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An Integrated Approach to Information Modeling for the Sustainable Design of Products

The design of more sustainable products can be best accomplished in a tradeoff-based design process that methodically handles conflicting objectives. Such conflicts are often seen between, environmental impact, cost, and product performance. To support such a process, this paper proposes the development of an environment where sustainability considerations are explicitly introduced early into the design process. This explicitness is provided by integrating the requirements information of sustainability standards and regulations directly into the design process. The emergence of the semantic web provides an interoperable environment in which the context and meaning of knowledge about the relationships among various domains can be shared. This work presents an ontological framework designed to represent both the objectives that pertain to sustainable design and the applicable sustainability standards and regulations. This integrated approach not only can ease the adoption of the standards and regulations during a design process but can also influence a design toward sustainability considerations. The usefulness of this model integration is demonstrated by an illustrative brake disk rotor and pads case study. The results show that both the standards and criteria may be considered at early design stages by using this methodology. Furthermore, it can be used to capture, reveal, and propagate the design intent transparently to all design participants. [DOI: 10.1115/1.4027375]

Keywords: sustainable product design, ontology, engineering design, LCA, sustainability standards

1 Introduction

Design considerations are most effective when brought into a design process as early as possible, when design flexibility is normally greater in that the impact of any design change is mitigated. In their review, Ramani et al. [1] assert that early design considerations are even more important with the emergence of sustainable design. Sustainable product design can significantly affect the environment, economy, and societal well-being in a number of positive ways. In spite of the need, integration of sustainability considerations has progressed slowly. An ASME survey [2] supports the notion that design engineers are motivated to comply with current sustainability standards. The survey finds strongest sustainability interest among engineers to reduce energy and emissions. The survey also shows that organizations are most interested in compliance with regulatory requirements, and are most likely to only consider green methods that are cost competitive.

To support these current thrusts, this paper proposes that sustainable design can be facilitated by introducing the guidelines provided by sustainability standards into early decision making criteria. The review by Ramani et al. [1] also identifies some challenges with the early design stage adoption of the needed sustainability considerations. Included among these considerations are support for decision making over an entire product lifecycle and modeling the information in an interoperable manner. To this end, this work explores the integration of guidelines for standards with the authors' earlier work in decision making for sustainability.

In recent work [3], the authors introduced a normative decision analysis method for the sustainability-based design of products (NASDOP). NASDOP deploys life cycle assessment (LCA) mathematical models with compatible life cycle costing (LCC) models to consider both environmental and economic objectives during the evaluation of design alternatives. This work builds upon the prior work [3] in an important way. It provides a framework in which information pertaining to any applicable standards and regulations (henceforth only referred to as standards) is revealed transparently. Consequently, this information may influence the decision making process by highlighting criteria and constraints for consideration while also informing the decision maker during the articulation of preferences among the criteria considered.

A design process for sustainability often requires a comprehensive and holistic consideration of several distinct knowledge domains. Such an approach, if seamless, should improve upon the efficiency and effectiveness of a traditional design process that

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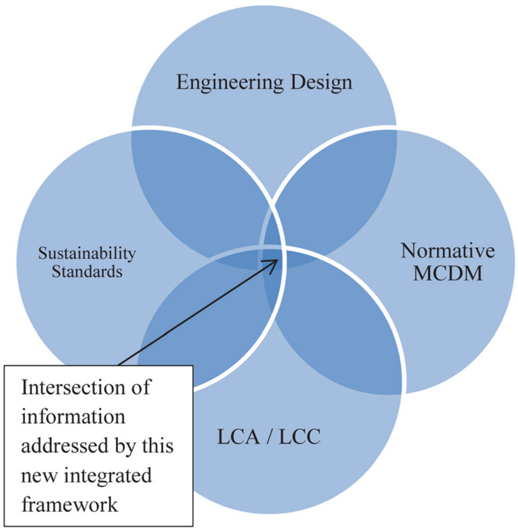


Fig. 1 Desired state of information models for a design

considers individual domains in a compartmentalized manner. However, integration of the major domains of a design process remains a topic of research. The work in this paper presents a novel approach to integrate the information models of four main domains to an extent not done in any known previous works. (Figure 1): engineering design, sustainability standards, normative multicriteria decision making, and LCA. The integration of all four of these domains will enable sharing of information in real time.

Section 3 details the key features of the new framework and its architecture. In Sec. 4, an illustrative case study is applied to demonstrate the framework's use in a design process. The final two sections discuss and summarize the results of this work. Section 2 summarizes prior works that have achieved some level of integration between two or more of the four domains of interest.

2 Related Works

First, this section looks at the relationship between LCA and other sustainability standards, indicators and metrics. An earlier approach established groups of key metrics represented within tools to serve as building blocks for the use of LCA [4], but it is not clear that the metrics used come from any established standards. More recently, a tool was developed to combine site dependent data from LCA with environmental performance indicators to support decisions by aggregating output data into a comprehensible index [5]. A study to support considerations within an enterprise examined the use of LCA data aggregated into a performance index with that of other indicators and metrics, such as those related to compliance or eco-efficiency measures [6]. One of the more comprehensive descriptions of all such information pertaining to the multiple product sectors, and the relationships among standards, indicators, metrics, tools, and criteria, such as LCA criteria, is available at the website of the National Center for Manufacturing Sciences (NCMS) for sustainability project initiative projects [7]. Therefore, this work uses the content of this work to create a categorized library represented by the related information model described in the following section.

Prior work related to the modeling of sustainability metrics, standards, and indicators within ontological frameworks is also of interest. Yang and Song [8] constructed an ontological framework to represent LCA and LCC parameter inputs to use with criteria defined by sustainability metrics for the potential evaluation of alternatives within a design process for sustainability. A National Institute of Standards and Technology (NIST) workshop with industry [9] proposed that further harmonization and consolidation is needed between regulations, standards, and metrics. In response, researchers from NIST proposed use of the Zachman framework [10] to organize information from sustainability standards to facilitate modeling of the content within semantic frameworks such as ontologies. Such a means to organize the information is helpful due to the large number of standards and metrics and the redundancies and gaps between them. Researchers at NIST built upon this work by introducing a method to reason upon such information within an ontology to determine where such gaps and overlaps in sustainability standards exist [11]. With this methodology, overlaps can be found where similar concepts appear in different standards, and gaps reflect divergence of the concepts in different standards. Here, ontological information models of different standards are mapped to each other. This mapping process involves setting classes and properties equivalent to others whenever possible. Such equivalencies are considered overlaps and the lack of equivalence was defined as a gap [11]. Reasoning may be done within the resulting ontology to determine which standards apply to specific products. Furthermore, an inconsistency of a specific product instance with a property value restriction imposed by the standards can indicate the lack of compliance of that product design.

Current literature [12–16] also emphasizes the importance of information modeling and its knowledge management pertaining to engineering design processes. The use of semantic web compatible ontologies has been shown to facilitate collaboration during distributed design and inform design decision making early in a design process, while also supporting interoperability of software tools deployed throughout the process. One such recent comprehensive review [12] highlighted the importance for the development of ontological frameworks to capture design related knowledge in a flexible and robust manner and to also capture design rationale to support decision making early in a design process.

From a perspective of a design process for products, an ontological framework was constructed at the University of Massachusetts at Amherst to facilitate the documentation of design rationale for distributed design throughout an entire traditional design process [15,17–19]. As a result, the information is dynamically linked between the domains that comprise a design process. The hyperlinks of these ontologies may be imported for public use from [20] into software such as Protégé [21]. Future developments are planned to improve upon the visual format for sharing information by use of software such as OntoWiki [22]. Additional modules in the framework support the modeling of information for decision making with a decision support ontology and with decision method ontologies [23,24], which represent various methods to evaluate design alternatives having various attribute values.

The decision support ontology and decision method ontologies are aligned with the principles of decision-based design, and as a result, can benefit a design process, especially when tradeoffs between conflicting objectives need to be considered for multicriteria decision making. Decision-based design is based on some fundamental principles as defined by Hazelrigg [25]. Normative methods based on utility theory, which evaluate alternatives based on the maximization of utility, were developed for applications that require a certain degree of mathematical rigor [26–29]. One such method is hypothetical equivalents and inequivalents method (HEIM) [28,30], in which the optimal set of weights among multiple criteria is calculated based on the strength of preference expressed by a decision maker during the ranking of hypothetical alternatives. The resulting set of weights is used to compute the multi-attribute utility (MAU) value of any design alternative.

The integration between the domains of normative multicriteria decision making and sustainable design has been limited despite the need. The often conflicting objectives of the triple bottom line for sustainability infer that multicriteria decision making methods are well suited to selecting optimal design solutions for sustainability. However, the introduction of usable normative methods to date has been limited. Thurston and her associates provided a constrained optimization methodology for sustainable product

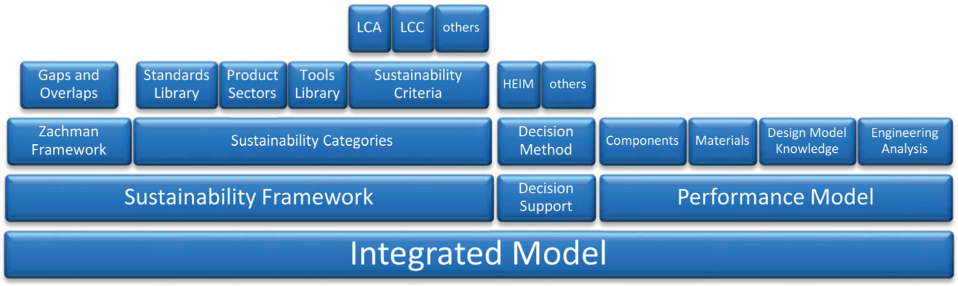


Fig. 2 Modular building blocks of the information model for sustainable product design

solutions [27,31]. More recently, HEIM was used to model the preferences of the decision maker in NASDOP [3]. Here, the uncertainties in the data from environmental emissions and costs were taken into account. For all of these reasons, the new ontological framework, introduced in this work, integrates the information used in this NASDOP methodology with this framework that includes the decision support ontology and a decision method ontology for HEIM.

The literature review, described in this section, alludes to the limited level of integration of information across domains in current design processes from the sustainability perspective. However, it can also be seen that these four main domains are all related to each other, and therefore, should not be modeled in isolation if the goal is to inform all participants in a design process. The work described in Sec. 3 provides such an integrated framework that dynamically links the information upon entry across these domains in a complete system.

3 Integrated Approach for the Sustainable Design of Products (IASDOP) Architecture Framework

Here, the IASDOP is described. Figure 2 illustrates the modular construction of the framework. The objects within these domains are dynamically linked appropriately by the relationships between them as shown and described in the following sections. The ontology file is available to import and use from its webpage [32]. The following sections highlight some of the key features obtained by this construction.

3.1 Standard Fit Within a Standards Library. Standard compliance has been identified as an important consideration in the design process for an enterprise [2]. The current process available to an enterprise to find a specific applicable requirement is inefficient at best due to the large number of standards and the corresponding missing and redundant information involved [9]. Selection of the appropriate standard depends greatly upon the product being designed. This suggests advantages with associations between standards and product sectors or the specific products within sectors. The sustainable standards guide [7] highlights the content pertaining to the top level standards, product sectors, and also, criteria that may be used to measure sustainability objectives.

Figure 3 shows the upper level taxonomy comprised of the sustainability categories and the relationships linking these main categories of standards, products, and criteria. Relationships are shown graphically as arc types in these figures from within Protégé. Included in this taxonomy is a categorized library of sustainability standards without exhaustive detail of the information in each standard, which would likely change over time and require updating. This way, the specific standards applicable to a given product may be instantiated anytime a design instance is developed. There is also always a possibility that a current or potential standard applicable to a certain product does not have a standard within the library. Such circumstances are attended to in Sec. 3.3.

3.2 Relationships to the Zachman Framework. Standards can be complex and it can often be cumbersome to find the information sought. Researchers at NIST proposed use of the Zachman framework [10] to break down the information in a standard into an organized structure. To facilitate creation of the standards information models, this work deploys the prescribed ontological structure of the Zachman framework into an ontological framework module. Figure 4 shows such relationships of the prescribed matrix within the ontological framework. The class "Cells" consists of thirty-six possible categories, each corresponding to one of six different rows and columns. The top level relationships are also shown in Fig. 4. Here, the top level row related to the context or objective scope of a standard is shown. Section 3.3 describes the key advantages that result from this ontological framework.

3.3 Revealing Gaps and Overlaps Between Standards. The ontological framework can be especially useful for establishing dynamic relationships between standards and products to which they apply. Researchers at NIST suggest use of the relationships on the top context level of the Zachman framework to identify such gaps and overlaps [11]. The method to detect and model gaps and overlaps within an ontology may be deployed when all pertinent information is modeled in the ontologies for the standards being compared. Such an approach may be practical when a defined and limited scope of standards apply to the design endeavors of an enterprise. Here, this work aims to provide a generic framework that could be used in any design process. Thus, a library and information models more limited in their depth and scope of represented knowledge is used.

There are two different ways that such a generic framework can be used during a design process with potential effectiveness. Information models can be created for any applicable standards using the previously prescribed methods [10,11]. Alternatively, information may be entered as it is sought during a design process. Thus, this framework supports introducing the guidelines and information provided by sustainability standards into a sustainable design process. This approach extends the definition of gaps introduced earlier [11] to include any requirement not yet specified in the existing standards library. Naturally, the depth of the standards' information models will determine the formalism and the extent of potential automation of these entries.

3.4 Revealing Constraints From Standards. From a design process perspective, an ultimate goal in modeling this knowledge which relates the standards and products is to define the applicable constraints for a given design situation. Survey information indicates that this is not usually a trivial task although rather important [2,9]. The diagram in Fig. 5 shows an example of how such relationships may be established within this framework. Here, the constraints imposed by the standards are revealed for a product. Furthermore, these constraints are revealed in the engineering model along with other physical constraints related to the design. Thus, information models from standards inform the design model of any compliance related requirements. The example in Fig. 5

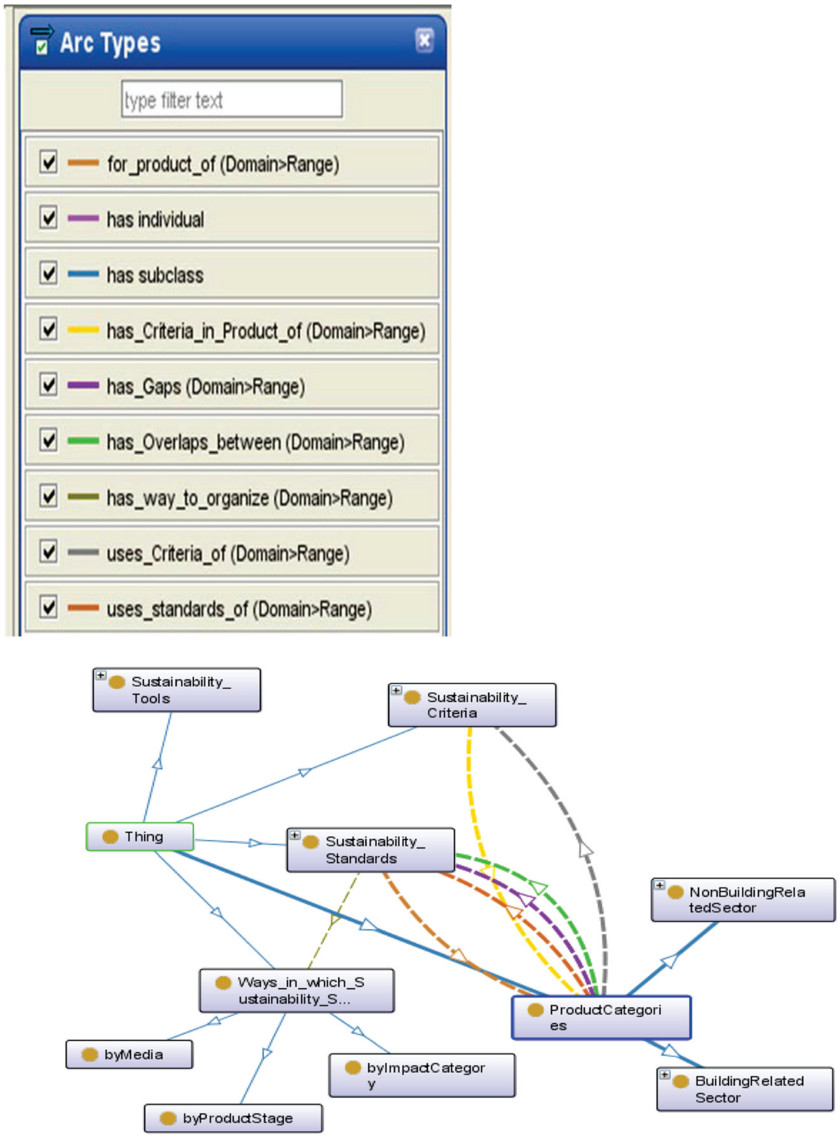


Fig. 3 Relationships in the sustainability categories ontology

depicts the case of a quantified regulatory limit. Depending upon the standard, some such constraints from standards may support mathematical modeling within constrained optimization programs, while others may be more qualitative and only applicable within information models.

3.5 The Integrated Framework. Other than the need to reveal the important constraints, a designer would also need to use this information within a decision model that reveals the rationale for selection of the most sustainable alternative. Here, other information models are integrated with those related to sustainability standards.

3.5.1 Three Information Models Combined. Figure 6 shows the class hierarchy of the taxonomy for sustainability criteria, which includes categories for LCA and LCC. Section 2 discussed some of the benefits of using multi-criteria decision making principles to design for sustainability. Efficiency and effectiveness of the early design stages should improve when all such criteria are considered together simultaneously in the same model rather than iteratively. To this end, ontological frameworks are integrated among sustainability, engineering design, and multi-criteria decision making (MCDM) domains.

Here, advantages are combined from an existing e-Design framework that captures and communicates information from a traditional design process [18], informs design model construction for decisions, and reveals decision rationale [23,24]. Such decisions should be made based on information pertaining to evaluation of the design option whose expectation has the highest value [25]. Such information can be defined concisely within the decision support ontology combined with a given situation's most suitable decision method ontology. Here, a decision method ontology is introduced to represent the methodology for modeling the preferences among different criteria by using HEIM. HEIM has been implemented effectively in a sustainable design situation [3]. Furthermore, the units ontology from NASA [33] is integrated within this framework to verify that consistent units are used appropriately. Figure 7 shows the mapping relationships between a design alternative instantiated in the decision support ontology and the information in the new LCA ontology. The "has_working_solution" relationship in the decision support ontology allows for the input of the information models of all criteria.

3.5.2 Products, Standards, and Criteria Relationships. Since each design situation will apply to a specific product, a design

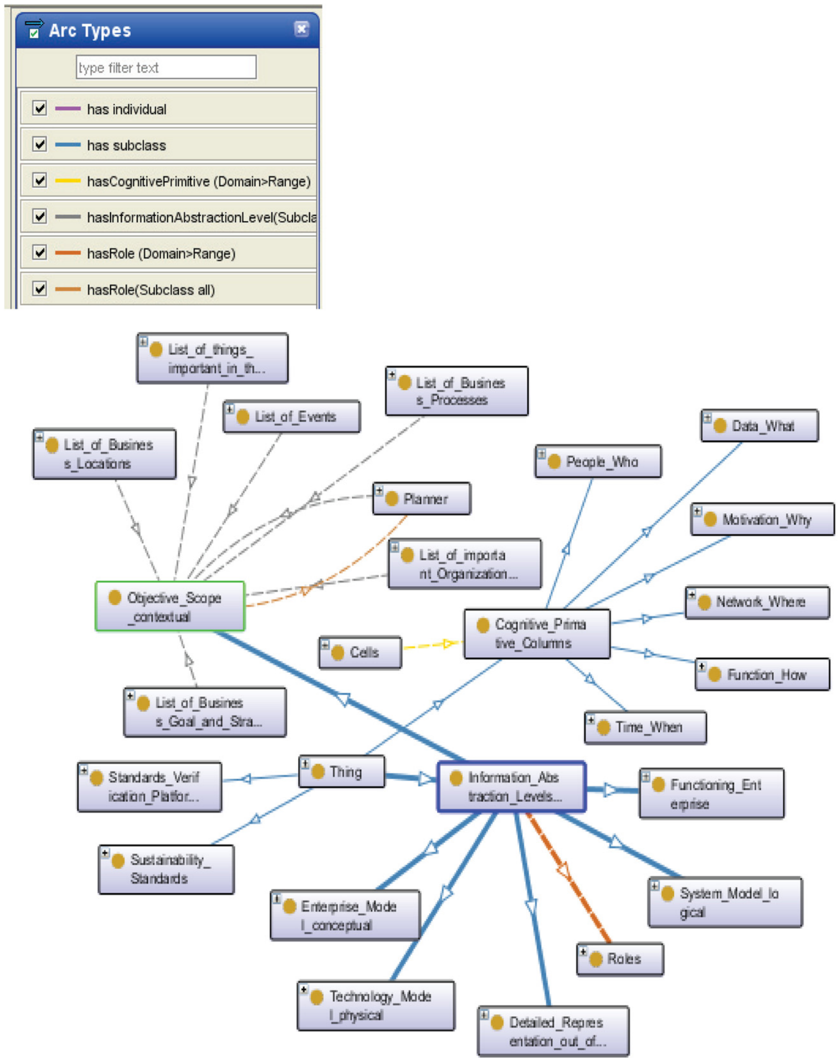


Fig. 4 Relationships of the Zachman framework deployed

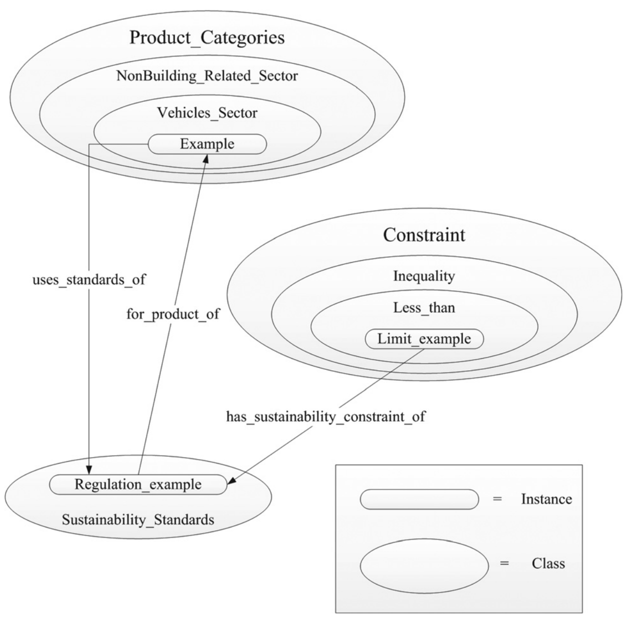


Fig. 5 Relationships to constraints in a design process

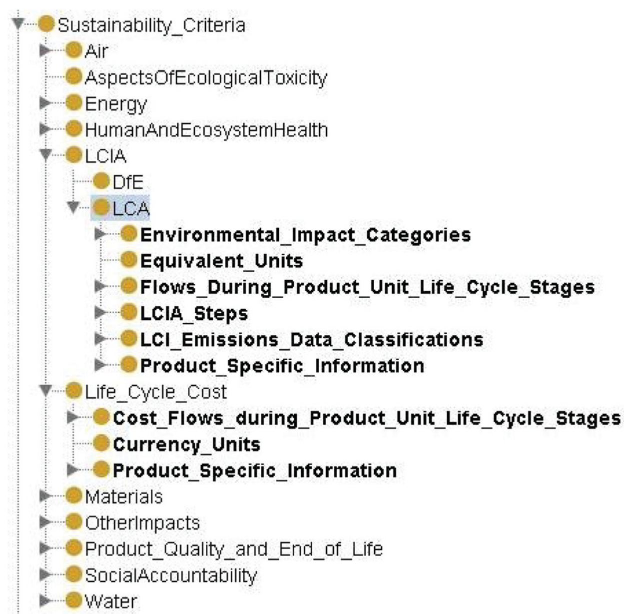


Fig. 6 Criteria including LCA and LCC

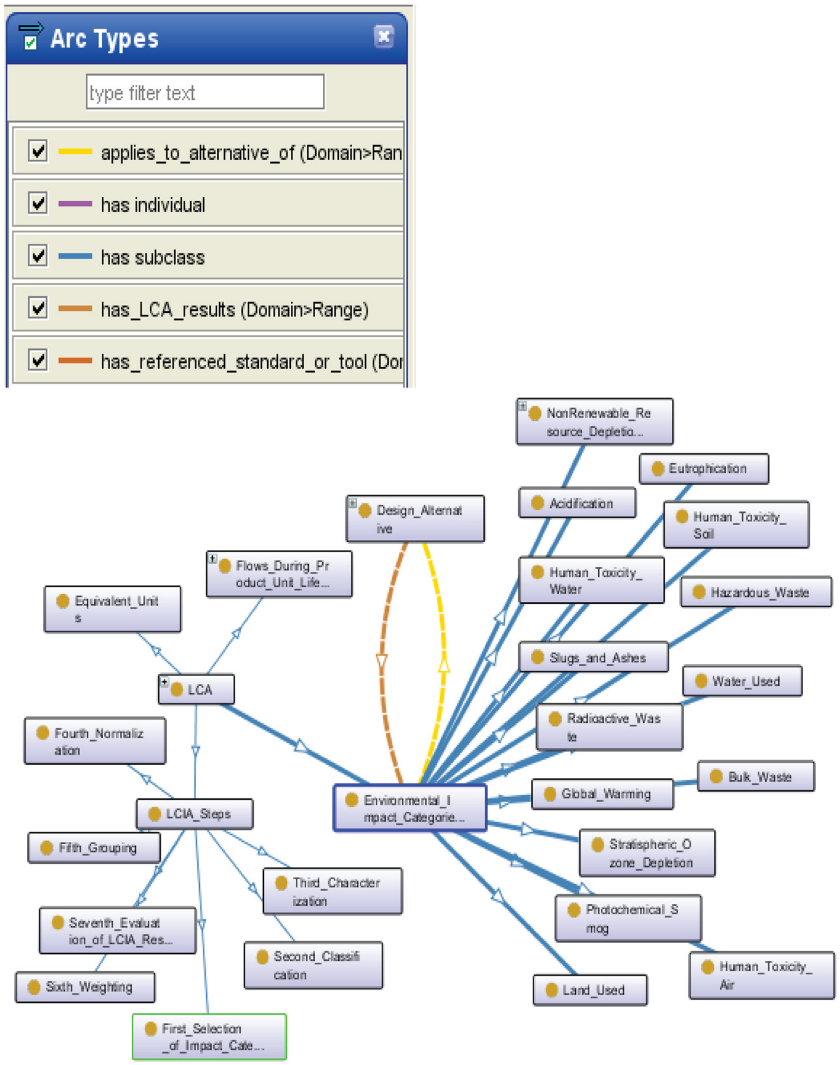


Fig. 7 LCA module construction

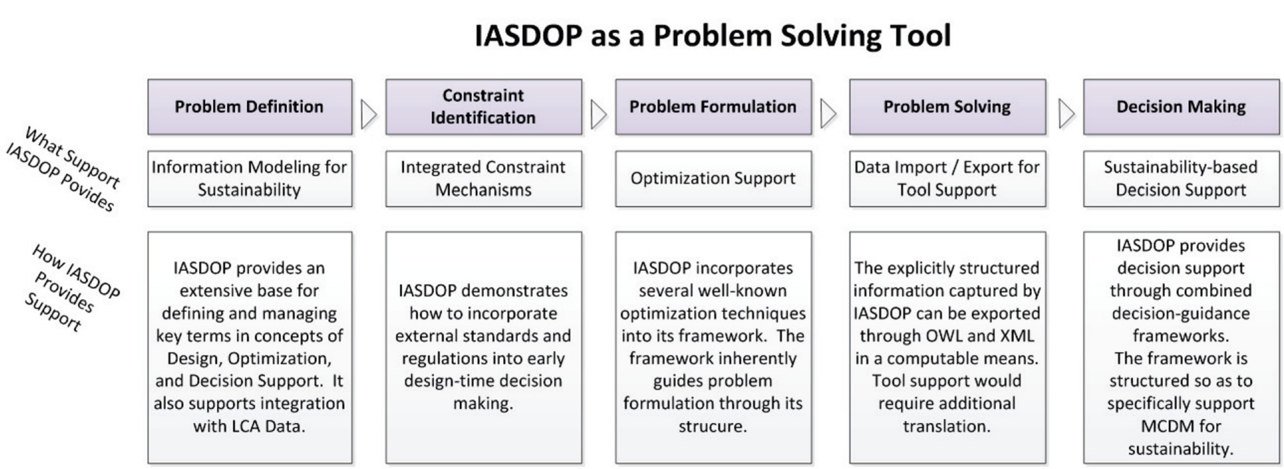


Fig. 8 Specific contributions of IASDOP to a successful design process for sustainability

instance consists of a unique set of applicable criteria and standards. Figure 3 shows how this framework directly associates the relationships between a product and its standards and criteria. In doing so, information about the critical elements of the decision model is revealed transparently. Furthermore, this could aid the repository development of consolidated standards and criteria in the context of the products to which they are most applicable.

3.5.3 Common Ontology for Constraints and Criteria. Constrained design optimization methods provide the means to

Table 1 Main design criteria and their independent variables

Subject instance in "Objective_Function" class	Relationship in "Objective_Function" class	Object instance or value
Comparative_cost	goal	minimize
	used_in_model	Brake_disk_and_pad_performance
	has_unit	Currency_units_USD
	has_objective_parameter	Variable_massPercentDisk
		Variable_tDisk
		Variable_tPad
	considered_in	Evaluation_to_Maximize_MAU_utility_value
Greatest_environmental_impact	goal	minimize
	used_in_model	Brake_disk_and_pad_performance
	has_unit	Equivalent_units_Pt
	has_objective_parameter	Variable_massPercentDisk
		Variable_tDisk
		Variable_tPad
	considered_in	evaluation_to_Maximize_MAU_utility_value
Stop_distance	goal	minimize
	used_in_model	Brake_disk_and_pad_performance
	has_unit	meter
	has_objective_parameter	Variable_massPercentDisk
		Variable_tDisk
		Variable_tPad
	considered_in	evaluation_to_Maximize_MAU_utility_value
Minimize_weight	goal	minimize
	used_in_model	Brake_disk_and_pad_performance
	has_unit	kilogram
	has_objective_parameter	Variable_massPercentDisk
		Variable_tDisk
		Variable_tPad
	considered_in	Evaluation_to_Maximize_MAU_utility_value

consider criteria and constraints simultaneously. The approach of this work advocates modeling information from standard requirements as constraints. Even in cases when such requirements cannot be expressed in the same mathematical model for optimization, the information model can reveal such constraints transparently to alert designers of the need for compliance verification by deployment of the semantic reasoning method [11] described in Sec. 2. Section 2 also points out that in spite of the need to combine sustainability standards with objectives such as the minimization of environmental impacts; such prior work has been very limited.

In recent years, LCA has evolved into a prescribed method to measure value in terms of environmental impacts. LCA determines impact criteria based on standards of ISO 14040-14044, TRACI,[2] and others. A number of different LCA methods were developed to characterize, group, normalize, and weight the impacts for assessment. This framework uses the EDIP 2003 method within SimaPro for consistency with the NASDOP methodology that was developed to deploy multi-criteria decision making for sustainable product design [3]. Relationships between modules in the framework provide the connection of resulting environmental impact information to information about the evaluation of design alternatives that inform the decision making process in the decision support ontology. Figure 7 shows the representation framework for established LCA methodology. The context of criteria shown in Fig. 6 indicates that multiple criteria related to sustainability could be involved in a model.

3.6 The Integrated Design Process. Due to the integration of the framework, the rationale of the design situation and the applicable standards combine to inform the pertinent optimization model. From there, the optimal design alternative can be identified in parallel with the inspection of compliance to any applicable standards. Since every product design is different, this IASDOP framework is constructed with the flexibility to accommodate a wide array of design situations. The following section describes the use of the fully integrated IASDOP framework and the enabled design process in one such actual design case study. This case study illustrates how these presented advantages of IASDOP specifically contribute to a successful design.

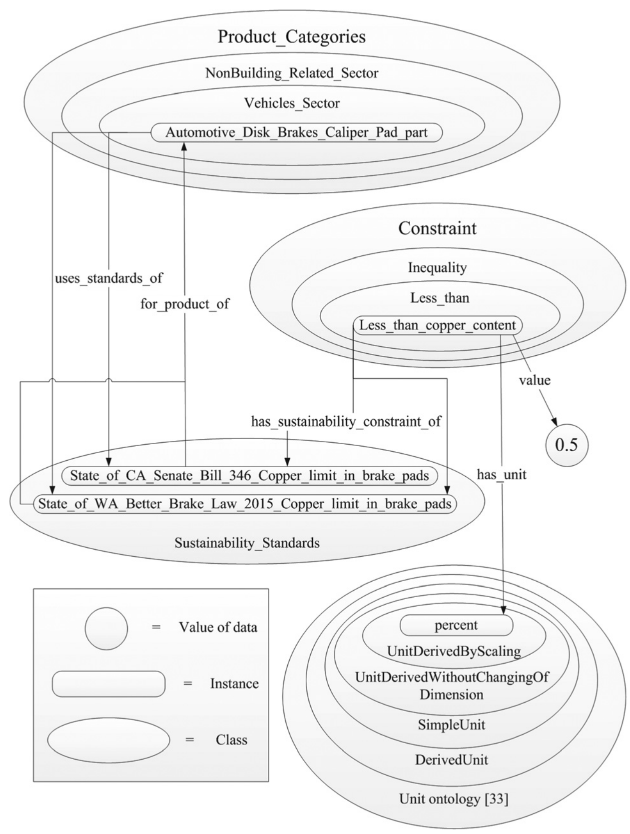


Fig. 9 Modeling of a constraint imposed by sustainability standards

[2]http://www.epa.gov/nrmrl/std/traci/traci.html

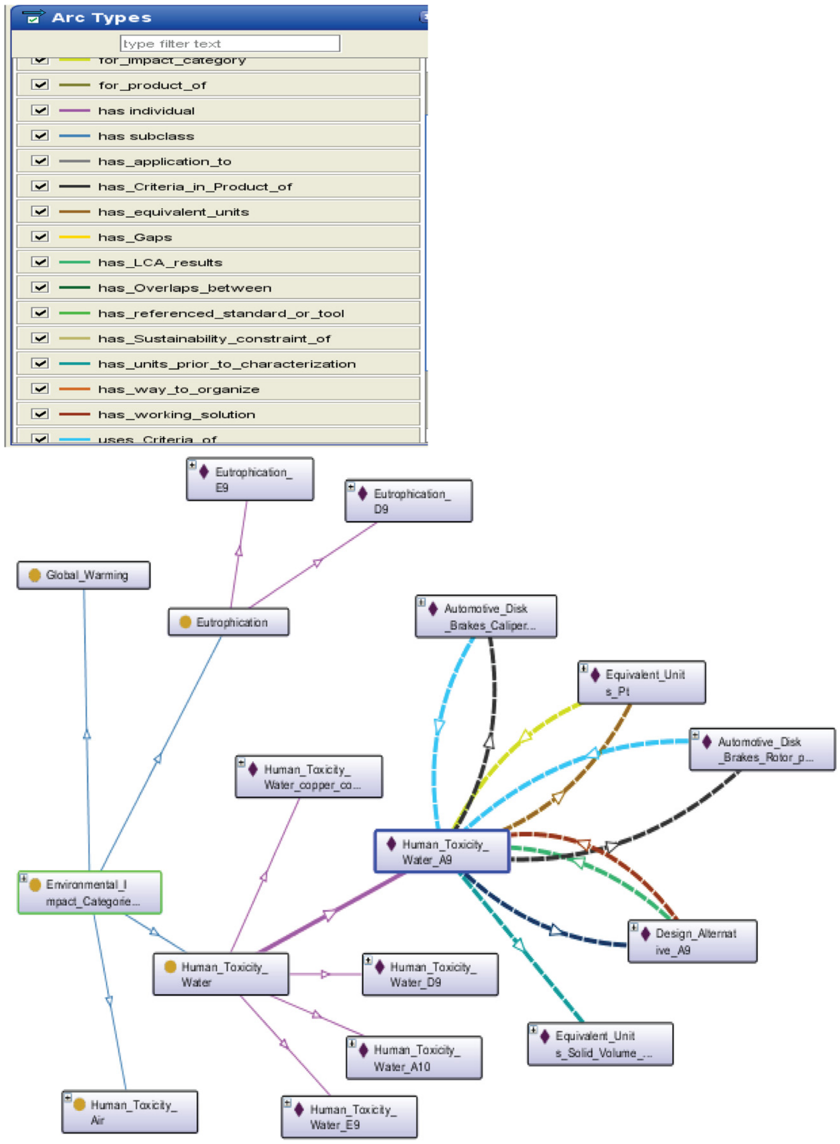


Fig. 10 Use of information from LCA to compare impact results among alternatives

4 Case Study: Sustainability of Brake Disk Rotor and Pads

This case study has been divided into five sections. Figure 8 shows the specific contributions corresponding to Secs. 4.2–4.6. This outline specifies and illustrates improvements to a design process by the support of sustainability considerations.

4.1 Brake Disk Rotor and Pads. This case study uses IAS-DOP to capture and communicate information about the utility evaluation for the optimal set of automotive brake disk rotor and companion pair of caliper pads. In this case, it is assumed that a five year life of these parts is desired along with other assumptions reasonable for a typical midsized passenger automobile. Mathematical models were constructed based on conventional engineering formulations [34] to estimate results. Here, it is assumed that consumers desire the performance objective of minimizing the vehicle stopping distance subject to the performance constraints of adequate heat dissipation, a temperature limited to less than 77 °C, and adequate rotor and pad thickness remaining at the end of five years of typical use.

4.2 Problem Definition: Information Modeling for Sustainability. Some research provides engineering data for the most common rotor materials [35], and more general information is available regarding caliper pad material options. Thus, each possible material combination may reasonably represent a design alternative. Independent variables consist of the geometry of the parts, which in this case is limited to the initial thickness of the rotor and pads and the percentage of the rotor that is solid. Most rotors have hollowed fins to increase convective cooling. Other than material type, the weight of the parts is the most significant factor for the minimization of the impacts given by both LCA and LCC. Stopping distance was found to be independent of weight and geometry whenever all performance constraints are satisfied. These performance constraints, such as assuring that the brake materials dissipate heat quickly enough and do not wear too thin during the product life, are different from constraints imposed by sustainability standards, which will be explained shortly. In the interest of optimizing for sustainability considerations, the weight for each material combination alternative was optimized. Here, the optimal geometry of the parts was determined for each alternative. Models to generate solutions were developed within

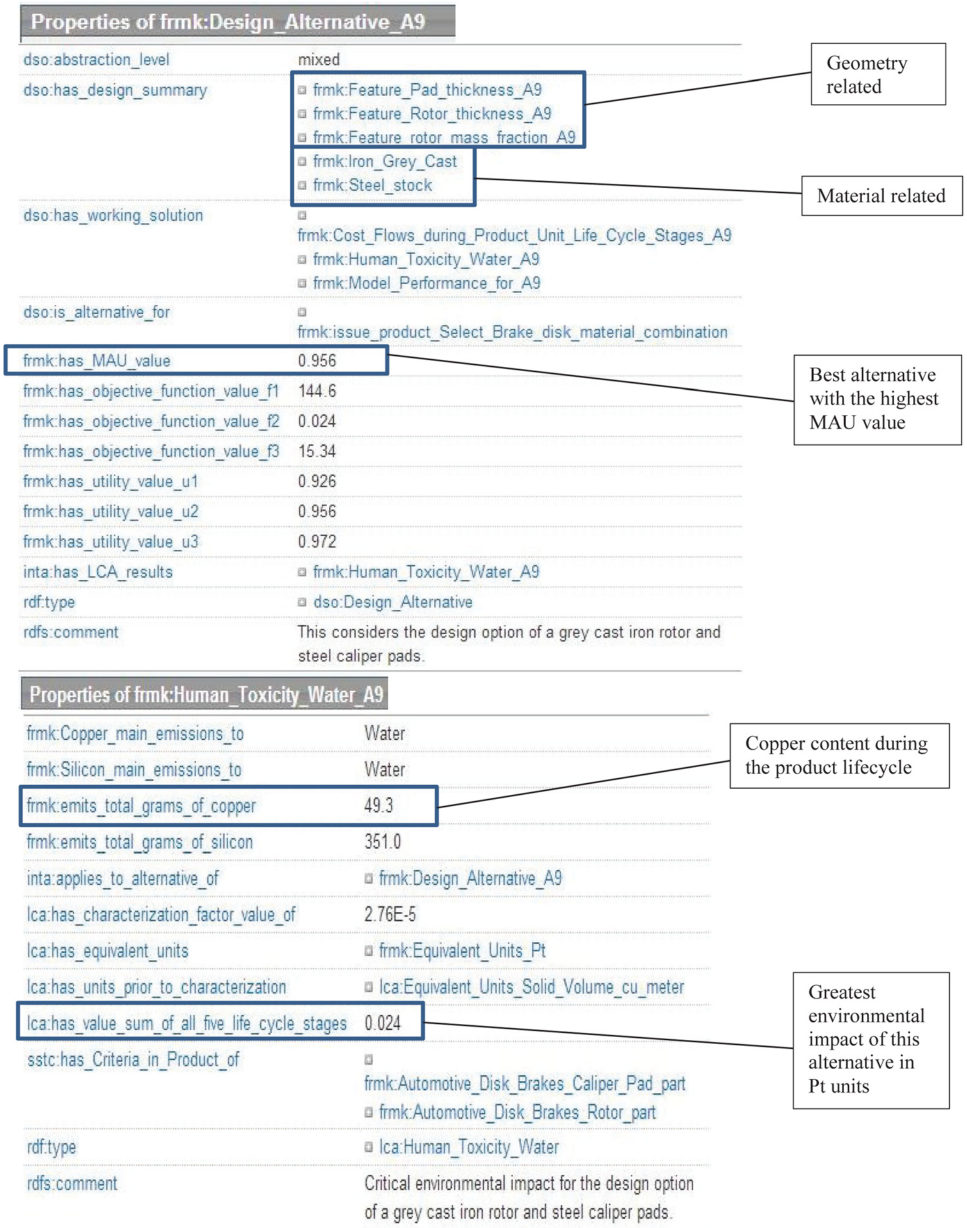
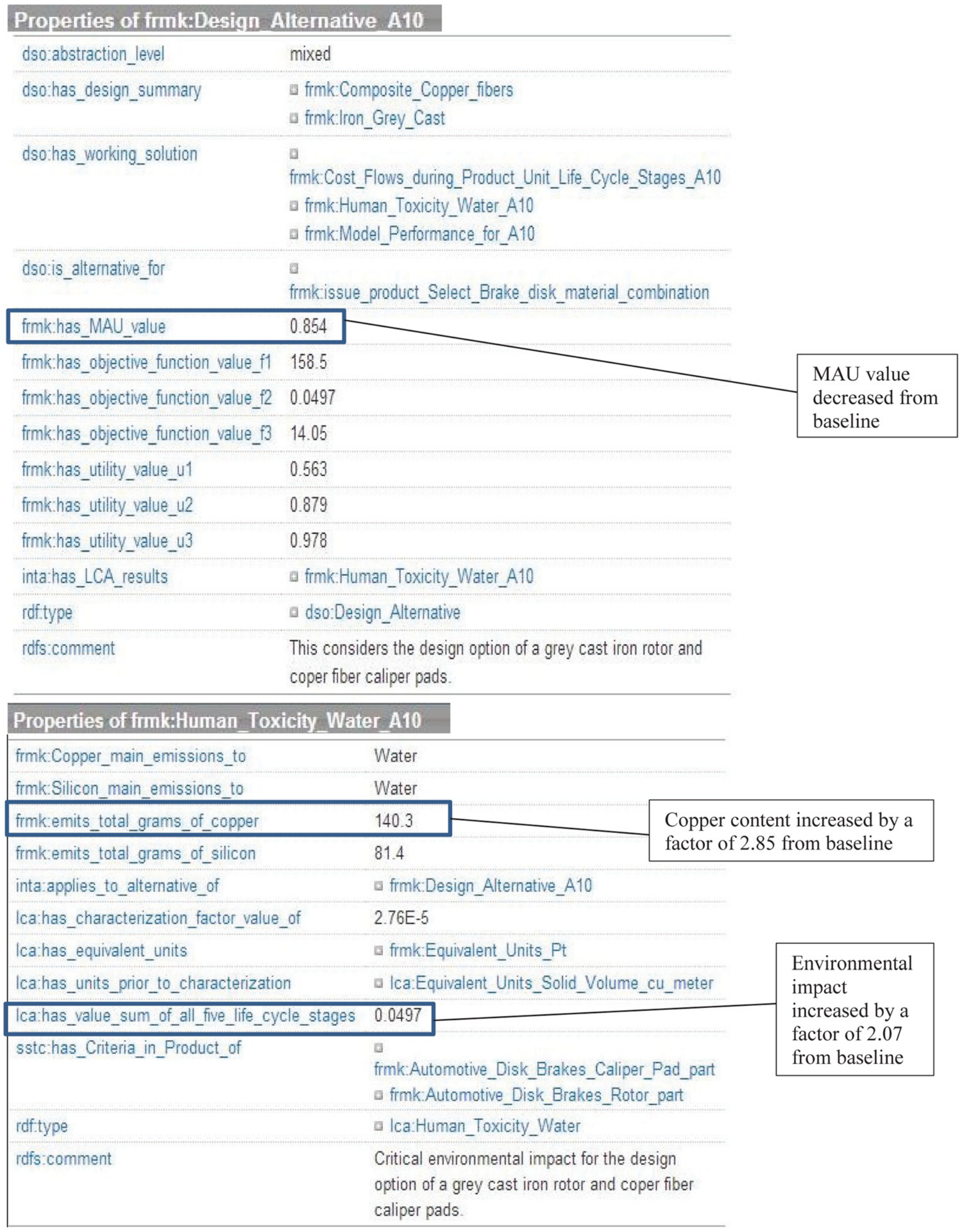


Fig. 11 Results of the most preferred design alternative—baseline for comparison

Parametric Technology Corporation's MathCAD software [36]. Optimization capabilities of Phoenix Integration's ModelCenter software [37] with their MathCAD plugin were deployed to optimize the mass for each design alternative subject to the performance constraints.

LCA results were estimated using SimaPro software [38] based on some reasonable assumptions given the data available for each of the common material combinations. LCC was estimated from available generic searches for cost data. The information mentioned here was modeled appropriately in the IASDOP framework. Section 2 discussed the need to satisfy the triple bottom line multiple objectives for sustainability of preserving the environment, the economy, and the interests of the stakeholders in society. Thus, optimization was done among the three main objectives of minimization of vehicle stopping distance, as well as the minimization of environmental and cost impacts over the product's life cycle. Table 1 highlights the information model created to represent these three main objectives and their associated variables.

4.3 Constraint Identification: Integrated Constraint Mechanisms. The first step involved a search to find the specific standards and regulations that apply to the design situation. A general web search for those applicable to this product design reveals three potentially consequential regulations, which all pertain to material selection in this design process. Brake caliper pads were often made from asbestos material in the past, later raising human health and safety concerns [39]. Related standards were documented as instances within the framework of categorized standards. It is also possible for a standard of concern to not yet be modeled in the framework. Standards may be most applicable to certain product groups, such as limits on copper content to 0.5% in these brake disk parts due to concerns about the cause of some toxic substances in water. The application of some standards to a certain product may require more investigation. For example, disk brakes emit dust during operation, and silica dust concentrations are limited for health reasons [40]. These various standards were modeled in relation to the design instance of this specific product within the integrated framework. This was accomplished by the



Properties of frmk:Design_Alternative_A10	
dso:abstraction_level	mixed
dso:has_design_summary	frmk:Composite_Copper_fibers frmk:Iron_Grey_Cast
dso:has_working_solution	frmk:Cost_Flows_during_Product_Unit_Life_Cycle_Stages_A10 frmk:Human_Toxicity_Water_A10 frmk:Model_Performance_for_A10
dso:is_alternative_for	frmk:issue_product_Select_Brake_disk_material_combination
frmk:has_MAU_value	0.854
frmk:has_objective_function_value_f1	158.5
frmk:has_objective_function_value_f2	0.0497
frmk:has_objective_function_value_f3	14.05
frmk:has_utility_value_u1	0.563
frmk:has_utility_value_u2	0.879
frmk:has_utility_value_u3	0.978
inta:has_LCA_results	frmk:Human_Toxicity_Water_A10
rdf:type	dso:Design_Alternative
rdfs:comment	This considers the design option of a grey cast iron rotor and coper fiber caliper pads.

Properties of frmk:Human_Toxicity_Water_A10	
frmk:Copper_main_emissions_to	Water
frmk:Silicon_main_emissions_to	Water
frmk:emits_total_grams_of_copper	140.3
frmk:emits_total_grams_of_silicon	81.4
inta:applies_to_alternative_of	frmk:Design_Alternative_A10
lca:has_characterization_factor_value_of	2.76E-5
lca:has_equivalent_units	frmk:Equivalent_Units_Pt
lca:has_units_prior_to_characterization	lca:Equivalent_Units_Solid_Volume_cu_meter
lca:has_value_sum_of_all_five_life_cycle_stages	0.0497
sstc:has_Criteria_in_Product_of	frmk:Automotive_Disk_Brakes_Caliper_Pad_part frmk:Automotive_Disk_Brakes_Rotor_part
rdf:type	lca:Human_Toxicity_Water
rdfs:comment	Critical environmental impact for the design option of a grey cast iron rotor and coper fiber caliper pads.

Fig. 12 Results of an alternative with some copper content in the caliper pads

use of the framework as described in Secs. 3.1–3.5. Figure 9 shows the constraint imposed by the sustainability standards related to copper content in a common engineering design model. Thus, sustainability standards are informing the design model as Sec. 3.4 emphasizes.

4.4 Problem Formulation: Optimization Support. The framework allows modeling of sustainability standards and criteria within a shared configuration. Any relationships between standards and criteria can extend to modeling of design information in that constraints can influence design criteria. Furthermore, constraints and criteria can potentially be modeled in the same design optimization formulation if they can be expressed as mathematical functions with the same independent variables. Current standards usually are not expressed in such a mathematical format. However, such sustainability constraints and criteria may be included in the same information model as highlighted in prior figures and sections.

Section 3.5 highlights the integration of information models for sustainability, engineering design, and multi-criteria decision making. Use of this framework initially to identify the standards and regulations transparently can lead to identification of criteria related to minimization of critical environmental impacts. This is done by using the ontological module for LCA, which is built into the sustainability criteria category of the framework. Figure 10 shows this case study within the LCA module of the framework.

4.5 Problem Solving: Data Import/Export for Tool Support. This case study illustrates that this decision making process, which is outlined in Fig. 8, of selecting the optimal design alternative combines several considerations simultaneously. The information is integrated among the four domains shown back in Fig. 1 by dynamically linking information across domains by the relationships set up in the ontological framework. Not only is this study looking at three different attributes in multi-criteria decision making, but it also reveals three different standards or regulations that should be met. It is assumed that caliper pads made from asbestos should not be considered due to the obvious health risks. The information in this model reveals that rationale. The means to comply with the standards that limit copper and silica content is

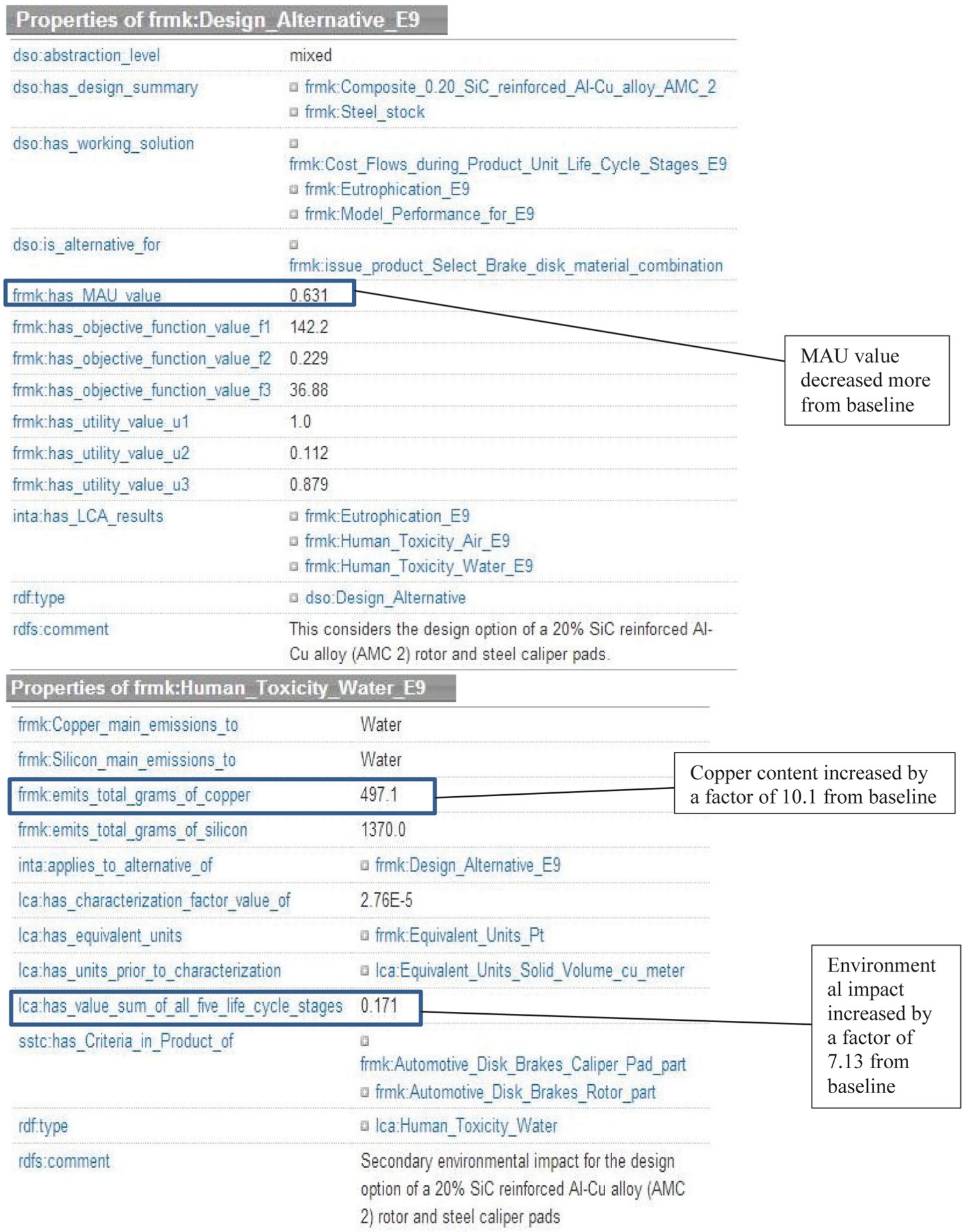


Fig. 13 Results of an alternative with increased content of both copper and silicon in the rotor

not quite so obvious. Since LCA is assessed for each material combination alternative anyways, perhaps that information can help.

Figures 11–13 illustrate this by showing the specific results for both LCA and multi-criteria decision making side by side for three of the alternatives. The instantiated ontology is shown from OntoWiki software [22] in these three figures. Figure 11 represents the results of the best feasible choice, which was evaluated to have the highest MAU value. Here, instance locations of the optimal design geometry and material are shown and specifics would be revealed by simply double clicking on such desired instance links in the ontology. SimaPro generates estimates of all the main environmental impact groups, but usually one specific impact exceeds all the others. For this alternative, human toxicity in water content has the greatest impact. This material combination is a grey cast iron rotor with steel caliper pads. Assumptions are made during LCA and LCC, because the data is not always available for the exact materials and processes involved in the life cycle of every product design. Regular cast iron and steel materials may have less impact and cost than many other materials that may require more processing during the material extraction. This best choice is based on the preferences expressed in the HEIM information model. Use of the integrated framework allows dynamic linking of the information across the domains.

4.6 Decision Making: Sustainability-Based Decision Support. The inventory of copper and silicon emitted during the life cycle can also be inspected. Most of the emitted mass in these instances flows to the water rather than the air or soil. Thus, the standard for copper is more likely to apply than the standard for silica dust in the air in this case. Figures 11–13 also show the emissions to water of copper and silicon for the three alternatives illustrated. Figure 12 shows results for a grey cast iron rotor and a copper fiber composite caliper pad material. The copper fiber material is not likely to meet the standard for sale in the states of CA or Washington. It is interesting that the standard is based on the copper mass percentage of the material, but the information shown regarding the copper emissions to water may actually be more reflective of the impacts of concern. Either way, it is evident that both the human toxicity in water and the copper emissions to water are both nearly doubled or tripled when the alternative changes to the copper fiber material for the pads. Figure 13 assesses a rotor made from a 20% SiC reinforced Al-Cu alloy (AMC 2) instead of the grey cast iron rotor shown in Fig. 11. As a result, eutrophication of the water exceeds the human toxicity in the water as the most significant impact, and the impact approaches ten times more significant. It is interesting that the copper emissions to the water are also about ten times greater. Thus, there is some consistent correlation between the standards and the LCA criteria in this case. This shows that some understanding of relationships between standards and critical impacts can be gained early in a design process by the use of this framework. The resulting MAU values shown in Figs. 11–13 reveal the rank of these alternatives from best to worst.

5 Discussion of Results

The main objective of this work was to support informed design decisions for sustainable product design objectives through the early integration of sustainability standards and criteria. A successful result will ease the adoption of the pertinent standards and regulations and also influence a design toward the objectives related to sustainability. This work integrated information models from the four domains shown in Fig. 1 to demonstrate how such integration can benefit a design process for sustainability.

In traditional engineering design, requirements introduce constraints, which can influence criteria. Design involves a decision, among alternatives, that best satisfies the criteria, which define the issues. The decision may introduce more or new constraints for subsequent design iterations. A design process generates information, which can best be represented by information models accessible by all design participants. The findings in this work support the use of such established principles for sustainability considerations.

Furthermore, the case examined shows that some consistencies can be revealed between applicable regulations modeled by standards and environmental impacts determined by LCA. The process enabled by the IASDOP framework was shown to allow parallel inspection of information related to standards and design alternative selection. This work began with the premise that sustainability standards and regulations may be aligned with the triple bottom line objectives of sustainability. Although this may or may not be true depending upon the standard, a framework is provided in which the information is connected by the relationships. This connection should be evident in all cases. Although compliance with standards and regulations could require further validation, the intent shown in the information about the standards does have some alignment with the triple bottom line criteria in the case observed. Thus, efficiency and effectiveness may be improved by the use of this framework in many other cases as well. Since instantiation of the design information does involve some time and resources, design teams should evaluate the expected cost and benefits of using this method on a case by case basis. An additional benefit of the instantiation could be realized by the capability to query the information based on its context and meaning. Future work may investigate possible use of the reasoning and rules capabilities of the ontologies to identify any further potential to improve decision making.

Any such method becomes much more useful when the benefits can be realized as early in a design process as possible. The case presented here shows one example in which a sustainable design may depend exclusively upon the independent variables of the material and geometry of the components for their given use. Thus, the method deployed could be implemented at the early stages of conceptual design in some cases. The case studied here is one with a closed form solution that can be solved definitively given reasonable assumptions and accuracy expectations for each discrete potential material combination. Future work will look at more uncertain design situations that may involve response surface modeling from known data and the construction of surrogate models. The successful construction of reliable solution models that depend exclusively upon the geometry and material of the components should significantly aid the adoption of the methodology as early in a design process as possible.

6 Summary

This work presents a novel semantic framework to model the information of the domains necessary for the sustainable design of products. This unique approach considers both compliance with the applicable standards and also objectives compatible with triple bottom line benefits to the economy, environment, and stakeholders, in terms of performance delivered. Since the applicable standards and criteria are contained within the same information model in real time, the standards may be adopted more easily early on while the design may also be influenced more toward the triple bottom line objectives. Furthermore, the design intent is captured and revealed transparently to all design participants dynamically. The case studied shows that sustainable design may be considered earlier in a design process in such cases where the optimal design for sustainability depends upon material and geometry input variables exclusively.

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