type: 300 ton press machine
- Power Consumption: 30 kW
▪ <u>Clean Machine</u>
- Power Consumption: 0.5 kW
▪ <u>Cycle Time & Cost per Day</u>
- Press[1]: 30 sec & $1000
- Inspect[1]: 100 sec & $2500
- Clean[1]: 30 sec & $1000</td><td colspan="5">▪ <u>Additional Requirements</u>
- Steel: 3 kg per part
- Lubricant: 0.003 L per part
- Abstergent: 0.003 L per part
- Scrap Rate: 11 %
- Fraction Defective: 0.3 %</td></tr>
</table>

Table 2: Process specifications for common processes

<table>
<tr><th rowspan="2">Process</th><th rowspan="2">Resource</th><th colspan="3">Inputs</th><th colspan="3">Outputs</th><th colspan="2">Constraints</th></tr>
<tr><th>Item</th><th>Type</th><th>Unit</th><th>Item</th><th>Type</th><th>Unit</th><th>Item</th><th>Unit</th></tr>
<tr><td rowspan="4">Pack</td><td rowspan="4">Worker</td><td>Top Cover</td><td>Part</td><td>kg</td><td rowspan="4">Case</td><td rowspan="4">Product</td><td rowspan="4">kg</td><td>Cycle Time</td><td>sec</td></tr>
<tr><td>Bottom</td><td>Part</td><td>kg</td><td rowspan="3">Cost</td><td rowspan="3">$</td></tr>
<tr><td>Case Box</td><td>Material</td><td>box</td></tr>
<tr><td>Wrapping Paper</td><td>Material</td><td>each</td></tr>
<tr><td rowspan="2">Ship</td><td rowspan="2">Worker</td><td rowspan="2">Case</td><td rowspan="2">Product</td><td rowspan="2">kg</td><td rowspan="2">Case</td><td rowspan="2">Product</td><td rowspan="2">kg</td><td>Cycle Time</td><td>sec</td></tr>
<tr><td>Cost</td><td>$</td></tr>
<tr><td colspan="10">Additional Information</td></tr>
</table>

- *Case Box*
  - 20 products per box
  - Reuse rate: 50 %
- *Wrapping Paper*
  - 1 wrapping paper per part
  - Reuse rate: 100 %
- *Cycle Time & Cost per Day*
  - Pack: 60 sec & 2500 $
  - Ship: 30 sec & 2500 $

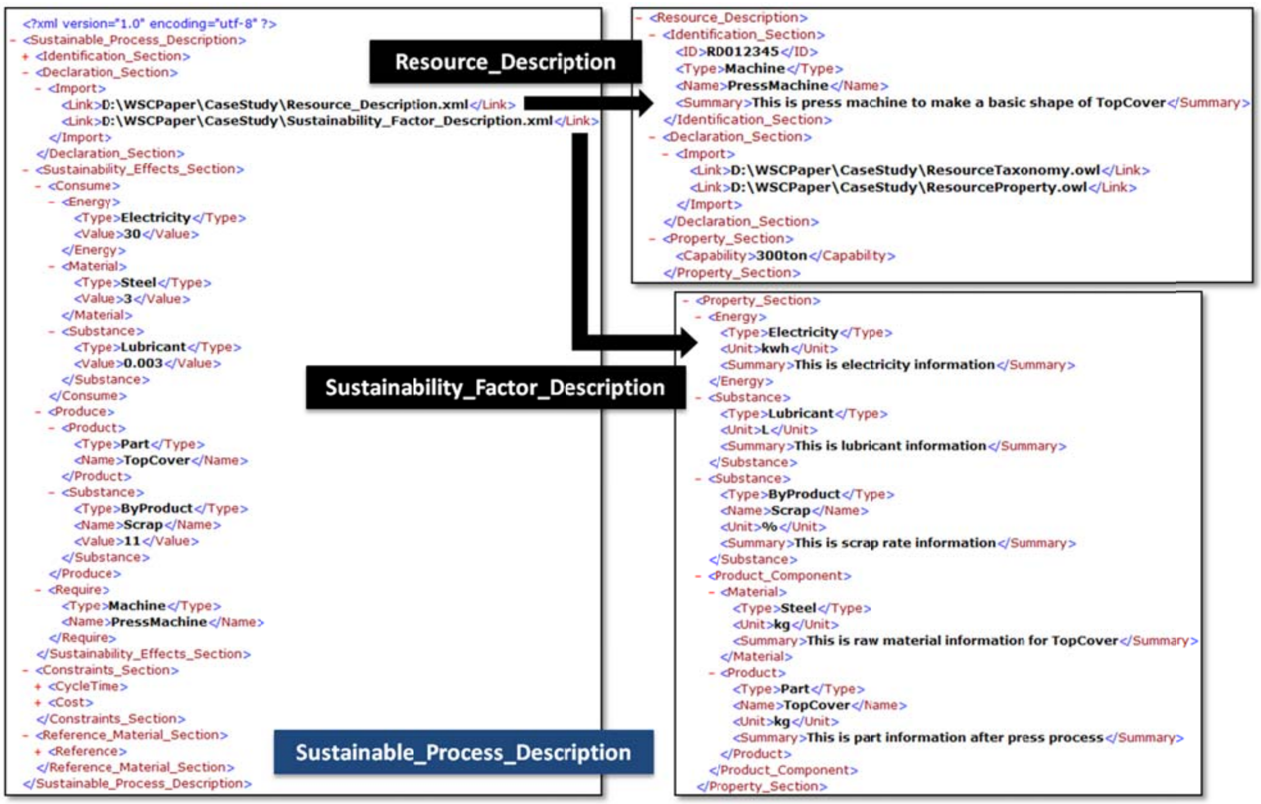

Figure 3: Sustainable process, resource, and sustainability factor descriptions using SPDM

4.3 Simulation Result Analysis

In this example, 10,560 cases (10,560 top covers and 10,560 bottoms) are to be produced a month. Producing these cases will require: 68640 kg of steel (31680 kg for top cover and 36960 kg for bottom); 68.64 L of lubricant (31.68 L for top cover and 36.96 L for bottom); 68.64 L of abstergent (31.68 L for top cover and 36.96 L for bottom); 5.28 L of ink; 73.92 kg of LPG (liquid propane gas); 24320 kWh of electricity (20800 kWh for press machine, 320 kWh for clean machine, and 3200 kWh for print/dry machine); 21120 wrapping papers (10,560 top covers and 10,560 bottoms) that are all reused; and 528 boxes, in which half of them are reused.

In addition to the finished product (cases), 7180.8 kg of steel scrap is produced as a by-product of the press process, 284.1 kg of steel scrap is produced due to defective products being rejected during the inspect process, and 193670.4 kJ of heat is generated by the print/dry process. The QUEST model has been enhanced by implementing algorithms to calculate these sustainability factors.

This example demonstrated the utility of the proposed framework for sustainability analysis by implementing a process analysis tool using SPM creation, SPM to simulation model mapping creation, transformation of SPM information to an executable simulation model using the mapping rules. This enabled SM process analysis of the simulation results.

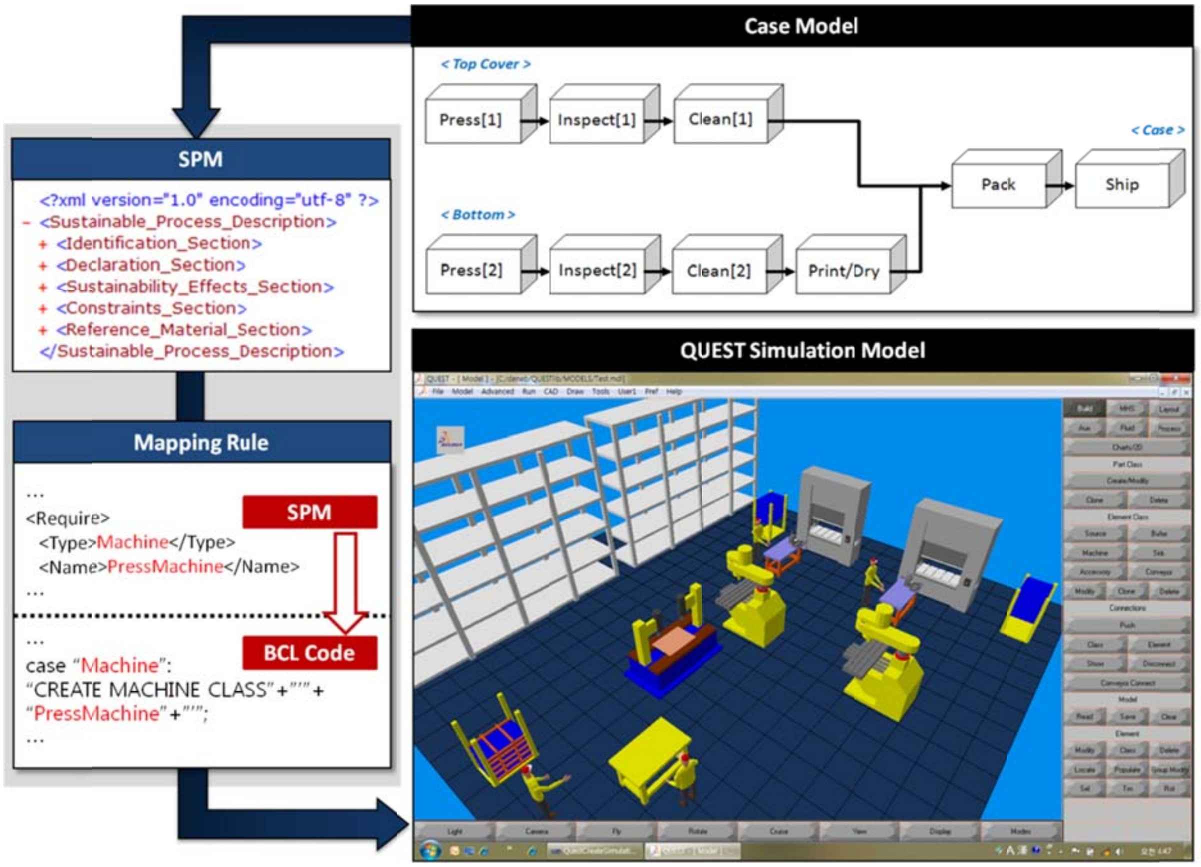

Figure 4: Sustainable process support tool for mapping between SPM and simulation model

5 CONCLUSION

This paper proposed a framework to support the development of computational and information models necessary for assessing the sustainability performance of manufacturing processes. The framework will provide common SM terminology and models definition, enable reusable tools creation, and provide V&V application guidelines. It will foster a common platform across manufacturers for better sustainability performance assessment and decision-making and increase interoperability between SM analysis applications.

By using a common approach for the creation of SM process information, the framework will enable the development of analysis platforms that can integrate simulation and optimization applications at different operational levels for different industries. The neutral SPM format described by the SPDM should lessen the effort needed for defining sustainability information about manufacturing processes and exchanging information between simulation and other engineering information systems by each manufacturer. The SPDM will describe the sustainability implications of the materials produced/consumed/transformed and the resources used by manufacturing processes. It will describe sustainability information for a single manufacturing process and for a collection of processes arranged in precedence graph.

Based on the SPDM requirements, reusable transformation components will be created to transform aggregations of SM process information into other forms suitable for optimization and other types of analysis. The V&V guidelines will provide the UQ requirements for input data measurement/collection, SPDM data representation, and output analysis to enhance model credibility. Features of the framework will address interoperability, scalability, reusability, modularity, and accuracy. The project team will consider the potential standardization of the SPDM, and carrying out industrial case studies using real data to demonstrate and validate the proposed framework.

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DISCLAIMER

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

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