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A Semantic Information Model for Capturing and Communicating Design Decisions

A semantic information model to improve reuse and communication of engineering design knowledge is presented in this paper. We consider design to be a process involving a sequence of decisions informed by the current state of information. As such, the information model developed is structured to reflect the conceptualizations of engineering design decisions with a particular emphasis on semantically capturing design rationale. Through the approach presented, knowledge reuse is achieved by communicating design rationale. A case study is presented to illustrate two key features of the approach: (1) seamless integration of separate modular domain ontologies and instance knowledge related to engineering design that are needed to support decision making and (2) the explicit documentation of design rationale through design decisions.

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1 Introduction

Many engineering design tasks can be classified as *redesign* or *adaptive* design tasks, in which a solution is realized by modifying a prior solution (or solutions) to meet new requirements [1]. During these design tasks someone other than the original designer reuses documented design knowledge for the same or similar application [2]. The ability to successfully reuse design knowledge is contingent on the effective communication between the original designer(s) and other designers.

Communication is not simply the exchange of data. It also implies conveying to others *what* was done and *why* it was done, i.e., design rationale [3]. Traditionally, designers have used such means as text documents, spreadsheets, presentations, drawings, and software tools to document the design history of an artifact. Shortcomings of traditional approaches include insufficiently documented design rationale, inaccessible design information, and manual, time-consuming search and retrieval. These shortcomings can hinder knowledge reuse. In Refs. [4–6], it is reported that designers spend 20–30% of their time simply searching for and absorbing information. Boston et al. [4] estimated that in some industries product development times may be increased by up to 48% due to information management problems. As the amount of information being generated during the product development process continues to grow, the need for computational frameworks to support the management and reuse of knowledge becomes increasingly critical [3]. Essential for proper knowledge reuse is the communication of design rationale. In this research, we focus on developing a formal semantic information model that facilitates the reuse of design knowledge by explicitly capturing design rationale.

Adaption and application of past design knowledge to new problems are difficult without understanding the underlying rationale of previous designs. Design rationale includes the reasons behind a design decision, the justification for a decision, the alternatives considered, and the argumentation that led to the decision [7]. In this context, it is clear that design rationale can be docu-

mented by focusing on explicitly capturing design decisions. Design decisions are made by logically evaluating possible design options and rationally selecting the most preferred course of action. The evaluation and selection is based on the current state of information and the decision maker's preferences [8]. To explicitly capture design rationale, we propose an information model structured to reflect the conceptualizations of engineering design decisions. Domain-specific concepts and relationships are explicitly defined to assist designers in documenting decisions. These relationships allow decision makers to easily utilize information that is relevant to a decision. The decision information model provides a semantically rich representation of the reasons and justifications behind design decisions. The approach taken in this research addresses a gap in the design rationale literature by directly tying design rationale to specific design decisions. Past research in design rationale has focused almost exclusively on the development of schemas.

The layout of the rest of this paper is as follows. In Sec. 2, related research is discussed. A detailed information model for communicating design knowledge and rationale is presented in Sec. 3. The information model is developed using ontologies and specifically the web ontology language (OWL). OWL provides a means for semantically representing the proposed information model but is not intrinsic to the conceptual development of the model presented. Throughout Sec. 3, an example is used to illustrate the approach developed. Section 4 provides a discussion of the research presented and the conclusions.

2 Related Research

Many methods for supporting design activities have focused on improved management of design knowledge. The methods and techniques developed can be classified based on whether or not design rationale or design history is captured.

2.1 Design History. Design history systems capture what was done but do not sufficiently record the reasons for choices [9]. Instead of explicitly documenting rationale, it is assumed that others will be able to infer design rationale based on the documented design activities. Recently, the development of design history systems in the form of design repositories and ontology-based frameworks has become popular. Design history frameworks specify a structured information model for organizing design knowledge. Such research includes [2–5,10–24]. Most of these works focus on

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creating metamodels of function, form, or behavior models of design artifacts. Some of the works, such as Refs. [2,24], do support documentation of modeling rationale. In Refs. [2,24], rationale associated with engineering analysis models and design optimization models is captured via specification of modeling assumptions, idealizations, and justifications. Although these information models do not provide a structured representation of design decisions, the design information captured is needed to support decision making. For example, a decision maker may reference the results of an analysis model to gain a better understanding of the predicted behavior of a design alternative. Consequently, design rationale frameworks should be capable of integrating design history information so that both the design process and rationale are documented together.

2.2 Design Rationale. Design rationale systems offer improved collaboration, reuse, maintenance, learning, and documentation [7]. To realize such benefits, the information must be captured in a structured manner. “Well-structured design rationales can help designers track the issues and alternatives being explored and their evaluations” [7]. A well-structured information model is necessary for improving design communication and reuse. The more prominent design rationale frameworks and tools are discussed here. Readers seeking a more comprehensive review of design rationale systems are encouraged to see the works of Refs. [9,25].

The issue-based information system (IBIS) proposed by Kunz and Rittel [26] in 1970 is generally accepted as the first design rationale system. The IBIS approach treats problem solving as an argumentative process. The elements involved with problem solving are specified as *topics, issues, questions of fact, positions, arguments*, and *model problems*. Issues are the fundamental primitives and take the form of a question. Positions are created to address an issue. Arguments in favor of or opposed to positions are put forth. Through this process, issues are resolved by making a decision to select a position. Design rationale tools that have been developed based on the IBIS method include GIBIS [27], REMAP [28], REMAP/MM [29], KBDS-IBIS [30], IDIS [31], and DRED [32].

A critique of IBIS led McCall [33] to augment the IBIS structure and create the procedural hierarchy of issues (PHI) approach. PHI adopts a broader definition of issue and uses a single *serve* relationship to identify influences between issues [34]. These changes enable the creation of simple issue maps that illustrate relationships between issues. Design rationale tools that have been developed using the PHI method include VIEWPOINTS [35], JANUS [36], and PHIDIAS [37].

The question, option, and criteria (QOC) approach [38] is a design space analysis method. Design space analysis seeks to explain why a particular design alternative was chosen from the set of all possible design alternatives [25]. Unlike IBIS and PHI, QOC guides the development of design options rather than focus on the arguments. Questions pose key issues for structuring the space of alternatives. Options are possible alternative answers to the questions. Criteria are the bases for evaluation and choosing among the options. The design rationale system DRARS [39] was developed using a variation of the QOC method.

The decision rationale language (DRL) developed by Lee and Lai [40] documents the rationale by describing how alternatives satisfy desired goals. Concepts within DRL include *decision problems, alternatives, goals, and claims*. DRL was implemented in the design rationale system SIBYL. Later in a survey and review of existing design rationale systems, Lee [7] identified the following three major layers to design rationale systems: *decision, design artifact*, and *design intent*. The DRL provides a way to model the decision layer.

Mocko et al. [17] developed a framework for representing the knowledge associated with design decision. Using ontologies, a formal vocabulary for developing models of design decisions and analysis models is presented. A base vocabulary of concepts con-

stitutes a generic domain representation that can be used to model analysis models and decision models. The base vocabulary consists of seven concepts, and the vocabulary can be expanded to allow for application specific information by including concepts that are subsumed by the base vocabulary. Standard reasoning approaches are used for organizing and querying existing concepts. The framework includes such concepts as analysis models and design requirements.

The methods reviewed all provide some information model for documenting rationale in a problem-solving scenario. Many of these frameworks identify similar concepts as critical for rationale capture and consequently provide the foundation for the development of other design rationale frameworks. However, the concepts and relationships between concepts within a design rationale framework will vary depending on the domain of discourse and intended services [7,25]. As our research is specifically focused on the capture of design rationale in engineering design, some of the concepts proposed by these frameworks may be unnecessary or insufficient. For example, in existing frameworks, issues and alternatives may be captured using text string descriptions. Relationships that create a semantic link between the issue and the component, product, or process that the issue is relevant to are missing. Similarly, the evaluation of design alternatives requires a detailed understanding of the alternatives. The design history of the artifact should be accessible from the design rationale systems so that such information is easily referenced. Mocko et al. [17] recognized this need and enabled decision makers to reference analysis models. Reference to the artifact design history requires an approach that is easily accessible and can integrate heterogeneous information resources. This requirement is further emphasized by the fact that most design projects that are large enough to warrant rationale capture will have more than one designer involved, and these designers may be distributed [9]. A framework that ensures communication of design knowledge between these partners is needed. The frameworks reviewed are not structured and represented to sufficiently address this notion.

3 Design Decision Rationale Framework

Our approach developed to improve design knowledge reuse adopts the idea of a *design rationale* and *design artifact history* layers from Lee [7] and adds a *reasoning service* layer. The design artifact history contains enterprise information (e.g., products, components, employee records, etc.) and artifact modeling information (e.g., functional models, form models, behavior models). The design rationale layer is used to explicitly document decisions and consists of the decision support ontology (DSO) and decision method ontologies (DMOs). The reasoning service layer consists of semantic-based logic rules that provide automated knowledge instantiation and design support for specific applications. The focus of this paper is on the development of the design rationale layer.

The basis of our approach is to utilize ontologies to structure the design artifact history and design rationale layers. Representing the design artifact history and design rationale in a computable manner allows information to be easily integrated and for the use of reasoning services to automate design knowledge retrieval. An ontology is an explicit specification of a conceptualization [41,42]. Ontologies provide a semantic-based approach to structure the concepts and the relationships between concepts within a given domain. A common ontology language is the OWL [43]. OWL is a developing information technology of the Semantic Web and is based in description logic. Description logic (DL) is a subset of first-order predicate logic used to formally represent knowledge of a domain. A DL knowledge base allows for the capture of general intensional knowledge and specific extensional knowledge [44]. A distinguishing feature of DL knowledge bases is the reasoning capability. Reasoning enables implicitly represented knowledge to be inferred from the knowledge that is explicitly contained in the knowledge base [44]. DL, together with

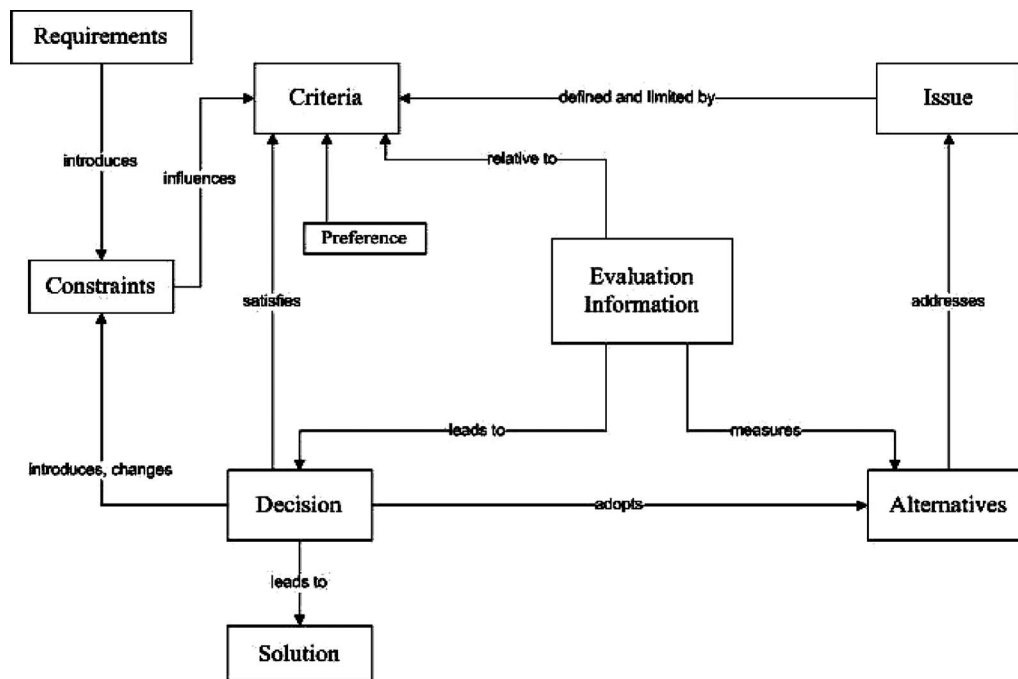


Fig. 1 Conceptual overview of the decision support ontology (augmented from Ref. [8])

domain-specific semantic rules, provides the necessary expressivity required to model product development domains and provides mechanisms for explicit and implicit knowledge documentation [45].

In this research, OWL-DL is used as the knowledge representation, and Protégé ontology editor [46] is used as the development environment. Throughout this paper, Protégé will be used to illustrate the framework developed. However, it is important to recognize that Protégé is not intended to be an end-user interface. The development of a user-friendly interface is a separate implementation task that has yet to be resolved.

3.1 Design Artifact History Ontologies. In previous research [20], a framework that facilitates the documentation and sharing of product development knowledge by formally defining domain-specific information models was developed. Information models to describe the concepts of *functional model*, *form model*, *behavior model*, and *optimization model* were developed to capture, share, and reuse engineering information. The concepts of *product*, *component*, *assembly*, and *organization* were also modeled to establish relationships between the engineering concepts modeled and the physical artifacts and enterprise resources (e.g., people and task). This set of modular ontologies exists as OWL documents and has been made available via the web.² Rockwell et al. [20] illustrated how it is possible to link to these modular ontologies via the web to create a customizable knowledge base. Inference rules for operating on information in the knowledge base can be used to manipulate instantiated information to assist designers. The integration of new information from other ontologies is done via description logic axioms, thus extending the existing inference rules to be able to operate on information across multiple ontologies.

The research from Refs. [2,20,24] provides a library of modular ontologies that enable the creation of a customized knowledge base for concisely documenting the design history of an engineered artifact. The design knowledge captured about the design history supports decision making and needs to be accessible to decision makers when making a decision about an artifact. In this

research, we leverage the ontological framework of Ref. [20] to document the design history of artifacts. In the following sections, ontologies for supporting the documentation of decision-making information are presented.

3.2 Design Rationale Layer-DSO and DMOs. Through this research, we seek to capture design rationale by explicitly documenting design decisions. The decision-based engineering design research community addresses the notion of design as primarily a decision-making process [47]. Decision methods provide a rational and systematic procedure for applying critical thinking to information, data, and experience in order to make a balanced decision [48]. Within the decision-based design community, there is a lack of consensus in the choice of a specific decision method or in how decision-based design should be implemented [49]. Furthermore, in practice, a variety of different selection and evaluation methods may be needed to proceed from customer requirements to a set of manufacturing specifications. As such, any decision support tool should be capable of accommodating various decision methods. To develop an information model that facilitates the communication of any decision method, the following approach was taken:

1. Develop a general decision-making information model that is independent of the decision method (i.e., the decision support ontology).
2. Develop smaller, complementary information models for specific decision methods that easily extend the DSO. These sets of ontologies that describe specific decision methods have been dubbed DMOs.

This approach allows detailed decision information to be concisely documented through the combination of the DSO and DMO.

3.2.1 Decision Support Ontology. The decision support ontology was developed to document design decisions and to expose the rationale behind decisions. The structure of the information model developed reflects a priori knowledge of decision making to support the communication of information independent of any specific decision method. Concepts and relationships of the DSO

²<http://edesign.ecs.umass.edu>

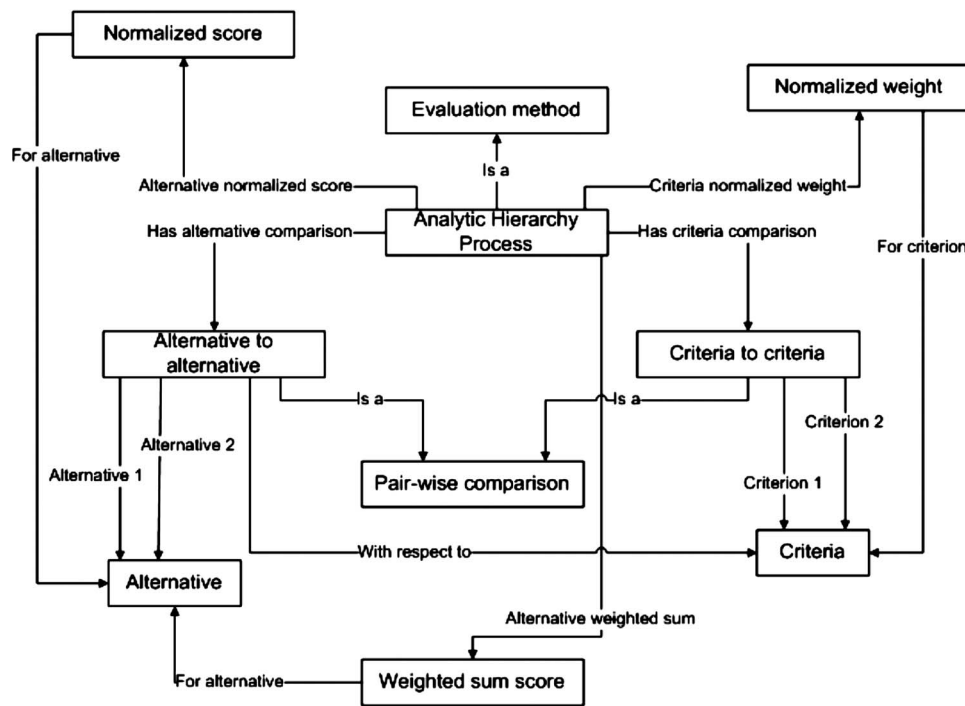


Fig. 2 Information model of AHP

are based on the works of Refs. [40,50–53]. Figure 1 provides a conceptual overview of the structure of the DSO. The major concepts and properties of the DSO were presented in detail in Ref. [19]. Here, some of the more central concepts are summarized.

The following basic types of information were identified as key decision-making concepts in engineering design independent of the decision method: *design issue*, *alternatives*, *criteria*, and *evaluation information* [8,54]. In Fig. 1, the boxes represent concepts, and arrows indicate relationships between concepts. An issue is a call for action to resolve some question or problem [8]. To address the issue, a set of possible solutions, or alternatives, are developed. Based on a set of criteria and *preferences*, an evaluation of the alternatives reveals which alternative is most preferred. Rational arguments either in support or opposing a particular alternative may also be part of the evaluation before a decision to adopt an alternative to resolve the issue is made. How well the decision addresses the issue is documented as the *outcome*. Use of the DSO facilitates documentation of decision information such as criteria, preference, and alternatives (including rejected alternatives) that is often left undocumented. Documentation of this information is critical to improve communication and for knowledge reuse as the preferred course of action (i.e., a decision) may change as preferences or criteria change. Without understanding the basis for a decision, it is not possible to understand why or when the preferred alternative changes and a different decision is made.

3.2.2 Decision Method Ontology. Decision method ontologies extend the DSO to allow for an explicit documentation of specific decision-making methods. Thus far, four different DMOs have been developed, one for each of the following five different decision methods: (1) decision matrix method, (2) analytic hierarchy process (AHP), (3) additive value theory, and (4) utility theory. In this section, the DMO for AHP (which will be referred to as AHP-DMO) is presented and integrated into the DSO. To demonstrate the implementation and utility of this approach, an example decision scenario is presented.

Analytic hierarchy process is a multicriteria decision-making method developed by Saaty [55]. The basis for AHP is that humans are better at making relative assessments than absolute as-

sessments [48]. Through the use of pairwise comparisons, the relative importance of each criterion is determined. Through AHP, a preferred alternative is identified by determining weighted scores for each alternative. Figure 2 illustrates the concepts and some of the relationships between concepts that are represented in the AHP-DMO. In Fig. 2, the boxes represent domain concepts (or classes), and the arrows represent object-type relationships between concepts. The *analytic hierarchy process* class relates information about pairwise comparisons, normalized scores, normalized weights, and weighted sum scores. Data type properties are used to capture the values of individual scores and weights.

As seen in Figs. 1 and 2, concepts such as criteria and alternative are common to both the DSO and AHP-DMO. The DL foundation of the representation provides mechanisms that allow for the integration of the ontologies and concepts. A *necessary* class restriction is a subclass restriction, making it possible to say that a concept from a DMO is a subclass of a concept from the DSO. A *necessary and sufficient* restriction is an equivalent class restriction that makes it possible to say that a concept from a DMO is equivalent to a concept from the DSO. Through the use of *necessary* and *necessary and sufficient* restrictions, common concepts from the AHP-DMO were integrated with concepts from the DSO.

Understanding how a DMO can be integrated with the DSO reduces the development time of a DMO. A DMO is meant to extend the DSO. As such, a DMO does not need to describe certain concepts that have been amply described by the DSO. For example, the concept of criteria has already been sufficiently described within the DSO. In the development of a DMO, the criteria concept only need include properties that are specific to the decision method that is being modeled. Other general properties relevant to criteria have already been described in the DSO. Once the DMO is integrated into the DSO, all criteria will inherit the additional properties.

This approach to integrating DMOs with the DSO is beneficial for four primary reasons: (1) It enables concepts to be leveraged. (2) Concept descriptions can be extended through inheritance mechanisms. (3) Property ranges can be extended to include relevant information. (4) Semantic rules are able to operate on information from different sources. Although only the AHP-DMO was

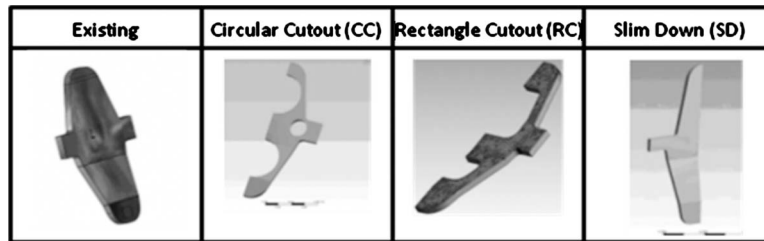


Fig. 3 Existing and redesign alternatives (in half symmetry) of transfer plate

presented in this paper, it is important to recognize that the framework has been developed to accommodate any decision-making method. AHP simply serves as an example.

3.3 Example Application of DSO and DMO. Here, a decision scenario is introduced to illustrate how the DSO, combined with the DMO, captures design rationale.

3.3.1 Decision Scenario Introduction. Using the ontologies just discussed, a knowledge base to capture design information about the design of aerospace circuit breakers was created. Concepts such as product, component, units of measurement, form model, analysis model, and optimization model were included in the knowledge base. The knowledge base was customized based on the circuit breaker design documentation provided by Sensata Technologies, Inc.³ To illustrate the utility of the approach developed, we used a design task provided by Sensata and worked on by senior engineering students at the University of Massachusetts Amherst. The task was to redesign the transfer plate of a circuit breaker intended for aerospace application. The transfer plate is a simple lever mechanism for transferring motion in the circuit breaker. Sensata provided the design documentation for the existing transfer plate. The main objective of the redesign task was to minimize weight. Constraints on the task were as follows: (1) Deflection must be less than 0.010 in., (2) the yield stress of the part may not be exceeded at any point, (3) the manufacturing process must be stamping, and (4) mounting means and force location cannot be changed.

Figure 3 shows the existing transfer plate design, as well as the three alternative redesigns that were developed. Preliminary stress and deflection analyses were conducted for each alternative. Based on the preliminary analysis, a decision as to which alternative to further develop was needed. To select the preferred design alternative, analytic hierarchy process was used. A Microsoft Excel implementation of AHP was documented in the knowledge base via the DSO and integrated AHP-DMO. The documentation of this decision within our decision support framework is presented next.

3.3.2 Capturing Design Rationale. The transfer plate design decision was documented through the design rationale layer. The decision was made to further develop the circular cut-out design. Here, the decision is walked through in reverse just as if someone were trying to understand the decision rationale.

The decision class of the DSO captures information including the selected alternative, a decision summary, the evaluation of alternatives, and any resulting constraints. Figure 4 illustrates the decision information for the transfer plate redesign captured using the DSO. Figure 4, as with Figs. 5–7, use the Protégé interface to illustrate the design information that has been instantiated. In Fig. 4, the circular cut-out design has been indicated as the selected alternative. To gain an understanding of the reasons why the circular cut-out design was selected, the decision instance is con-

nected to the evaluation of the alternatives through the *has evaluation* property.

Figure 5 shows the evaluation instance that was identified in the decision instance. As part of the evaluation documentation, the criteria for evaluation are identified through the property *criteria to consider*, which is linked to detailed descriptions of the criteria and preferences so that all decision makers clearly understand what the evaluation is based on. The property *has alternative* specifies the alternatives that were considered during the decision. The values of the *has alternative* property are linked to the design history of each alternative. In this example, the design history of each alternative includes geometric, analysis, and optimization models and results. Figure 6 illustrates the analysis model for the circular cut-out alternative that can be accessed via the design history. Connecting to the design history makes it easy for decision makers to access supporting documentation needed to make a well-informed decision.

In addition, within the evaluation documentation, a decision *recommendation* is provided. The basis for the recommendation comes from the decision analysis. The relationship between the evaluation instance and the decision analysis is made through the

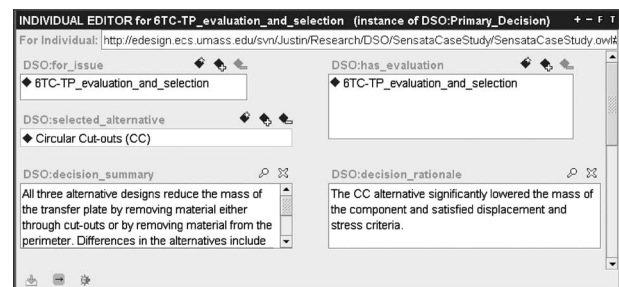


Fig. 4 Decision documentation from DSO

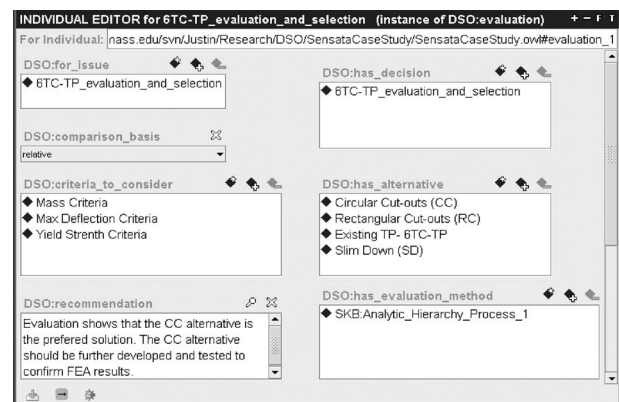


Fig. 5 Evaluation documentation from DSO (accessible through from the decision instance)

³Sensata Technologies is a producer of sensors and controls for manufacturers in the automotive, appliance, aircraft, industrial, and HVAC markets, Attleboro, MA.

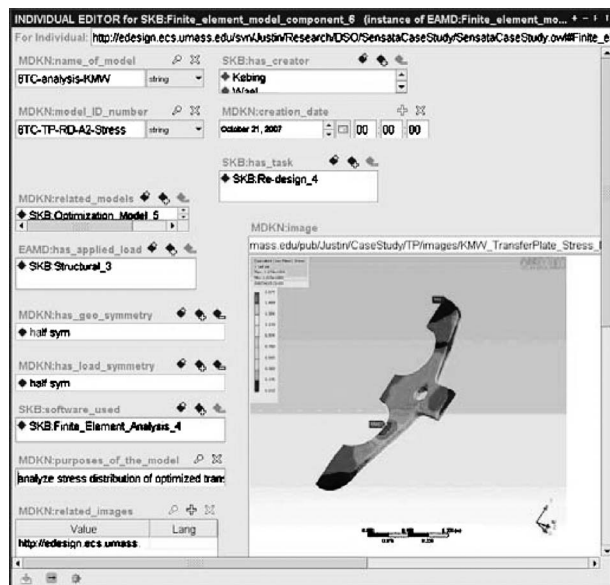


Fig. 6 Analysis model from design artifact history layer (accessible from the evaluation documentation)

has evaluation method property, which in this case links the DSO to the AHP-DMO documentation.

Figure 7 is the instance from the analytical hierarchy process class for the transfer plate selection that is identified through the has evaluation method property. This instance contains all the information about the AHP decision process. Using AHP to select the preferred alternative required pairwise comparisons and calcu-

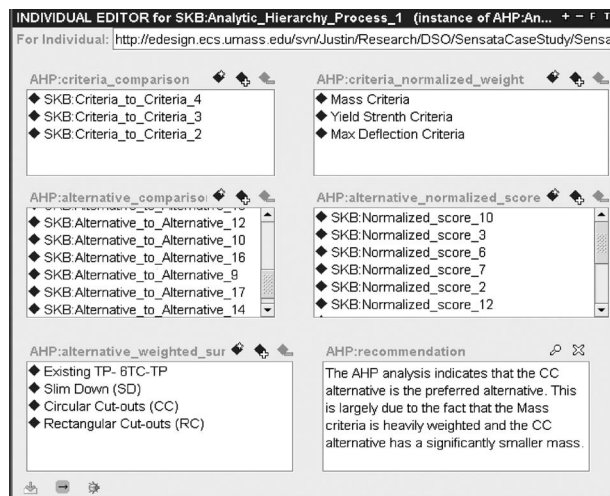


Fig. 7 Documentation of decision from AHP-DMO (accessible through the has evaluation method property from the evaluation documentation)

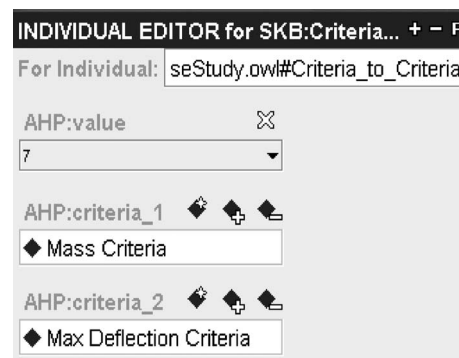


Fig. 8 Documentation of an evaluation for pairwise comparison

lation of normalized weights and scores. Table 1 shows the criteria pairwise comparison (using the nine-point scale described previously) and normalized weights for the transfer plate evaluation. In the same manner, the pairwise comparisons for the alternatives were completed, and calculations of normalized scores were carried out to determine the total weighted scores for each alternative. The pairwise comparisons and normalized weights were documented in the AHP-DMO through instances similar to the instance shown in Fig. 8. These individual bits of information are connected together through the analytical hierarchy process instance in Fig. 7 via the *criteria comparison*, *alternative comparison*, *criteria normalized weight*, and *alternative normalized score* properties. The weighted scores for the circular cutouts, rectangular cutouts, and slim down alternatives were 0.464, 0.231, and 0.165, respectively. From the AHP decision analysis, it is clear that all of the design alternatives would be improvements over the existing design, as the weighted score for the existing design was determined to be 0.140. The preferred alternative with a score of 0.464 is the circular cut-out alternative. Thus, the decision was made to further develop this design.

This decision scenario demonstrates how decisions are concisely documented through the use of the DSO and DMO. Pre-defined information fields assist designers as to what information is important to document, facilitating the documentation of information such as design alternatives and criteria that are often forgotten. Information about the design artifact history is easily integrated, allowing decision makers to access supporting design information. The DSO, together with the DMO, facilitates the reuse of design knowledge by exposing the underlying rationale. In the transfer plate example, the pairwise comparisons of the criteria reflect the decision maker's preferences. If the preferences were to change, a different decision may result. Since the pairwise comparisons are explicitly documented, it is straightforward for other engineers to understand how the decision was made and, in this instance, why the circular cut-out alternative was selected.

DMOs are used to extend the DSO to included decision-method specific information. For the AHP-DMO, this was seen with the pairwise comparison information. The other DMOs developed also add decision-method specific information. For example, the

Table 1 Criteria pairwise comparison

	Criteria comparison				
	Mass	Displacement	Y.S. factor of safety	Geometric mean	Normalized weight
Mass	1	7	7	3.66	0.78
Displacement	0.143	1	1	0.52	0.11
Y.S. factor of safety	0.143	1	1	0.52	0.11
				4.70	1.00

decision matrix method DMO includes importance weights for each criterion, the additive value theory DMO includes exponential and piecewise linear development of individual value functions, and the utility theory DMO includes concepts such as certainty equivalent, uncertainty, and risk. Although not presented in this paper, these DMOs are available on the web.⁴ The combination of the DSO and DMO provides a descriptive, rather than prescriptive, approach to documenting design decisions.

4 Discussion

The framework developed prompts a documentation of design rationale via design decisions. The decision support ontology provides an information model of general decision-making concepts independent of a specific decision method. Decision method ontologies are used to model the information that is relevant to specific decision-making methods and design decisions. With the integration of the DSO and specific DMOs, the framework is capable of capturing any decision-making method. Using DMOs and their semantic representation to complement the DSO schema is important in that it translates design rationale into actual design decisions. The DSO and DMOs have been represented using OWL. The underlying description logic formalism of OWL allows computers to comprehend documented information to provide a semantic-based approach. DL axioms enable computers to automatically identify common concepts across ontologies, thereby facilitating the integration of ontologies. Through DL axioms, integration of multiple ontologies with common concepts is possible. This was demonstrated by integrating the AHP-DMO with the DSO. Integration with distributed information over the web was also demonstrated by linking design rationale knowledge with design history knowledge. Although implemented using OWL, it should be recognized that the conceptual development of the approach taken is not dependent on OWL.

The framework developed has been presented as a means for humans to document and communicate design knowledge and rationale to other humans. As there are many decision analysis tools that assist in implementing a specific design method, ideally the information communicated via a DMO would be automatically generated as the output from a decision analysis software package and integrated into the DSO. With the information represented in OWL, distributed designers could easily share design knowledge across multiple software platforms. Design documentation would then become an inherent consequence of the design tools that designers already rely on. Furthermore, programs or methods written against the ontology-based framework would allow the output from a decision analysis tool to be operated on by another software tool. Thus, the framework would become a means of facilitating machine-to-machine interoperability.

The approach developed provides a semantic-based, web compatible means for distributed designers to communicate decision information regardless of the decision method. The semantic-based approach supports the development of a more sophisticated search and retrieval methods that are based on meaning instead of text string comparison. This can be achieved by extending OWL with the semantic web rule language, which allows for a powerful inference mechanism to act on a knowledge base. As the framework is built upon web technologies, the information is easily shared via the web. Representing core decision-making concepts in the DSO and allowing the DSO to be extended through DMOs means that the design rationale layer can be easily customized for any decision-making method.

Further research focused on exploiting the structure and relationships of the DSO to develop automated retrieval methods to assist designers in reusing past knowledge. For decision making in engineering design, the ability to automatically retrieve lessons learned from a knowledge base consisting of related design appli-

cations is important. Automated retrieval requires an algorithm to assess the similarity between past knowledge artifacts and current knowledge instantiations. Case-based reasoning (CBR) research has long investigated means for achieving automated similarity assessment and subsequent retrieval of information from a knowledge base. To illustrate the ease of application of CBR methods to ontological knowledge structure, Rockwell [56] extended the DSO to include the concept of lesson learned. Each lesson learned instance specifies the relevant application area and process. Here, the application area referred to the product/component that the originating issue was related to, and the process described the type of information contained within a lesson learned instance as it applies to the product development process (e.g., function, geometry, and manufacturing). The application area and process were used as indices for determining the similarity between each lesson learned and each issue instance. A distance-based approach was applied to the semantic structure of the information model to allow for partial matching when the indices were not exact matches. Thus, the retrieval mechanism used the indices and the structure of the information model to provide designers with relevant lessons learned. If a lesson learned instance was determined to be similar to an issue instance, a relationship that revealed this similarity between the two instances was created in the knowledge base. The most straightforward type of similarity match is when the indices for a lesson learned and an issue match exactly. The following was the pseudocode used for this situation:

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if (Issue A has Application Area X and Process Y) and
(Lesson B has Application Area X and Process Y) then
(Lesson B is relevant to Issue A)
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More complex partial matching and heuristic-based measures were also implemented as semantic rules and were used for assessing similarity. Full details of the automated retrieval method developed, and continuing research can be found in Rockwell [56].

Ultimately, the goal of a semantic-based approach is to also facilitate machine-to-machine interoperability. That is, many off-the-shelf decision analysis tools exist that assist in implementing specific design methods. Ideally, the information used in a decision analysis tool would be communicated via a DMO and integrated into the DSO. Designers and semantic rules could then access and operate on the imported knowledge, make changes if needed, and send information back to the decision analysis tool for a new analysis. This would also facilitate design documentation as engineers already rely on many design tools. If information could be exported from these tools in an OWL representation, then the design documentation would become an inherent consequence of using the design tool. Many of the techniques and technologies that needed to realize this ideal are not yet developed, and much research in this area is still ongoing.

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