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Standard representations for sustainability characterization of industrial processes

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ABSTRACT

Sustainability assessments are dependent on accurate measures for energy, material, and other resources used by the processes involved in the life cycle of a product. Manufacturing accounts for about 1/5 of the energy consumption in the United States. Minimizing energy and material consumption in this field has the promise of dramatically reducing our energy dependence. To this end, ASTM International [1] *has formed both a committee on Sustainability (E60) and a Subcommittee on Sustainable Manufacturing (E60.13).*

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This paper describes ASTM's new guide for characterizing the environmental aspects of manufacturing processes [2]*. The guide defines a generic representation to support structured processes. Representations of multiple unit manufacturing processes can be linked together to support system-level analyses, such as simulation and evaluation of a series of manufacturing processes used in the manufacture and assembly of parts. The result is the ability to more accurately assess and improve the sustainability of production processes. Simulation is commonly used in manufacturing industries to assess individual process performance at a system level and to understand behaviors and interactions between processes. This paper explores the use of the concepts outlined in the standard with three use cases based on an industrial example in the pulp and paper industry. The intent of the use cases is to show the utility of the standard as a guideline for composing data to characterize manufacturing processes. The data, besides being useful for descriptive purposes, is used in a simulation model to assess sustainability of a manufacturing system.*

1. INTRODUCTION

Sustainability assessments are often estimated based on studies of similar types of manufacturing processes. The accuracy of these estimates is critical for reliable life cycle assessments; however, coming up with accurate assessments can be problematic for a number of reasons, particularly with respect to manufacturing processes. The number of manufacturing processes is enormous, and the impact of the processes can vary considerably depending on a number of factors, including both how the process is conducted and the environment in which it is performed. When the sustainability factors for the actual processes have not been well studied and documented, then a sustainability analysis results in a rough estimate at best. A thorough study of all the processes involved in manufacturing a product can be quite costly and time consuming, as well as difficult due to the complexity. If standard procedures were available for

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conducting such studies and using the results, studies could be more easily reused, significant time and effort could be saved, and in the end sustainability assessments would be more reliable.

A manufacturing process is defined generally as any type of activity that uses some form of energy to transform material or intermediate products into an intended product. A manufacturing activity can be accomplished in multiple ways, thus creating a diverse set of alternatives [3]. There are similarities and differences among these alternatives in terms of energy, material, and other resources used as well as the quality of the resulting product. To evaluate the alternatives, measures of energy, material, and other resources need to be captured and communicated. A common information model and corresponding modeling methodology will facilitate this communication, especially between different domains, conveying process capabilities and operations [4].

Process characterization is a procedure to describe and categorize process performance and actual operations. In related work, characterization for manufacturing processes was defined [5]–[7] as an activity that identifies

- key inputs and outputs of a process,
- product and process information, and
- resource and process transformations.

The characterization defines the data and other information that will be needed for a sustainability assessment. Note that this same information will be useful for other types of assessments, however these other assessments are outside of the scope of this paper. The resource and process transformations may be represented as analytical functions [4], [8]–[10]. There have been some international efforts for systematic analysis and improvement of manufacturing through the use of unit process life cycle inventory (UPLCI), as part of the CO2PE! Initiative [11]–[13]. Environmental analyses of manufacturing processes have also been reported by several researchers [14], [15]. The new guide from ASTM International [2] complimentarily provides a standard format to characterize industrial unit manufacturing processes (UMPs). UMPs are the individual steps in manufacturing that add value through the modification or transformation of shape, structure, or a property of input material or workpiece. The guide is intended to help manufacturing industries and academia to collect the data needed to characterize individual manufacturing processes used in various analysis and research applications. One requirement for the collection format is the ability to “compose” or link individual UMPs together to create a network or system of UMPs. Such a network can be used to characterize the environmental aspects of a production system or product. The guide defines a generic structure to represent information and link multiple UMPs. This structure enables aggregation of data to support simulation and evaluation at the part, assembly, and product levels.

This paper discusses the applicability of the guide to address three industry needs: a) communication of detailed process information, b) composition of process models, and c) determining sustainability performance of manufacturing systems. The paper is organized as follows: Section 2 discusses the standard in the context of other standards-based approaches to manufacturing system modeling. Section 3 describes the application of the standard through three use cases. In the first use case, the guide is

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used to develop a descriptive document of UMPs for a manufacturing system. The second case highlights the usefulness of the guide to structure a simulation model of a production system. The third use case incorporates environmental impact assessment into the simulation model. Section 4 discusses the results and finally Section 5 concludes the current work with some insights for future work.

2. MANUFACTURING PROCESS CHARACTERIZATION

Industry practices to compute and compare sustainability of manufacturing processes are inconsistent because of a lack of uniform methods to represent manufacturing processes and equipment performance. There is much work to be done for manufacturers to characterize their systems and collect the data needed to understand the trade-offs that they face. To address this concern, ASTM International [1] is developing standards to assist in characterizing industry manufacturing processes for sustainability-related decisions. Three of these standards were recently published. *E2986-15 Standard Guide for Evaluation of Environmental Aspects of Sustainability of Manufacturing Processes*, provides guidance for manufacturers on how to conduct a sustainability study in order to improve their practices [16]. *E3012-16 Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes*, provides guidance for the actual characterization of manufacturing processes [2]. *E2987/E2987M-16 Standard Terminology for Sustainable Manufacturing*, includes terminology applicable to sustainable manufacturing [17]. Other standards under development within the E60.13 Subcommittee emphasize how to evaluate many of the important factors for environmental assessment and include:

- *Classification for Waste Generated at Manufacturing Facilities*,
- *Guide for Integration and Reporting of Environmental and Social Sustainability within the Manufacturing Supply Chains*,
- *Standard Specification for Net-Negative Landfill Waste Manufacturing Processes*.

Sustainability is a multi-criteria decision making problem. Virtual evaluation of manufacturing options is fundamental to making the "right" decisions in the face of so much complexity. Virtual evaluations are infrequently accomplished by SMEs today because they are too time consuming, costly and of limited utility. Standards should enable these types of evaluations to be conducted more easily by providing the "plugs" for virtual representations of manufacturing processes. The connectors on the plugs represent the actual flow of material, energy, and information between manufacturing systems within a manufacturer's unique environment. These plugs become the building blocks from which virtual representations of manufacturing systems can be put together, shared, and reused. These plugs can be used in simulation environments for evaluation of the trade-offs within that environment. As long as manufacturing processes have a "plug" they can be built into multi-criteria evaluations. E3012-16 standard, the focus of this paper, defines the characteristics of these new plugs from an environmental point of view, for virtualizing manufacturing processes. An earlier report provides a survey and analysis of manufacturing process models and identifies the relationships between manufacturing process and sustainability performance

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information [6]. The study found that some of the models already included or could be extended with information needed to characterize a process with environmental aspects of sustainability [4], [18]–[21]. The review highlights the similarities in the type of information captured and the opportunity for a standard format for UMP modeling. The ASTM standard brings together this understanding and sets the stage for more fundamental representation of manufacturing processes.

The E3012-16 standard outlines a process characterization methodology and proposes a generic representation (see Figure 1) from which manufacturers can derive specific UMP representations for meaningful sustainability performance analysis. According to the guide, environmental characterization identifies

- UMPs, their associative key performance indicators (KPIs), and the boundaries that define the UMP. KPIs are quantifiable and strategic measurements that reflects an organization's critical success factors in terms understanding and improving manufacturing performance [22].
- UMP specific attributes, specifically the inputs, manufacturing resources, product and process information, and outputs for chosen UMPs, and
- transformation functions and key UMP specific variables required for calculating transformation equations.

The UMP is represented graphically as is shown in Insert Figure 1. Transformation functions are used to describe the transformation of inputs to outputs. These transformations are enabled through the use of information contained within the

Resources and Product and Process Information elements. Transformations include changes in

- material (e.g., mass change, phase change, structure change, deformation, and consolidation),
- energy (e.g., include chemical, electrical, thermal, mechanical, and electromagnetic),
- information, such as production metrics (e.g., throughput and overall equipment effectiveness) or environmental metrics (e.g., energy, material, water, emissions, and waste).

Transformations create the data needed to establish a baseline measurement for these metrics (e.g. energy in kWh). The generic representation shown in Insert Figure 1 is comprised of input, output, resources, and process and product information and is used as a template for collecting key information about a specific UMP. The instantiated UMP model is structured using a formal representation and an XML format that enables machine interpretation.

Insert **Figure 1** Schematic for a generic UMP

3. USE CASES FOR STANDARD REPRESENTATIONS

This section focuses on three use cases where the standard can be applied to characterize and model a manufacturing system using UMPs. Each use case illustrates a specific industrial need further demonstrating different functionality that is enabled through the use of the guide. The use cases were done in collaboration with a pulp and paper manufacturing plant. In the first use case, the standard guide is used as a means to capture, document, and communicate processes in the pulp and paper plant. The second use case focusses on developing and populating a simulation model of a manufacturing system. The third use case demonstrates the effectiveness of the standard within a simulation tool for environmental assessment.

3.1. USE CASE ON INFORMATION COLLECTION AND COMMUNICATION

The goal of the first use case is to document processes in terms simple enough for practitioners from the paper industry without knowledge of the processes to understand the operations. The document was developed using the methodology from the guide. The document starts by identifying all the UMPs. In this use case, transformation functions were used to describe the main material and product flows, as well as energy use. Note that the inputs and outputs did not include specific chemicals or details, but only conceptual categories of chemicals and materials. A simple questionnaire and related discussion was helpful to sort out the needed information and the relationship between processes.

For this use case, the entire manufacturing system was divided into UMPs deduced from the principal process steps that the company and the industry in general use. This resulted in UMP representations such as steam generation, water treatment, dissolvers, deinking, washing and rinsing, mixing, and paper machines. The paper machines were the primary focus for sustainability and performance review, since they consumed the most energy, and had high operational costs. The paper machines were

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further divided into four parts based on the company's traditional breakdown of paper machines.

Each instantiation of a UMP was then described in the structured way defined in the E3012-16 standard. The description included a diagram listing inputs, outputs, product and process information, resources, transformations, and KPIs such as exemplified in Figure 2. By combining several of the instantiated UMPs (see Figure 3), an overall understanding of the manufacturing system is created. The result was a fairly brief document that could be used for communications and discussions on a general level. The document helped to relate operational KPIs to the actual operation.

The company successfully used the document with two new employees to learn and perform a project on the manufacturing system. The document, including models of the processes in standard format, was useful for internal communication within the company. The company earlier produced a number of individual documents describing the processes, but lacked an overall systems view, which lead to long lead-times for new employees to grasp the total system. The use of simple descriptive transformation functions enhanced their understanding of the UMPs.

Insert **Figure 2** Example of instantiation for one of the plant processes

Insert **Figure 3** Example of the overall operation description presenting a systems view

DOI: 10.1115/1.4033922

3.2. USE CASE TO BUILD AND POPULATE A SIMULATION MODEL

This use case focused on the suitability of the guide to collect the information needed to build and populate a simulation model of the manufacturing system using UMPs. Discrete event simulation (DES) is widely used to model manufacturing systems' material flow (Andersson et al. 2012). DES tools can be very useful in analyzing different what-if scenarios of manufacturing processes to assess their effectiveness and identify bottlenecks of the system. In this use case, AutoMod, a DES tool, was used to simulate the process of converting bulk reels of paper into different types of smaller packages of paper. The standard was assessed in its capacity to aid in the creation of the simulation model.

When planning a DES model, information such as the following are needed:

- inputs for the different resources,
- the order in which the materials and products are processed through manufacturing system,
- capacity of resources used in the manufacturing process, and
- transportation flows for material and products through the entire manufacturing process.

The guide can be used to gather information on the inputs to the manufacturing processes and the material going through the manufacturing processes to become finished products. Note that process specific information needs to be adapted according to the system under study. For example in this use case, conveyers and fork lifts need to be modeled as individual UMPs to represent the manufacturing system as a whole (See

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Figure 4). Further, manufacturing specific information such as the types of loads passing through the process, the conversion rates between these different loads and the production cycle-time, as well as the specific metrics for the different resources, is needed.

Figure 4 shows how the standard can be adapted to display information about the movement of materials and products using flow simulation. This can be done by adding descriptive text to the arrows in between the boxes describing the UMPs. This text specifies the type of transport the different arrows represent and describes the routing rules and flow priorities for the specific factory. These boxes can also be accompanied by symbols for buffers and vehicles. Different colored arrows can give a visual representation to some of the aspects and logic of the transportation system. Information describing process availability and data concerning the product, production cycle and down times can be captured. This information is factory specific and more tailored towards a specific UMP, which is required to create a sound DES model. The UMPs can contain conversion equations for transforming inputs to outputs that are specific to the factory processes being modeled. For illustrative purposes, the numbers in Figure 4 represent the flow of material, energy or any metric between UMPs P1-P5 [23].

Insert **Figure 4** Example of composed model adapted to support information for flow simulation

DOI: 10.1115/1.4033922

3.3. USE CASE IN SUPPORT OF ENVIRONMENTAL DECISIONS

This use case explores the use of the standard as a guideline for structured environmental assessment. By using DES (as in use case 3.2) in combination with lifecycle assessment data, more rigorous environmental decisions can be made [24]. The EcoProIT tool is a result of such an effort [25]. The EcoProIT tool uses a DES model to calculate and assess energy consumption and material usage. Figure 5 briefly describes the data structure of EcoProIT. The material and resources used can then be aggregated downstream in the product lifecycle and hotspots or bottlenecks can be identified, analyzed and improved. The following data are generally needed to model a production system for assessment [26]:

- processes in the production system,
- information about the processes such as capacity, reliability, quality, cycle times, consumptions for different tasks and states for the processes, and
- sequence in which products are processed.

The above list correlates well with product and process information as identified in the E3012-16 standard for information structuring and assessment. The E3012-16 standard and the characterization methodology can be useful in the EcoProIT tool once the environmental assessment goal is conceived. The standard provides a generic guideline to collect information on the inputs, resources, product and process information that are transformed into the desired output.

Insert **Figure 5** Data structure and relations in EcoProIT

The following list summarizes the compatibility between the standard and the EcoProIT tool specifically:

1. Identify UMPs to model in the system: This step can be related to identifying the processes for modelling. To enable assessment including facilities and auxiliary energy use, this step needs to include the location of processes including cell or dependent resources. In EcoProIT Tool this location is created through a location based hierarchy.
2. Identify process attributes, including inputs/outputs, information, process and product information, and the resources used: Process and product information in the tool includes job definition, state definitions, including cycle times, breakdowns, and repair times. All numbers are measured and modeled using primarily statistical distributions, but can also be determined with equations as proposed in the standard.
3. Identify transformations of material, energy, and information and describe them as functions: The transformation in the E3012-16 standard is generic. In EcoProIT, the transformations consist of specific assemblies of intermediate products to a new primary product and use of input energy and material. The transformations used to calculate emissions in EcoProIT have very specific structures due to the specific results in a DES model.

This shows the standard can be valuable when used in conjunction with tools for structured environmental assessment.

DOI: 10.1115/1.4033922

4. DISCUSSION

The E3012-16 standard describes how to collect and structure data about UMPs. It describes the needed information for transformations functions to compute material and energy use. Transformation equations are developed differently depending on the intended use. For descriptive purposes, linear and simplified approximation functions may be preferred. For use in simulation software, functions depend on the specific software and the modelling techniques used. For example, physics-based models or DES models would require sets of functions and attributes specific to physics or DES. The standard provides a generic representation that is adaptable to suit specific needs. The standard also provides standard terminology, naming conventions and a structure for data, as well as a methodology to collect the data. In order to apply the E3012-16 standard for individual purposes one must understand the domain of the implementation. For a DES model, information such as capacity, time, and reliability parameters are needed. In the use case in Section 3.3, such information can be used to compute inputs and outputs or simply visualize the results. For example, an analyst can visualize the results of producing a certain number of products in terms of energy consumption, or the transportation of material and the buffer capacity between the manufacturing processes.

During the use case with DES, it was also observed that the system dynamics simulation methodology can also benefit from the E3012-16 standard. The variables connecting each UMP are declared by equations in the same manner as in system dynamics. This could potentially be pursued as another use case.

Academic and industry practitioners have expressed interest in creating reference models for general industrial manufacturing processes from which specific simulation models could be derived [13], [27]. Such models must be adaptable for new applications and the specifications should expand as people use and add new data. Capturing the dynamics and granularity of the data on every level is impractical. Such models need to only capture the minimum and sufficient details. The E3012-16 standard describes a general structure for this process.

Implementation of information models based on the standard could be the basis for an accessible database of industrial process models structured as UMPs. To realize a repository of UMPs would require an adaptable structure and framework where users retrieve old and add new UMPs. Parameters for the UMPs need to be stored and categorized for different scenarios with references to time, version, product, job, process, machine, make, etc. Such a structured repository will allow effective searches for UMPs based on specific requirements [28].

5. CONCLUSIONS

This paper discusses the effectiveness of the E3012-16 standard [2] based on three use case scenarios. The first use case showed the usefulness of the standard for communicating information about particular processes. Specifically, the resulting document in the use case showed how individual manufacturing processes were perceived by the company and served as a means to facilitate the understanding of overall holistic system performance.

DOI: 10.1115/1.4033922

The second use case applied the E3012-16 standard specifically to data acquisition to create a DES model. The standard was useful for gathering information on the inputs of the manufacturing processes and the order of material flow through the manufacturing processes to become finished products. Note that DES has additional requirements on data structure and inputs such as logic on overall system levels, which are application specific. This needs to be considered on a case-by-case basis. As these requirements emerge there is opportunity to extend the standard.

In the third use case, environmental assessment in EcoProIT was done with the E3012-16 standard. Note that the information collected via the standard must be complemented with specific data on how the input material was produced when it enters the model, in order to understand the complete lifecycle for the products produced.

The E3012-16 standard can potentially be used alongside Life Cycle Assessment (LCA) approaches when assessing the sustainability of industrial processes, since it focusses on individual manufacturing processes. Future work will include use cases, focusing on how the standard can be used to generate the much needed Life Cycle Inventory (LCI) data on manufacturing processes, for purposes of sustainability assessments.

Standards are the means by which more sustainable practices can be broadly implemented. As we gain new understanding of the assessment methods and trade-offs that are being made in manufacturing, it is important that best practices are quickly implemented and ASTM International is providing an opportunity for doing so.

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DISCLAIMER

No approval or endorsement of any commercial product by the National Institute of Standards and Technology is intended or implied. Certain commercial software systems are identified in this paper to facilitate understanding. Such identification does not imply that these software systems are necessarily the best available for the purpose.

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Figure Captions List

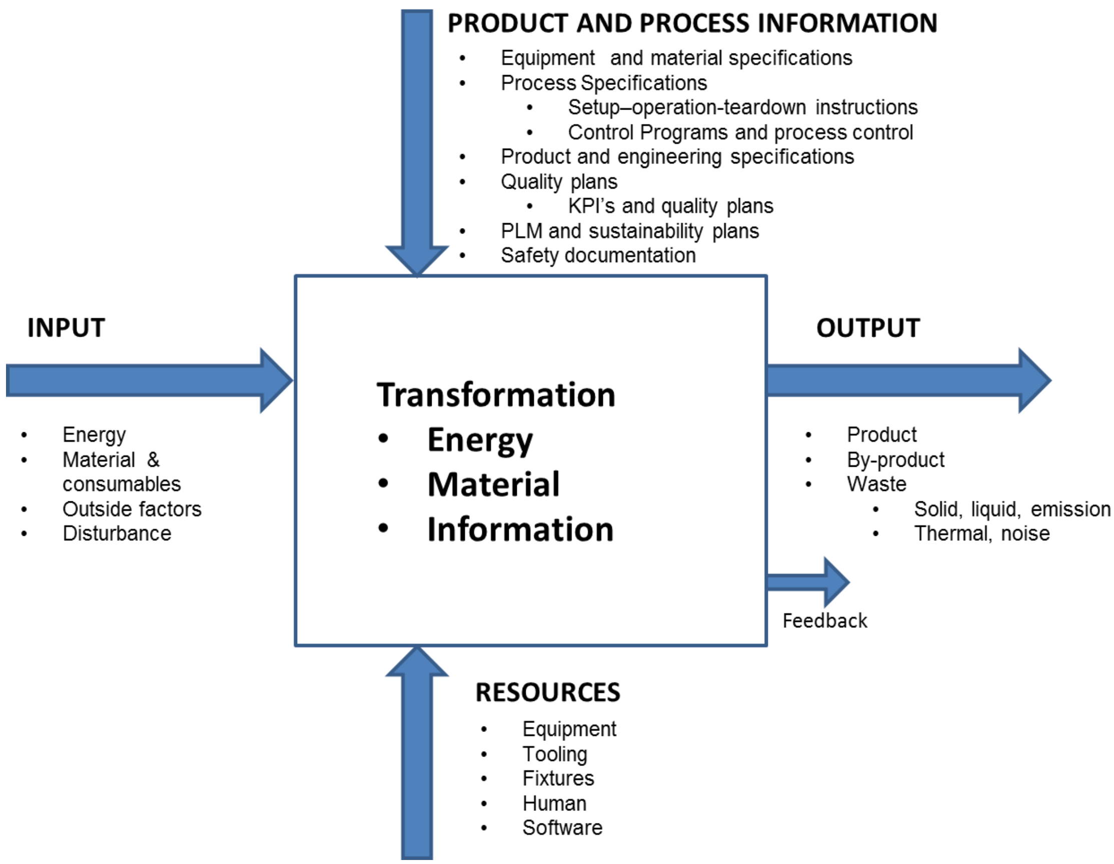

Figure 1 Schematic for a generic UMP

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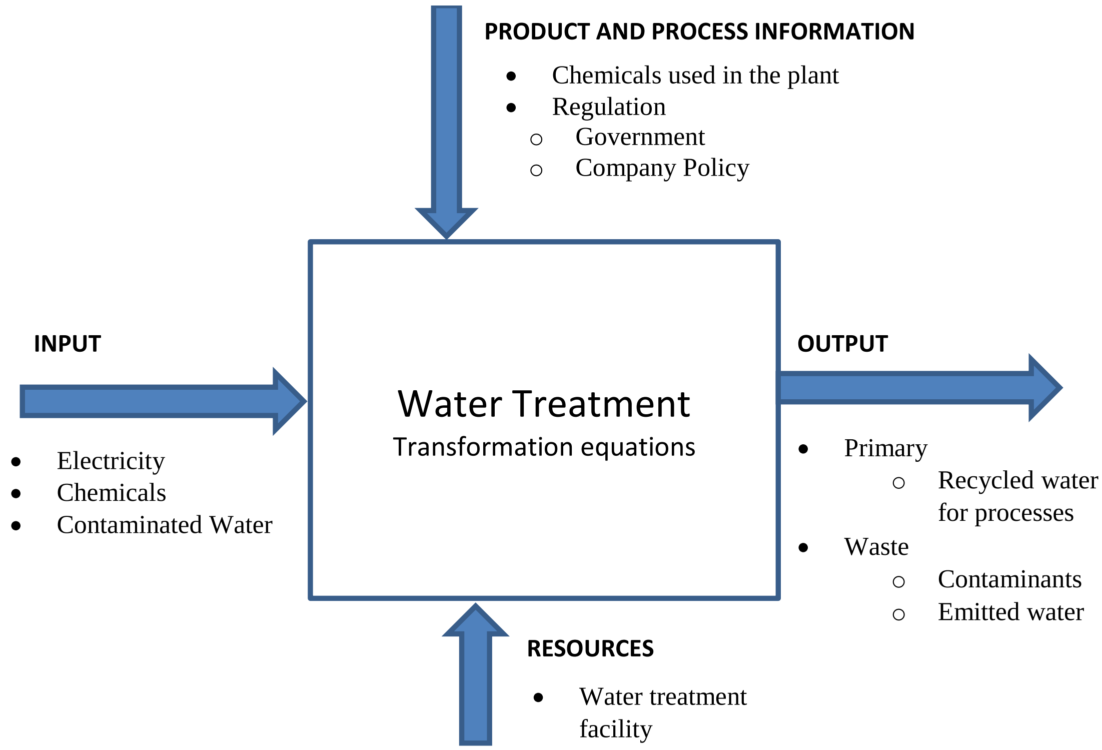

Figure 2 Example of instantiation for one of the plant processes

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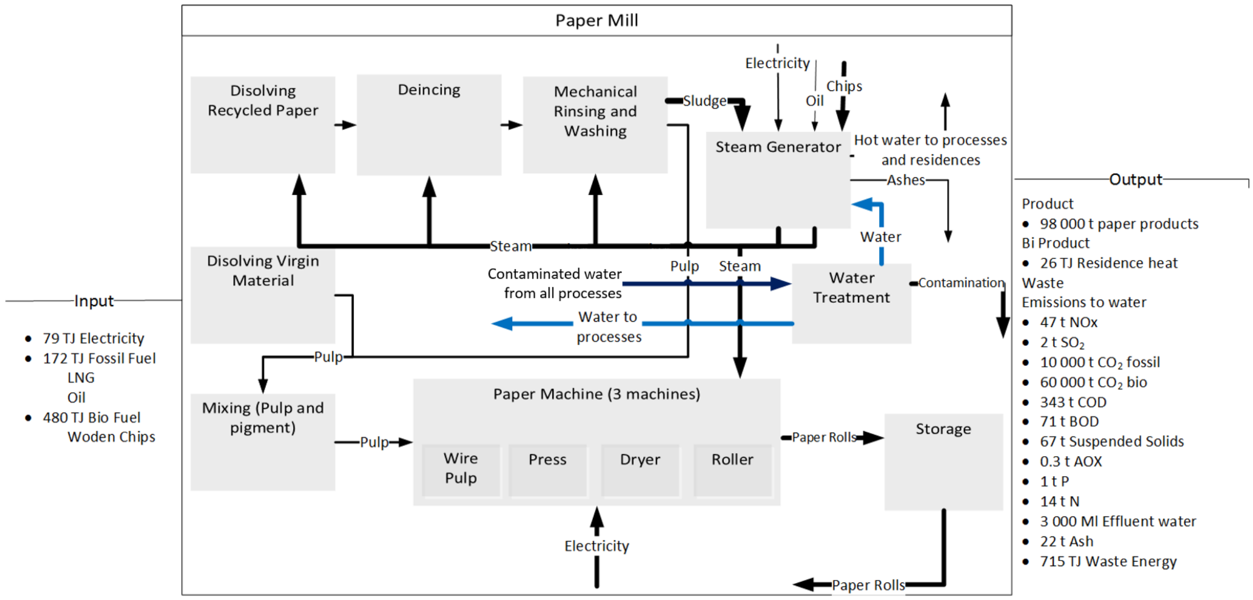

Figure 3 Example of the overall operation description presenting a systems view

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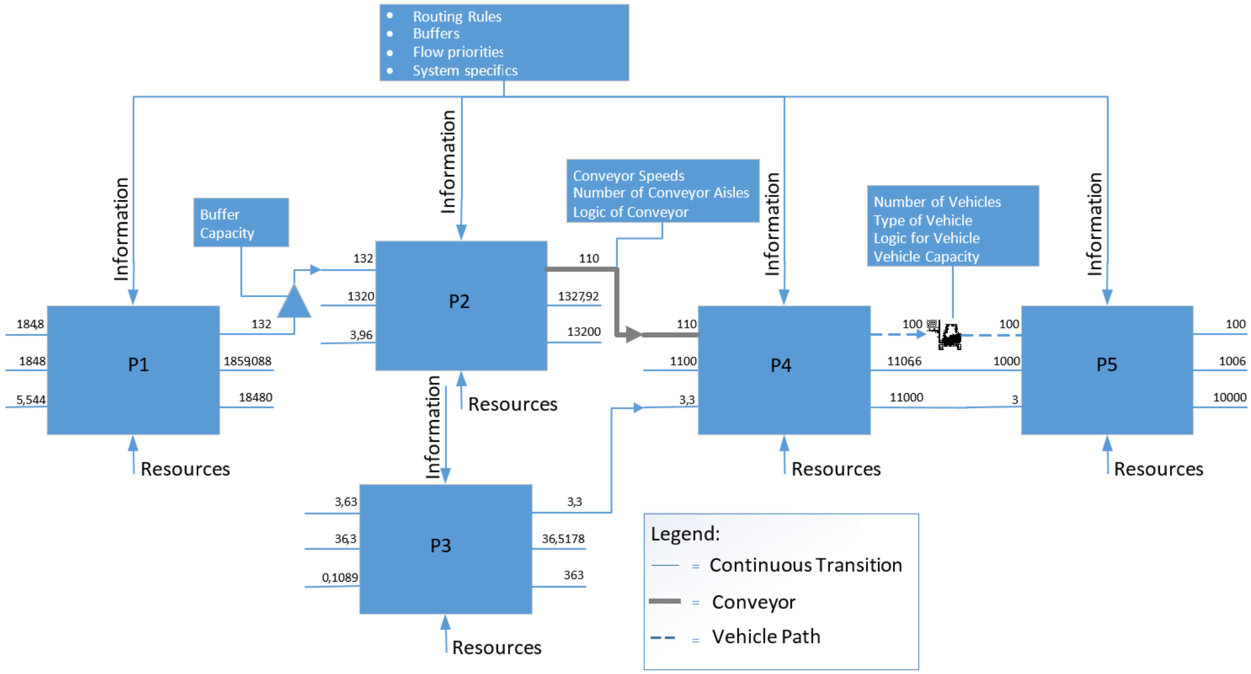

Figure 4 Example of composed model adapted to support information for flow simulation

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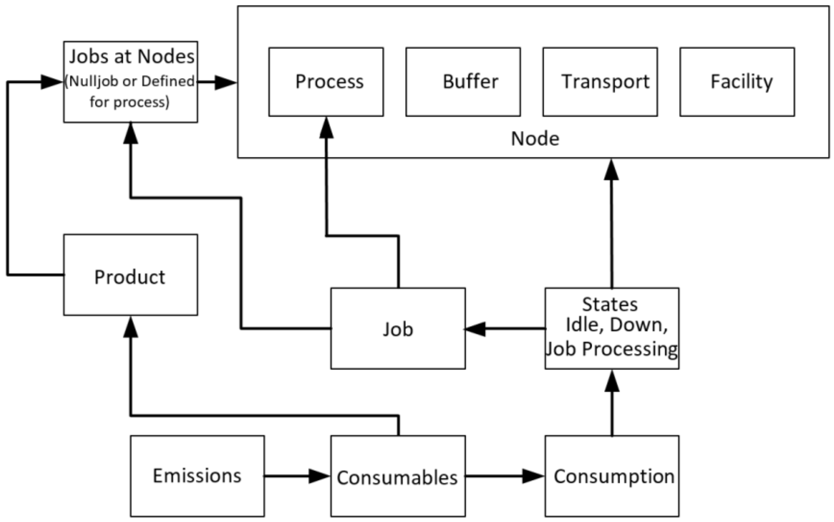

Figure 5 Data structure and relations in EcoProIT