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TOWARDS THE SYNTHESIS OF PRODUCT KNOWLEDGE ACROSS THE LIFECYCLE

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ABSTRACT

Product lifecycle management is an important aspect of today's industry, as it serves to facilitate information exchange and management between most, if not all, stages of a product's existence. As exchanged product information is inevitably subjected to multiple transformations and derivations, information transparency between lifecycle stages can be difficult to achieve. Synthesizing representations of product information across the lifecycle, by creating a lifecycle-stage-independent platform, can provide transparent access to information for both upstream and downstream applications.

In this paper, we review previous and ongoing efforts using ontologies as a means to support information integration and interoperability throughout the lifecycle of a product. We propose that existing efforts can be leveraged to create an upper-tiered ontology for product information. The resulting ontology, a core model for product lifecycle information, would support the synthesis and exchange of product information across lifecycle stages, improving access to this information and facilitating lifecycle thinking.

We discuss the use of ontologies as a means to create and link paradigm-independent representations. We discuss the translations that product information may face when integrated through ontologies, and the extent to which the integrity of the information can be preserved across the lifecycle. We investigate the role of information quality in the exchange and evolution of product information across the lifecycle. Finally, we discuss the application of an upper-tiered ontology, particularly the advantages offered by increased transparency and interoperability, as a means to support lifecycle thinking for mitigating a product's sustainability impact.

LEVERAGING PRODUCT LIFECYCLE MANAGEMENT

The product lifecycle connects distinct stages of a product's existence across a lifespan. Common expressions used to refer to the span of the product lifecycle are "cradle to grave" and "cradle to cradle." Each of these refers to the lifespan of a product beginning at conception and finishing at "end of life," where end of life may be disposal or renewal, through means such as recycling or remanufacturing.

Traditionally, lifecycle management techniques have allowed companies to reduce costs by organizing and dissipating product-specific information at different stages of a lifecycle [1]. Lifecycle management began with a focus on data, in the form of Product Data Management, or PDM systems. The idea of data management has long since extended into knowledge management. As noted in [2], "Unlike PDM systems which focus on managing data, Product Lifecycle Management (PLM), at its core, is a process which supports capture, organization and reuse of knowledge throughout the product lifecycle." PLM is influenced by knowledge from various stakeholders, helping manufacturers to manage "stages of existence" as a product progresses through its lifecycle [3]. PLM "seeks to fill the gap between enterprise business processes and product development processes [2]."

In today's industry, advances in information management systems such as PLM have allowed manufacturers to better communicate with their supply chain, within their own companies, and across lifecycle stages. The capacity to which information can be managed across lifecycle stages is influenced by the accessibility of product information at each stage. As information becomes more accessible, the ability to manage information across the lifecycle increases. Significant factors that influence the accessibility of information across the lifecycle include how information is structured and represented..

Given the importance of information and information exchange during the lifetime of a product, information requirements cannot be satisfied by a single standardized representation. The methods used to capture and communicate information vary between the stages of a product's lifecycle. Information representations are often tailored to the information needs of a specific lifecycle stage or stakeholder. For instance, information representations may vary based on the application objective, the standard adopted, the model employed, or any custom stakeholder requirements. The many information representations employed across a lifecycle can make the synthesis of information, and as a result information transparency, difficult to attain.

TOWARDS INFORMATION TRANSPARENCY

Information transparency refers to a mechanism by which the uncertainties in information are managed to better coordinate external and reverse flows [4, 5]. In other words, it addresses our ability to obtain a value and the certainty at which the value can be obtained. Information transparency between lifecycle stages can be difficult to achieve, as product information is inevitably subjected to multiple transformations and derivations. We envision transparency can be attained through a holistic understanding of product lifecycle information exchange: what information is being recorded; when information is being recorded (lifecycle stage); where, if any, information exchange occurs between lifecycle stages; why (for what purpose) is the information being exchanged; and how (what, if any, is the transformation) the information is exchanged.

As noted, product information comes in very diverse forms. Earlier work at the National Institute of Standards and Technology (NIST) reviewed the coverage of various information standards across the product lifecycle and from multiple viewpoints (Product, Process, and Enterprise)[6]. The motivation behind this work was to understand what methods/languages were available to represent product information at different lifecycle stages, and what, if any, synthesis was possible. While the work discussed in [6] focused primarily on coverage, later works further addressed the need for interoperability between these standards. In [7], Fiorentini et al. discussed the advantages of representing product information using ontologies. In [8], Fiorentini et al. discussed the use of ontologies as a means for harmonizing information between standards.

Related research has noted that semantics, coupled with open standard representations, are essential to the future of product knowledge management. In [9], Fenves et al. discuss the evolution of product data exchange, identifying many of the demands associated with the exchange of data between systems. They note that "consensus-based open standards will form the basis for the future global information exchange in a seamless manner and that they will need work towards developing semantics-based approaches."

As a step towards information transparency, we begin by reviewing ontological representations of commonly employed information modeling paradigms used throughout a product's lifecycle. We envision a framework that synthesizes these paradigm-independent representations of product information into a unified model, and that such a model can lead to newfound transparency of the exchange of product information between lifecycle stages.

LITERATURE REVIEW: ONTOLOGY TRANSLATIONS OF PRODUCT INFORMATION REPRESENTATIONS

Traceability of product information through the lifecycle requires the identification of key product information artifacts, and an understanding of how information is exchanged through different stages of the lifecycle. Towards traceability, and our goal of lifecycle synthesis through standards, we turn to ontologies and the use of the Semantic Web. Ontologies, as a means of providing an explicit specification of a conceptualization [10], have been the focus of many efforts for providing a neutral platform for the exchange of product data.

In [11], Rachuri et al. explored the use of information modeling techniques to facilitate information interoperability between different stages of the product lifecycle. In [8], this work was revisited in the context of ontologies, specifically OWL (Web Ontology Language). The authors concluded that OWL sufficiently supports the practical requirements of PLM applications. This position was supported in [12], where the extent to which OWL supports product information was investigated. Works such as these have supported the growth and adoption of OWL as a means for information exchange at and between different stages of the product lifecycle.

This section discusses numerous previous and ongoing works that have sought to use ontologies for product information representation. Many of these works are based on existing standards. Others are based on product information models or PLM systems. Others are original ontologies that leverage key concepts from various sources. Here, we review existing works before proposing that an aggregation of the key concepts in these standard-based ontologies can be used to harmonize information flow across the product lifecycle.

Leveraging Existing Standards

Initiatives to translate existing standards into ontologies have come in two forms. Some have taken the approach of creating full representations of existing standards in an ontological language. Others have created the profiles needed to translate information from the standard to an ontological representation. Each of the standards in Figure 1 has been translated into, or previously existed in, the Semantic Web's OWL.

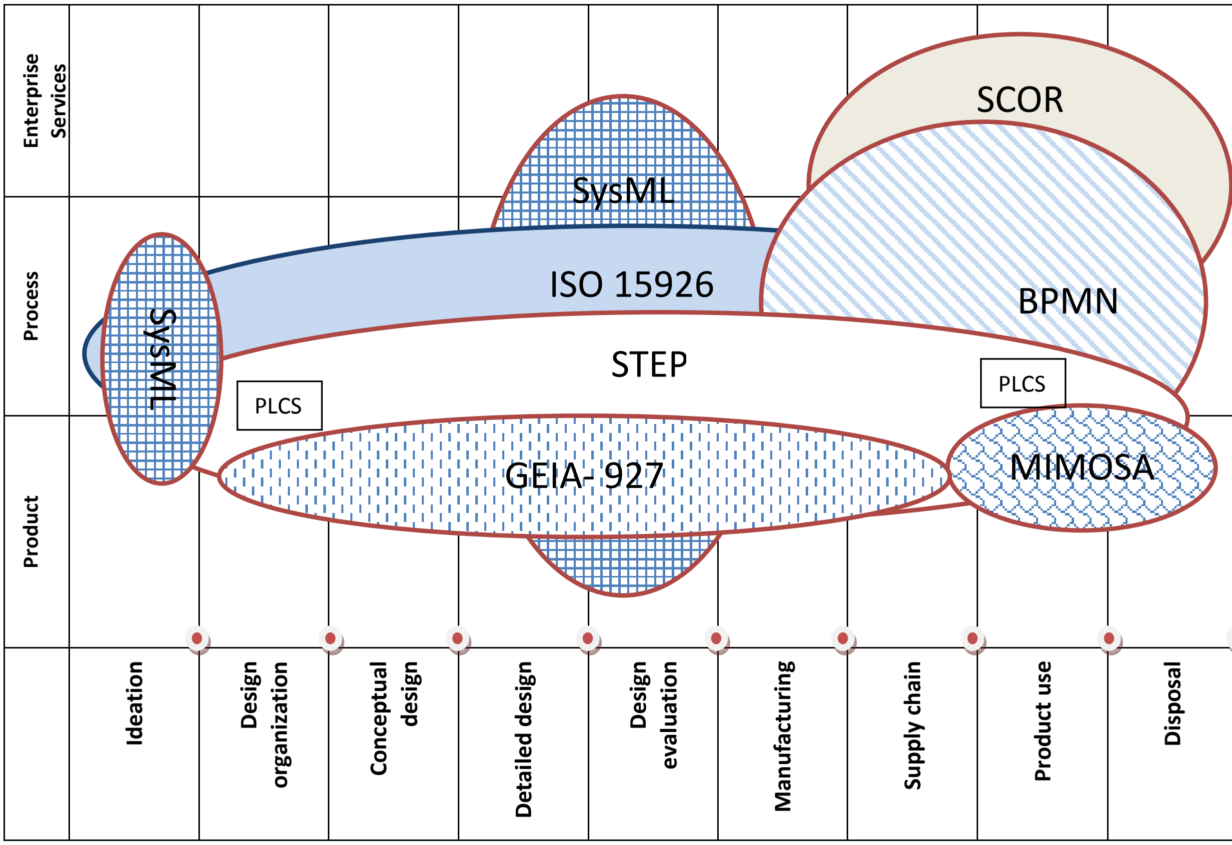

Figure 1. Standard coverage with ontology representations across the lifecycle. Overlapping standards (hidden layers) continue on defined path.

McKenzie et al. [13] recognized the need to share information between software systems for successful information management across the product lifecycle. As an alternative to custom interfaces, they proposed the use of standard file format-based ontologies to exchange data across the lifecycle. Their research resulted in a repeatable methodology for creating an ontology from a native CAD file, by way of ISO 10303, informally known as the Standard for the Exchange of Product model data (STEP), with currently available software. A complex product model is created in 3D CAD software and exported using the STEPstandard. They contend that ontologies allow for machine reading and automatic translation of information. As such, an open source file converter is used to translate a STEP file from EXPRESS (which STEP is encoded in) to XML. The XML file is then converted to the OWL file format by way of an ontology editor, providing an OWL representation of a STEP model (coverage in Figure 1).

Similar work by Barbau et al. also sought to create OWL translations of STEP by means of the tool OntoSTEP [14]. They acknowledge differences between modeling languages at different lifecycle stages and maintain that, to build a coherent knowledge base, it is necessary to consolidate product information encoded in different languages. Unlike the approach used by McKenzie et al., the OntoSTEP approach directly translates the STEP schema and its instances to OWL. The OntoSTEP translation can then be integrated with any OWL ontologies. They noted that semantic models offer additional benefits such as reasoning, inference procedures, and queries on enriched legacy CAD models.

Graves has explored integrating SysML with OWL2 [15]. Graves argues that suitably restricted SysML block diagrams can be translated into OWL2 and maintain the ability to represent the detailed information necessary to model a system design. His work aims at a partial unification of SysML and OWL that is sufficient for modeling the structure of complex systems (coverage in Figure 1). Though not intended to be a direct translation from SysML to OWL, any unification requires similar information artifacts between the two languages to be identified and mapped.

European researchers have developed a BPMN (Business Process Model and Notation) ontology within OWL-DL (Description Logic) (coverage in Figure 1). BPMN provides the ability to represent the complex process semantics needed by technical users while maintaining relatively intuitive to business users [16]. Foundazione Bruno Kessler formalized the BPMN ontology in OWL-DL as a means for providing a terminological description of the language and enabling the representation of a BPMN process as a set of individuals and assertions [17]. Given its robust capabilities, BPMN is available to various stakeholders and multiple lifecycle stages.

There have been several research initiatives aimed at developing OWL ontologies from the SCOR (Supply Chain Operations Reference) model. The SCOR model provides a unique framework that links business processes, metrics, best practices and technology features into a unified structure to support communication amongst supply chain partners and to improve the effectiveness of supply chain management [18]. Supply chain information requirements inherently address multiple stages of product lifecycle management. Vegetti et al. [19], Lu et al. [20], Zdravkovic et al. [21], Sakka et al. [22], and others, have all worked in developing different ontological versions of the SCOR model (coverage in Figure 1). The result of their work has provided extended SCOR coverage into the later stages of the product lifecycle.

There has been some success in developing data exchange standards completely within OWL. ISO 15926 [6] is a standard for data modeling and interoperability support with a Semantic Web specification. ISO 15926 also provides an upper ontology and a reference data ontology [23]. It was originally developed for the Oil and Gas industry (originally as an extension of STEP efforts, ISO 10303-221), but is generic enough that it can be used for other types of product information exchange and integration. Unlike many of the other PLM standards discussed in this review, ISO 15926 (coverage in Figure 1) is specified in, not translated to, OWL. This coverage mirrors that of STEP.

Both GEIA-HB-927 [24] and MIMOSA OpenO&M [25] have readily available ontology-based specifications (coverage in Figure 1), simplifying the translation process. In fact, the development of GEIA-HB-927 (or GEIA 927) began with ISO 15926, as the basic building block on which data models from PAS20542 [26] replaced with ISO 10303-233:2012 , Systems engineering data representation)[27], ISO 10303-212 (electrotechnical design and automation) [28], and ISO10303-239 (Product Life Cycle Support, PLCS) were integrated [29]. The primary aim of GEIA 927 is to provide lifecycle coverage through a top-level integration model and unified schema that integrates the best available schemas for data representation of modern complex systems [30]. The work outlined in this paper in some sense very much echoes some of the goals put forth in GEIA 927, while also building on them.

As seen in Figure 1, OWL translations of existing standards provide coverage to a significant portion of the product lifecycle, and across multiple viewpoints. The next section discusses specialized OWL representations, developed from information models or PLM system schemas. These representations both extend and complement the coverage shown in Figure 1.

Leveraging Product Models and PLM Systems

In addition to the standards discussed in the previous section, initiatives have been taken to represent product information using elements of the Semantic Web without directly translating an existing standard, but instead represent through product models or schemas.

Patil et al. [31] proposed the Product Semantic Representation Language, or PSRL, as a means of providing formal representation of product data semantics throughout the product's lifecycle. The language, based in OWL, uses the core product model (CPM) as a foundation, a product model that is now embedded in many product models and languages[32]. More recently, a similar, CPM-focused model, was developed at NIST, the Semantic Product Meta-Model.

The Semantic Product Meta-Model (SPMM) [33] provides a core product model to support different stakeholder viewpoints across the product lifecycle and enable multi-view engineering simulations. The multilevel product-modeling framework enables stakeholders to define product models and relate them to physical or simulated instances. Like PSRL, the meta-model is based on the earlier work with CPM and CPM2 [34]. There are also plans to extend this work with a semantic version of the Open Assembly Model (OAM) [35]. SPMM, like PSRL, provides additional granularity to its respective coverage area (coverage in Figure 2).

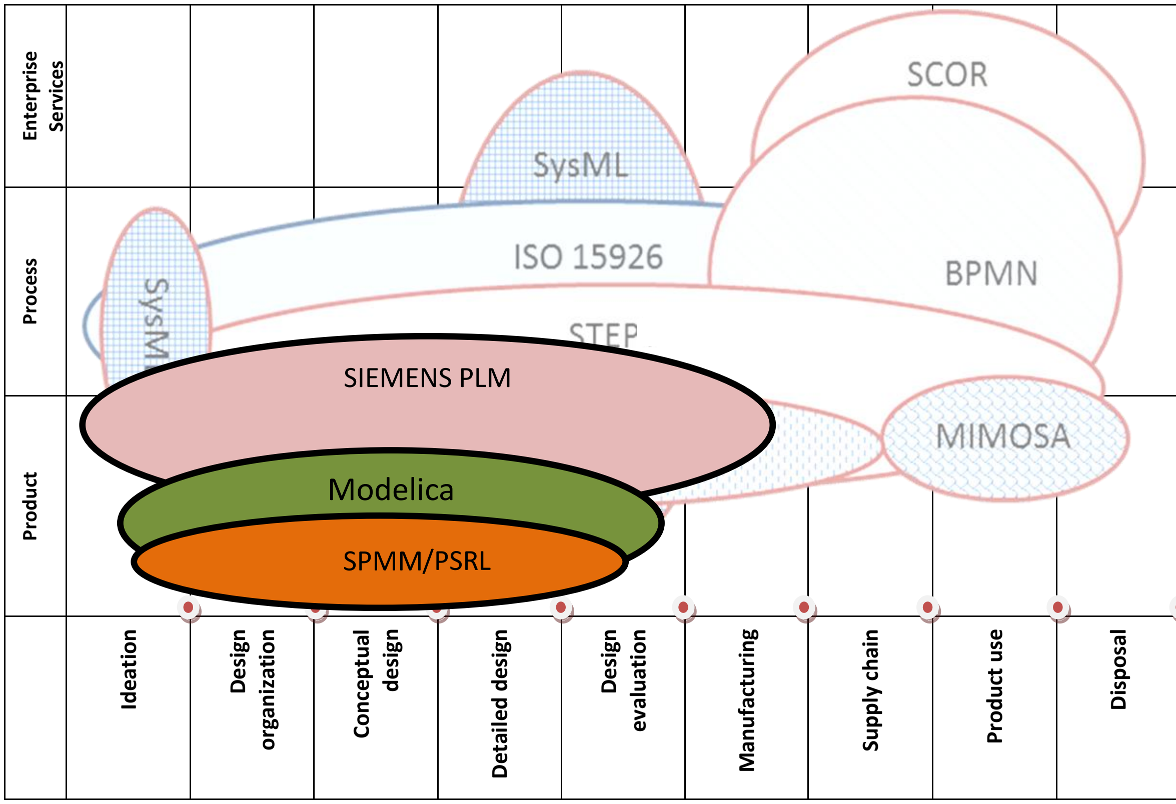

Figure 2. Extended Coverage through product models and PLM.

At Linkoping University, Pop et al. [36] have explored the use of OWL for representing the Modelica language. Modelica is an object-oriented, equation-based language for multi-domain modeling of large, complex, heterogeneous systems [37]. While the intent of Modelica is to facilitate communication between software platforms using multi-domain models, these platforms exist at various stages of a product lifecycle, mostly in the early phases. Therefore, Modelica can become a de facto model for representing product lifecycle information for users. More recent works have resulted in the development the Modelica MultiBody OWL ontology [38]. Similar to the CPM works, Modelica representations (coverage in Figure 2) offer coverage alternatives.

Though not built natively in an ontology language, the Siemens PLM XML schema [39] is an XML representation openly available for download. While the schema is not in OWL, the explicit XML tags provide a solid foundation for the future conversion. The open availability of the schema highlights the sense of awareness that steps need to be taken to make product lifecycle information more transparent.

As shown in Figure 2, the representations discussed in this section complement the coverage of Figure 1. They offer specializations and alternatives at different stages of the lifecycle.

Product Lifecycle Ontologies

The works discussed in this section have independently leveraged ontologies to develop product representations for various applications. Many of these works partially leverage various existing languages and models. These works again complement the works discussed in the previous two sections.

Kiritsis et al. [40] [41] have explored the Semantic Web as a means for "Closed-loop" PLM systems. The FP6 IP 507100 PROMISE project [42] addresses the development of smart or "intelligent" products using advanced sensors, processing, and reasoning. Their work leverages several product standards including those associated with ISO 10303-239, as well as MIMOSA and ISO 15926. They have identified key information concepts within these standards that they then use in the development of an ontology model for PLM. They have described their work as "the first efforts towards ontology-based semantic standards for product lifecycle management and associated knowledge management and sharing." Further work by the group [43] discusses the initial efforts and motives for converting existing PLM models into ontologies and OWL [44]. They developed an ontology model of the Product Data and Knowledge Management Semantic Object Model (SOM).

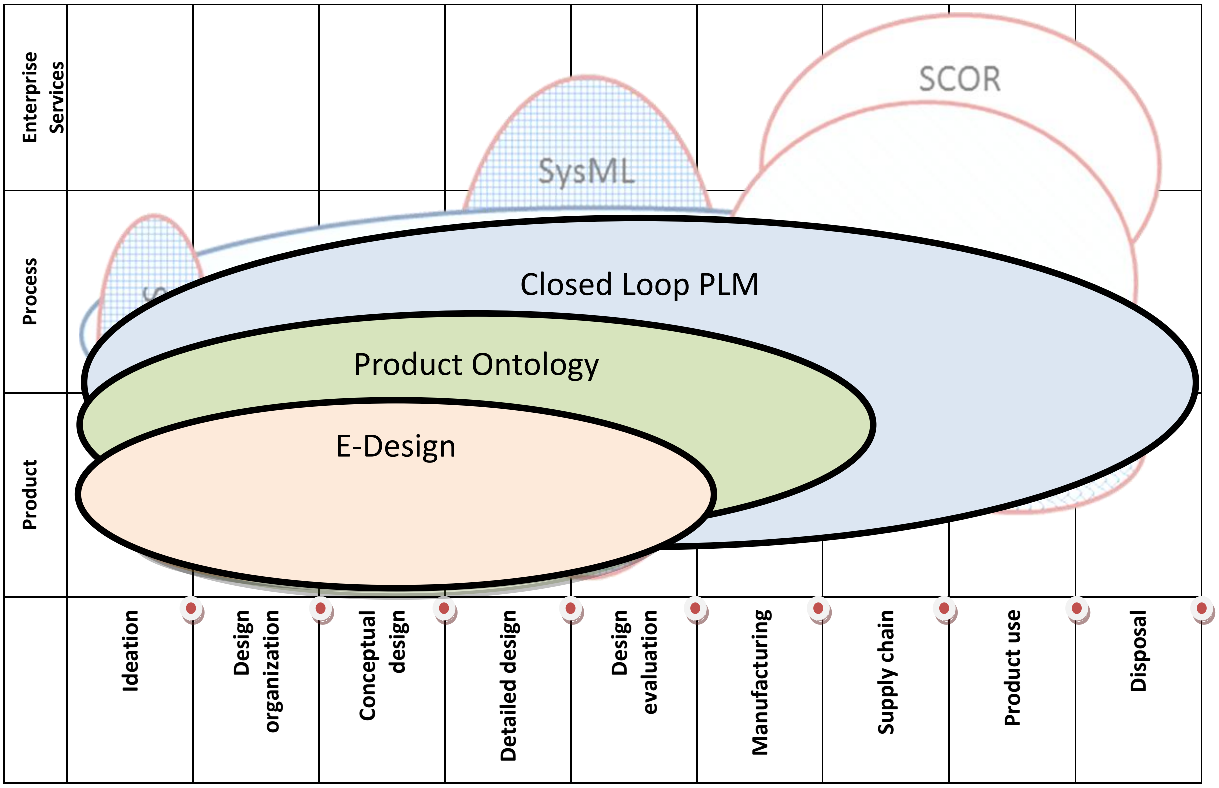

Figure 3. Enhanced Lifecycle coverage through independent efforts.

Researchers at CRAN (Centre de Recherche en Automatique de Nancy) [45] [46] have worked towards the development of the Product Ontology. While they do not attempt direct translations of existing standards, they advocate ontology techniques as a means for representing and preserving product information. They propose a product ontology as a "common model" for embedding and preserving essential product information along a lifecycle while minimizing the loss of semantics. Unlike the "top down" approach discussed in this paper, their "bottom up" approach identifies key information through available technical data. While this work does not live in OWL, its ontology foundations allow for relatively straightforward translations. This work leverages both ISO 10303 and IEC 62264 standards. The coverage map in Figure 3 shows how these efforts complement those discussed in the previous two sections.

A team from the National Science Foundation's (NSF) Center for e-Design at the University of Massachusetts has developed a comprehensive set of OWL ontologies that cover several stages of the product lifecycle. The E-Design Framework was developed to provide a conceptual framework for representing product knowledge, focusing mostly on early design stages [47]. The framework consists of multiple modular ontologies, including ontologies for conceptual design [48], design analysis[49], and design optimization [50]. While this work does not leverage existing standards, it does leverage various sources including publications and other software representations.

Lee et al. [51] proposed an ontology-based knowledge framework with three product knowledge types and four layers, or levels of abstraction. The three knowledge types are axioms, knowledge maps, and specialized knowledge for a domain. The four layers consist of a product context model, a product-specific model, a product-planning model, and a product-manufacturing model. They developed a system to help knowledge engineers create, edit, infer, and visualize product knowledge.

Each of the efforts discussed in this section replicate, to some extent, representations available through accepted standards and models. However, each effort offers its own unique approach. This uniqueness, though providing alternatives to information representation and exchange, can also complicate information synthesis.

TOWARDS A PRODUCT LIFECYCLE UPPER-TIERED ONTOLOGY

In [52], Mostefai et al. discuss ontologies as a means to integrate product information throughout the lifecycle. Their approach exploits the idea of "common knowledge concepts" shared across lifecycle stages. In their paper, they discussed the challenge of abstracting information with semantics across lifecycle stages. They find that, at the price of some comprehension, ontologies can be used to support common semantics shared by different lifecycle phases. The following sections discuss a similar approach, but one rooted in existing works, and elaborate on the need to preserve information quality when exchanging information across the lifecycle.

The concept behind an upper ontology is to provide a common understanding/ reference for distributed domains. The most well-known upper ontologies, such as CYC [53] and SUMO [54], are meant to serve as a means for developing large-scale ontologies through domain-specific ones. One of the main challenges faced by upper ontologies is the need for peer acceptance. They depend on others to both align with them and/or contribute to them to expand their domains, which, in general, have shown to create significant challenges. An upper-tiered ontology based on the works discussed above would streamline these challenges by developing on pre-existing product information paradigms and translations.

An upper-tiered ontology to support product lifecycle management would provide a common platform for mapping and integrating standard-based information models. In essence, it would provide a core model for facilitating information exchange and promoting transparency across a lifecycle. However, the applications of such an ontology are constrained by the amount and quality of the information they are able to support.

To address the quality of information, we now discuss the notion of information quality, or IQ [55-57]. To address IQ, here we will adopt the definition derived by Ying and Zhanming [55]. Table 1 shows the four classifications of information quality, and the related dimensions.

Table 1. IQ classification and dimensions from Ying and Zhanming [55].

Classification	Dimensions
Syntactic	Conformability
	Integrity
	Timeliness
Semantic	Complete
	Concise
	Accuracy
	Currency
Pragmatic	Applicability
	Clarity
	Value
	Interactivity
Physical	Accessibility
	Security
	Maintainability
	Speed

For the remainder of this section we will focus on IQ as it pertains to the Syntactic, Semantic, and Pragmatic classifications. We address some of the specific challenges related to attaining information transparency while preserving information quality. We discuss the importance of maintaining the quality of information through translations. We discuss how multiple translations may influence the extent to which transparency can be achieved.

Preserving Quality of Information

To preserve syntactics and pragmatics, the information exchange capabilities of any upper-tiered ontology must be focused, with strict boundaries defined. Core concepts should be identified based on the primary directives of each information paradigm, and the resulting overlapping concepts when different representations are integrated across the lifecycle. Because an upper-tiered ontology leverages information paradigms from all stages of the product lifecycle, these core concepts may not often directly translate in terms of level of detail, granularity of information, and intent. For instance, at the early stages a primary directive may be based on performance requirements, while later stages may focus on manufacturing or even shipping requirements.

Many of the information paradigms discussed were developed to represent information artifacts at a particular lifecycle stage, and not necessarily information from other lifecycle stages. As a result, issues may arise when accessing information using translated representations at different lifecycle stages. These issues may include the inability to represent the information as initially intended or even loss of information. Information must maintain some granularity across translations, so when necessary only the applicable information is accessed and pragmatics are preserved. This highlights the need for a very structured, adaptable language as an intermediate, and addresses why many have chosen to use ontologies, specifically the Semantic Web.

Ontology as an interlingua can facilitate information preservation well because semantics between overlapping and related concepts can be formally specified and therefore retained. Unlike interlingua developed using syntactical languages like XML Schemas, developers have the ability to choose to merge overlapping concepts into a single concept. This merging leaves some semantics ambiguity to ensure that the information is more mappable and better preserved between information translations (while sacrificing semantics).

Preserving Semantics

Different languages use their own syntax and semantics. By altering the semantics and syntax the information is represented in, the meaning may also be altered [58]. It is important to understand that the expressivity of a language can influence how information is represented and interpreted. Because of this, an important part of translating between languages is preserving semantics.

Because we are discussing the use of an interlingua between many different information paradigms across a product's lifecycle, preserving semantics is essential. However, it is also a significant challenge. Many of the languages discussed here are founded on different platforms, often impeding interoperability. Meaning is often lost in transformations between these languages, even without an intermediate language.

The preservation of semantics requires that certain information about source or target representations be captured and made accessible during the translation process. Translation mechanisms should be able to preserve knowledge such as information about naming, namespaces, structure, granularity (element vs. attribute), ordering, or even value representation. The expressiveness of the interlingua used in translation will directly affect how well semantics are preserved.

OWL is based on Description Logic (DL), which is a subset of First Order Logic (FOL). Many of the information paradigms discussed earlier, such as the EXPRESS modeling language, are more powerful than OWL in terms of expressiveness. However, OWL does have many advantages. It has a flexible data structure, as all information is broken down into triples representation. Its data types are based on the internationally accepted XML standard allowing it to carry information in multiple formats and locales. OWL operates under the open world assumption, which is useful when addressing potential unknowns during lifecycle integration. For instance, the open world allows conflicting, yet translatable, information to pass through OWL intermediary without creating conflicts. These abilities, and the expressiveness of DL, have shown to provide ample means for preserving semantics in translations. Ultimately, however, the preservation of semantics will depend heavily on the extent to which they were preserved during existing translations.

SUSTAINABILITY IMPLICATIONS

The previous section discussed the challenges of maintaining the quality of information as it passes through different representations across the lifecycle. The extent to which quality is preserved directly affects the applications in which any knowledge can be used. This section addresses the role of information transparency in the context of sustainability applications.

PLM systems are still in their infant stages as far as realizing potential sustainability evaluations they can provide [59]. Designing for sustainability means the entire product lifecycle should be taken into consideration. However, the heterogeneity of sustainability-related product information is a result of the fundamental differences between many of the stages, such as manufacturing, use, and disposal. In addition, sustainable implications may come from many directions, including product design, process design, or supply chain. To measure sustainability impact as a totality, the impacts resulting from each stage must be independently evaluated and subsequently made available for upstream decision-making. This requires information transparency and a meaningful formal representation of product data semantics throughout the product's lifecycle [31].

By leveraging existing ontological works, an upper tiered ontology can synthesize a general product structure for providing information traceability across a lifecycle. In the context of sustainability, material information becomes of particular interest [60]. We believe the synthesis of material information can facilitate the development of a material "meta-model," [61] in essence, a "model of material models." As the proposed upper ontology would comprise of multiple different modeling paradigms across the product lifecycle, by identifying only the properties associated with the transition of material information across the lifecycle, a meta-model can essentially be created for material information (Figure 4).

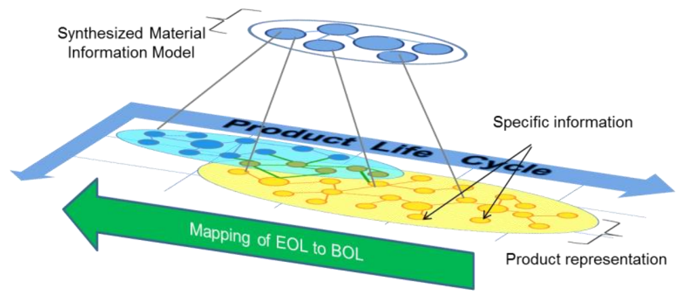

Figure 4. Synthesized material model.

A "material meta-model" could act as a guide for identifying how material information will be represented when exchanged through the product lifecycle. By referencing a "material meta-model" when entering material information at different stages of the product lifecycle, one could gain insight into information availability as it propagates through different lifecycle stages. Such insight during data entry could lead to more robust material information, and as a result improved decision making when considering sustainability.

In [57], Ameta et al. find that, in general, there is room to improve IQ for sustainability. However, they find that the IQ insufficiencies mostly relate to insufficient support for sustainability-specific metrics and uncertainty. As such, the IQ of our upper-tiered ontology approach parallels what is currently available for sustainability IQ across the lifecycle. The upper-tiered ontology approach, however, offers a unique advantage as it can be expanded as new standards are adopted and developed. Such an ontology can provide a foundation for extending lifecycle information with sustainability-specific information, such as that available in standards. This is shown by D'Alessio et al.[62] when mapping sustainability standards to product information, and again by Eddy et al.[63] as a means to incorporate sustainability information into early design time.

SUMMARY

Product lifecycle management is an important aspect of today's industry, as it serves to facilitate information exchange and management between most, if not all, stages of a product's existence. Synthesizing representations of product information across the lifecycle, by creating a lifecycle-stage independent platform, can provide transparent access to information for both upstream and downstream applications.

In this paper, we reviewed previous and ongoing efforts using ontologies as a means to support information integration and interoperability throughout the lifecycle of a product. We discuss the development of an upper-tiered ontology to further synthesize product information across the lifecycle. We discussed the extent to which the quality of the information should be preserved when translating information across the lifecycle. Finally, we discuss how our proposed approach could be leveraged in the development of a material meta-model to support lifecycle thinking in terms of sustainable impact.

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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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