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ENGINEERING DESIGN ONTOLOGIES – CONTRASTING AN EMPIRICAL AND A THEORETICAL APPROACH

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ABSTRACT
This paper presents the result of the research that compares two previous and separate efforts of the authors to develop engineering design ontologies with a longer-term aim to produce a useable and theoretical sound ontology. The research methodology adopted was to examine each of the concepts and relations contained within each of the ontologies, *Design Ontology*, *EDIT*, with respect to the other. The comparison process resulted in examination and evaluation of both ontologies, with a few minor changes resulting from this. Also the importance and need for two different views, one which is theoretical sound, while another that is applicable is recognised and argued.

Keywords: Ontology, indexing knowledge, design theory and empirical research

1 INTRODUCTION
Engineering design researchers are increasingly interested in the development of an ontology for engineering design. An ontology can be described as an formal specification of a shared conceptualization, which can be taxonomically or axiomatically based [1]. The motivation for developing an ontology includes knowledge sharing and developing a standard engineering language. One particular motivation is to provide a structured basis for navigating, browsing and searching information through the hierarchical descriptions of the ontology. This is especially useful when designers are not aware of the information available or have difficulty in forming suitable queries. Designers can retrieve the documents by submitting natural language queries or navigating the ontology space.
The starting points of this research are the two previous and separate efforts of the authors to develop ontologies: 1) the *EDIT* (*Engineering Design Integrated Taxonomies*) built upon empirical research [2] and 2) the DO (*Design Ontology*) built upon theoretical background [3]. This research aims to compare both efforts and approaches with a longer-term aim to produce a useable and theoretical sound ontology. By combining both understandings it is hoped to better support engineers when generating, visualizing, structuring and classify knowledge, and to support engineering designers in problem solving and decision making.

2 BACKGROUND
A long list of literature brings descriptions of ontologies and their intended purposes for the different areas of human activities. In the product development research area, motivation for building ontologies arises from needs in the business process reengineering (where we need an integrated knowledge model of the enterprise and its processes, organisations, goals, and customers), in distributed design among multicultural teams (where different participants need to communicate and solve problems), and in concurrent engineering and design [4]. Therefore, the use of ontologies in product development could be divided as a foundation into the following categories:

- The business processes formalization;
- Achievement of full interoperability between different participants (humans and computer systems) of development process;
- Effective implementation of engineering knowledge management methods and tools.

The approaches undertaken for the development of both ontologies are described together with the approach to integrate these efforts.

2.1 *EDIT* - Engineering Design Integrated Taxonomies

Engineering Design Integrated Taxonomy (*EDIT*) was developed through a systematic methodology aimed at gaining a cognitive understanding of engineering designers [5]. The ontology was developed within the context of the aerospace industry and its primarily application is in managing design documentation through the provision of an indexing structure. One of the motivations for developing *EDIT* was to provide a visible indexing structure to users searching for knowledge. There are two main advantages in having a visible indexing structure: (1) assists designers to focus their queries through browsing or navigating the indexing structure; and (2) overcome difficulties of search engines not understanding the context of a query. As search engines improve, they are better at retrieving relevant results. However, even if search engines are able to understand the precise context of a query, they can only be as good as the original query. *EDIT* was developed by conducting interviews within two aerospace companies and analysing designers' descriptions of their design processes.

Eighteen designers were interviewed to understand how designers described the process of designing of particular product from two companies, from which the root concepts of the ontology were elicited. *EDIT* consists of four root concepts as shown in Figure 1:

1. The *design process* itself, i.e. a description of the different tasks undertaken at each stage of the design process. For example, conceptual design, detail design, brainstorming.
2. The physical *product* to be produced, i.e. the product (component, sub-assemblies and assemblies) using part-of relations. For example, a cup or the handle of a cup. In the case of designers working on a sub-assembly or a component of the whole product, the components and assemblies that share a physical or a functional interface with, what is being designed would also be considered. For example when designing a turbine blade, the disc that holds the blade also needs to be considered to ensure the interface between the disc and blade is appropriate.
3. The *functions* that must be fulfilled by the particular component or assembly. For example, one of the functions of a compressor disc is to secure the compressor blade or one of the functions of a cup is to contain liquid.
4. The *issues*, which are considerations the designer must take into account whilst carrying out the design process. For example, considering the unit cost or manufacturing considerations.

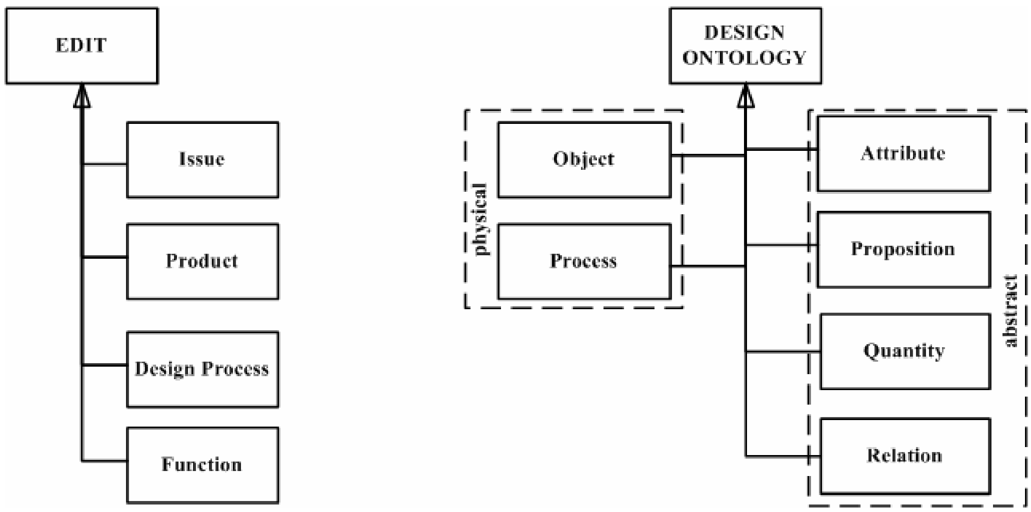

Figure 1. EDIT and DESIGN ONTOLOGY root concepts

The root concepts formed individual taxonomies within the ontology and were validated through indexing a set of 92 documents. Relationships between concepts were extracted as the ontology was populated with instances. The methodology employed during *EDIT* resulted in the development of a generic methodology to develop engineering design ontologies that can be found in [5]. The methodology contains six stages each with at least one clear evaluation step, and is summarized in Figure 2. Each of the three columns illustrates the methodology; research methods employed and;

evaluation procedure for each of the six stages. Each of the rows (excluding title row) represents the six stages of the methodology.

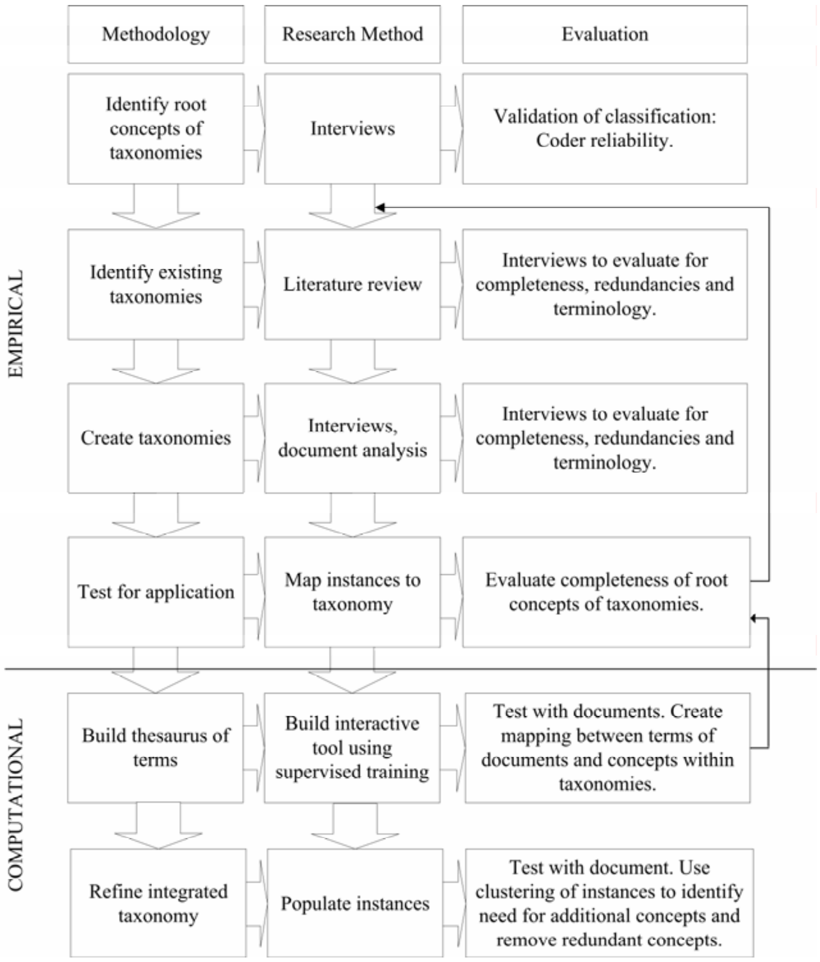

Figure 2. EDIT Methodology for building ontology

2.2 DO – The *Design Ontology*

The *Design Ontology* project has started with the recognition of the "design-as-a-product" ontology as a main presumption for the successful knowledge management and exchange among different participants in product development process. Therefore, in building a general design ontology, the domain description vocabulary has been defined as a desired research result, representing the research aim and constraining the research project. Keeping with the guidelines of the general ontology development process, the *Design Ontology* building process was conducted in six stages following the previously mentioned *EDIT* methodology, however the research methodology employed focused upon understanding engineering design theory rather than the described empirical approach (Figure 2). Accordingly to the methodology, empirical research has included domain documentation analysis (theoretical models, industrial reports, and software documentation), identification of the key concepts and relations between them, and classification of the concepts and relations into taxonomies. The existing achievements in developing of the Genetic Design Model System - GDMS [6] have been selected as a main theoretical background because it seems to be able to capture the totality of results created in product development projects, and it is a more comprehensive in comparison to other design/product model systems that can be found in literature. After extraction of the vocabulary entities, the main concepts has been characterized and formally defined. As the result of the previous process the vocabulary contents has been classified into six main subcategories divided between physical and abstract world as is shown on the Figure 1, according to SUMO (Suggest Upper Merged Ontology) proposal [7]. Categorization of the relations that exist between the concepts based upon their logical properties of symmetry, reflexivity, and transitivity was the next step of the research. The ontology has been evaluated based upon coder reliability, which takes into consideration the agreement of the relevant experts in the researched field and subtract the percentage of the agreement that can be expected from chance. In the final step of the research, a computer thesaurus has been created using the Ontoprise® ontology development environment (*www.ontoprise.de*). Using the thesauri, the knowledge evolved during a real product development case study was described, and the set of instances created were used for the ontology model to check consistency and for refinement.

3 RESEARCH METHODOLOGY

The research methodology adopted was to examine each of the concepts and relations contained within one of the ontologies, *Design Ontology*, with respect to the other, *EDIT*. Since not all of the concepts and relations contained in *EDIT* are contained in *Design Ontology*, this process was then repeated but starting with *EDIT*.

The ontologies were examined in order to:

- Identify concepts that were in common, these may have had different labels.
- Identify concepts that were only present in one of the two concepts
- Identify relations employed between concepts, for those that were common between the two ontologies, and to understand the relationships between the different concepts within each of the ontology. This is important as even if both ontologies contained the same concepts, their placement within the ontology could be different due to the relations employed between them.
- Compare the placement of common concepts in each of the two ontologies.

During the comparison process, both ontologies were also validated through examination against one another. The evaluation focused upon:

1. What is missing and is redundant from *Design Ontology*?
2. What is the applicability of *Design Ontology*? Identifying concepts which are too abstract for specific purpose.
3. What is missing and is redundant from *EDIT*?
4. Evaluate the theoretical background of *EDIT*. Hence, moving from a concrete and specific case study to a generic ontology.

4 RESULTS

The first comparison of the ideas behind the two approaches and their results brought out the understanding of the main difference between them: the starting point of the *Design Ontology* is to describe the "design as a product", and of *EDIT* is to describe "design as an activity", incorporating product and process. Realizing this difference was the key for the understanding of the nature of the ontologies' concepts and relations necessary for the characterization of their overlapping, and mapping between the two ontologies. The quick overview through the ontologies' proposals and the way they were presented brought out another difference. The hierarchical structure of the *Design Ontology* elements represents the *is-a-kind-of* relationships, highlighting in such way taxonomy of the general and more specific concepts and elements of the different kinds. In contrast, the structure of the *EDIT* contains different kinds of relationships between concepts: *part-of, type-of* and *has-a*. Because of this understanding, authors have decided to separately consider the nature of the concepts and the nature of the relations in order to ensure the observation of the possible mapping on the same level.

4.1 Mapping of the Concepts

At the start of the research, it was recognised that mapping all the concepts directly from the one ontology to another was not an expected resulted. After the preliminary research, authors have concluded that it could be relatively easy to map the top level concepts, because their definitions are easily understandable and similar from both the theoretical and the practical viewpoint (Figure 3). For the concept on the lower levels, the situation was not so obvious, because the concepts of the same kind in one ontology might be in different places in the second ontology.

The mapping of the concepts from the *EDIT* to the concepts in DO could be done as follows:

- The *product* (*EDIT*) could be mapped to the concept of the *material object* (DO) because they both represent the physical result of the product development process.
- The *design process* (*EDIT*) could be mapped to the concept of the *process* (DO) because both represent the chain of activities that should be completed in order to define the physical product.
- The *issues* (*EDIT*) could be mapped to the concept of *design attribute* (DO) because both

represent the considerations that should be addressed by the engineers during the product development process in order to describe their solutions.
- The *function* (*EDIT*) could be mapped to the concept of *function* (DO) as they both represent the functions or the expected purpose that each product (including component and assemblies) should address.

Mapping of the concepts in the opposite direction, from the DO to the *EDIT*, brought out more problems, described as follows:

- In DO *content bearing objects* exists explicitly as physical object that are bearing some informational content (e.g. document). As a contrast, *document* is not explicit defined as a concept in *EDIT* but utilise the ontology to be indexed, and is an instance, which any numbers of concept may be linked to.
- *Operation* is defined in the DO as the smallest single step of the *activity*, but it is outside of the scope of *EDIT*, it is too prescriptive and therefore was not mapped. The *transformation* defined in the DO could be mapped to the *phase* of the *design process* in *EDIT*, and the *activity* from the DO responds to the single *task* defined as a smallest part of the *phase* in *EDIT*.
- In DO *organisational attributes* are related to each concept and relation (e.g. time of the creation, id, who create, time of the last change, etc.). In *EDIT* they are implicit, linked to the particular *document* as source of the concepts and relations between them.
- The concept of the *flow* from DO could be mapped to the *energy flow function* in the *EDIT*, and the DO concept of *effect* could be mapped to the *energy effort function* in the *EDIT*.
- DO abstract *propositions* like *ideas, facts, principles, plans*, etc. in *EDIT* exist only implicitly and are described in *documents*, so they cannot be directly mapped.
- DO concept of the *collection*, including the concepts of the *groups*, *assortment* and *family*, cannot be mapped into *EDIT*, because those concepts were not anticipated by the *EDIT*. In the same situation is the whole domain of *quantities*.

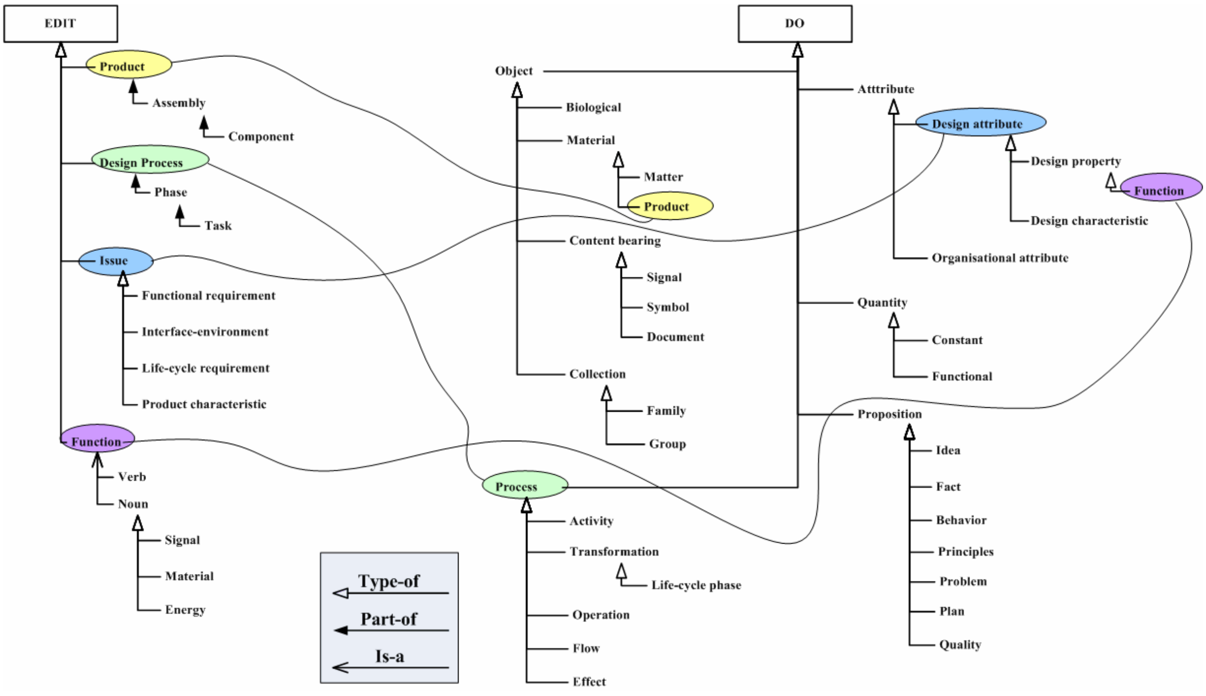

Figure 3. EDIT and DS mapping on the top level

4.2 Mapping of the Relations

Mapping of the relation was only possible on a general level. The reason for this is that in *EDIT* all the relations besides those mentioned *part-of, type-of* and *has-a* are dynamic [8]. They are not part of the *EDIT* definition and they are generated dynamically as the result of a search through knowledge sources (documents) based upon prescribed rules and differ from the case to case. In contrast, DO specify the relation taxonomy as a static structure, and the instances of relations could be only defined based upon these rules.

The three main relations that are part of the *EDIT* taxonomies definition could be mapped to DO as follows:

- *Part-of* (*EDIT*) relation could be mapped to the *compositional relation* as is defined in DO, describing the relation between the complex entities and its constituent.
- *Has*-a (*EDIT*) relation are utilized by taxonomies that are part of the *EDIT* and could be mapped to the class of the *general relations* (DO) describing that an entity is characterized by another entity. *(e.g. function is characterized by verb and noun)*
- *Type-of* (*EDIT*) relation is used by in both proposals as a main relation that is utilized for building the taxonomies – in DO for the whole concepts' taxonomy in a form of the *is-a* relation and in *EDIT* for describing the *issues* and *function* taxonomies.

The seven main class of the relations described in DO could be mapped to *EDIT* as follows:

- *Compositional relations* (DO) could be mapped to the *part-of* relation (*EDIT*) as is explained before.
- *Spatial relations* (DO) could be mapped to the physical relations that could be derived between the *product* and another *product* in *EDIT*, representing the physical connection that exists between the *products* and *issues-product characteristic-geometry-geometric interface*.
- *Case role relations* (DO) represent the role of an entity in a process and therefore could be mapped to the relations that could be derived between the *design process* and *issues* domains (*EDIT*).
- *Dependency relations* (DO) could be mapped to the functional relations that could be derived between the *product* and another *product* (*EDIT*), representing the abstract connection between the two products.
- *Influence relations* (DO) could be mapped to the relations that could be derived between the *issue* and another *issue* (*EDIT*) and also between the *components*, representing the abstract connection between them.
- *Temporal relations* (DO) could be mapped to the *phase* structure in *design process* taxonomy (*EDIT*), representing the time line of the *design process*.
- *General relation* (DO) could be mapped to the relations that could be derived between the four main taxonomies (i.e. top four root concepts) contained within *EDIT*.

4.3 Evaluation of the mapping

The ontologies were evaluated in contrast to the methodology from which they were developed- *Design Ontology*, which is based upon a design theory was examined for its applicability to an applied industrial context, whereas *EDIT*, which is empirical derived and for a particular application in mind was evaluated for its theoretical background.

Evaluation of Design Ontology

During the process of comparing the ontologies, some of the concepts within the *Design Ontology* were re-evaluated. These changes were made as a result of the comparison with *EDIT*, the changes were made if the original concept (or its position within the ontology) was inconsistent, or if it was beyond the limits of an ontology for engineering design. One of the difficulties with an ontology that has a theoretical basis is setting the limits and boundaries, by having a particular purpose (i.e. a concrete application) it is easier to evaluate whether a concept is necessary, and to understand it is positioning.

The *object* domain should be reconsidered in order to understand if/how it differs from the concept of *material* domain. In *EDIT* - *material* is used as part of the *function* taxonomy together with the concepts of *signal* and *energy*, based upon the work of [9, 10]. *Object* in *EDIT* is embedded much deeper- i.e. at a lower lever than in *Design Ontology*. The thinking behind this is related to literature which describes energy, material and signal as the three main concepts that pass through a technical system. Similarly, the *energy* (DO) should be reconsidered in order to be moved from the *process* domain into the *functional qualities*, representing the amount of something that could be measured by standard units.

The concept of *symbol* was removed from the ontology, as was *abstract-propositions-element*, as it was believed to be beyond the boundaries of the ontology. In addition, the following concepts were moved within the *Design Ontology*:

- *Flow*, and *effects* were moved from process to *abstract- quantities-functional quality* domain
- *Abstract-propositions-behaviour* were moved to *attributes*
- The concept of *signal* as a physical *content bearing object* was reconsidered to being *abstract*.

Evaluation of EDIT

The comparison of *Design Ontology* with *EDIT* resulted in the addition of family and assortment related to product. Secondly, as *EDIT* is created primarily to provide a visible browsing and navigational structure when searching for knowledge, and as an ontology to index engineering knowledge. A difference between the treatment of *material, energy and signal* within *EDIT* and *Design Ontology* became apparent; these are treated as abstract within *EDIT*, which is not the case within *Design Ontology*. *Function* is an abstract concept, i.e. the *function* that a product (component or assembly) needs to fulfil may exist before a concept or a product exists. The *function* taxonomy within *EDIT* uses combination of verbs and nouns – the nouns are not all abstract concepts e.g. under *material* there is *material-solid object*. But the use of them as a combination to represent a function means that the concept is now abstract. As a noun independent of a *verb-noun* combination (describing a function) *material-solid* object is physical, and similarly *human* (part of *function-noun-material-human*) maps directly to *Design Ontology physical-object-biological-human*. This difference is related to the application of the ontology - the material, including human and material object are physical, but the use of them as part of a combination of verb-noun is abstract. If *material* were place as physical (and therefore not part of the function taxonomy), it would be difficult for a user (engineering designer) to locate for example, solid object when trying to describe a *function* as the concept will be located away from *function*.

4.4 Need for more than one view

It was found that a theoretical view point may ensure that the concepts and relations are mapped correctly. However, there is a difference between a theoretically consistent ontology and one that is accessible for engineering designers to use. For example, product is a central view point when searching for knowledge, if the concept of the product is to be placed consistent to the theoretical approach (as employed by *Design Ontology*), it would appear as part of the attributes in entity-physical-object-material object and hence would be embedded very deep within the ontology or in *EDIT* would be part of the function-noun-material-solid object. In the application of *EDIT*, and indeed many Engineering Design ontologies, the physical product (or service) is a central view for the users of the ontology. Hence there is a strong argument for *Product* to be at a much higher level, than it would otherwise be. Therefore, there is a need for two different views for an ontology, one which is theoretical sound, and contributes to engine design theory and understanding, while another in a view that is applicable. For each new application we may need new classes below the top level of the *EDIT* ontology, however the theoretical ontology does not necessarily need these.

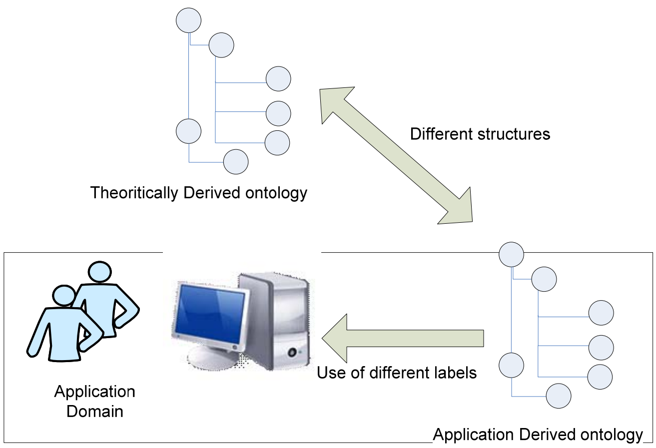

Figure 4. Application and theoretical derived ontologies

Figure 4 illustrate the two ontologies, with communication between the theoretically derived and one derived with a particular application in mind. The two ontologies may exist with different structures, but overlapping concepts. The ontology derived for a particular purpose, may use different labels for concepts in different context and for different users, however the concepts, relations and structures stay the same.

5 CONCLUSION

The comparison of the two separate ontologies, *Design Ontology* with a theoretical foundation and *EDIT*, with an empirical foundation has been undertaken. The process of comparing the ontologies required a deep understanding of the concepts, classes, relations contained within both ontologies. The comparison process enabled the researchers to gain a deep understanding of an alternative research approach to their own, and to validate the two ontologies. Despite the different approaches employed, the vast majority of concepts and classes were common to both ontologies. All of the top levels contained in *EDIT* could be found in *Design Ontology*, however the taxonomies (e.g. function, and issues) may be fragmented and placed in different locations. That is some of the concepts could be found in more than one place, e.g. nouns that are physical, but when used in combination with verbs to describe a function become an abstract concept. The comparison process resulted in an evaluation of both ontologies, with a few minor changes resulting from this.

It was found that it is difficult to set the boundaries of a theoretical ontology - by confronting these with an applied ontology *EDIT* some of the boundaries became apparent. Without testing a theoretical ontology it is difficult to assess the validity, in terms of usefulness for the particular application. Similarly, an ontology that is based empirical with a particular purpose in mind, such as *EDIT* which is primarily focused on indexing of engineering design knowledge may be presented from the viewpoint of the user in that particular application, hence concepts may be placed differently from theory. These conclusions point to the need to have more than one view for an ontology- a theoretical sound ontology is not necessary applicable to a specific application.

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