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REQUIREMENTS ANALYSES TO SUPPORT A MATERIAL INFORMATION MODEL FOR SUSTAINABILITY

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ABSTRACT

Materials, and therefore material selections, influence the sustainable impact of a product from beginning to end-of-life. With improved access to material information, product designers can attain newfound insight into the sustainability implications of their design decisions. Insight to lifecycle tradeoffs requires access to both upstream and downstream information at design time. This access can be facilitated by information transparency between the different information representations assumed by a product throughout its lifecycle. A well-constructed Material Information Model (MIM) can provide the necessary access, and therefore the desired insight.

In this paper we present an initial set of requirements that a MIM for sustainability must support to provide the desired design-time information access. Using these requirements as guidelines, we then analyze several information representations currently available for information management at various stages of the lifecycle. We compare and contrast the extent to which these representations meet the information needs of the MIM, using example implementations as guidelines. We discuss the level to which information synthesis may be achieved given the varying degrees to which the MIM requirements are met. Finally, we introduce where synthesis challenges lie and the steps required to overcome them.

INTRODUCTION

The overall sustainable impact of a product is a summation of sustainability implications from all stages of a product lifecycle, from material extraction to product disposal. Implications may directly relate to the product, such as the product's recyclability, or indirectly relate, such as the environmental impact of shipping outsourced components across seas. Regardless of the stage when a sustainable impact is recognized, the essence of the product, the material that gives it mass, likely plays a significant role. Sustainable impacts result from material extraction, from material processing, from material transportation, from material forming, from material machining, from material disposal, and so on. Material choice greatly influences the overall sustainable impact of a product's design [1].

Let us use the example of a car to examine how material choice can affect the sustainable impact of a product. It is well known that the weight of a car affects its fuel efficiency, and in turn greenhouse gas emissions [2]. This understanding would indicate that aluminum is the better choice for manufacturing a car with reduced greenhouse gas emissions, rather than steel, which has a higher density. However, further investigation into the processes required to produce and recycle the two materials reveals something different. When processing the metals, steel actually emits less $CO2$ eq/Kg than aluminum, and as a result, when considering all lifecycle stages, steel is in fact the more environmentally friendly material [2]. Although aluminum is the superior material at the use stage, steel performs better in the material extraction and disposal stages. This example serves to show that materials impact the entire lifecycle of a product in different ways, and information is needed from each stage to fully understand the implications of a material choice.

Materials, and when appropriate material information, provide a common underpinning throughout each stage of a product's existence. However, access to this information is restricted by the many different ways materials are understood and represented. As a product progresses through the stages of its lifecycle, transformations often occur where the characteristics of the material are altered. Even when the characteristics of a material are preserved, the perspectives from which the material is viewed may change. This variability is reflected in the many different ways material information is captured, stored, and presented.

To address variations in the way material information is used, and increase transparency of material information as it exists across the lifecycle of a product, we examine the development of a synthesized model to support material information transparency, or a material information model (MIM). The concept of a MIM [3] is to provide a platform that supports multiple representations of a material property at different levels of granularity. A MIM will facilitate access to material information across lifecycle stages, allowing a better understanding of sustainability tradeoffs of design-time decisions.

SUSTAINABILITY IMPLICATIONS ACROSS THE LIFECYCLE

It is well understood that early design-time decisions can predetermine a substantial amount of a product's overall cost [4-6]. The same implications apply to a product's sustainability, where early decisions significantly influence its overall impact [7]. When addressing the sustainability implications of a product, the more information related to the implications of a material, the more informed the designer's material selection can be. This section discusses the role of material information at various stages of a lifecycle and the insight a designer might gain about any sustainable impacts. Improved access to material information from all stages of a product lifecycle facilitates a designer's ability to incorporate sustainability into design-time decision making.

The earliest stages of a product's life most often come in raw form, whether from material extraction or recycled materials. The sustainability implications of raw materials can differ significantly depending on the material, especially when using earth metals. Tradeoffs may be made between not only extracted and recycled materials, but also the energy intensity by which these metals are obtained. Logistics also come into consideration as different materials are more readily available in different geographic locations. With improved access to information from the earliest stages of a product's existence, designers may achieve a better idea of the amount of resources that must be committed to obtain the needed materials.

Sustainability considerations at the manufacturing stage can not only reduce the impact of a product, but also significantly reduce the overall cost of creating a product [8, 9]. These cost reductions come by improving efficiency, and reducing energy and material wastes. In addition to the raw materials used in the creation of a product, waste also comes from the processing materials. Further insight into machining intensities and process materials could provide designers with new tradeoffs that may have previously gone unexplored.

Sustainable thinking has had considerable influence on how supply chains are viewed [10, 11]. Transportation costs have come under new scrutiny, especially when shipping overseas. New studies on sustainable impact have led to seeking solutions closer to home, either through insourcing or local suppliers [12]. Further understanding into material implications at design time would provide designers the opportunity to reduce many supply chain or logistics complications up front.

A more indirect implication of material selection is packing needs. More brittle materials will need additional packaging in order to ensure safe transport. Additionally, some materials may face environmental constraints such as moisture and temperature. The implications of packaging requirements can be quickly felt when mass-producing and shipping large quantities.

For designers, the use stage is by far the most understood stage of a product's lifecycle. This stage prescribes the performance and reliability requirements that designers plan for. After the use stage, however, the impacts of design decisions are less understood, as end-of-life considerations are becoming less restrictive. What once was thought of as simply "disposal," now includes considerations such as recycle, remanufacture, or repurpose. An early understanding of how design decisions may influence end-of-life alternatives allows for the development of more sustainable products.

For the MIM to help designers make informed decisions, the correct information must be made available from each stage. The information available from each viewpoint is often customized to the stakeholder's specific needs. For designers, this information may relate to the performance and reliability characteristics of a product. For manufacturers, the information may be more specific to process or sourcing needs. For suppliers, the information may focus on requirements and cost points. Throughout the lifecycle of a product, numerous standards and information representations are used to meet specific needs and to support decision making at all levels of an enterprise and supply chain.

The next section reviews standard information representations used at different stages of a product lifecycle. We introduce the standards and briefly discuss how they may be deployed in practice. We later discuss how to leverage the representations to obtain lifecycle stage-specific material information.

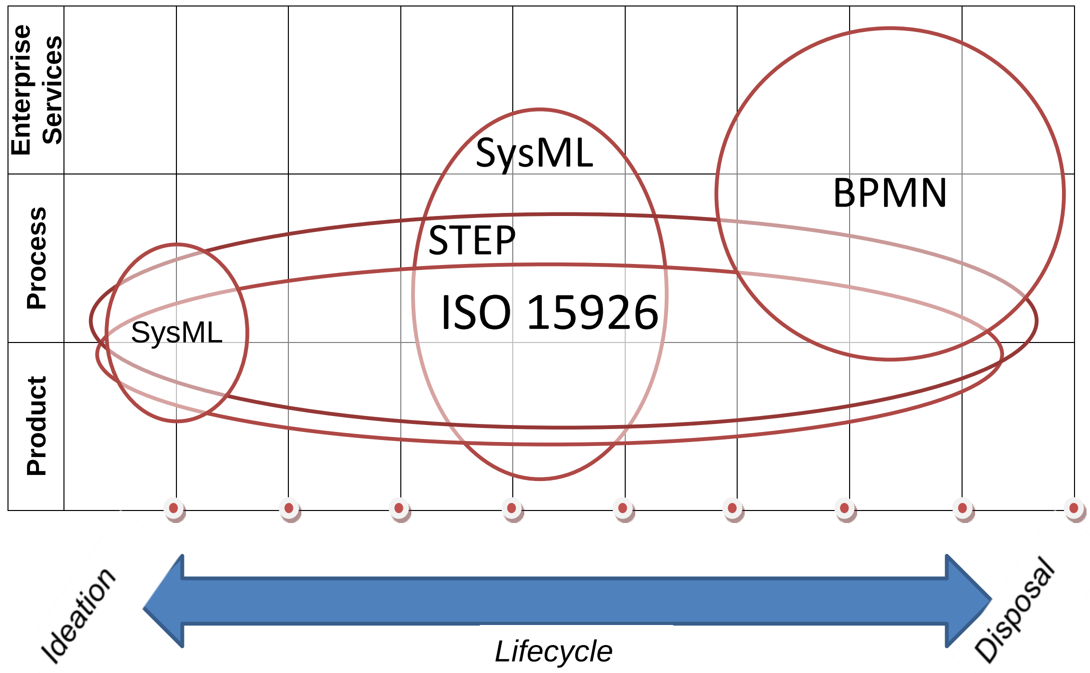


Figure 1: Lifecycle coverage of selected representations

MATERIAL LIFECYCLE REPRESENTATIONS

In previous work, researchers at the National Institute of Standards and Technology (NIST) explored how existing standard representations may be leveraged to synthesize material information across a product's lifecycle [14]. The authors demonstrated that although material information requirements may differ at different stages of the lifecycle, and their representations may differ, some level of synthesis can still be achieved.

In this section we present several standard representations (Figure 1) from different stages of a product's lifecycle and review the type of information that they capture. Each standard selected covers one or more of the lifecycle stages from the product, process, or enterprise viewpoints. Together they provide coverage across the entire lifecycle. We introduce the standard, discuss the lifecycle stages the standard was developed for, and provide some insight into what we hope to learn from the material information captured by each standard.

BPMN

Description: The Business Process Model and Notation (BPMN) [15] is a graphical notation for describing business processes. The goal of BPMN is to support users requiring various degrees of complexity. This means developing a notation that is able to illustrate complex process semantics that technical users need, while remaining accessible to business users. Processes modeled in BPMN can be automatically translated into executable processes, allowing both manufacturing and business processes to be modeled in the same environment, thus facilitating interoperability between the shop floor and office area. BPMN is targeted at users, vendors and service providers that need to communicate business processes in a standard manner [16].

Lifecycle coverage: BPMN most appropriately represents information from the manufacturing, supply chain, product use and disposal at the product, process and enterprise levels.

Research focus: Given its target audience, BPMN may provide enterprise-level information about materials that other standards do not support. This information could provide valuable insight into the supply chain. The shop floor to office interactions could potentially provide valuable insight into process requirements as well as insourcing vs. outsourcing criteria. The relatively generic notation allows us to model information outside its intended scope.

SysML

Description: The Systems Modeling Language (SysML) [17] was introduced to facilitate the development of component diagrams. It provides a graphical syntax and grammar appropriate for systems engineering applications. "It supports the specification, analysis, design, verification and validation of a broad range of systems and systems-of-systems, including hardware, software, process, personnel, information and facilities." [18] SysML utilizes many of Unified Modeling Language's (UML) [19] packages while adding the ability to create requirements diagrams and parametric diagrams [20].

Lifecycle coverage: SysML has the ability to cover ideation and design organization lifecycle stages at the product and process levels. It also covers detailed design, design evaluation, and manufacturing at the product, process and enterprise services levels.

Research focus: SysML supports systems integration, so the modeling techniques used could prove to be important. The system-level interactions between product and process are an important part of understanding the implications of material choice from design-time decisions.

ISO 15926

Description: ISO 15926 [21] was developed to facilitate the exchange and reuse of complex plant and project information in the oil, gas, process and power industries. It is, however, sufficiently generic that it can be used for a wide variety of information exchange and integration [22].

Lifecycle coverage: ISO 15926 has the ability to cover product and process information over the entire lifecycle, as shown in Figure 1.

Research focus: As a PLM-oriented (Product Lifecycle Management) standard, ISO 15926 provides insight into how lifecycle interoperability is approached with the application of recent advancements in information modeling, implementation methods, and the federated use of reference data. The standard provides insight into how others address the different levels of granularity necessary to represent material information across the product lifecycle and a range of viewpoints and domains of discourse.

ISO 10303

Description: ISO 10303 [23], informally known as STEP (STandard for the Exchange of Product model data), serves to exchange information between CAx systems and other product data management/enterprise data modeling systems. ISO 10303-221 [24] (functional data and schematic representation of process plants) is very similar to ISO 15926. They both use the same generic information model in conjunction with reference data libraries, e.g., ISO 15926-4 library [21].

Lifecycle coverage: ISO 10303 can be used to represent product and process information over a significant portion of the lifecycle [13].

Research focus: The ISO 10303 model is very similar to that of ISO 15926 but with a different focus. Comparing and contrasting ISO 10303 with ISO 15926 in the requirements analyses will provide valuable insight into product-specific lifecycle needs while also providing unique perspectives on lifecycle information challenges. ISO 10303 also contains material-specific packages such as ISO 10303-235 [25] and ISO 10303-45 [26].

The analyses in this paper focus on these representations: BPMN, ISO 15926, ISO 10303, and SysML. These four representations reflect information exchanges across all facets of the product, process and enterprise lifecycles (Figure 1). In the following sections we discuss the alignment of material information through these various lifecycle representations.

MATERIAL INFORMATION MODEL

The concept of an information model developed to facilitate the integration of material information throughout a lifecycle was introduced above. This section provides further detail on the MIM. A high-level outline of its goals is followed by a detailed set of requirements analyses.

The proposed MIM has one clear high-level goal: to make sustainability-related material information from throughout the lifecycle available for design-time decision making. However, the directions and steps necessary to accomplish this goal are not as straightforward. To satisfy the high-level goal of a MIM, we propose five sub-goals (Tables 1-5) that should be satisfied [3]. Each sub-goal is defined by a desired set of capabilities. The more capabilities each analyzed standard is able to satisfy, the better able it is to support each sub-goal. The five sub-goals are as follows:

For better materials selection- This sub-goal addresses material-specific properties and the impact they may have on sustainability. As discussed, material choice greatly affects the sustainability impact of a product at all stages of its lifecycle. This category of requirement addresses the extent to which the material properties are captured to support lifecycle thinking. It includes material performance at different lifecycle stages and the ability to communicate between stages.

For design-time decision making- This sub-goal builds on the previous category. It addresses the notion that the material model should not only support the necessary material information to make sustainable decisions, but should present it in a manner that enables informed decision making. Designers need to be provided the information at design time in a manner that enables them to better understand the tradeoffs at hand.

For material tracking- Material tracking can facilitate better accounting for material-related impacts across each stage of the lifecycle. This sub-goal addresses the ability to aggregate material information, while addressing traceability and verification, throughout lifecycle stages and across the supply chain. Among other things, it is also important for reporting.

For improved accuracy in lifecycle assessment- Improved accuracy promotes more informed decision making. Accuracy related to material information in lifecycle assessments can be addressed with specific metrics, such as incorporating material, energy, and waste use based on actual measurements rather than estimates or other sustainability criteria (i.e., sustainable sourcing).

For improved information management- With the large amount of material-related information anticipated, it is necessary to manage it efficiently. This sub-goal addresses information management capabilities of each standard, including mapping between levels of granularity, integrating with LCA tools/ data structures, and providing information based on requirements/ viewpoints of stakeholders.

The next section discusses, in greater detail, each of these five sub-goals. From these analyses we hope to achieve a better understanding of material information needs at different stages of the product's lifecycle and obtain insight into how a unified MIM may best satisfy lifecycle needs.

REQUIREMENT ANALYSES

In this section we analyze the extent to which the selected standards are able to satisfy the desired capabilities for each of the five sub-goals identified for a MIM. Each sub-goal is outlined in a table using the desired capabilities, and each information representation is analyzed and mapped to the table to state whether or not it is capable of providing the desired capability.

For each of these information representations, we have reviewed a wealth of published information, including standards and related documents, to determine the representations capabilities. Details include identifying specific property types and their associated data types (String, Float, Boolean, etc.) that address desired requirements. If there is evidence that a capability can be provided by an information representation, we indicate it with a Y in tables 1 - 5. When two representations have a Y for a particular capability, both provide the capability, but not necessarily in the same way or in the same level of detail. The omission of a Y does not necessarily indicate that an information representation does not offer a capability, but rather that we do not have any evidence to suggest the capability is supported. Included in this section is also a set of figures which illustrate how each standard may meet some of the identified MIM requirements.

IMPROVED MATERIAL SELECTION

Six desired capabilities were identified to support the sub-goal of supporting material selection. A careful review of each standard leads to the conclusion that each supports material selection in its own unique way. Here, each capability desired to support the sub-goal of material selection is reviewed in the context of the select standards. Table 1 summarizes the results.

1) **Allow material selection based on customer performance requirements, specifications (indexing), and/or functions of multiple properties (performance index) associated with product and process properties:**

ISO 15926, SysML and ISO 10303 all have explicit notations for representing performance requirements while BPMN does not. BPMN offers a generic data object in which performance requirements can be represented [27]. Comparatively, BPMN focuses more on processes than modeling specific properties. Figure 2 shows how one might use BPMN to model material selection based on material performance requirements. In this example, the diamond shaped gateway node allows for material selection based on whether a drill bit will be used on porcelain, glass or diamond. It serves to show the relationship between performance requirements and material choice. ISO 15926 and ISO 10303 both provide basic support for the desired functions/requirements of a product, but neither is as comprehensive as SysML [28-30]. SysML allows for requirements modeling through its text based requirements diagrams, which are tailored to support this MIM requirement. It provides an identifier for each requirement, the origin, a textual description, a classification, risks/consequences and verification of requirements [29]. The advantage to SysML is that it has a dedicated construct to model requirements. However, a notable drawback is that it is text-based [31]. Figure 3 demonstrates how SysML can model customer requirements for a drill.

TABLE 1. MIM FOR BETTER MATERIALS SELECTION

A Sustainability Material Information Model (SMIM) will provide the ability to…..	BPMN	ISO 15926	ISO 10303	SysML
Allow material selection based on customer performance requirements, specifications (Indexing), and/or functions of multiple properties (performance index) associated with product and process properties.	Y	Y	Y	Y
Provide Gate-to-Gate process information (relative to material and energy efficiency) at design time/ Capture interactions between material properties and processing requirements.	Y	Y	Y	Y
Account for effect of material choice on product lifespan (better durability, desirability)	Y	Y	Y	Y
Allow material selection based on different sustainability metrics (i.e. better recycling/remanufacturing ratio)	Y	Y	Y	Y
Provide material information to engineers from other lifecycle stages, such as material sample information and product related aspects (Factor in "costs" associated with the material from other life-cycle stages)	Y	Y	Y	Y
Capture interactions between design characteristics and material/process interactions.	Y	Y	Y	Y

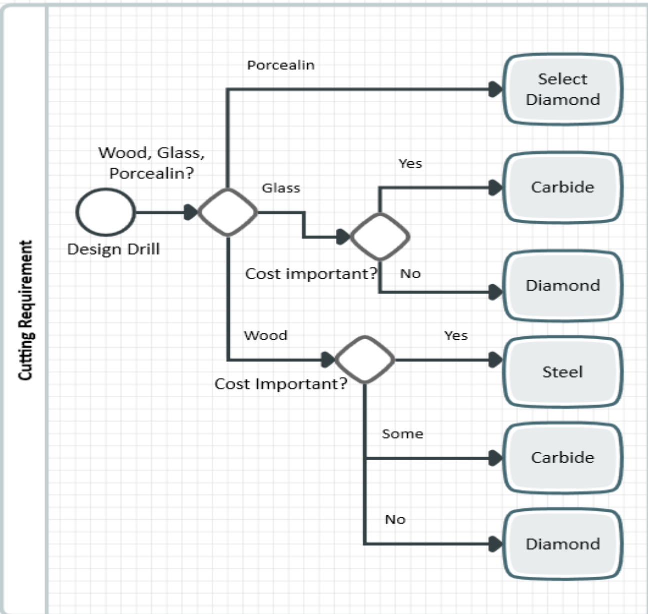


Figure 2: Requirement 1 in BPMN

2) Provide Gate-to-Gate process information (relative to material and energy efficiency) at design time/ Capture interactions between material properties and processing requirements:

Each of the information representations reviewed is able to support the product-process interactions that this capability requires. SysML model elements can support material properties that can be further refined by processing requirements, also as shown in Figure 3. SysML can specify the inputs and outputs of physical entities such as fluids, gases and energy [29]. Similarly, ISO 15926 defines a relationship that indicates whether matter, energy or both can be transferred between objects [32]. ISO 15926 seems most apt to meeting this requirement as it is a standard specific to providing lifecycle process data. BPMN differs from the other representations as it is meant to support this requirement from a more general business perspective [27].

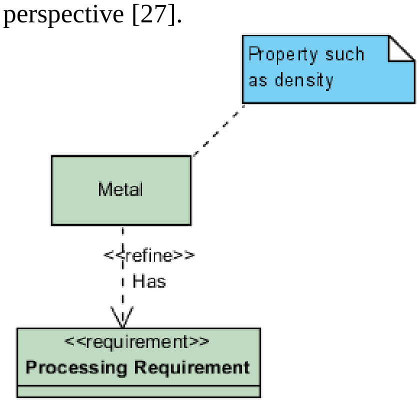
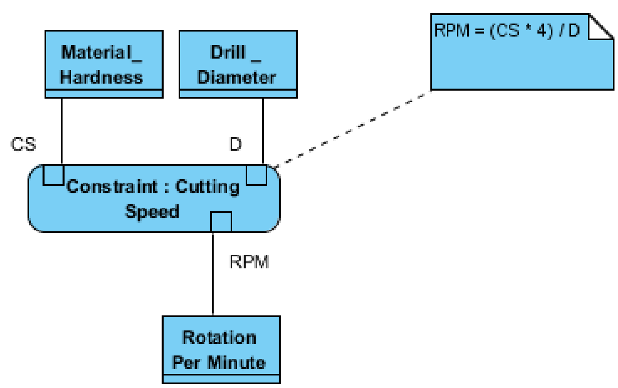


Figure 3: Requirements 1, 2 in SysML

3) Account for effect of material choice on product lifespan (better durability, desirability):

All four representations are able to provide this capability, but they differ in that SysML and ISO 15926 have terms that specifically address it. BPMN and ISO 10303 have generic terms that are capable of accounting for product lifespan. SysML can provide insight into a product's lifespan by monitoring critical properties (e.g., latency), physical properties (e.g., weight) and other properties (e.g., reliability and cost) [29]. For instance, SysML allows for analyzing the impact of material choice on durability through its parametric diagram, as shown in Figure 4. Specifically, Figure 4 shows how material choice affects the cutting speed of a drill and cutting speed affects the lifespan. ISO 15926 can also model lifespan-related properties and supports a surface analysis, which could provide insight into the aesthetics of a material. BPMN is capable of modeling properties such as durability and lifespan but it does not provide the specific constructs [15]. Similarly, ISO 10303 has a generic description attribute that can support properties such as durability but is not specifically intended to describe a material's effect on product lifespan [28].



4) Allow material selection based on different sustainability metrics (i.e., better recycling/ remanufacturing ratio):

SysML supports model-based metrics with the ability to define how well requirements are met. It provides the ability to measure a material using sustainability metrics such as recycling/remanufacturing ratio [29]. Similar to requirement three, SysML can model sustainability using the parametric diagram. It allows us to alter material selection, which in turn affects sustainability of a product. ISO 15926 supports this capability to a lesser extent through the concept of recycling [30]. BPMN can model sustainability properties but does not specifically support them [33]. ISO 10303 offers the most support of the four as it provides material identification, performance data, environmental constraints and simulation models to aide in material selection [28].

5) **Provide material information to engineers from other lifecycle stages, such as material sample information and product-related aspects (Factor in "costs" associated with the material from other lifecycle phases):**

For this analysis, we extend the concept of "cost" beyond a monetary amount. With this understanding, ISO 15926 models the cost of goods/activities and supports estimations. BPMN supports the concept of cost by using cost intervals or average cost [34]. ISO 10303 has a basic support of cost, as it provides cost information in terms of contract details [28]. SysML has the most comprehensive method of calculating costs as it allows for incorporation of a detailed cost analysis throughout the lifecycle [20].

6) **Capture interactions between design characteristics and material/process interactions:**

This capability is similar to that of 2), but with greater focus on the design requirements. Parts of a product may undergo several processes before all features can be incorporated. ISO 10303 defines the tools, setups, and positions necessary to develop these product features [35]. Figure 5 displays how ISO 10303-235 can show the interaction between properties and processes using the process_property_association entity. It is more comprehensive than ISO 15926, though ISO 15926 is able to define properties derived from specific processes. SysML describes interactions between and within systems but does not specifically address the interactions between design characteristics and materials as ISO 10303 does [36]. BPMN allows us to model processes quite well. Within these processes, gateways can create branches based on material choice, similar to what was shown in Figure 2. Furthermore, data objects can add material/process property information to the diagram.

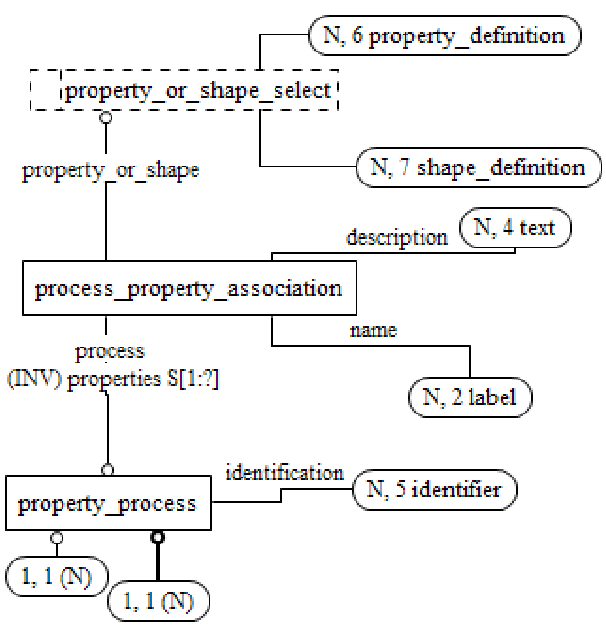


Figure 5 : Requirement 6 ISO 10303

PROVIDE METRICS TO SUPPORT DESIGN-TIME DECISION MAKING IN TERMS OF SUSTAINABILITY

As seen in Table 2, all four representations provide the ability to support sample material information and account for decision space alternatives. ISO 15926 accounts for a decision space to weigh alternatives, provides test data and gives insight into hazards associated with a material choice [30]. BPMN accounts for decision space alternatives and provides feedback data from different processes [27]. ISO 10303 provides material information over different phases, including test data and sample information after processing [28]. SysML provides test information, documentation for changes in products over the lifecycle, tradeoff analysis and a decision space [20]. The biggest deficiencies of each representation are supporting transparency between models and providing insight into use-stage efficiency. The six capabilities are further detailed below and summarized in Table 2.

1) **Provide material metrics to processes in Gate-to-Gate operations to predict efficiency of processes**

SysML, ISO 10303 and ISO 15926 all support test data over the lifecycle, while BPMN does not. SysML provides test data via test cases, with the ability to indicate whether a requirement is verified [29]. ISO 15926 provides material test data by modeling data such as the flow rate of a pump [32], and ISO 10303 supports data used in testing or analyzing a design.

TABLE 2. MIM FOR METRICS FOR DESIGN-TIME DECISION MAKING

A Sustainability Material Information Model (SMIM) will provide the ability to…..	BPMN	ISO 15926	ISO 10303	SysML
Provide material metrics to processes in Gate-to-Gate operations to predict efficiency of processes		Y	Y	Y
Account for material information in different phases (material phase change) during manufacturing processes to predict efficiency		Y	Y	Y
Provide material sample information after processing /feedback (outputs of processes).	Y	Y	Y	Y
Account for decision space for alternatives	Y	Y	Y	Y
Provide insight into material choice impact on use-stage efficiency when applicable		Y		
Support connection/transparency between product and process models				

2) Account for material information in different phases (material phase change) during manufacturing processes to predict efficiency of processes

SysML, ISO 10303 and ISO 15926 are capable of offering different degrees of support. SysML allows us to track changes along the lifecycle of a product [29]. ISO 10303 provides material information in different phases, indicating the lifecycle stage or maturity of data [28]. ISO 15926 provides information at the design, engineering construction operation, maintenance, decommissioning and demolition phases. As BPMN does not specifically address materials, it does not support this requirement as the others do.

3) Provide material sample information after processing /feedback (outputs of processes)

This is similar to 1), but addresses feedback as opposed to feed forward. ISO 15926 provides feedback/output by describing system performance, including inputs and outputs. ISO 10303-239 provides operational feedback, which includes "the observed configuration, location, state or properties of an actual product and the communication of work requests to resolve issues arising from feedback on its usage [35]." SysML provides feedback/output by representing the steps of a process, including inputs and outputs [37]. BPMN represents feedback/output data by indicating the results and outputs of a process [27].

4) Account for decision space for alternatives

BPMN accounts for decision space alternatives by regulating the flow of processes. It breaks down a process into different loops based on a user specified mechanism, allowing for numerous alternatives [27]. This differs from ISO 15926, which provides a competitor product analysis. SysML provides parametric relationships to assess how decisions can affect certain properties. ISO 10303 does not explicitly support this requirement, but does support material alternatives, including test data and sample information after processing.

5) Provide insight into material choice impact on use-stage efficiency when applicable

ISO 15926 provides hazard and risk analysis, both of which could give insight into the use stage of a material [30]. However, that is the extent that these representations are able to explicitly address this requirement.

6) Support connection/transparency between product and process models

This capability focuses on the connection between two distinct models—the product model and the process model. While they all support some product/process interaction, none explicitly support transparency between two distinct model types.

FOR MATERIAL TRACKING

All four representations allow for supply chain authentication but none support all desired capabilities. This is because none of the four representations reviewed specifically address sustainability across the supply chain, therefore limiting the need for discussion. SysML does support authentication and traceability, which allows us to extract information throughout the lifecycle that is relevant to a particular requirement [38]. ISO 15926 describes the relative location of items and provides verification of whether or not a product contains the intended items. BPMN provides supply chain authentication, as well the ability to map material information to requirements [27]. ISO 10303 provides traceability by specifying the transaction of goods along with the conditions specified by the buyer and seller [39]. The material tracking capabilities are summarized in Table 3.

TABLE 3. MIM FOR MATERIAL TRACKING

A Sustainability Material Information Model (SMIM) will provide the ability to…..	BPMN	ISO 15926	ISO 10303	SysML
Provide supply chain “authentication” verification –whether or not a product contains a certain substance	Y	Y	Y	Y
Provide supply chain traceability for sustainability metrics				
Aggregate similar sustainability metrics across supply chain-from component to assembly to product				
Support the mapping of material information to regulations and reporting requirements	Y			

FOR IMPROVED ACCURACY IN LIFECYCLE ASSESMENT

Each of the representations were specifically reviewed for how well they address sustainability-specific information. Representations were assessed to determine whether they provide definitions for measurement of material, energy, and waste, and whether they can map materials to product category rule [40] definitions and functional units. SysML contains a standard item definitions package, which defines information, material and energy flow [20]. The ParaMagic [41] extension to SysML can use information from a manufacturing model in SysML to solve parametric equations relating to carbon dioxide emissions, energy consumption, and waste mass generation for a particular manufacturing scenario in Mathematica [42]. The other representations, however, do not offer direct support of lifecycle assessment. Each offered indirect support through uncertainty quantification capabilities. Table 4 summarizes the capabilities each representation offers in terms of supporting lifecycle assessment.

TABLE 4. MIM FOR ACCURACY IN LIFECYCLE ASSESSMENT

A Sustainability Material Information Model (SMIM) will provide the ability to…..	BPMN	ISO 15926	ISO 10303	SysML
Provide definitions for measurement of energy, material, and waste (MEW) use.			Y	Y
Support classification of MEW based on sustainability criteria (i.e. sustainable sourcing)				
Ability to map materials to product category rule definitions and functional units used therein				

FOR IMPROVED INFORMATION MANAGEMENT

This sub-goal is perhaps the most ambiguous of the five, as it addresses information-specific capabilities. As with the other analyses, we again focused on identifying explicit support for each of the 11 capabilities. As seen in Table 5, each representation has strengths and weaknesses in the coverage of the MIM requirements; overall, however, they appear consistent in providing desired capabilities.

1) Ability to provide material information based on requirements/ viewpoint of each stakeholder (Language/ Detail/ etc.)

All four representations provide information based on different viewpoints, allowing users to get the specific information that they need. SysML conforms to the perspectives of different stakeholders by providing traceability to a desired viewpoint. [20]. ISO 15926 captures data relating to each user and merges it, also allowing users to extract only what they need [43]. ISO 10303 identifies the point of view of represented data and establishes the specific requirements [28]. BPMN differs from the other representations in that it only includes customer and supplier perspectives. However, this is understandable as BPMN is a business-specific notation [44].

2) Integrate with and simultaneously support CAx/ PLM/ ERP/ CAPP material information

ISO 10303 is a standard for representing and exchanging CAD information so it handles this requirement well. However, the other representations do not seem to specifically address this need.

3) Supports "null" values –missing data

ISO 15926 has a null class, which does not have any members. ISO 10303 contains a null string value while BPMN contains an empty activity [27] . This helps greatly in representing missing values.

4) Support mapping between different levels of detail and/or granularity

ISO 15926 supports mapping between different levels of granularity by representing information at abstract, class and entity levels [45]. BPMN also supports information at different levels of granularity through sub-processes, collapsed sub-processes, and expanded sub-processes [27]. SysML facilitates moving between layers of information by either adding or removing information as needed [46]. While the ISO 10303 representation was not explicit in this requirement, the other three representations do an adequate job of addressing this requirement.

5) Support mapping from and between different data sources

SysML can map to Modelica [47] and vice versa. SysML was developed in coordination with AP 233 so there are mappings between the two standards [48]. In general, this capability mostly requires third-party support. The OWL (Web Ontology Language) specification of ISO 15926 also supports mapping from and between data sources.

6) Ability to represent different forms of property representations (graph, table, linear/non-linear equations)

ISO 10303 best supports this requirement as it includes mono-detail drawings, multi-detail, tabulated drawings and lists. These different views allow us to represent information in the most clear and precise manner [28]. The others also support this requirement, but with extensions.

7) Provide assessment metrics expressed as a function of control variables for representing trade-offs

This capability assesses tradeoffs as functions of control variables. While all four representations provide insight into the tradeoffs of making a decision, none seem to allow the use of functions for control variables.

8) Fit to modular structure: should include a library of metrics, association to process model, and expressions of material consumption

This capability provides a collection of metrics, associations to process models and expressions of material consumption. While all the representations can represent these properties, none provides a library or collection of these properties.

9) Provide means for mapping material properties

As discussed in the materials selection section, all four representations support material properties. They also support mapping material properties, but to different extents. BPMN differs from the other representation in that it does not natively support mapping material information but the notation is generic enough that it is capable of meeting this requirement. SysML, ISO 10303 and ISO 15926 all have material-specific constructs that allow them to meet this requirement.

10) Support the classification of material properties

ISO 15926 is the only standard that addresses this requirement as it contains a term that compares different properties [32]. The others may be able to indirectly provide similar support.

11) Ability to Integrate with LCA tools/ data structures

SysML can be exported in the Extensible Markup Language (XML), which facilitates information exchange between standards that support Metadata Interchange (XMI) [20]. SysML can also integrate between various LCA tools, which greatly expands the scope of its lifecycle coverage [49]. Work has also been done to integrate ISO 10303 and ISO 15926 with the CASCADE model, [50] which supports LCA.

TABLE 5. MIM FOR IMPROVED INFORMATION MANAGEMENT

A Sustainability Material Information Model (SMIM) will provide the ability to…..	BPMN	ISO 15926	ISO 10303	SysML
Provide material information based on requirements/ viewpoint of each stakeholder (Language/ Detail/ etc.)	Y	Y	Y	Y
Integrate with and simultaneously support CAx / PLM / ERP /CAPP material information			Y	
Support “null” values –missing data	Y	Y	Y	
Support mapping between different levels of detail/granularity	Y	Y		Y
Support mapping from and between different data sources		Y		Y
Represent different forms of property representations (graph, table, linear/non-linear equations)			Y	
Provide assessment metrics expressed as a function of control variables for representing trade-offs				
Fit to modular structure: should include a library of metrics, association to process model, and expressions of material consumption.				
Provide means for mapping material properties	Y	Y	Y	Y
Support the classification of material properties		Y		
Ability to integrate with LCA tools/ data structures		Y	Y	Y

DISCUSSION

The requirements analyses of the four information representations shows that each has strengths and weaknesses with respect to the coverage of MIM requirements. Some standards perform well in some areas and not as well in others. While it is useful to consider each sub-goal separately to better understand the capabilities of each information representation, it is important to keep the single high-level goal in mind. As such, there is much to be learned from the strengths of each information representation and how each contributes to the high-level goal of material integration for design-time decision making. Further investigation into how each information representation is able to meet different capabilities will provide valuable insight into solving the synthesis challenge. Insight into how capabilities are met may provide guidelines to attain similar capabilities with other representations. Evaluating the MIM requirements against these standards can help to identify areas where further standardization may be useful.

While the desired capabilities are proposed to support the sub-goals of a MIM, it may be difficult or impractical to provide them all. In practice, it may be found that decision making needs are best met through a specific subset of these capabilities. As the goal of a MIM is to support sustainable thinking and informed decision making, there is an inherent necessity for the MIM to effectively communicate tradeoffs. The more tradeoffs the MIM is able to support the more successful the model is likely to be in supporting sustainable thinking.

When considering what capabilities are most important for the MIM to provide, communicating information outside of sustainability should also be considered. Sustainability-related tradeoffs are less likely to be made if they compromise the functional or cost requirements of a product. If cost and performance tradeoffs are not well understood, there is little likelihood design considerations will be made for sustainability.

For instance, consider a carpet product designed with sustainability in mind. To properly assess the impact of any decision, we have to look at how the decision affects other design criteria throughout the lifecycle. A product that is designed to be environmentally friendly but is not functional is not very useful and vice versa. These goals can be conflicting but do not always have to be. In this case, alternatives were explored for PVC fibers often used in carpet backing, considered volatile organic compound. They function well but also harm the environment. Focusing on performance requirements while also considering sustainability implications, the manufacturer developed a spray to replace the traditional backing. It proved to be easier to install and easier to replace, while reducing the need for VOC's [51]. A successful MIM will facilitate the exploration of design spaces to help designers understand where tradeoffs may be made.

CHALLENGES

The multiplicity of ways that information is represented across the lifecycle of a product makes it difficult to assess its overall sustainability impact. Many aspects of a product are modeled in vastly different ways. Standards may be used to provide some synthesis between applications. However, there is even variance amongst how standards are implemented. We need to reconcile this variability in order to synthesize material information throughout the lifecycle.

For a MIM to be useful for understanding tradeoffs and making design decisions early in the lifecycle, lifecycle information needs to be integrated and presented in a common format. Ontologies provide a mechanism for both integration and synthesis. This was demonstrated in [14]. Ontologies provide a way of semantically describing information in a specific domain/setting, giving meaning to words and expressing relationships. An ontology can provide a neutral format to represent information from each of the representations reviewed. Completed and ongoing works have resulted in ontological representations of several information representations, including ISO 10303 [52], SysML[53], BPMN[54] and ISO 15926 [55]. We hope to leverage works such as these in the future integration and synthesis challenges we anticipate during the development of the MIM.

CONCLUSION AND FUTURE WORK

A MIM will allow us to consider the lifecycle impacts of material selection during design time decision making. For instance, let us consider the "aluminum vs. steel" example presented in the introduction. The goal of the MIM is to provide insight into the less-prevalent downstream implications of design time decisions. When comparing steel and aluminum, a successful MIM would provide the designer with insight into the processing and other lifecycle costs of each material. This information would allow the designer to make a more informed decision when designing for sustainability.

This paper discussed the extent to which several standards from across a lifecycle may provide insight into sustainability information through different material representations. What we have not yet discussed are those information representations specific to materials. There are a number of standards that specifically address material information, which will be covered in a future publication. To be successful, a MIM will need to address how to synthesize not only standards such as BPMN, SysML, ISO 10303 and ISO 15926, but also the material specific standards.

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DISCLAIMER

Certain commercial products may have been identified in this paper. These products were used only for demonstration purposes. This use does not imply approval or endorsement by NIST, nor does it imply that these products are necessarily the best for the purpose.

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