Sustainability through Lifecycle Synthesis of Material Information

Paul Witherell[1], KC Morris[1], Anantha Narayanan[1], Jae Hyun Lee[1], Sudarsan Rachuri[1], Soundar Kumara[2]

[1]Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, USA

[2]Department of Industrial and Manufacturing Engineering, Pennsylvania State University, University Park, PA, USA

Abstract

The synthesis of material information across lifecycle stages will lay the foundation for a material information model to support sustainable decision making. This paper explores how material information is represented in select standards that address product and process information at different lifecycle stages. We discuss some of the challenges in synthesizing information between these standards, and explore the use of ontologies as a means to create and manage material information across a lifecycle. We discuss the potential benefits of fully synthesizing material information across the lifecycle, and the potential applications of a material information model that possesses this capability.

Keywords:

Material Information Model, PLM standards, information modeling, ontologies, sustainable manufacturing

1 INTRODUCTION

Historically, the development of products has been optimized based on three primary drivers: quality, cost, and time to market (throughput). Today a new driver has emerged: sustainability [1]. Sustainability has become a principal business driver brought about by customer demand for products to be more "green" and "friendly." The perception of what makes a product "sustainable" can be difficult to pinpoint. This is especially true when focusing on the manufacturing of products, where decisions are not always as simple as "using recyclable materials." 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.

Manufacturing for sustainability requires an integrated systems approach that spans the product lifecycle. Metrics from each stage of a lifecycle can be optimized to better support a sustainable system; however, focusing on any single stage in the product lifecycle in isolation could result in suboptimal solutions and unintended consequences. Evaluation not only within, but also *across* lifecycle activities is critical to the fundamental understanding of sustainable manufacturing. Material selection plays an important part in determining total lifecycle impact. For example, creating products out of lower impact materials may result in less energy and material use in the production of a single product but may end up jeopardizing the longevity of the product and result in the production of more goods to meet the same need—incurring a greater impact on society.

We believe that available technologies can be augmented to provide new insight into the sustainability implications of decisions across the lifecycle of a product. Industry realized years ago the need to collect and manage information across lifecycle stages. To interoperate with the software used at different stages of a product's lifecycle, Product Lifecycle Management (PLM) systems provide a means for information exchange, often in a standardized way. While the information managed by different tools is often specific to a lifecycle stage, there is also "common" information that passes between stages. In this paper, we discuss how sustainability assessment can be integrated with traditional product management techniques through standards, materials, and material properties.

This paper reviews several standards that are available at different lifecycle stages to describe an approach for building a sustainability-focused integration infrastructure. Section 2 highlights materials and their role in lifecycle synthesis and sustainability. Section 3 surveys the types of standards used across the lifecycle, and how material information is used. Section 4 discusses the technical challenges of synthesizing material information across the lifecycle; both in terms of integrating engineering information at the semantic level and in terms of the necessary information technology to support such integration. This section also demonstrates a general approach to integration. Section 5 identifies ways our material synthesis approach can move forward and the potential impact.

2 SUSTAINABILITY THROUGH SYNTHESIS OF MATERIAL INFORMATION

As noted, sustainability considerations are becoming increasingly important during the manufacturing stages of product development. Currently, however, sustainability assessment is typically performed after much of the early design and process plan has already been decided.

The current state of the art for sustainability assessment, Lifecycle Assessment (LCA), relies on knowledge about how a product will be sourced, manufactured, used, and disposed. LCAs are often complex and calculation intensive. We propose that by making material information more transparent we can expand the quality of the material information available during early design stages. We believe this new transparency can supplement methods currently used by LCA tools while also providing new design-time insight into sustainability implications.

At the highest level of abstraction the one physical characteristic that all manufactured products have in common is that they are composed of materials. Materials can provide the connection between the virtual world of design and the physical world of manufacture, as a primary function of manufacturing is the manipulation of materials. Materials provide a common thread to connect all stages of the product lifecycle. As such, materials can also serve as a basis for sustainability measurement.

Lifecycle impacts can be more efficiently assessed when incorporating metrics associated with materials. When focusing on the manufacturing stages, these metrics include actual measures of energy and material usage during manufacturing. As other stages of the lifecycle are incorporated, the impacts begin to vary. As Allwood et al note, "the environmental impacts of materials production and processing, particularly those related to energy, are rapidly becoming critical [2]." To better understand the impact of material choice during design and manufacturing, the impacts from all lifecycle stages need to be made more transparent. This transparency can be achieved through the lifecycle synthesis of material information.

The first step to incorporating material considerations from across the lifecycle into design time evaluation is to understand the use of material information at different stages of the product lifecycle. Material information is inherently interconnected between lifecycle stages, and any impact assessed, regardless of stage, should reflect contributions from other stages. However, due to many different viewpoints (Figure 1), the necessary integration and synthesis can be a challenge. To address this challenge, we turn to PLM systems and standards.

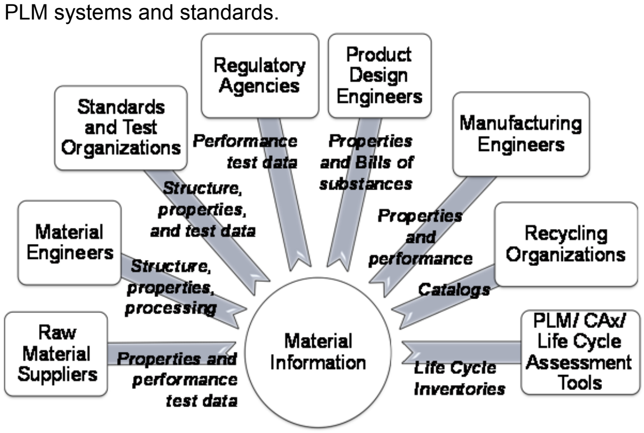

Figure 1: Different views and uses of material information.

3 MATERIAL INFORMATION IN THE PRODUCT LIFECYCLE

New capabilities in PLM tools are trending them away from a file exchange platform towards a more integrated knowledge management system [3]. Industry is embracing this shift, as it allows more granular information exchange across domains, platforms, and regions, providing a new level of support to both distributed and concurrent product development. These advancements mean material information can, and is being, integrated across those stages of the product lifecycle captured within the system. PLM developers have been successful in using material properties to provide point assessments at different lifecycle stages. Though PLM systems have continued to advance lifecycle analysis capabilities, they come with several caveats because they are proprietary. Namely, users may be forced to conform to a specific PLM platform and partner applications, and they are restricted to the lifecycle stages supported by the specific PLM system. However, to accommodate increasing information requirements, PLM tools are supporting information exchange to and from different systems[4, 5], and these exchanges often involve standards.

Standards deployed within a product's lifecycle may provide information representations at distinct stages of the product's life, as well as across stages of the lifecycle. As product information becomes increasingly granular, information standards increase in both numbers and detail. Much of this increase is a result of stage-specific and stakeholder-specific needs. Depending on the need, the differences in how material is represented in the different lifecycle stages can be great, and the overlap, if any, is not always simple to identify. This creates difficulties when trying to synthesize material information across a lifecycle.

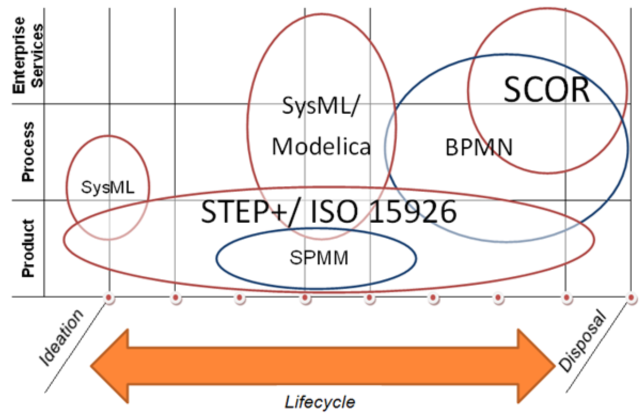

Figure 2: Sample of standard coverage across lifecycle. Derived from [6].

The type of information associated with a material, and how this information is represented, depends on the information requirements of the different lifecycle stages. As shown in Figure 2, common product information representations can differ not only across the product lifecycle, but also within a stage. Representations can depend on the viewpoint of the stakeholder. For instance, representations may vary depending on whether the information is engineering specific, or related to the product via process or enterprise information [6, 7].

The result of the many different representation needs is a conglomerate of material information that does not often synthesize well. The material information may vary by factors such as material property type, granularity of material information, expression of material information (function vs. value), unit of material information (unit vs. mass), and even the basic representation structure of the material information. Here we review several different standards that are used to represent product, process, and enterprise information across a product's lifecycle. We specifically look at the intent of the standard, who may adopt it, and how material information is represented. We then review examples of how standards have been previously leveraged to achieve some form of lifecycle synthesis for materials.

3.1 Design and planning stages

At the early stages of the lifecycle, information requirements focus mostly on design details. These may be the most critical stages, as the earliest stages of the product lifecycle determine about 70% of the overall product costs [8-10]. This cost translates into a significant resource commitment in early design, and therefore plays an integral part in determining the sustainability impact of a product. It is important to make as much sustainability-related information as possible available during the early stages of a product's development.

Material information at the earliest stages of the product lifecycle traditionally focuses on metrics needed to meet performance, quality, and cost requirements. The information is often used to make predictions such as how a product will perform under specific loading conditions, how durable a product is under cyclic conditions, or cost implications. The information necessary to predict such implications varies greatly depending on the nature of the product.

Material representation at the design stage varies in detail depending on the application. Work at the National Institute of Standards and Technology (NIST) on the Core Product Model (CPM) [11] and later the Semantic Product Meta Model (SPMM) [12] focused on developing core representations of product information, providing placeholders for material without defining many specifics.

Standards such as ISO 10303 (commonly known as STEP)[13] and ISO 13584[14] have been developed to support product requirements, but also offer additional material detail. Part 45 of STEP contains generic structures for material information. These structures are specialized for different purposes in the Application Protocols (AP) of this standard. For example, AP 235, the application protocol for "Materials information for the design and verification of products," is specially developed for modeling information related to the mechanical design of products.

Aside from component design, in product development processes the supply chain can also complicate material information management. Supply chain considerations require accessing information from different viewpoints. In addition, companies with similar viewpoints may still use different standard representations. Standards used in the supply chain will be discussed further in Section 3.3.

3.2 Manufacturing stages and systems

Manufacturing stage standards focus on the processing and production aspect of products. Material information may include details on process materials, (i.e., coolant or lubricant), tooling materials, or the raw material being processed (i.e., material inventory or material storage requirements). In general, the material information represented at these stages supports the manufacturing of a product within a system.

The standards used during manufacturing may depend on the type of manufacturing (discrete, batch, continuous). For instance, ISA88 [15] is a standard for batch control that is applied to production processes. ISA88 has been adopted mainly by manufacturing companies and focuses on batch manufacturing, while also addressing some supply chain of products/processes.

Other standards, such as ISA95 [16] or IEC 62264 [17], integrate production processes with the supply chain at the enterprise level. For instance, ISA88 and ISA95 complement each other as ISA88 focuses on automating the control of machines and devices while ISA95 (standard for integration of enterprise and control systems) meshes the information between manufacturing systems and resource planning.

Some standards used during the manufacturing stages are not specific to manufacturing, but to systems in general. Standards such as the Systems Modeling Language (SysML) [18] or Modelica [19] provide a means for connecting enterprise, process, and product points of view. For instance, SysML supports the specification, analysis, design, verification and validation of a broad range of systems and systems-of-systems - including hardware, software, information, processes, personnel, and facilities.

As mentioned, it is important to make as much information as possible available during the earlier stages of product development. Information from manufacturing stages is important to understand how the processing and assembly of different components will affect a product's sustainability impact. This information can also be used to assess the material and energy efficiency of processes used in product creation.

3.3 Use to end-of-life stages

The later stages of the lifecycle often fall under the enterprise perspective. From the enterprise perspective, stakeholders are concerned with operations information. These stages will focus on information related to business decisions, such as logistics (including supply chain), product life span, product support, and product disposal. Information standards such as the Supply Chain Operations Reference (SCOR) model [20] or the Business Process Model and Notation (BPMN) [21] are often employed in these stages. For instance, SCOR helps companies to examine supply chain configuration and processes. It is used to identify, define, and measure metrics across the entire supply chain.

In regards to the type of material information found in enterprise representations, the material information may include details such as quantity and cost of materials. Details specific to the end-of-life product representations may include metrics such as recyclability or amount of material recoverable. End-of-life material information plays an important role when determining the sustainability impact of a product.

3.4 PLM standards and synthesis approach

Until now, we have discussed how standards may be used to represent material information at different stages of the product lifecycle. Now we will look at how product information standards have been used in broader lifecycle applications.

In the past decade, the Department of Defense has extensively investigated lifecycle interoperability through different product representations [6] [22] [23]. One such effort came in the development of GEIA-927[22]. Primarily based on ISO/TS 18876[24] and ISO 15926-2[25], GEIA-927 also builds on and integrates several existing standards for product information. A similar effort, the Adaptive Modeling Language [23], provides the ability to integrate and automate product configuration, visualization, design, analysis, manufacturing, production planning, inspection and cost estimation through standards. These efforts demonstrate the synthesis of different standards across the lifecycle, and the opportunities such a synthesis can provide.

The approach discussed in this paper is very similar to the integration approach used in the development of GEIA-927, where instead of replacing information models we explore their synthesis to "facilitate the exchange of data concepts…by harmonizing disparate standards into a single object model [26]." Here we place a focus on *material* synthesis, and the impacts this synthesis may have on making more sustainable decisions.

Towards this end, we discuss some of the challenges faced when synthesizing diverse material information and then discuss how some of these challenges may be overcome. A material model can be developed to synthesize material information regardless of lifecycle stage, stakeholder, or representation.

4 TOWARDS SYNTHESIS OF MATERIAL INFORMATION

Synthesis of material information across the lifecycle requires the development of an information structure that is able to meet representation challenges at each stage while ensuring that the integrity of the material information is preserved across stages. We will call this information structure a "material information model." The challenges encountered in creating the material information model come in two varieties: the challenges of conceptual integration of material information and the challenges of integrating different representational formats.

4.1 Challenges of materials information synthesis

The need to address requirements of multiple stakeholders is the root of many synthesis challenges. Each stakeholder in different product lifecycle stages has different views for material information; however, this does not mean the associated information is independent. The material representations in the proposed material model need to capture the core properties of material usage in product development, and make this information accessible at different lifecycle stages. Often times, such as when addressing the supply chain, changes to material information at one lifecycle stage will propagate to other stages. This means that not only should the material information model be able to provide stakeholder-specific information at different stages of the lifecycle, it should also provide traceability across the lifecycle. These two requirements create many information representation and management challenges.

The material information model needs explicit relationships between product requirements, functions, behaviors, geometry, tolerance, and manufacturing process information so as to provide engineers with enough information to select the best material for their product design and manufacturing. Three types of concerns that such a material information model must address are [27]:

1. Capturing relationships between items of data from divergent perspectives
2. Addressing challenges in measurement and detail
3. Supporting the consistent and correct exchange of material information across systems

A material information model must have the ability to represent a wide range of material properties across a wide variety of materials. As new types of engineering materials are constantly being developed, material information must be treated as an open-world problem. The material information model must be able to support the inclusion of new types of materials and new material properties. The material information model must be able to capture variability in property types in a concise and reusable way. For instance, some material properties may be variables, depending on factors such as ambient temperature or pressure.

Because material information is used across a wide range of domains, our material model must support wide ranges of detail and granularity. Material information may exist as generic concepts at the bulk level such as density, or very detailed properties at the micro-structure level. In general, it is impractical for a single system to be able to handle properties at such a wide range of abstraction levels. However, for our use of material information, it is important to properly separate these concerns, and maintain traceability across these degrees of detail. It must be possible to generalize or specialize the material information model as necessary.

Finally, the material information model must address a variety of data interchange issues between different representations. The model should support data presentation and interchange schemes that make it easy for human readability and machine processing.

4.2 Challenges of representation formats

In standards used throughout the product lifecycle, material information exists in many different languages and formats, both across the lifecycle and between stakeholders. Various information representation formats may be applied to represent material information, and each has its own advantages and disadvantages. While each format is often very specific, most can be grouped, each group with its own pros and cons. Here, we review some of the most common formats used in product lifecycle and material information, and some of the challenges they may present when pursuing material synthesis.

Tabular representation systems, such as relational databases, are relatively easy to design, fairly customizable, and are well supported by a wide range of tools. However, these systems are not very powerful in conceptual modeling, and offer limited support for expressing associativity of concepts[28]. They cannot support a complex and associative material information model, one that can represent the same information at multiple levels of detail.

Markup languages, such as the Extensible Markup Language (XML), allow the identification of concepts and properties, and support a tree like organization scheme. While XML supports the representation of properties, it does not enforce constraints on relationships or provide enough semantics to directly support any form of verification.

Object-oriented modeling paradigms, such as the Unified Modeling Language (UML) and SysML, are excellent for conceptual modeling when the concepts are fairly well understood high level concepts. However, they face problems of scalability and expressivity when encountered with very detailed information[29].

An increasingly popular type of format, known as ontologies, has emerged as a means for information representation, a format with the ability to represent relationships and constraints based on formal semantics. Several ontology-based languages have emerged in the past decade, the most popular of which is the Web Ontology Language (OWL). OWL is a representation language for ontologies and offers many of the same advantages of XML while also providing further capabilities. OWL supports the organization of concepts and relationships that allows for easy expandability, and also supports verification through inferencing. Information from different sources may be synthesized in an OWL ontology by using various mechanisms, such as assertions or equivalencies. In the following subsections, we describe an initial effort on synthesizing material information across product representations using an OWL ontology.

4.3 Synthesis through OWL

The previous section discussed various obstacles faced in the development of our material information model. These obstacles can be overcome with the development of a material information model that meets two primary needs: the necessity to be able to synthesize many types of information at many levels of detail, and the necessity to be able to integrate languages possessing different representation formats. With these needs as our main drivers, our initial efforts have focused on ontologies and the role they can play in material synthesis.

Other researchers have recognized the same benefits and opportunities offered by ontologies, and as a result various efforts have led to different standards being translated into OWL. Several of these works were selected to demonstrate the synthesis of material information between lifecycle representations.

Proof-of-Concept OWL Synthesis

To demonstrate the synthesis of material information we obtained OWL representations of the following formats: SPMM [12], ISO15926[30], ISA95[31], and SCOR[32]. These four were selected as they covered most lifecycle stages, as well as many of the stakeholder viewpoints described. With a focus on materials, a new ontology was created.

The information related to materials was mapped between ontologies (See Figure 3). The level of abstraction of material differed significantly between these standards, creating challenges when synthesizing the information. Although the “path” to a material definition differed greatly depending on the standard, common groupings were created and the information was synthesized through the OWL ontology.

Figure 3 is a very basic example, which demonstrates how differences in granularity and usage of material information can be overcome in the development of a single representation. By adding additional structure to the ontology in Figure 3, a more direct synthesis could have been achieved. The next two sections will discuss how OWL was used to overcome the two main challenges highlighted in Section 4.1 and 4.2.

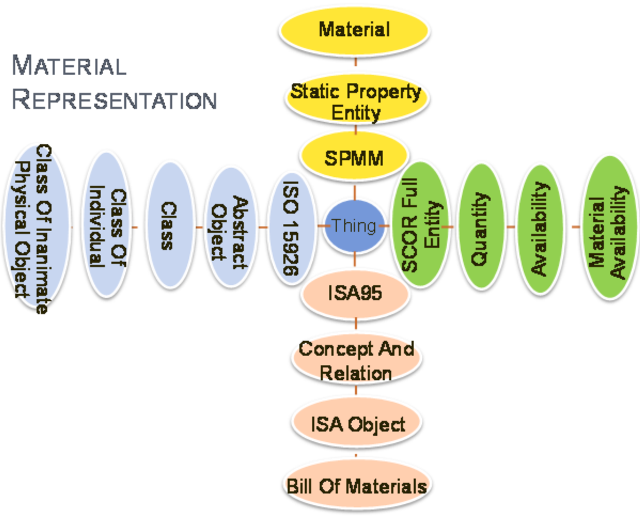

Figure 3: Concept of synthesizing material information.

Addressing Material Complexities

The abilities of OWL to group similar classes and to specify equivalence were key in this proof-of-concept. The hierarchical nature of ontologies provides an intuitive way to address the material information complexities. Specializations can be used to address not only material information at different levels of abstraction (i.e., quantity vs. mass), but also at different levels of granularity (i.e., additional information at same level of abstraction). New classes can be continuously added to specialize existing ones, providing a grouping mechanism for associating similar classes as well as equivalent classes with added detail and closer associations. OWL semantics also allow for classes to be declared "equivalent," essentially creating a single concept from two and simplifying material traceability. Through inferencing, OWL also allows for the automatic association of information based on defined semantics [33].

Addressing Representation Format Challenges

The variety of expressiveness offered by different representation formats often make it difficult to maintain the integrity of mapped information. When synthesizing information, OWL can be used to address the challenges presented by representation formats in much the same way it did with material complexities. While some formats can be translated directly into OWL, such as XML, others can usually be translated with minimal guidance and support. The grouping and equivalence mechanisms discussed earlier are also supportive of representational challenges.

Because of the appeal of OWL's capabilities, many of the challenges faced in the synthesis of these standards have already been addressed by various research communities, including translating many of the standards discussed in Section 3 into OWL as well as the standards identified in this section. Further work involving the continued development of our proof-of-concept synthesis will be discussed in Section 6.

5 SUSTAINABLE DECISION MAKING THROUGH MATERIALS

This section discusses how improved access to materials and material properties can lead to better decisions regarding sustainability impact. Table 1 lists some of the notable benefits achievable with a completed material information model. This section will discuss several of these benefits in further detail.

Table 1: Role of Material Information Model.

Material information use-case	Material information requirements
Allow material selection based on customer performance requirements (Indexing)	Different abstraction levels, property representations
Bring Gate-to-Gate process information (relative to material and energy efficiency) into design	Integrated process and product metrics
Account for effect of material/process choice through product lifespan (durability, aesthetics)	Associate product and process information
Allow material selection based on recycling/remanufacturing ratio	Sustainability information of materials
Provide material metrics to processes in Gate-to-Gate operations to predict efficiency	Material test data information
Account for material information in different phases (material phase change) during manufacturing processes to predict efficiency	Material information in different phases
Provide material sample information after processing (outputs of processes)	Material output information
Provide supply chain traceability for sustainability metrics	Material synthesis and verification

Manufacturing process parameters influence productivity and efficiency of manufacturing process. In addition to a material's physical properties, other factors such as material availability, price, delivery time, lot size, geometry, and quality test information are necessary inputs for manufacturing processes. The material information model can play a significant role in determining parameters for sustainable manufacturing process planning. A successful material information model will not only be able to provide this information as input to applicable stages, but also pull from and incorporate available information from other stages. By further incorporating indexing mechanisms into the material model, insight can be provided into the potential impact of changes in the magnitudes of values at different lifecycle stages.

A successful material model will not only provide information for assessing sustainability, but also simplify the information management aspects of material information. A successful material information model will support multiple representations of a single material property. As noted earlier, different stakeholders may refer to the same material property in different ways. For example, in one stage, a property may be represented per unit, while in another stage it may be represented for a bulk or composite material. One stakeholder may represent a varying material property as an equation, while another stakeholder may represent the same property as a table. Another example is when a property such as "work" is measured in Joules at one case, and "man-hours" in another. The material information model will have the ability to represent different levels of granularity of material information. By supporting varied representations of essentially the same concept, the material mode can facilitate the integration of processes from varied domains.

Another area where the material model can improve sustainability assessments is through better material tracking in product development, including the supply chain. The transparency of material information across the supply chain can be enhanced by synthesizing standards and representations that are implemented at different stages of the product lifecycle. On the macro scale, material tracking can be used to calculate how much and what types of material are being used, thereby facilitating planning for reductions and substitutions. The tracking of what materials are used, where and when, also supports the implementation of efficient recycling and reclamation programs.

Finally, the material model will provide the ability to map between material information in design and material sample information in manufacturing process planning. Material selection in the design stage should propagate through complex relationships in order to predict impacts on 1) product performance, 2) product life-span, 3) manufacturing process efficiency, 4) development cost, and 5) environments. A well-developed material information model should enable engineers to select materials in the design stage by considering their impacts in later stages. This is essential for ensuring that the sustainability-related design decisions are followed through into production, allowing fine-grained control over parameters to achieve improved sustainability. To successfully address some of challenges presented by product and process integration, more detailed and specific material information representations must be incorporated. This will be discussed in future work.

6 DISCUSSION AND FUTURE WORK

In this paper we discussed the potential impact of improved material management in sustainability assessments. We reviewed common information representations used throughout a product's lifecycle and demonstrated the synthesis of their material-related information. Each representation offers a unique perspective on material information, and a synthesized model from these representations can offer many advantages. However, when fine-grained control is needed, more material-centric information representations must be considered. Future work will look into how more material-centric information representations, such as MatML [34], can be leveraged to address specific material information needs.

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