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IDENTIFYING THE MATERIAL INFORMATION REQUIREMENTS FOR SUSTAINABLE DECISION MAKING

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ABSTRACT

Materials play a central role in product manufacturing, contributing to each phase of product development in the form of either a component or process material. As the product revolves around materials, so does much of the product information. Material information plays a significant role in the decision making process at any stage of the product life cycle, especially with respect to the sustainability of a product. Material information in the manufacturing stages of a product's life cycle will relate to the processes used in manufacturing and assembling individual components. The material properties may determine what processes can be used and how these processes should be controlled.

To support sustainable manufacturing, the impacts of material choice should be considered during design, when resources are being committed. When comparing material alternatives at design time, it is not as simple as saying one material is "more sustainable" than another. Many different factors determine the sustainability of a product, and each of these factors may be influenced by multiple material properties represented through various information requirements. In order to develop a material information model that can satisfy these information requirements, we need to carefully study the requirements from an information modeling perspective. In this paper, we use activity models to describe design and manufacturing scenarios that rely on the availability of proper material information for sustainability decision making. We will use these models to first define specific scenarios and then to identify the types of material information that is typically required in these scenarios, and collect and categorize key concepts. Based on this study, we will make recommendations that will aid the development of a useful material information model for sustainable decision making.

Keywords: material information, sustainable manufacturing

1. Introduction

In today's economics, sustainability has become a principal business driver [1]. Sustainability is both consumer driven and industry driven, with benefits ranging from increased consumer appeal to reduced production costs. Sustainable manufacturing practices are becoming commonplace in industry, often as a means of reducing production costs by reducing or eliminating the production of waste. Despite the industry-wide push to make advancements in sustainable manufacturing, the science for measuring sustainability performance metrics (i.e., energy and material efficiency) remains immature.

It has long been understood that material information plays an important role in manufacturing in general. We propose there is a more prominent role to be played by materials and material information in support of sustainable manufacturing initiatives. In the context of sustainability, material selection plays an important part in determining total life cycle impact. As a common thread to connect all stages of the product life cycle, materials can serve as a basis for sustainability assessment, particularly during manufacturing. As Allwood et al. note, "the environmental impacts of materials production and processing, particularly those related to energy, are rapidly becoming critical [2]."

As we will explain in Section 2, many advances have been made in assisting the selection of the right materials based on certain functional and cost requirements. However, the extent to which material information can be leveraged depends on the context in which it is used. Material information that may be useful in one application may be of no consequence in another. For instance, the information necessary to make informed decisions about product performance may be different from the information used to determine recyclability. In this paper, we explore what information is useful for material selection in sustainable manufacturing. Specifically, we will define several use-case scenarios in which material selection impacts decisions when manufacturing for sustainability. These scenarios will allow us to precisely identify the role of material information within an explicit context. By clearly defining how material information is used in each scenario, we can achieve a better understanding of what material information requirements should be considered to support sustainable manufacturing.

Using the Unified Modeling Language [12] (UML) activity diagrams allows us to illustrate different manufacturing scenarios and study the material information requirements necessitated by each scenario. Based on these requirements, we provide some insights into developing a material information model for sustainable manufacturing. By covering a wide range of scenarios, and identifying core decision criteria, we will be able to develop a robust material information model to support sustainable manufacturing.

2. Background

In this section, we review some background information related to material information modeling.

2.1 Standards Related to Material Information

Material selection based on design requirements is not a novel concept, and materials have long been defined in a manner in which more informed design decisions can be made. Materials are a key component of the design information that dictates the performance of a product design. Engineers need material information to select the best material available to meet the performance specifications of their designs. Engineers need material information to select the proper manufacturing processes. Today, engineers need material information to identify processing parameters which will make the manufacturing processes highly productive and have low environmental impacts.

To make material selections, engineers often rely on material databases. These databases provide deliberately structured repositories on which material selections can be made. They are often organized to support decisions based on traditional considerations such as performance and costs. While the metrics used to define material attributes may differ slightly between different databases, common underpinnings remain.

While the nature of design and production requires common understandings, standards have emerged that make implicit understandings explicit. Standards play an important role in the development and deployment of material databases. Material information standards can be used to build material databases or to import and export material information from different material databases. Material information standards provide conceptual models and information exchange formats. Conceptual models in standards provide definitions and descriptions of material information, and information exchange formats depict how to represent material information.

MatML [17] is one of the more comprehensive material information standards available. It is an XML-based information standard for the interchange of material information. MatML efforts were initiated by NIST in 1999, and evolved to version 3.1 of MatML schema in 2004. The motivation behind the development of this standard was to provide a common syntax that would allow different communities to define domain-specific structures that would support their needs.

Some material information models have been developed specifically for supporting sustainability efforts. Since regulations like RoHS [4] and REACH [5] have emerged in the market, manufacturing companies need an information standard to report material types and amount in a product explicitly across the supply chain. IPC-1752A [6] is an XML-based information standard to report bills-of-substances in a product. It also includes a material information model though it is rather simpler than the aforementioned standards.

Outside of standards developed specifically for materials, there are other standards that include dedicated material information models. ISA-95 [7] is an international standard for information exchange between manufacturing execution systems and enterprise applications. The ISA-95 information model includes a material information model which is used to describe inputs of manufacturing processes in process planning and execution. OAGIS (Open Applications Group Integration Specification) [8] is also an international standard which defines a common business language for business applications. OAGIS provides the definition of business messages in the form of Business Object Documents (BODs), and BODs include a material information model.

Part 45 of ISO-10303 [18] is a material-specific portion of the standard that describes how to represent material properties in product design. It is an integrated resource for material properties. Integrated resources are a shared library of common definitions which can be reused to develop application protocols specific to an information exchange context. For example, part 45 is used in AP 235 - an application protocol for engineering properties for product design and verification [19].

Standards such as these embody the idea that different applications, and different contexts, require different understandings of material information. The next section will look at the role of material information in material selection.

2.2 Material Selection for Manufacturing

Traditionally, the selection of a material for producing a part or product has primarily been decided based on three factors: function, shape, and process [10]. In order for a part or product to perform a certain function, the selected material must have attributes that match the properties required to fulfill the desired function. To make a part of a desired shape, the material undergoes a manufacturing process, such as machining, drilling, joining, etc. The process affects the desired shape, precision, and cost. Certain shapes and certain tolerances are required to fulfill certain functions, and these affect the choice of processes. The interaction of materials with these

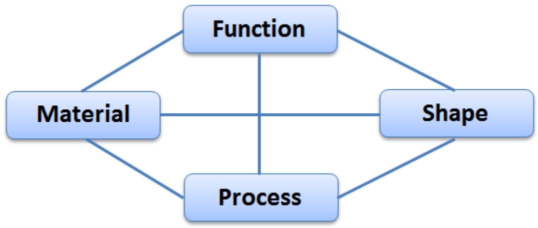

Figure 1: Interaction between function, material, process, and shape [10]

three factors is at the heart of the material selection process (Figure). Different methods have been deployed to support these interactions and inform material selection. These methods can provide some insight into what information drives material selection.

Ashby [10] proposed a systematic material selection procedure as follows: 1) translate design requirements into functions, 2) screen materials using constraints, 3) rank using objectives, and 4) seek documentation. The first step interprets design requirements as engineering functions and represents them in constraints, objectives, and free variables. For example, a beam design can be described as a design that can support a certain bending load (constraint) with minimum mass (objective). In this case, free variables can be a cross-section area or choice of materials. In the second step, all materials are checked for whether they satisfy the constraints. If some of the materials do, they are candidate materials. The candidate materials are ranked by objectives. Top candidate materials are then double-checked through their documentations before a final material is chosen. Documentation can be a history of material usage or failure reports.

Material property charts such as those proposed by Ashby are a useful way of exploring a material information model to screen materials. The property charts are known as material bubble charts because they classify materials based on two material properties, which usually represent a design conflict in objectives and constraints. For example, a bubble chart with density and strength as x- and y-axis shows plots of materials and it shows bubbles of materials reflecting range values of the material properties. A measurement to find candidate materials is a performance index, which is a function of two material properties of the bubble chart. For example, strength/density can be an index to find strong materials at low mass. Selection methods such as bubble charts provide important insight into how material information can be organized, and support difficult trade-off scenarios.

Now that we have discussed some of the intricacies involved with material selection based on design requirements, we next discuss how to define these requirements in such a way that the material implications can be better understood. Here, again we discuss material selection based on design considerations; however, in addition to the interactions described in Figure 1, we must now consider a new factor – sustainability. In addition to mechanical and functional requirements and tolerances, sustainability brings in additional

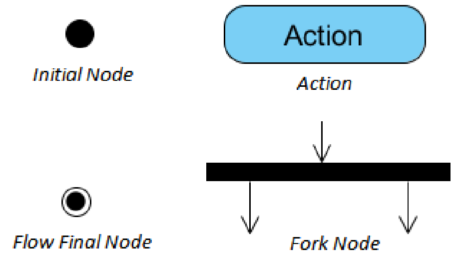

Figure 2: UML Activity Diagram Elements

concerns of resource (energy/material) efficiency, hazardous substances, product longevity, and various other life cycle issues. This discussion begins with information modeling and, more specifically, activity models.

2.3 UML Activity Diagrams

The Unified Modeling Language (UML) [12] is a general-purpose modeling language standardized by the Object Management Group (OMG). UML consists of a set of graphic notations. UML activity diagrams are graphical representations of workflows as sequences of actions or activities represented by rounded rectangles and flows represented by directed lines.

UML activity diagrams are typically used for modeling business processes, by capturing the actions of a single usage scenario. Activity diagrams are constructed using different types of nodes and edges, as shown in Figure 2. The *Initial Node* signifies the start of the scenario. *Actions* denote specific steps in the scenario, and are connected by *Control Flow* edges. Various control nodes control the sequencing of activities. These include *Decision Nodes*, *Merge Nodes*, *Fork Nodes* and *Join Nodes*. For example, the *Fork Node* branches the flow from one action to multiple parallel actions. The *Flow Final Node* denotes the end of the scenario.

In the following sections we use UML activity diagrams to define specific scenarios involving sustainability considerations. The scenarios serve as guidelines for identifying the specific types of material information that are needed to support sustainability goals.

3. Sustainable Manufacturing Scenarios

In this section, we describe a set of scenarios related to sustainable manufacturing, and discuss the material information requirements highlighted by the scenarios. We begin with several scenarios where the role of material selection can be clearly demonstrated. We then focus on one specific activity, and demonstrate how the activity model provides an environment where the material information necessary to make informed decisions can be explicitly identified.

The models below identify process requirements for the scenarios described. Some of these process information requirements are material related. The process requirements must be mapped to material information model requirements, which can then be used to build a material information model that satisfies the requirements of the scenario. The scenarios described in this paper are simple, high level scenarios to

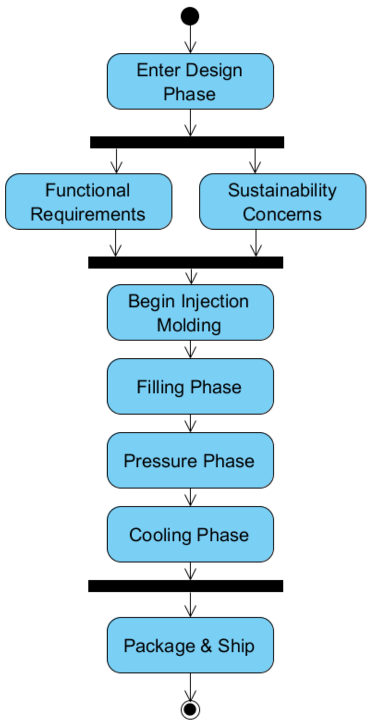

Figure 3: Injection molding scenario

illustrate the approach. Work is being done on creating more detailed scenarios in order to extricate more complex material information requirements, and will be published in a subsequent, more detailed article.

3.1 Manufacturing Process Sustainability

First, we will discuss a simple scenario where the sustainability implication of material selection is meant to be straightforward. Figure 3 shows a scenario where the injection molding process is used to produce a certain part. In this diagram, the "Enter Design Phase" action begins the design phase of the product, which consists of the actions "Functional Requirements" and "Sustainability Concerns". In our scenario, we would like to incorporate sustainability decision making during design in addition to addressing the usual functional requirements. But first, let us look at the later manufacturing phase. The injection molding process begins with the filling phase, where the molten polymer is filled into the cavity. Filling speed is normally limited by shearing in the polymer. High thermally stable materials can be filled at a higher rate. When the mold is 90% to 95% full, the process switches to the pressure phase, where the material moves to maximum pressure and low speed. This is followed by the cooling phase, after which the cooled part is ejected. There are other steps in the injection molding process, which are not displayed in Figure 3.

Each of the injection molding phases requires the use of energy and materials. The amount of energy used in each of these phases, and the amount of material used/lost depends on how chosen materials interact with the various process steps from the time the injection molding process begins to the time it ends ('gate-to-gate'). In order to make sustainability decisions in the early design phase, the material information model must be able to capture downstream gate-to-gate process

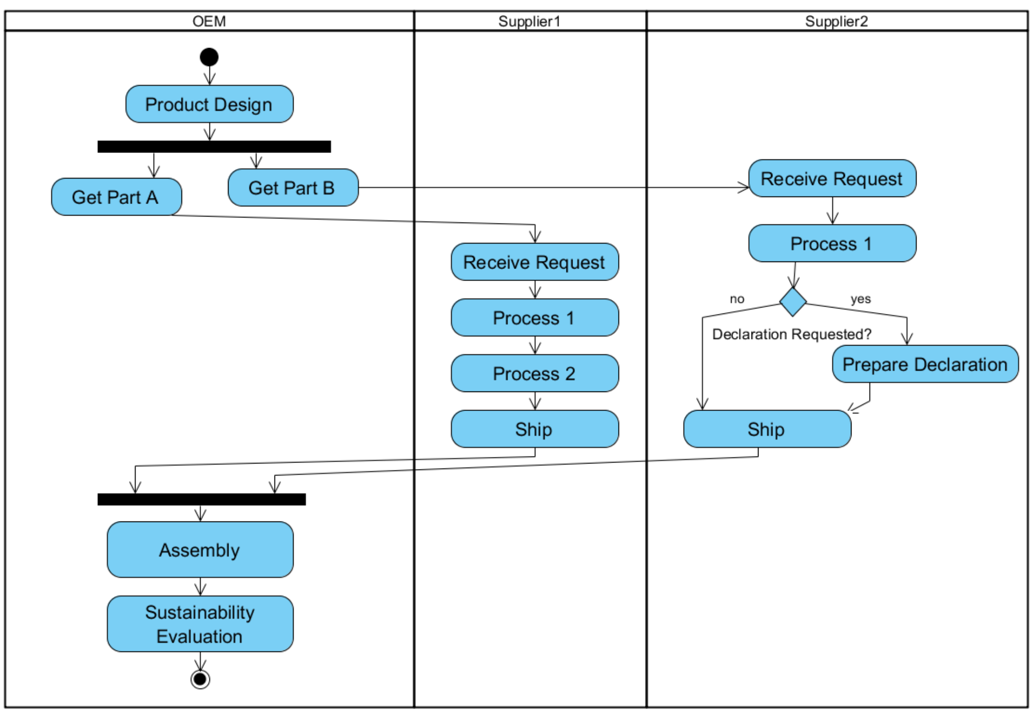

Figure 4: Supply Chain Scenario

information and make it available in a way that can be incorporated into the design model. Based on this scenario, one of the high level requirements of the material information model can be framed as follows:

> **Requirement**: Provide gate-to-gate process information (relative to material and energy efficiency) at design time to capture interactions between material properties and processing requirements.

This high level requirement can be specialized for various types of manufacturing processes and material handling scenarios. The basic purpose of this requirement remains the same.

3.2 Sustainability Across the Supply Chain

Figure 4 shows a scenario where an OEM (Original Equipment Manufacturer) orders two parts from two different suppliers, which are then assembled to make the product. The OEM wishes to perform a sustainability evaluation on the final product.

In order to make a reliable sustainability assessment, it is important for the OEM to have sustainability information from each of their suppliers. In this scenario, two parts are produced by two suppliers. The suppliers have their own processes, and associated energy and material usage. Not all suppliers may be prepared to provide the information required for sustainability assessment to the OEM. In the case of the RoHS regulation, a special material declaration standard, the IPC 1752, was developed to assist in supplier's material declarations, so that OEMs are able to make declarations of RoHS compliance of their final products. While the IPC 1752 has been successful in addressing a particular requirement, it is impractical to develop point solutions for each new requirement. Based on this scenario, we can frame the following high level requirement for the material information model:

> **Requirement**: Support the aggregation of similar sustainability metrics across the supply chain-from component to assembly to product for sustainability assessment.

There are two levels at which this requirement can be handled – by capturing different sustainability metrics in the model and by capturing the material properties from which various sustainability indices may be derived. In either case, it is important to integrate the information with other product and process models, so that sustainability assessments may be made on various manufacturing scenarios and across the supply chain.

3.3 Manage Multiple Sustainability Metrics

Sustainable manufacturing is a new and diverse domain. There is no single 'sustainability index' that can satisfy all sustainability requirements. Often, a selected set of sustainability metrics appropriate to a given scenario must be chosen for sustainability evaluation. Such a scenario is shown in Figure 5.

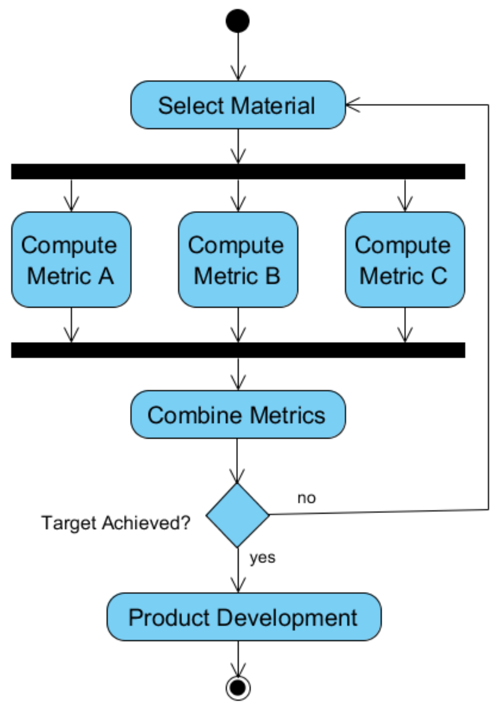

Figure 1: Managing Multiple Sustainability Metrics

In this scenario, a manufacturer has chosen three sustainability metrics to perform sustainability evaluation. These metrics are calculated independently for the chosen material, and combined to a unified value for the purpose of evaluation. If the manufacturer's target is reached, then the selected material is chosen for product development. If not, other material choices are investigated, and the process is repeated until a satisfactory material is found. The high level requirement for a material information model supporting this scenario can be framed as follows:

> **Requirement**: Allow material selection based on different sustainability metrics (e.g. better recycling/remanufacturing ratio).

While the high level requirement can be stated in simple terms, the impact on the material information model is bigger. As in the case of the previous scenario, this requirement can be supported in two ways – by capturing the different sustainability metrics directly in the model; or by capturing the material properties from which various sustainability metrics can be calculated. For this scenario, the latter option is advisable, as new metrics for sustainability evaluation are constantly being developed. Another important aspect of this requirement is to feedback information that can be used during material selection, based on calculated metrics. For example, Ashby's property charts [10] may be used to select alternate materials based on sustainability metrics calculated using the material information model. By modeling the material properties appropriately and integrating them with the

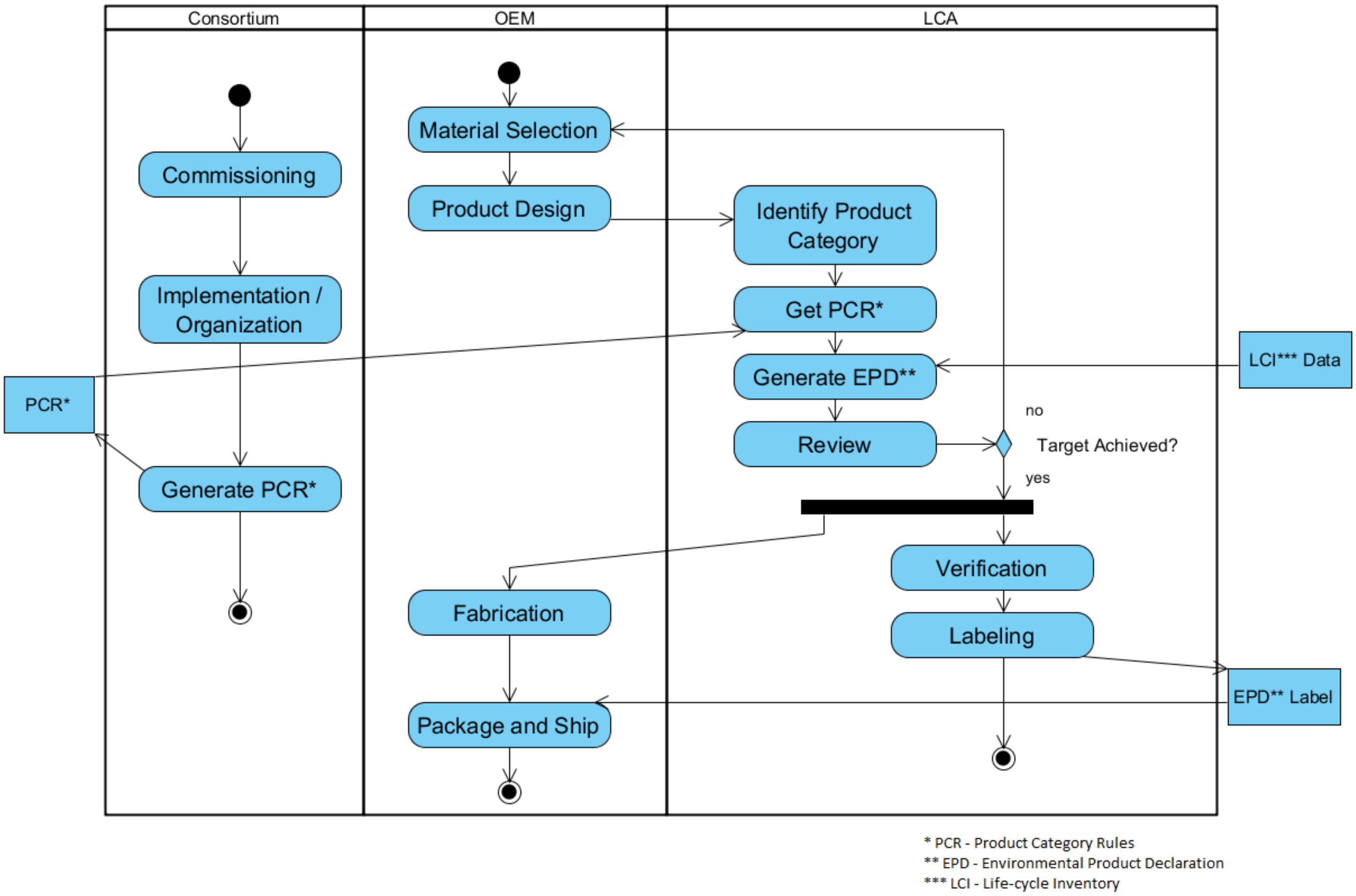

Figure 2: Generating an Environmental Product Declaration

calculation of sustainability metrics, this feedback loop can be closed.

3.4 Support Environmental Product Declarations

An Environmental Product Declaration (EPD) [11] is a standardized way of communicating the environmental performance of a product or system. EPDs are standardized by ISO 14025 [13]. In order to enable practical and objective comparisons of declarations made by similar products, EPDs must comply with specific prerequisites. To achieve this, common and harmonized calculation rules have been established to ensure that similar procedures are used when creating EPDs for similar products. These rules are called Product Category Rules (PCRs). PCRs are developed by a consortia of manufacturers and engineers, formed for specific categories of products. Once a PCR is developed for a category of products, EPDs can be generated for specific products in that category.

Figure 6 shows a scenario where a manufacturer wishes to prepare and review an EPD for a product based on an initial design and production plan. With the availability of the correct information, it will be possible to generate a preliminary EPD, which can be reviewed to check if the manufacturer's sustainability performance targets are achieved. The first column in the activity model in Figure 6 shows the process of creating the PCR for that product category. Once a PCR is created, it is added to a library of PCRs. The generated document object is shown by the rectangle on the left. The manufacturer's work flow is split into two columns. The middle column shows the design and production activities. The right column shows the life cycle analysis activities. The primary activities here are getting the appropriate PCR, and generating the preliminary EPD based on the design. To enable the generation of this EPD, the material information model must be able to integrate with the PCR, and supply the required information from the design model. Being able to generate a preliminary EPD will allow the manufacturer to review the declaration to match organizational goals. When the material information model is well integrated with the EPD data, it will be possible to have a feedback loop that can guide the material selection and product design processes. This creates the possibility to evaluate and achieve organizational sustainability goals right from the design stage. The high level requirement for the material information model based on this scenario can be framed as follows:

Requirement: Ability to map materials to product category rule definitions, and generate environmental product declarations from material information.

The activity model for the scenario shows some of the details of the information interactions involved in performing some of the actions. The "Generate EPD" action involves retrieving a PCR document, and performing a life cycle analysis using life cycle inventory (LCI) data [14] along with the material information model to generate the environmental product declaration document. There are many other data interactions involved in this and the previous scenarios, but these are omitted in this paper to maintain clarity. This scenario illustrates that the material information model for sustainable manufacturing must be able to interface with PCRs, which are based on the ISO 14025 standard, and LCI databases, and may come in many proprietary formats. It must also be possible to trace the information generated in the EPD back to the original material model for this product.

4. Activity Models for Material Selection

Section 3 reviewed four UML activity models developed to explicitly define scenarios where material considerations were necessary to support sustainability goals. These activity models were developed to discourage the ad-hoc development of a material information model to support sustainable decision making. By explicitly defining different design scenarios, we can better understand the role of material information and what considerations must be made in support of sustainable manufacturing. This section will discuss how the activity models discussed in Section 3 will be further utilized to provide insight into material information requirements.

Each activity model discussed in Section 3 was accompanied by a specific requirement. These requirements could be interpreted as "functional needs" of a material information model. The more functions a material information model is able to provide, the more robust it will be.

Each of the activity models in Section 3 were divided into columns. Each column depicted a different viewpoint of the required material information. Between the four models some of these viewpoints are repeated. Some of the roles, such as "Actions" and "nodes," are repeated also. By identifying patterns such as these, we intend to gain further understanding of the material information that supports material selection for sustainability. Through scenario definition, we will gain understanding of how material information is used to make sustainable decisions.

The different viewpoints seen in the activity models provide insight into some of the roles a robust material information model will play. For instance, Figure 6 we see that material information is used by a consortium, a manufacturer, and a tool. To satisfy the needs of the consortium and manufacturer, the information should be human readable. To satisfy the needs of the LCA tool, the information should be computable. As scenarios are added, new roles and viewpoints will be incorporated. The challenge of the material information model will be to satisfy the needs of each of these roles and viewpoints.

The different activity models support different levels of details. One of the main challenges of any material model to support sustainable manufacturing is determining the level of detail that must be represented. By explicitly modeling scenarios as UML activity diagrams, we are able to add or subtract detail as needed. By manipulating the details of each scenario we can provide a better understanding of the level of detail needed by the material model.

As this work continues we will further define scenarios that may occur where material selection will play a role in sustainability impact. By exploring different scenarios, we intend to identify the key material information that is used in material selection in each scenario. After identifying this key material information, we intend to use what we learn to develop a robust material information model that supports sustainable material selection in future real-world decisions.

5. Conclusions and Future Work

Sustainable manufacturing brings together many different concerns across different domains. Some of these have been addressed in traditional manufacturing, particularly in terms of cost of resources such as energy and material. However, sustainability raises many new issues that must be supported by new technologies and new ways of solving problems. One of the important changes necessary is the development of a material information model that is tailored towards addressing sustainability related issues in manufacturing. In order to build a robust material information model, it is important to consider a wide range of sustainable manufacturing scenarios, and study the material information requirements raised in these scenarios.

In this paper we presented a small representative set of such scenarios. We demonstrated the use of UML activity diagrams as a means for explicitly defining scenarios where considerations had to be made specific to sustainable manufacturing. The activity models helped us break down the design and production activities into their component actions, allowing us to explicitly identify sustainability related material information requirements, and their connections to the processes involved. Using well-defined activity models, we can clearly identify where sustainability considerations need to be made, and investigate what role material information plays in supporting sustainable thinking.

As an initial investigation into the use of UML activity diagrams to elucidate sustainability material information, we limited ourselves to a high level treatment of the scenarios. In our future work, we will break down these scenarios into more detailed components, working in conjunction with our industry partners. These will deal with real world examples of material information requirements related to sustainability. The insight gathered by studying these detailed scenarios will be used to construct a material information model for sustainable manufacturing.

Disclaimer

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