FSB University of Zagreb / Faculty of Mechanical Engineering and Naval Architecture

THE DESIGN ONTOLOGY
Contribution to the Design Knowledge Exchange and Management

(short English version, original in Croatian)

by

Mario Štorga

A thesis submitted to the University of Zagreb

for the degree of

Doctor of Philosophy

Department of Design and Product Development

Faculty of Mechanical Engineering and Naval Architecture

University of Zagreb

Zagreb, Croatia

2005.

SUMMARY

The Design Ontology – Contribution to the Design Knowledge Exchange and Management

Keywords: formal design model, design ontology, genetic design model system, thesaurus, taxonomy, knowledge management

In order to comprehend the main features, advantages and shortcomings of the traditional and distributed product development an extensive multidisciplinary literature overview is given at the beginning of the thesis. Analysis of the activities, methods and tools included in development process resultet with the proposal of domain ontology as a base for the knowledge management and exchange among different participants. Therefore, the product knowledge vocabulary as the first step in building product development ontology has been defined as a desired research result representing the research aim and to constrain the research project. In the methodology for development of the vocabulary two steps could be identified: empirical research and computer implementation. Empirical research has included domain documentation analysis (theoretical models, industrial reports, 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 [Mortensen, Andreasen 1999] has been selected as a theoretical background of the presented research. GDMS has been selecetes because it seems to be able to capture the totality of results created in product development projects, and it is a more comprehensive comparing to the 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 previously described process the vocabulary contents has been classified into six main subcategories divided between physical and abstract world. Categorization of the relations based upon logical properties of symmetry, reflexivity, and transitivity is one of the thesis results. The vocabulary has been evaluated by testing proposal reliability based upon method that takes in consideration the agreement of the relevant experts in the researched field and subtract the percentage of the agreement that can be expected from chance. As a next step in the research, the computer thesaurus has been created using the *Ontoprise®* ontology development environment. Using the thesauri, the knowledge evolved during the real product development has been described, and created set of the concepts and relations instances has been used for the vocabulary model consistency checking and refinement. Dissertation finishes with the proposal of the methodology for the vocabulary implementation based on the three-tier architecture of the system for the knowledge management and exchange.

Acknowledgement

This research is part of funded project "Models and methods of improving the computer aided product development" supported by the Ministry of Science and Technology of the Republic of Croatia. The presented research is result of the co-operation with the research group of Section of Engineering Design and Product Development, Technical University of Denmark. Therfore, the presented thesis was supervised by Prof. Dorian Marjanović, University of Zagreb Croatia and Prof. Mogens Myrup Andreasen, Technical University of Denamark. I would like to express my gratitude to both of them for the knowledge and expertise in their guidance of the work as well as for creating inspiring and creative research atmosphere. I would also like to thank to all other collegues at both univeristies for the professional and friendly help their provide me during my research.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

1. Introduction

It is generally recognized that possessing and utilizing engineering knowledge is one of the enterprise's most important assets, decisively influencing its competitiveness (Abecker et al. 1998). Large engineering projects involve the resources of many different clusters of cooperative subjects (human and computer) in the given situation. Each cluster makes its own contributions, and the overall success of the project depends in large measure on the degree of integration between those different clusters throughout the product development process. Product development (PD) context as the main object of the product development projects, is defined in previous work (Štorga and Andreasen 2004) as the entire body of data, information and engineering knowledge related to design itself and its circumstances, that evolves throughout the product development efforts. In addition to the dynamic and complex nature of the PD context an enormous problem in the coordination of large engineering projects is the diversity of backgrounds the various groups of engineers bring to their respective role. As a consequence, many engineers use apparently identical symbols (words, signs, etc.) with different meanings for describing concepts in product development domain and utilize those descriptions in different ways. To avoid such ambiguity it is necessary to define a unified vocabulary that may lead to the formal design model for articulating PD context instantiations in appropriate design situations.

The ability to fix a product development domain vocabulary and its meaning is critical for true concurrent engineering and engineering knowledge exchange and management (Perkhart et al. 1994). A key to effective integration of product development resources is the accessibility of rich ontologies characterizing each of the domains addressed during the product development process. For instance, access to a manufacturing ontology that includes constraints on how a given part is manufactured can aid designers in their design of a complex product by giving them insight into the manufacturing implications of their design concepts. Similarly, access to a engineering ontology that includes constraints on how a given part is to function given a particular shape or fit can aid process planners in their development of the appropriate manufacturing processes. A commonly accessible collection of relevant ontologies thus permits more efficient engineering knowledge exchange and management, and arising from various sources within the enterprise.

With this research motivation, this document present results of the research project aimed to the development of a *Design Ontology* founded on the Genetic Design Model System (GDMS) (Mortensen 1999, Hansen and Andreasen 2002). Presented formalization of the GDMS allows discussion on creation and utilization of more definite design models comparing to the existing descriptive models in the research area.

2. Research aim and methodology

Usually different domains have different terminologies or distinctive vocabulary used to describe characteristic concepts that comprise the particular domain. But the domain space is not revealed in its corresponding vocabulary only. In order to form the logically correct statements about a situation in a domain, rules and restrictions governing the way terms in vocabulary should be utilized, must be provided and clarified. Such rules and restrictions are often called domain axioms. The role of axioms is to constrain the meaning of the terms in a vocabulary sufficient to enable consistent interpretation of statements based on the vocabulary. Only with this additional information available, it is possible to understand both the nature of the individual concepts that exist in the domain and the associations they bear to one another. Domain vocabulary together with set of precise definitions (axioms) in literature is usually considered as domain ontology (Perakath et al. 1994). A related motivation for the researches on the building of domain ontology is the standardization of terminology in order to realize description, explanation, understanding and reusing of domain knowledge.

The ability to determine a product development domain vocabulary in the context of engineering knowledge management seems to be important for the integrated product development. The presumption of effective product development could be existence of product development ontologies, distinctive for the different viewpoints of different participants throughout the development process.

The *Design Ontology* should be considered as a first step in a research with a long term goal of defining "general product development ontology", because a product (design) as the result of the product development projects could be easily identified as the common object of interest across the greatest part of the product development activities.

2.1 Ontology definitions

The concept of ontology generates a lot of controversy in discussions that are outside the scope of this research, however a brief introduction follows.

The concept of ontology is generally thought to have originated in early Greece and occupied Plato and Aristotle. Students of Aristotle first used the word 'metaphysica' (literally "after the physics" because these works were placed after his works on physics) to refer to the work their teacher described as "the science of being 'in the capacity' of being" More precisely, ontology in philosophical sense concerns determining what categories of being are fundamental and asks whether, and in what sense, the items in those categories can be said "to be". In the last decade, the word ontology became a relevant word for the knowledge engineering community that has borrowed it from philosophy and has given its meaning a twist (Corcho 2003). Important research issues of the knowledge engineering community is not what the nature of being is, but what an artificial system has to reason about to be able to perform a useful task (Borst 1997).

The Neches and colleagues (Neches et al. 1991) proposed the new definition: "Ontology defines the basic terms and relations comprising the vocabulary of a topic area as well as the rules for combining terms and relations to define extensions to the vocabulary". Such descriptive definition explicates building blocks of ontology, and gives some vague guidelines: the definition identifies basic terms and relations between terms, identifies rules to combine terms, and provides the definitions of such terms and relations. In one of the recent and often used definition Studer and colleagues (Studler et al. 1998) claim: "Ontologies are defined as an explicit formal specification of a shared conceptualization". Conceptualization refers to an abstract model of some phenomenon in the world by having identified the relevant concepts of that phenomenon. Explicit means that the type of concepts used, and the constraints on their use are explicitly defined. Formal refers to the fact that the ontology should be machine readable.

Today, ontologies are widely used in different areas (natural language processing, knowledge management, e-commerce, intelligent integration information, the semantic web, etc.) being matter of research of different research communities (i.e. knowledge engineering, database and software engineering). To "popularize" or simplify it Uschold and Jasper (Uschold et al. 1999) provided a new definition for the concept of ontology: "Ontology may take a variety of forms, but it will necessarily include a vocabulary of terms and some specification of their meaning. This includes definitions and an indication of how concepts are inter-related which collectively impose a structure on the domain and constrain the possible interpretations of terms."

It may seem that there is not much difference between ontology and a data dictionary. However, a data dictionary is typically a compendium of terms together with definitions for the individual terms stated in natural language. By contrast, the grammar and axioms of the ontology are stated in a precise formal language with a very precise syntax and a clear formal semantics. Consequently, ontologies are far more rigorous and precise in their content that a typical data dictionary. The advantage of formal definitions is that they provide formal base for the logical reasoning based upon statements built using the definitions; the disadvantage is that these definitions are much more difficult to construct.

Ontologies can be built around a single taxonomy or several taxonomies and their relationships (Gilchrist 2003). Associations between ontology entities and real objects (in a domain of discourse), as well as the constraints on and between domain entities are explicit thus minimizing the risk of misunderstanding logical connections within the domain. Domain ontologies are therefore aimed to capture consensual data, information and knowledge in a generic and formal way, so that it can be reused and shared across different applications (software) and by different groups of people.

2.2 Roles of an ontology in the product development

In the product development area, motivation for building ontologies is the integration of the models in different sub domains of the development process into a coherent framework (Uschold 1996). This 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.

The utilization space of the product development ontologies could be sub divided into the following categories:

- Foundation for the business processes formalization;
- Foundation for achievement of full interoperability between different participants (humans and computer systems) of development process;
- Foundation for the effective implementation of engineering knowledge management methods and tools.

The idea behind the research presented in this document was that implementation framework built around proposed *Design Ontology* should provide the features for solving the existing difficulties in effective achievement of the engineering knowledge management and exchange:

- ontology provides formal syntax and semantic definitions necessary for the unambiguous articulation of the knowledge
- different ontology abstraction levels help in avoiding the situated nature of knowledge management
- semantic rules and deduction mechanisms resolves complexity of the knowledge model
- semantic interoperability based on ontology is a communication medium between heterogeneous participants (human and computer) in the product development processes.

2.3 Ontologies research in engineering design area

Several research groups have emphasised the importance of a sharable ontology for systematic exchange and management of the engineering knowledge in engineering design field. One of the first research projects in engineering design field is ontology called YMIR (Alberts et al. 1994) that specifies taxonomy of concepts for engineering design which define the semantic of design knowledge in multiple engineering domains. The concepts of YMIR represent generalisation of the concepts used in the individual design domains, such as electrical engineering, mechanical engineering, and civil engineering. The same ontological basis was used for the integration of the design synthesis knowledge and design standards in design process.

The ontology of generic design activities based on published literature and corroborated by design practice was presented in work of the Sim and Duffy (Sim et al. 2003). Is ontology categorised the activities as design definition, evaluation and mangement. The ontology of generic design activities is seen as providing a consistent and coherent description of the interpretation of typical design activities upon which design education, system developers and design researchers can further work in design research and practice.

Ontology-based systematization of functional knowledge has been presented in the work of Kitamura and Mitzoguchi (Kitamura et al. 2004). The main contribution of this research is a framework of systematization of design knowledge about functional decomposition that has been deployed at electric industry in Japan with successful results.

Ahmed in her work (Ahmed 2005) presented the empirical research study aimed at understanding how designers described the process of designing a particular component or assembly and use this understanding to identify the key concepts for a method of indexing design knowledge. The presented method is intended to capture engineering design knowledge as part of a knowledge capture system and was evaluated on the real industry examples.

In one of the recent contributions in this research field Darlington and Culley (Darlington et al. 2005) concerns development of ontologies for supporting engineering design. In this research authors explored the process of developing ontologies for use in real world problem solving and showed, by example implementation, how the ontologies that have been developed to capture suitable domain knowledge might be used for the purposes of supporting engineering design requirement capture. This research is illustrating in one way the general potential of ontologies for engineering design process support.

The research on *Design Ontology* presented in this document is focused on the result of the design process while most of the presented approaches are focusing the process itself among the other issues. The other important difference with mostly of described approaches is that the *Design Ontology* is defined in terms of well-founded and widely accepted theoretical basis that exists in the design research area (excluding the YMIR built based upon System Theory), and is one of the rarely attempts to formalize those foundations that are existing as a background of the number of the researches in this field. In the same way presented research brings kind of questioning on theoretical background consistency, and possible add a new value and understanding in a manner of the categorization and explanation of the nature of the different kind of relations that exist between the terms that are used in domain of discourse.

2.4 The ontology building process

Any ontology development process is focused on understanding of the concepts in the particular domain from multiple perspectives. Researchers from varied field such artificial intelligence, philosophy, data management, mathematics, engineering, and cognitive science study ontologies using the different foundations and methods. That is the reason why the building of the ontology differs from traditional information capture activities and breadth of the knowledge captured.

The ontology life cycle process is usually a discovery process and requires extensive iterations, discussions, reviews and introspection. It requires a process that incorporates both significant expert involvement as well as the dynamics of an ontology engineering group effort. The general ontology life-cycle process could be summarized by the following phases (Perakath et al. 1994; Lenat at al. 1990; Uschold et al. 1995; Gruninger et al. 1995, Kayed, A., 2002):

- Building - there are many attempts to define a methodology for ontology construction but the necessary steps could be summarized as:
    - Organizing and scoping. This phase involves establishing the

purpose, viewpoint and boundary for the ontology development project.

- o Data collection and analysis. This phase involves acquiring the raw data needed for ontology development. Main data sources are the domain experts' publications (scientific articles, thesis, reports, and industrial papers) relevant to the circumscribed ontology. Collected data should be analyzed to facilitate an ontology extraction, by following activities: listing the concepts of interest in the domain, identification of the concepts that are on the boundaries of the ontology, looking for and individuate internal systems within the boundary of the description.
- o Ontology development, refinement and validation. This phase involves developing an initial ontology from acquired data. Initial set may refer tentative terms, attributes and relations that are subject to further inquiry before final change of status. The ontology structures are then instantiated with actual data, and the result is compared with the ontology structure. Refinements to the initial ontology are incorporated to obtain a validated ontology.

- Manipulating - an ontology query language and mechanisms should be provided for browsing and searching; efficient lattice operation; and domain specific operations.
- Maintaining - ontology developers should be able to syntactically and lexically analyze the ontology, add, remove, and modify definitions, translate from one ontology language to another in order to ensure portability and extension of the developed ontology.

Keeping with the guidelines of the general ontology development process was aimed in the research presented in this document to the formalization of a *Design Ontology*. The *Design Ontology* building process was conducted in six stages following the EDIT methodology (Ahmed et al. 2005) (see figure 1), however the research methodology employed focused upon understanding engineering design theory rather than the empirical approach.

Each of the rows on the figure 1 (excluding the first heading row) represents one of the stages, and the three columns represent the: stage description (column one), the research methodology employed for this stage (column two) and the evaluation undertaken for this stage (column three). The first four stages were based upon empirical research methods thus stages five and six employed computer tools and were determined based on the results of the first four stages outcome. The particular research steps are presented in following sections.

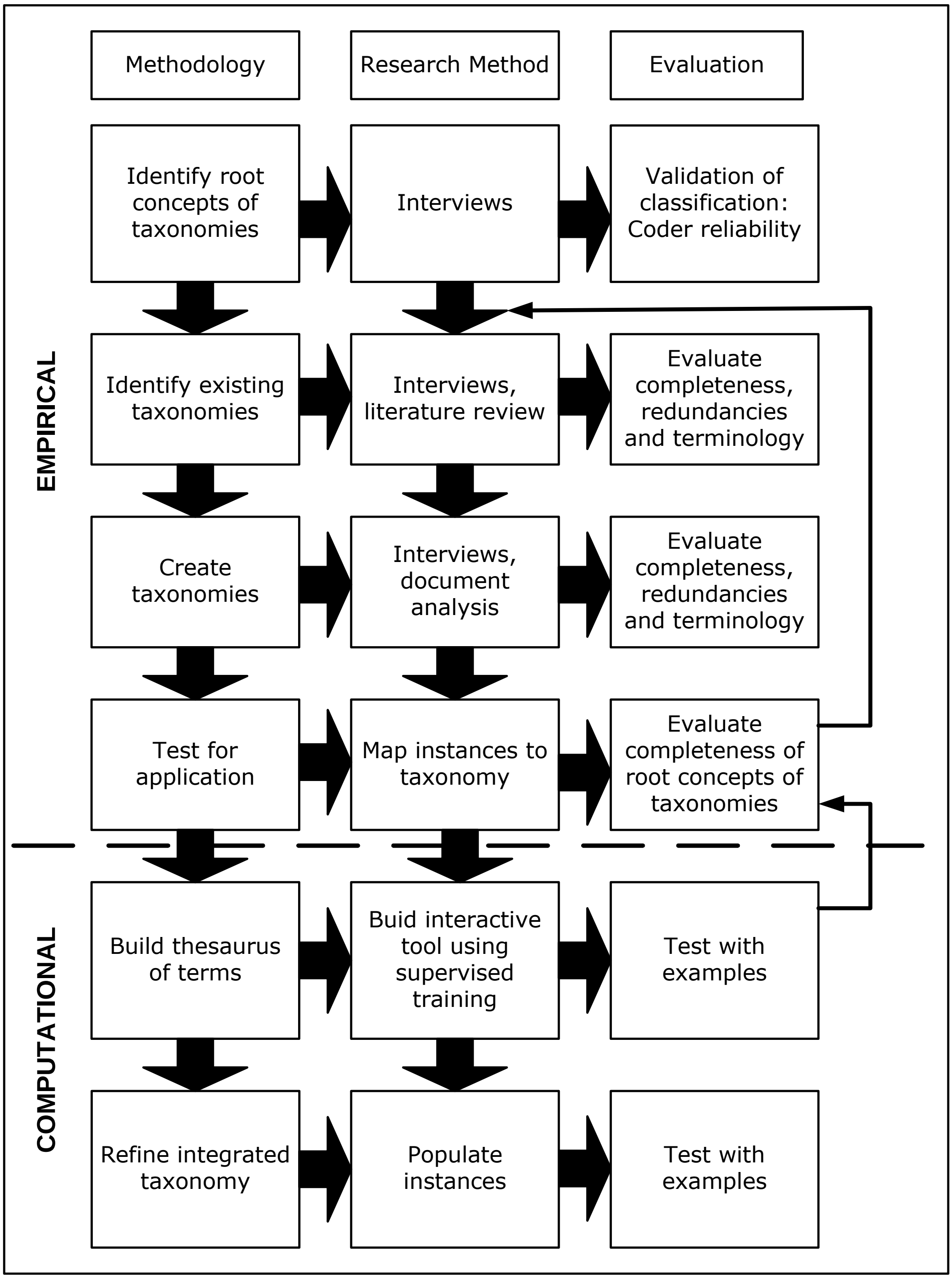

Figure 1 Methodology for building integrated taxonomies (Ahmed 2005)

3. Building the Design Ontology

Different models of design and design process which attempt to represent the essence of design, contribute to the design science and engineering practice in their own way (Duffy and Andreasen 1995). Interesting thing about these models is their variety and the fact that they emphasise different aspects, according to the interpretation or findings of the author(s). Theoretical design models are mainly built upon the "reality" of design and main objective of the different research projects is to continually evolve theoretical models into the tools and methods to support engineering design. The reality and models act as criteria for critical and objective evaluations of the consequent tools, and when employed as tools they affect the "reality" in which design is taking a place. To better explain the role of the *Design Ontology* that was considered in presented research project, the traditional design modelling research approach proposed by Duffy and Andreasen (Duffy et al. 1995) was extended for the role of the ontology (see figure 2).

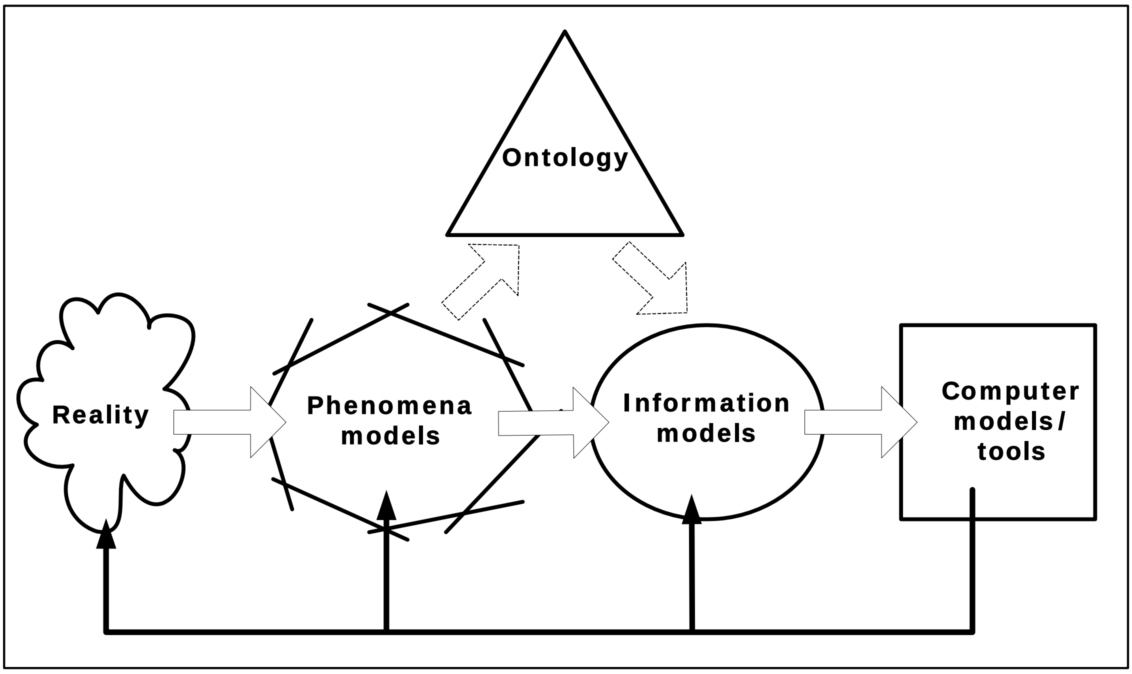

Figure 2 Role of ontology in transformation from reality to computer model (extended after Duffy *et al.* 1995)

Phenomena models are primarily based upon observation and analysis of the "reality" of design, and the uses of the tools employed. Where appropriate, these models could be developed in more detail as information models and further as computational models/tools. Since the most of the contemporary phenomena models contribution are models that are informal, author believe that would be necessary to define the formal framework for articulating the phenomena models content in order to ensure reliable exchange and management of the knowledge about phenomena. Therefore the presumed role of the ontology is to provide the way for a community to agree upon the meanings of terms used to reason about the entities of the phenomena and the relations between them before implementation of that knowledge as informational and computational models.

As an extension to the traditional association relations that exists between information elements in traditional information models, relations in ontology include other kind of the relations, as well as the rules or axioms related to their behaviour. In such way, the more automatic reasoning could be performed on the captured statements, and new statements could be derived based on them.

One of the existing phenomena models in the design research field - the Genetic Design Model System (GDMS) proposed by Mortensen (Mortensen 1999), was chosen in this research as a main foundation and source for extracting the content of the *Design Ontology*. Built upon strong theoretical background including the Theory of Technical Systems (Hubka et al. 1988), Theory of Properties (Hubka et al. 1988), Theory of Domains (Andreasen 1980), Design Process Theory (Hubka 1976, Pahl & Beitz 1988) and Theory of dispositions (Olsen 1992), GDMS seems to be able to capture the entirety of results created in product development projects, and it is a more comprehensive compared to the other design/product models described in literature (see table 1).

Table 1 Relating the GDMS to existing design model systems (Mortensen 1999)

Authors: / **Models types:**	**Krause 1988**	**Blessing 1994**	**Anderl & Grabowski 1991**	**Salminen & Verho 1991**	**Tomiyama 1989**	**Gielingh 1989**	**Rosenman & Gero 1998**	**ISO STEP 1997**	**Meerkam 1995**	**Erns & Verhulst 1995**
Model object: The life-cycle										
Technology model	■									
Transformational model	■			■			■			■
Relation property model	■			■			■		■	
Product life model	■								■	
Model object: The design										
Working organ model		■	■	■	■	■	■	■	■	■
Function model	■	■	■	■	■	■	■		■	
Inherent property model	■	■		■			■			
Part model	■	■	■	■	■	■	■	■	■	■
Model object: The life phase system										
Life phase system model	■			■						
Inherent property model	■			■						
Model object: The product assortment										
Product family plan										■

GDMS proposal is aimed to capture and maintain the results from engineering design, to handle design synthesis, design rationale, multiple views on design object, and to be reused for the new development projects. The results of the GDMS research project are presented as proposal of the genetic design language contemplated as the set of the infinite designs which are synthesized, based on a design vocabulary and syntactical rules (Mortensen 1999). The principal contents of GDMS have been described by three domain languages (Hansen et al. 2002): transformation-, organ-, and part language. Each of the languages points out the concepts of different types which can be utilized for creating the formal design models.

In order to face semantic diversity of the possible relations between the different terms in all three domains, and to assume the integrity and a certain robustness of the formal model, at this stage of presented research it was necessary to formalize a general structure of GDMS. In order to achieve the useful formalization of the information structure, the proposal of Mekhilef and colleagues (Mekhilef et al. 2003) about four levels of formalization procedure: epistemological-, domain-, application-, and project modelling level, has been followed.

3.1 Epistemological modelling level

The epistemological modelling level in general is established by defining the general set of entities and possible associations between them in order to correct in logical sense describe the situation in a domain of discourse at the highest level of abstraction. Common sense domain knowledge (knowledge typical of the general population) is usually an important aspect needed for establishing this level (Mekhilef et al. 2003). In addition, the engineering domains require a perspective that is more structured, normative and based on scientifically acceptable views of reality, being less tolerant on contradiction and inconsistency, compared to common sense.

In information science, an upper ontology (top-level ontology, or foundation ontology) is considered as an attempt to create an ontology which describes very general concepts that are the same across all domains. The aim is to have a large number on ontologies accessible under this upper ontology. It is usually a hierarchy of entities and associated rules (both theorems and regulations) that attempts to describe those general entities that do not belong to a specific problem domain. There are several available upper ontologies like Cyc (www.cyc.com), BFO - Basic formal Ontology (www.ifomis.uni-saarland.de/bfo/home), GFO - General Formal Ontology (www.onto-med.de/en/theories/gfo/index.html), SUMO - Standard Upper Merged Ontology (suo.ieee.org), but no one has yet gained widespread acceptance as a de facto standard.

By the overview of existing proposals it is possible to emphasize some distinct advantages of SUMO (Niles et al. 2001) proposal:

- The SUMO is the working effort sponsored by open-source engineering community. This means that potentially users of the SUMO upper ontology can be more confident that this upper ontology will eventually be embraced by a large class of users.
- The SUMO was constructed with reference to pragmatic principles. Any

distinctions of strictly philosophical interest have been removed from proposed upper ontology.

- The SUMO is mapped to the entire WordNet® lexicon (wordnet.princeton.edu). That mapping provides a link between formal content expressed in SUMO and natural language, paraphrasing on such way the hard-to-read logical inscription of axioms into natural language.

Based on such understanding, the SUMO (Niles et al. 2001) has been selected as an epistemological foundation for building the *Design Ontology*. SUMO is an effort by IEEE (www.ieee.org) collaborators from the field of engineering, philosophy and information science, aimed at creation of the framework by which disparate participants may utilize a common knowledge and from which more domain-specific ontologies (i.e. design, manufacturing, etc.) may be derived. SUMO is intended to express and provide definitions for the most basic and universal concepts that are generic and abstract that is general enough to address (at a high level) a broad range of different domain areas. Today, SUMO is a collection of well-defined and well-documented terms, interconnected into semantic network and accompanied by a number of axioms.

At the highest level, terms in SUMO are organized into a single taxonomy (see figure 3) rooted at Entity, representing the most general concept used for a definite descriptor that refers to all physically existent things and all abstract, mentally represented things in the real word.

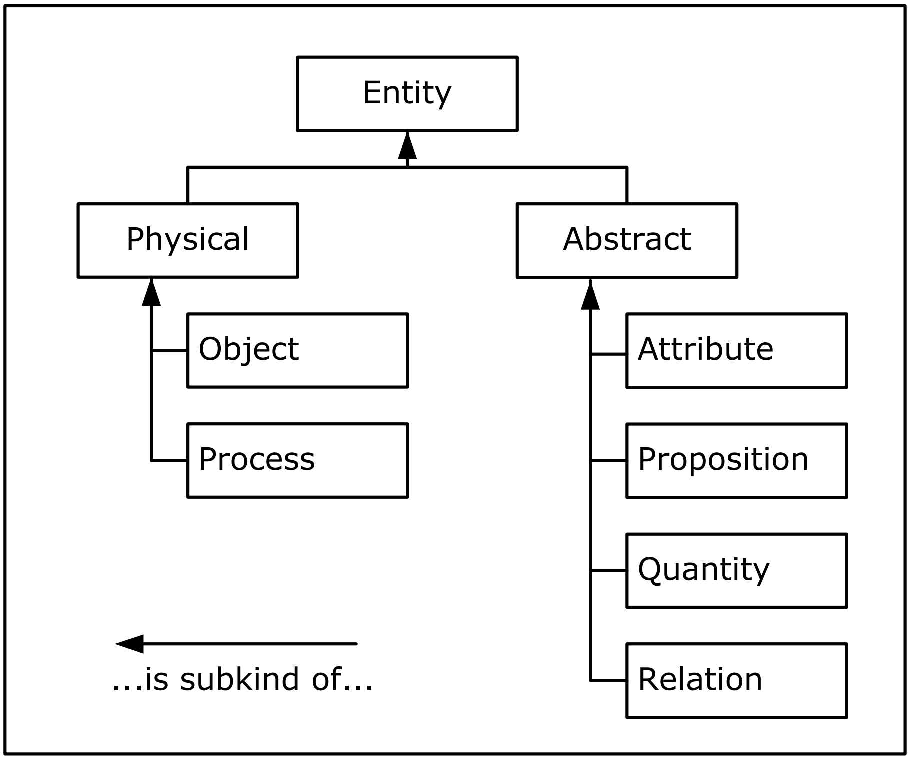

Figure 3 SUMO high level taxonomy (SUMO)

At the top level of the SUMO hierarchy, the concept of Entity subsumes concepts of Physical and Abstract, where former category includes everything that has a position in space/time, and the latter includes everything else. From the viewpoint of the *Design Ontology* building project, the concept of Physical subsumes the disjoint concepts of

Object and Process. The concept of Object is the most general concept of the Entity that exists in space. The concept of Process corresponds to any sustained phenomenon or one marked by gradual changes (space/time). Returning to the highest level distinction in SUMO hierarchy, the concept of Abstract subsumes four disjoint concepts relevant for the *Design Ontology*: Attribute, Proposition, Quantity, and Relation. The concept of Attribute includes all qualities, properties, etc. of an Entity that are not regarded as Object. The concept of Proposition corresponds to the notation of semantic or informational content. The Quantity concept is understood as a count independent of an implied or explicit measurement system together with a particular unit of measure. The concept of Relation is an abstraction belonging to or characteristic of ordered Entity tuples and connects two or more concepts.

In order to formally define concepts expressed in SUMO, the meaning of every particular SUMO term requires careful understanding of its associations to the other terms defined in SUMO. Definitions of all terms in SUMO are formalized in the form of axioms with the purpose to constrain interpretation of terms, and to provide guidelines for automated reasoning systems. An example of such an axiom is:

"#PHYSICAL is an Instance of Physical if and only if there Exists #LOCATION, #TIME so that #PHYSICAL is Located at #LOCATION and #PHYSICAL Exists during #TIME".

The axiom coded in formal logical language SUO-KIF (Niles et al. 2001) is presented with:

```
(<=>
(Instance #PHYSICAL Physical)
(Exists
        (#LOCATION #TIME)
        (And
                (Located #PHYSICAL #LOCATION)
                (Time #PHYSICAL #TIME))))
```

3.2 Domain modelling level

The domain modelling level is established by a set of formal informational structures that describe a situation in particular domain of discourse. This level should be generic in a given domain (product development domain in the case of this research project) and constrained by the content of the epistemological foundation (SUMO upper ontology in this case). According to the results of previous research on GDMS (Mortensen 1999), knowledge about the product/design as the result of the development process is centred on four different conceptual model object or viewpoints (see figure 4):

- *The design* - defines functional, organ and part view on the design/product; inherent properties that are posses by design/product itself, i.e. strengths, ductility, etc.; and design/product view relevant for the different meetings during its life cycle

- *The life cycle meetings* – technology model which define the meetings during the product life; product life model; activity model describing intended and realised activities for the meeting between the design and the operand/environment; and relational property model for the meetings, i.e. costs, lead time, quality, etc.
- *The life phase systems* – model of the systems that gradually realise product life, i.e. production, sales, services with inherent properties
- *The product assortment* - a design normally belongs to the product family or product assortment that can be described by plan that consists of assortment/family elements structure and constraints between them.

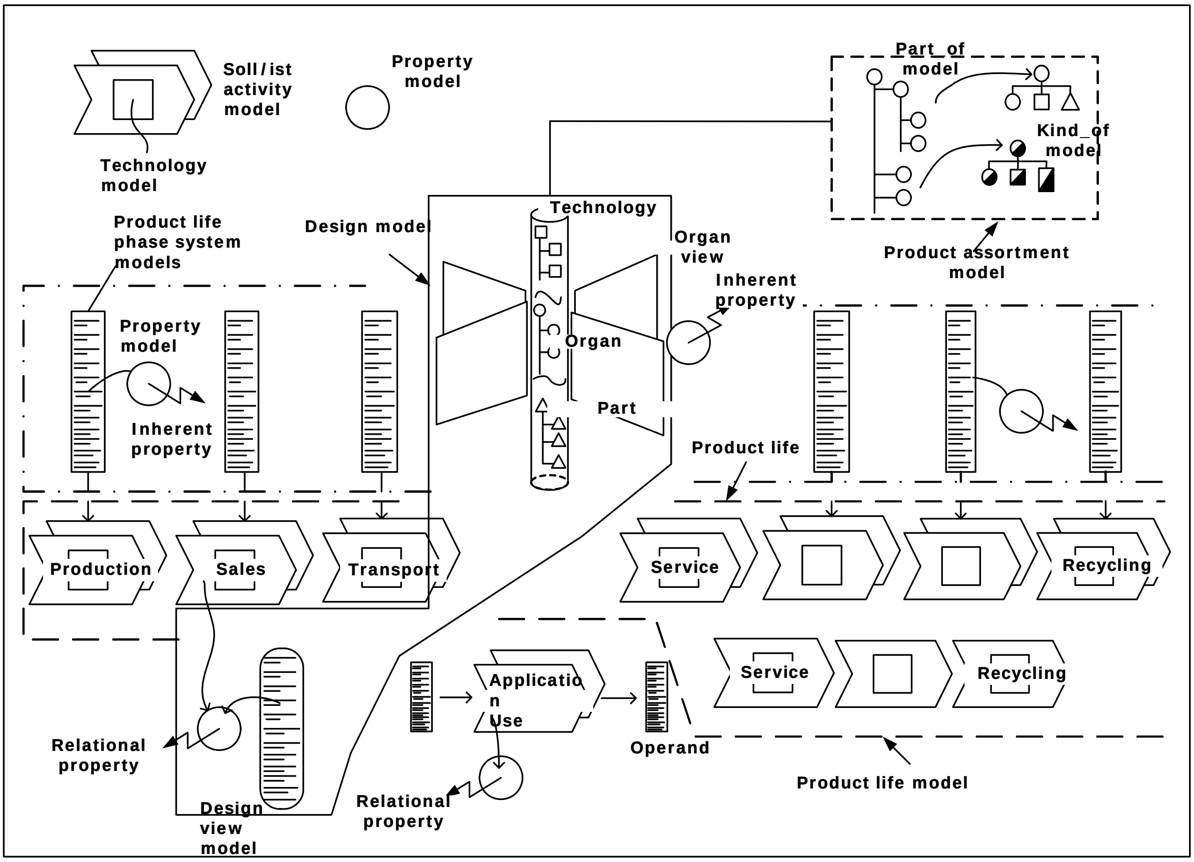

Figure 4 Model systems for product life cycle (Mortensen 1999)

At this stage of research competency questions were applied on those viewpoints to find out more about reasoning, synthesis, selection, documentation, business aspects, organizational responsibilities, etc. Enquiring questioning followed the basic idea, that the product cannot be designed without articulating the design process and fit to product life cycle aspects. That procedure provided us the foundation for the extraction of the main *Design Ontology* terms and associations between them.

The basic terms were defined at the beginning following with the related terms. At this point of research many terms were discarded and duplicates were removed. The terms have been categorized based on SUMO top level concepts (see figure 3), so that terms closely related by nature to each other appear close together. As the result of this stage, the initial *Design Ontology* have provided the intended semantics of the vocabulary and laid the foundations for the specification of terms' definitions in formal language. The final proposal of *Design Ontology* vocabulary is presented in more details in section 4.

3.3 Application and project modelling levels

The application modelling level should be a reuse and extension of a domain level specific for an application in particular domain of discourse (for example configurable design, design for X, etc.). Terms at this level should be organized to characterize specialization of common features specific for the implementation of a domain model in particular use case. As the next research step, the several extensions of the proposed *Design Ontology* are planned. For example, extension covering additional terms and rules needed for achievement of the full traceability among the PD context during a specific design episode (Štorga 2004), will be of especially importance.

The project modelling level in addition extends an application modelling level to include information about additional relevant concepts found within specific implementation project in real working environment, depending on the situation and requirements of the real product development environment. These additional concepts could arise for instance from the specific synonyms for the general defined terms that are used in particular company, customer specifications, company design policies, company internal procedures (regarding organization, safety and confidential tasks, quality standards), company procedures related to implemented PDM or ERP systems, etc.

4. The Design Ontology vocabulary proposal and the terms taxonomy

The first proposal for the *Design Ontology* vocabulary, after extracting and analyzing the core concepts had an informal form, consisting of terms and definitions expressed in natural language. All the extracted terms were categorized and their definitions were derived accordingly to the SUMO and GDMS origins. The terms have been chosen as far as possible to match the natural use of English language. As the result of the described analyze, about 180 different terms of wide variety was extracted and their definitions in natural language were provided. It should be noted here that was not possible to find generally definitions for all terms in theoretical background, especially for the ones that can be in the same time considered as abstract or as physical (design for example is sometimes in the literature used as an abstract specification of the product, idea planned to be realized in a future time, or physical object that is composed and represented in drawings, computer and physical models, etc. having intention/is intended to satisfy or solve a problem).

4.1 The general concepts of ontology

The construction of ontologies for engineering domains requires several modifications in the high level terms' definitions and understanding compared with the more traditional conceptualization (Perakath et al. 1994). The first of these modifications has to do with the notion of a term kind. Generally, a kind is a category of entities that are bound together by a common nature, a set of properties shared by all and only the members of the kind. On the traditional conceptualization, to describe the world via ontology is simply to identify the nature of each relevant kind in a given domain. But ontology is not determined by the natures of things in the domain so much as the roles those things are to play in the domain from semantic perspective. Because those roles might be filled in any of a number of ways by things that differ in various ways, and because legitimate perspectives on a domain can vary widely, it is too restrictive to require that the instances of each identifiable kind in a domain share a common nature. Consequently, engineering domain ontologies require a more flexible notion of kind. The point of the weaker conditions is to allow something to count as a member of the kind even without meeting the stronger conditions of the traditional conceptualization. The too rigorously defined membership conditions are simply too inflexible to capture the subtleties of categorization and grouping in human engineered systems (Perakath et al. 1994).

As the further step, it is important for the purposes of ontology to clarify the term property and attribute from the ontology building process viewpoint. An attribute is best thought of as a mapping that takes each member of a given set of individuals to a single specific value. By contrast, a property is intuitively not such a mapping. Rather, properties are just characteristic of thing, "way thing is", abstract, general characteristic that individuals share in common (Perakath et al. 1994). Practice has confirmed that in the course of building ontology it may initially be unclear whether an identified notion is best thought of as a property or as an attribute.

Of course, there are other general features that individuals exhibit, although jointly rather than individually, namely, connections, or associations, or as they shall be referred here, relations. The relations in the *Design Ontology* proposal are binary; they hold between two entities. This constrain arises from the methodology and tools used in the ontology building process. Relations are identified by abstracting away from the particular features of individuals and, hence, are often characterized as being of a higher (i.e. roughly, more abstract) logical type than the individuals that exemplify them. Of specially importance for the ontology building process is "subkind-of" relation. The notion of subkind encompasses the notion of generalization/specialization, that is, occurrences of the subkind relation in which the subkind is naturally thought of as a special case of a more general concept. This relation was used in building taxonomies of the *Design Ontology* vocabulary.

To summarize, ontology identifies and organizes the relevant kinds, their properties, and the network of relations between them within a specific application domain. In the following sections and tables 2, 3, and 4 the overview of the *Design Ontology* vocabulary and related taxonomies are presented.

Table 2 Taxonomy of the Objects and Processes

<table>
<tr><th colspan="2">Physical</th></tr>
<tr><th>Object</th><th>Process</th></tr>
<tr><td>• Biological object
o Human (Person)</td><td>• Activity</td></tr>
<tr><td rowspan="3">• Collection
o Assortment
o Family
o Group</td><td>• Flow</td></tr>
<tr><td>• Operation</td></tr>
<tr><td>• Reaction
o Effect</td></tr>
<tr><td>• Content bearing object
o Document
o Signal
o Symbol</td><td rowspan="2">• Transformation (Changing)
o Life cycle meeting
▪ Planning
▪ Designing
▪ Manufacturing
▪ Assembling
▪ Testing
▪ Packaging
▪ Transporting
▪ Selling
▪ Installing
▪ Servicing
▪ Recycling
▪ Disposing
o Technical process</td></tr>
<tr><td>• Material object
o Artefact
▪ Product
• Technical product
o Assembly
o Engineering component
o Equipment
o Form feature
o Device
o Organ
o Plant
o Transf. organism
o Material
o Matter</td></tr>
</table>

Table 3 Taxonomy of the Attributes and Propositions

Abstract	
Attribute	Proposition

• Design attribute
  o Design characteristic
    ▪ Beschaffenheit characteristic
      • Dimension
      • Form
      • Manufacturing method
      • Surface texture
      • Tolerance
    ▪ Compositional characteristic
      • Position
        o Orientation
    ▪ Structural characteristic
      • Activity chain
      • Component structure
      • Operation chain
      • Organ structure
  o Design property
    ▪ Function
    ▪ Inherent property
    ▪ Relational property
      • Aesthetic prop.
      • Delivery and planning prop.
      • Economic prop.
      • Ergonomic prop.
      • Functional prop.
      • Law conformance prop.
      • Liquidation prop.
      • Manufacturing prop.
      • Operational prop.
    ▪ Task
	• Arrangement
	  o Composition
	  o Constitution
	• Behaviour
	• Element
	• Fact
	  o Argument
	  o Assumption
	  o Data
	• Idea
	• Information
	• Plan
	  o Design
	  o Project
	  o Specification
	• Problem
	  o Need
	    ▪ Requirement
	    ▪ Wish
	• Quality
	• Solution
	• System
	  o Environment system
	  o Executive system
	    ▪ Biological system
	    ▪ Technical system
	  o Information system
	  o Management system
	  o Society system
	  o Transformation system

• Organisational attribute
  o ID
  o Name
  o Phase
  o Rate
  o State
  o Time stamp
  o Type
	• Technology
	  o Natural principle
	  o Technical principle
	• Whole

Table 4 Taxonomy of Realtions

<table>
<tr><th colspan="2">Relation</th></tr>
<tr><td rowspan="2">Case role
Input
Instrument
Operand
Operator
Output</td><td>Influence
Influence on
Opposing
Supporting</td></tr>
<tr><td rowspan="2">General
Alternative
Criteria
Deliver
Describe
Have
Satisfy
Realise</td></tr>
<tr><td>Compositional
Conceptual
Member of
Element of
Material
Component of
Material of
Portion of</td></tr>
<tr><td rowspan="2">Dependency
Aim
Cause
Base of
Consequence
Depend on
Condition</td><td>Spatial
Direct contact
Interact
Contain
Bearing
Non-direct contact</td></tr>
<tr><td>Temporal
After
Before
Co-occur</td></tr>
</table>

4.2 Objects

The concept of *Object* corresponds roughly to the kind of ordinary physical entities. Accordingly to SUMO, definition of *Object* is: "something whose spatiotemporal extent is thought of as dividing into spatial parts roughly parallel to the time axis". *Objects* can be categorized further as: *Biological Object* that can act on its own and produce changes in environment; *Material Objects* whose parts have properties that are not shared as a whole; *Content Bearing Objects* that expresses information; and *Collections* which members has position in space/time and can be added or subtracted without thereby changing the identity of *Collection* itself. The main terms extracted from GDMS and categorized as the Objects are:

BIOLOGICAL OBJECT: Human, Person

MATERIAL OBJECT: Apparatus, Artefact, Assembly, Device, Engineering Component, Engineering Connection, Equipment, Form Feature, Interface, Machine, Material, Matter, Mechanism, Organ, Product, Subassembly, Surface, Technical plant, Technical Product, Transformational organism

CONTENT BEARING OBJECT: Document, Signal, Symbol

COLLECTION: Assortment, Family, Group

Human as the top level concept of the biological object is defined as the any living or extinct member of the family Hominidae that could take the role of the operand or operator in the technical process. *Matter* is defined as that which has mass and occupies space, the tangible substance that goes into the makeup of an object. *Material* is defined as the matter of the specific kind from which the material objects are made. *Technical Product* is defined as the product that in technical process realises necessary effects for the transformation of the operand form the input to the output state satisfying the needs. *Document* is defined as the writing that provides information. *Signal* is defined as an object that is carrying information during the communication and *Symbol* is defined as an object that is used during the communication for the expressing information. *Assortment* is defined as a collection containing a variety of sorts of physical entities, *Family* is defined as a collection of different variants of the same kind of physical entities, and *Group* is defined as a collection of any number of physical entities (members) considered as a unit.

4.3 Processes

Processes represent a sustained phenomenon or one marked the way on which things are gradually changed. By its nature, *Processes* typically involve two sorts of change: change in kind and change in state. In a combustion process, for example, there is a transformation of some quantity of fuel into kinetic energy and exhaust gas; the fuel is destroyed and quantity of kinetic energy and exhausted gas result. By contrast, a process in which ice is melted simply involves a change state of a given quantity of water from frozen to liquid; the water itself is not destroyed, but only altered. Besides, *Processes* can have a specific purpose for the agent who performs it. The definition of

Process accordingly to SUMO is: "the kind of Entities that happen and have temporal parts or stages". The *Process* is whole of the participants "inside" it which have *Case Roles* in a *Process*, and a space/time dimensions. The main terms extracted from GDMS and categorized as a Process are:

> **PROCESS:** Activity, Assembling, Changing, Designing, Disposing, Effect, Flow, Installing, Life cycle meeting, Manufacturing, Operation, Packaging, Planning, Reaction, Recycling, Selling, Servicing, Technical process, Testing, Transformation, Transporting

Activity is defined as any specific process included in the progress of the technical process. *Flow* is defined as any uninterrupted stream or discharge of the process. *Life cycle meeting* is defined as transformation that is act of encountering of the technical product and other systems for some common purpose. *Operation* is defined as a step in a chain of the activities necessary for the performing of the transformation. *Reaction* is defined as process occurring due to the effect of some foregoing stimulus. *Technical process* is defined as the transformation during which the exploitation of the technical product during the necessary effects for the purposeful change of the operand are realized in order to satisfy the needs.

4.4 Attributes and Design Attributes

The definition of *Attribute* accordingly to SUMO is: "the quality for which we cannot or choose not to regard into sub kind of Object". Based on the background theory, in presented research was necessary to specialise the sub kind of a *Design Attribute* on the first sublevel. The *Design Attributes* can be categorized following the background theories as (Hubka et al. 1988): *Internal (Design characteristics)* and *External (Design properties)*. *Internal attribute* is any *Design attribute* that describes constitution of the design, i.e. its shape, dimension, surface, structure etc. *External Attribute* is any attribute that a design has by virtue of *Internal Attributes* and is influenced from environment. Some of the *External Attributes* are *Relational* (describe behaviour of the meetings between a design/product and life phase system), and other are *Inherent* (describe behaviours of a design/product in a certain environment depending on material, manufacturing method, etc). Besides the *Design attributes*, the *Organizational attributes* important for the administrative tasks were also specialized. The main terms extracted from GDMS and categorized as Attribute are:

> **ORGANIZATIONAL ATTRIBUTE:** Identity, Name, State, Status, Phase, Rate, Time-stamp, Type

> **DESIGN CHARACTERISTIC:** Activity chain, Beschaffenheit characteristic, Component structure, Composition characteristic, Dimension, Form, Manufacturing method, Organ structure, Operational chain, Structural characteristic, Surface texture, Tolerance, Position, Orientation

> **DESIGN PROPERTY:** Aesthetic property, Distribution property, Delivery and planning property, Economic property, Ergonomic property, Function, Functionality property, Inherent property, Law conformance property, Liquidation property, Manufacturing property, Operational property, Relational property, Task

Beschaffenheit characteristic is defined as design characteristic that describes the features of the technical product like form, dimension, tolerance, manufacturing method, surface texture. *Compositional characteristic* is defined as the design characteristic that describes the spatial arrangement of the elements in relation to each other and to the whole. *Structural characteristic* is defined as the design characteristic that describes the manner of construction of whole and the disposition of its elements. *Function* is defined as the design property of what technical product is built and used for. *Task* is defined as a part of the function in a manner of a specific piece of work required to be done as a duty of the particular engineering component.

4.5 Propositions

The SUMO definition of *Propositions* is: "The Abstract entities that express a complete thought or a set of such thoughts". The *Propositions* are not restricted to the content expressed by individual sentences of a language. They may encompass the content expressed by theories, books, and even whole libraries. It is important to distinguish *Propositions* from the *Content Bearing Objects* that expresses them. The *Proposition* is a piece of information but a *Content Bearing Object* is an *Object* that represents this information. The main terms extracted from GDMS and categorized as a *Proposition* are:

> **PROPOSITION:** Argument, Arrangement, Assumption, Behaviour, Biological system, Composition, Constitution, Data, Design, Element, Environmental system, Executive system, Fact, Idea, Information, Informational system, Management system, Natural principle, Need, Part, Plan, Problem, Project, Quality, Requirement, Society system, Solution, Specification, Stage, System, Technology, Technical principle, Technical system, Transformational system, Whole, Wish

Arrangement is defined as a manner of what the elements are ordered. *Behaviour* is defined as the action or reaction of the entity under specified circumstances. *Element* is defined as simple entity that is the constitutional part of the whole in the abstract sense. *Fact* is defined as a proposition which truth could be proved. *Idea* is defined as a content of the cognition, something to think about. *Information* is defined as a set of facts based upon the conclusions could be drawn. *Need* is defined as anything that is necessary but lacking. *Plan* is defined as a specification of the activities which is intended to satisfy a specified purpose at some future time. *Quality* is defined as the level of the excellence of the observed entity. *Solution* is defined as a method for solving a problem. *System* is defined as a group of independent but interrelated elements comprising a unified whole. *Technology* is defined as rule or law concerning a natural phenomenon or the function of a technical system. *Whole* is defined as an arrangement of the elements that are considered together.

4.6 Quantities

The *Quantities* are defined in SUMO as: "any specification of how many or how much of entity there is". There are two sub kinds of *Quantity* further defined in SUMO: *Number* and *Measurable quantity*. A *Number* is specification of how many of something there is. A *Measurable quantity* is a measure of some quantifiable aspect of the modelled world and need not be material, such as 'the shaft's diameter' (a constant length) and 'the stress in a loaded deformable solid' (a measure of stress, which is a function of three spatial coordinates). Aside from the dimensions of length, time, velocity, etc., non-physical dimensions such as currency are also possible. The main terms extracted from GDMS and categorized as a *Measurable quantity* are:

> **MEASURABLE QUANTITY:** Constant quantity, Functional quantity, Unit of measure

4.7 Relations

The *Relations* are in SUMO defined as general associations which can be shared by distinct pairs (triples, etc.) of individuals. From the analysis of the theoretical foundation (GDMS), author concluded that the necessary domain axioms can be specified based on the different associations between the terms i.e. cause, connects, follows, is sub kind of etc. The further research identified a huge diversity of relations in the product development modelling domain and for the most of them there does not exists unambiguous explanation of their meaning in the background theories. In different theoretical design models, most of relations are characterized as causal, only to denote their existence, without further explanation of their nature. The big number of uncategorised and undefined relations that create the complex semantic network between extracted terms in *Design Ontology* has been highlighted as the one of the biggest obstacle in fully formalization of GDMS structure.

In order to formalize the meaning of the different relations, the first step was a characterization of the different association by their nature and characterization of commonly used relations that exists between terms. The standards and literature provide little guidance on what different kinds of semantic relation appear in design models (Hubka et al. 1988, Perakath et al. 1994, Salustri et al. 1999, McKay et al. 2004, Pavković et al. 2002). In order to make useful characterization, associations were grouped and defined by axioms considering logical properties of symmetry, reflectivity and transitivity for each specific group.

Compositional relations

The *Compositional relations* are kind of *Relations* that capture semantic of whole/element concept based on the logical theory of structures – Mereotopology (Salustri et al. 1999). The compositional relations are antisymmetric, irreflexive and transitive by their nature. The main terms extracted from GDMS and categorized as a *Compositional relations* are:

> **COMPOSITIONAL RELATION**: Component of, Element of, Material of, Member of, Portion of

Component of denotes that a simple material object is a physical part of material object (i.e. organ/transformational organism, engineering component/assembly, assembly/device, etc.). *Element of* denotes that a simple entity is functional element of complex entity (i.e. fact/information, assembly/product structure, operation/operational chain, element/set, etc.).

Material of denotes that one material object is partly made of some material (i.e. material/engineering component, etc.). *Member of* denotes the fact that a physical entity is a member of some collection (product/product family, product/assortment, human/group, etc.). *Portion of* describes the relationships between two entities, one being included in the other (i.e. constant quantity/functional quantity, etc.).

Spatial relation

The *Spatial relations* are kind of *Relations* that capture semantic of the geometric, physical and other form of connections, contacts or interactions between physical entities. The *Spatial relations* are irreflexive and symmetric or antisymmetric. The main terms extracted from GDMS and categorized as *Spatial relations* are:

> **SPATIAL RELATION:** Bearing, Contains, Direct contact, Enclosures, Interacts. Non-direct contact

Direct contact denotes that two entities are in physical contact (i.e. engineering component/engineering component, organ/organ, surface/surface, etc.). *Contains* denotes that one entity are taking the space occupied by other entity (i.e. engineering component/engineering component, etc.). *Non-direct contact* denotes that two entities are not in physical contact but they are components of the same complex entity (i.e. engineering component/engineering component, organ/organ, surface/surface, etc.).

Case-role relations

The *Case-role relations* are the kind of *Relations* relating the spatially distinguished roles of the different elements of the *Process*. The relations are antisymmetric and irreflexive by their nature. Case-role includes, for example, the agent, patient or destination of a transformation that take a place during the particular process. The main terms extracted from GDMS and categorized as a *Case-role relation* are:

> **CASE-ROLE:** Input, Instrument, Operand, Operator, Output

Input denotes the state of the operand at the beginning of the transformation process (i.e. material object/design characteristic, etc.); *output* denotes the state of the operand at the end of the process. *Instrument* denotes that an entity is a tool for creating transformations in a specific technical process (i.e. material object/process, etc.). *Operand* denotes that an entity is object of transformations in a specific technical process (i.e. information/technical process, matter/technical process, energy/technical process, etc.). *Operator* denotes that an entity is an active creator of a transformation in a specific technical process by exerting the effects that drive and guide the process (i.e. management system/transformational system, executive system/transformational system, informational system/transformational system, etc.).

Dependency relation

The *Dependency relations* are kind of *Relations* that capture semantic of the fact that one entity in domain depends existentially on another entity. The *Dependency relations* are antisymmetric, irreflexive and transitive. The main terms extracted from GDMS and categorized as a *Dependency relation* are:

DEPENDENCY RELATION: Aim, Base of, Causes, Consequence, Depends on, Factor, Presumption for, Purpose, Reason, Responses, Results, Stimuli

Aim denotes that an entity is an intended (planned) purpose or is a reason for existence of another entity (i.e. specification/design attribute, etc.). *Causes* denotes that an entity is reason for progress, activity or existence of another entity (i.e. design property/design characteristic, etc.). *Consequence* denotes that an entity is a product, result, or response on existence, activity or work of another entity (i.e. need/problem, transformation/need, etc*.). Depend on* describes that an entity existentially depends on another entity (i.e. compositional characteristic/organ, etc.).

Influence relations

The *Influence relations* are kind of *Relations* that capture semantic of the fact that one entity has some effect or impact on another concept. The *Influence relations* are antisymmetric and irreflexive. The main terms extracted from GDMS and categorized as an *Influence relation* are:

INFLUENCE RELATION: Influence, Opposing, Supporting

Influence denotes that an entity has influence on progress, activity, or existence of another entity (i.e. life cycle meeting/relational properties, etc.). *Opposing* denotes that an entity challenge correctness of another entity (i.e. argument/solution, etc.). *Supporting* denotes that an entity support correctness of another entity (i.e. argument/plan, etc.).

Temporal relations

The *Temporal relations* are kind of Relations that capture semantic of the time depend relations between entities, based on the temporal logic. The *Temporal relations* are antisymmetric, irreflexive and transitive. The main terms extracted from GDMS and categorized as a *Temporal relation* are:

TEMPORAL RELATION: After, Before, Co-occur, Follows, Proceeds

After denotes that the time interval of activity for an entity starting latter on a time progression line than ending time interval of activity for another entity (i.e. process/process, function/function, etc.). *Before* describes that the time interval of activity for an entity ending before on a time progression line then starting the time interval of activity for another entity (i.e. process/process, function/function, etc.). *Co-occur* denotes that an entity exists or is active in the same time interval as another entity (i.e. process/process, function/function, etc.).

General relations

The *General relations* are kind of Relations that capture semantic of very general predicates, and therefore were not possible to characterize them into one of previously explained categories. The main terms extracted from GDMS and categorized as a General relations are:

GENERAL RELATION: Alternative, Criteria, Delivers, Describes, Has an attribute, Realises, Satisfies

Alternative denotes that an entity could take a place of another entity (i.e. engineering component/engineering component, concept/concept, etc.). *Delivers* denotes that an entity by its activity delivers another entity (i.e. executive system/effect, etc.). *Describes* denotes that an entity indicate, express, picture, represent another entity (i.e. design property/behaviour, design characteristic/constitution, function/activity, etc.). *Has an attribute* denotes that an entity is determined by another entity (i.e. engineering component/task, society system/problems, etc.). *Realises* denotes that an entity physically realises another entity (i.e. organ structure/working principle, assembly/organ, effect/technical process, etc.). *Satisfies* denotes that one entity fulfils some requirement or expectation (i.e. product/need, etc.).

5. Evaluation and formalization of the Design Ontology

After structuring the initial vocabulary proposal, the next step of the research on the *Design Ontology* was evaluation and developing the formal design model based on the extracted and categorized terms.

5.1 Proposal evaluation

Following the research methodology proposed by Ahmed and others (Ahmed at al. 2005), the set of interviews is conducted in order to test the reliability and completeness of the vocabulary taxonomies proposal. The initial categorisation of the terms was carried out by one person. The proposal was therefore tested for reliability using Cohen's Kappa coefficient of reliability (Bakemann 1997). The relevant experts form the research area analysed the proposal and their opinion is then compared to proposal made by main researcher to carryout the proposal reliability. The Kappa coefficient takes the actual percentage agreement and subtracts the percentage agreement that could be expected form chance. The experts that were interviewed have got the taxonomies proposed by researcher, and detail explanation of the terms. It was expected from the experts to consider taxonomy proposal, and give their opinion about – agree or disagree with terms categorization. In a case of disagreeing, they were asked to explain the reasons, and propose own categorization for particular term. There was not any time limit on this process.

The results analysis was done in two steps. In the first, the reliability of the categorization between two main kinds, Physical and Abstract were calculated. The Kappa coefficient calculated was 0,87 which is indicative of high reliability. If we take a closer look at the results of the method, it could be revealed that for the 17 terms experts had different opinion form the proposal, and most of them was originally categorized to belong to the abstract kind (see figure 5).

In a second step, analysis of the Kappa coefficient for the six main subkind taxonomies was done. The Kappa coefficient calculated was 0,88, indicating the high reliability. The most of the questionable categorization for the experts was for the terms without clear definitions in the background theories, namely Relations (see figure 6). Through the theoretical background that was used as the base for the terms extraction, the relations between the terms used in definitions (verbs) or relations drawn in the graphical representation of the models are not further defined or explained in details. Therefore the confusion about some relations and its usage in ontology was probably caused by this fact. As an opposite example, there are terms categorized as processes, without any complains from the experts. Besides, domain experts were asked if they considered any terms that were not included in the proposal. Based on described analyse, definitions of the terms and proposed taxonomies are additionally improved and modified following the experts' suggestions, and as the result, final *Design Ontology* proposal (presented in section 4) is defined.

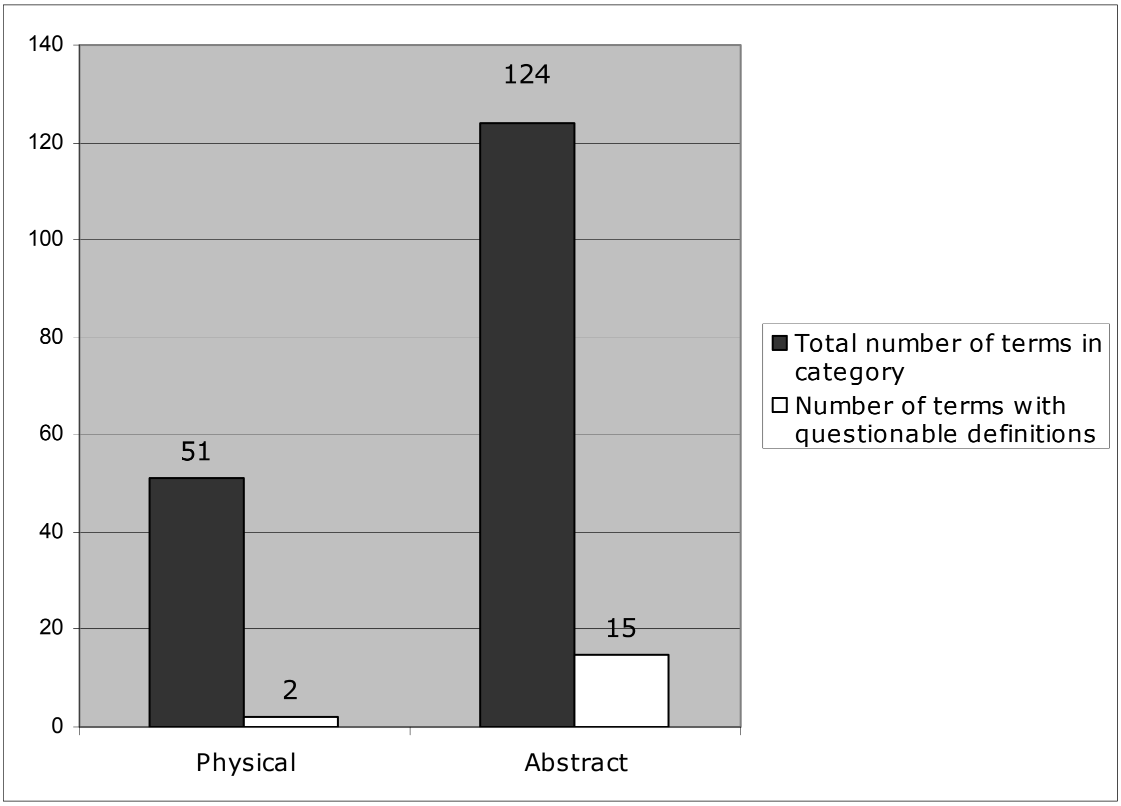

Figure 5 Main categories evaluation result

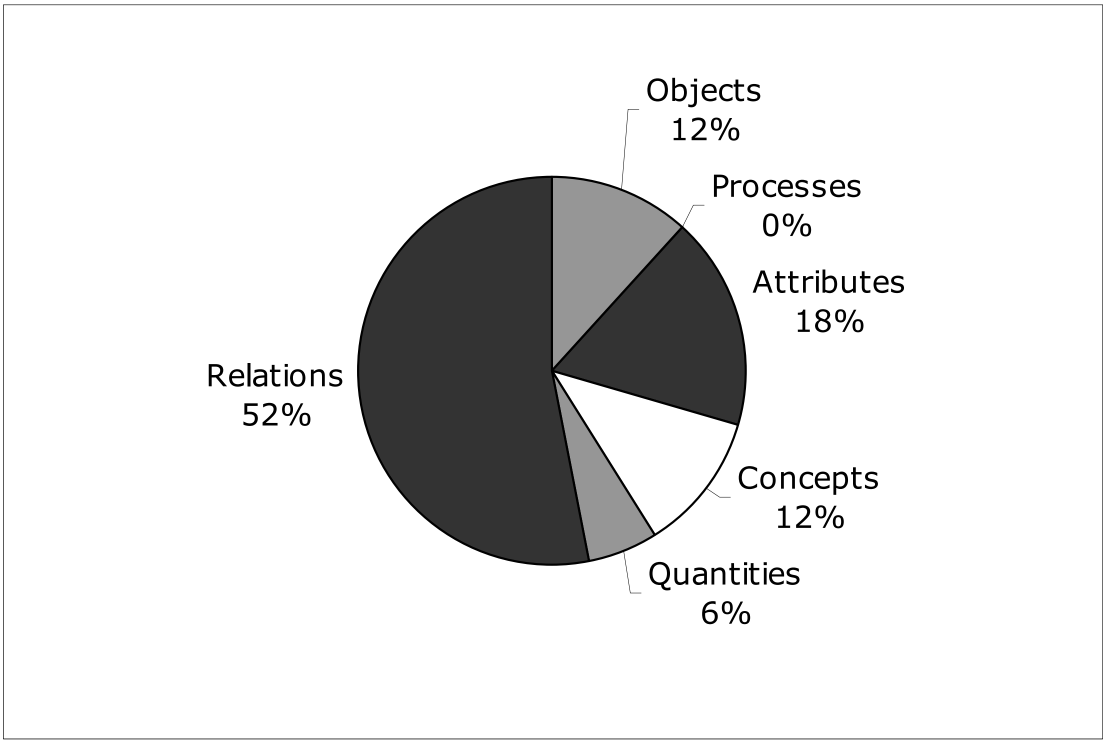

Figure 6 Abstract category evaluation result

5.2 The Design Ontology implementation

Building thesaurus

The last step of the presented research was ontology implementation and refinement. With this goal, the proposed *Design Ontology* structure was instantiated with actual data in order to articulate the data information and knowledge evolved throughout development of the real products. The software tool that has been used in this phase is OntoEdit® developed by Ontoprise GmbH, Karlsruhe, Germany (Sure et al. 2002.). OntoEdit® is an ontology engineering environment supporting the development and maintenance of ontologies by using graphical means. The paradigm of OntoEdit® supports developing of the concept hierarchy, axioms, and instantiations as much as possible independent of a concrete representation language. The OntoEdit® includes inference mechanism and knowledge base that can be used to test ontology and its axioms. As the result of the inference sequence, the new knowledge can be inferred based on the existing statements and axioms in the ontology. There is also a possibility for enabling and disabling specific axioms for testing purpose. The OntoEdit ® also tackles several aspects necessary for the evaluation of the formal ontology by checking whether the ontology fulfils the requirements specified during the first stage of the ontology building process:

(i) Test sets of instances and axioms can be used for the analysis of typical queries;

(ii) A graphical axiom editor in combination with an underlying inference engine allows for logical error avoidance and location;

(iii) Competency questions about situation in domain might be formalized into queries and evaluated by using the facilities of (i) and (ii);

(iv) A namespace mechanism allows for using the facilities (i) – (iii) collaboratively.

The implementation begun with building the knowledge tree by mapping every particular term from the *Design Ontology* proposal to the OntoEdit® concept hierarchy tree and defining the relations in a manner of OntoEdit® relational axioms. Relations are additionally constrained by adding the additional axioms describing the logical properties of every relation's group.

Besides relational axioms, it was found that there exists the huge number of possible complex domain axioms that are connecting and constraining the usage of the vocabulary terms. It was decided to include in research at this phase only few of them in order to show how it works as a part of the formal model. Complex axioms together with ontology completeness theorems that specify necessary conditions for formally rigour ontology will be objective of the future research efforts. An example of simple axiom that was extracted from the background theories and was formally defined is the example of compositional overlapping that was not included in vocabulary as a relation, but could be defined by additional domain axiom:

FORALL X,Y,Z Compositional overlapping (X,Y) <-

(EXISTS Z (Z[#Compositional relation->>X]

AND Z[#Compositional relation->>Y]

AND NOT equal(X,Y))).

This axiom could be interpreted as follows: two complex entities are compositional overlapping if exists only one simple entity that is by any compositional relation connected with the both complex entities. Last row in previous formalization exists in order to prevent inference of such conclusions for the single simple entity.

Applicative testing

As the test application case, products information examples from the book of Hubka, Eder and Andreasen (Hubka et al. 1988) were used. This book illustrates examples based upon the theoretical background that was used in this research, and therefore was considered as a convenient for the *Design Ontology* testing in this research phase. The main advantage of these illustrative examples is that they are focused on the conceptual phase of simple product development process, and include mainly non-geometrical information about particular product like requirements, functions, organs, processes, etc. support of what was the focus of presented research. Most of this information in these examples exists in informal format as sketches, notes, tables, what was the reason for creating instances of the terms based on *Design Ontology* manually. For every example, a hundreds of terms and relations instances were created. As the final result the rich semantic network representing the formal description of the knowledge evaluated during the specific product example development process was derived (see figure 7).

The created sets of terms and relations instances were used for further consistency checking of the proposed formal design model. While the generation and validation of test cases through terms and relations instances allows detection of the semantic errors, it does not really support the localization of errors in the formal model. The complex set of relational and domain axioms often result with the interaction between the axioms when they are processed.

Thus it is frequently very difficult to overview the correctness of the set of axioms and detects the faulty ones. In principle there exist three types of problems with confirming the axioms:

- Axioms contain typing errors like variables not specified by a quantifier, typos in concept names or relationship names etc.
- Axioms contain semantic errors, i.e. the rules do not express the intended meaning.
- Performance issues, like axioms defined such that evaluation needs a lot of time, which is not always easily recognizable by the user.

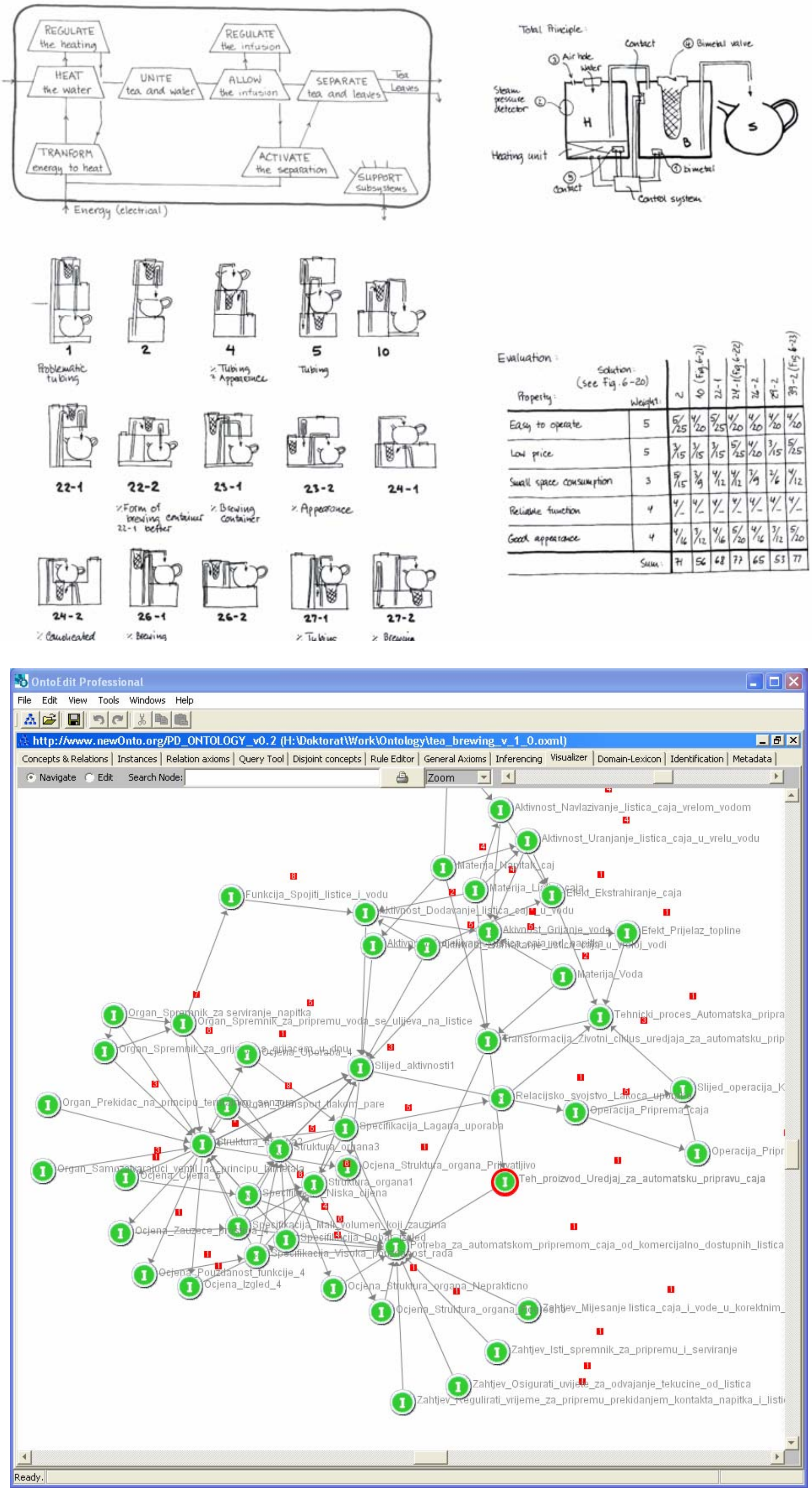

Figure 7 Visualization of the Coffee Maker instantiation of the *Design Ontology*

In order to locate problems, OntoEdit® environment takes advantage of the inference engine, which allows introspection and debugging of the whole formal model. Axioms are tested by posting semantic queries based upon one may pursue several alternatives in order to solve the possible errors in formal model:

- First, a very simple but effective method for validation of the axioms including test cases is based on switching off and on axioms or parts of the axiom premises. The different answers from OntoEdit® inference engine then allow drawing conclusions about possible errors.
- Second, for a given query the results and their dependencies of existing test instances and intermediate results may be examined by visualizing the proof tree. This proof tree shows graphically which instances or intermediate results are combined by which rules reaching the final answers. Thus the drawn inferences may be traced back to the test instances and semantic errors in rules may be discovered.
- Third, the inference engine may be "observed" during evaluation. A graphical presentation of the set of axioms as a graph structure indicates which axiom is evaluated at the moment and also shows which intermediate results have already been created up to now and thus "have flown" in the axiom graph to other axioms. This also gives a feeling about time needed to evaluate particular rules.

Based on such consistency checking procedure, the *Design Ontology* proposal got a last refinement.

Implementation framework

There are several requirements concerning knowledge based systems for supporting complex tasks in technical domains (Abecker et al. 1998):

- Collection and systematic organization of information from various sources - paper and electronic documents, databases, e-mails, CAD drawings, and the heads and private notes of individuals
- Minimization of up-front knowledge engineering - prospective users have little or no time to spare for requirements and knowledge acquisition
- Exploiting user feedback for maintenance and evolution - must be enabled to point out deficiencies and suggest improvements without significantly disrupting the usual workflow
- Integration into existing work environment - directly interface to the tools currently used to do the work, including word processors, spreadsheets, CAD systems, simulators, and workflow management system
- Active presentation of relevant information - actively remind designers of helpful information and be a competent partner for cooperative problem solving

To perform tasks that are complex, difficult, and important by nature the human experts in product development need considerable skill and knowledge. Such knowledge tasks deal with the acquisition, creation, packaging, and application of engineering knowledge, and can be increasingly identified inside the core work processes, which are linked to them by exchange of information, decisions, and documents. Thus, the development processes naturally provide the context for performing, analyzing, and supporting engineering knowledge tasks. Following the proposal of Abecker and colleagues (Abecker et al. 1998) authore adopt a three-lavel model as sketched in Figure 8, which points out the main issues to be addressed when implementation a system for realizing context-sensitive, active engineering knowledge management in product development. The architecture of the proposed framework is reflection of the main principle: by representation of the explicit relationships between formalized knowledge elements, the knowledge content becomes available for the processing and reasoning.

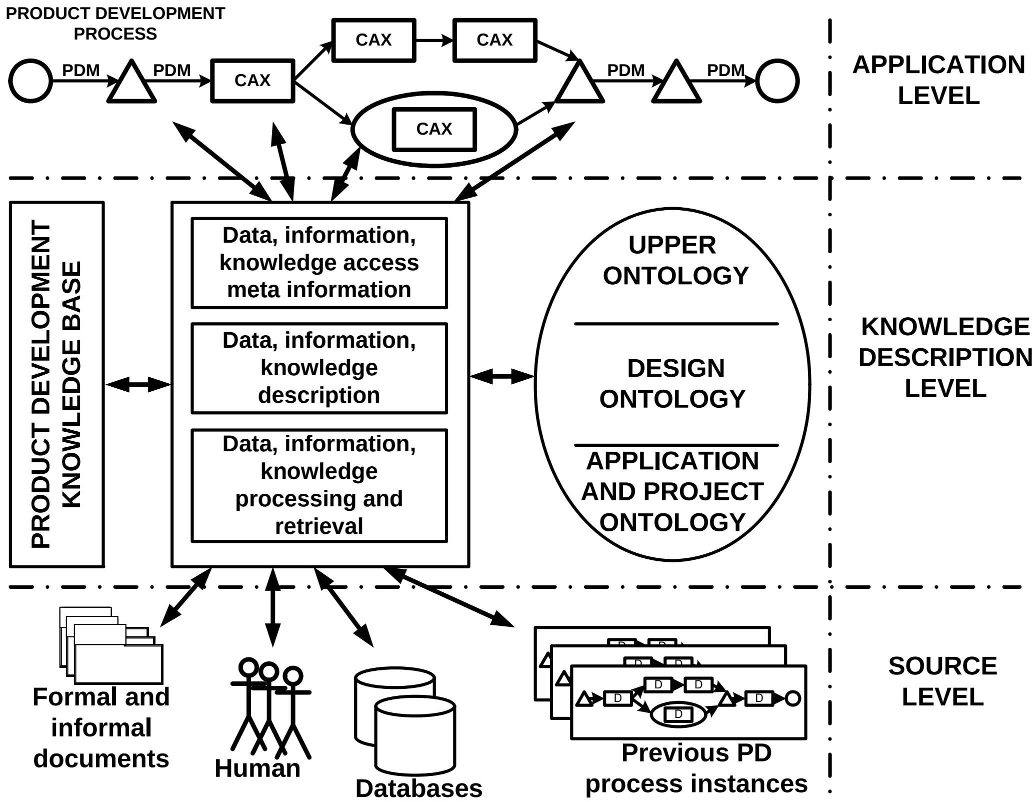

Figure 8 ***Design Ontology*** **proposed implementation framework (after Abecker** ***et al.*** **1998)**

Because proposed implementation framework relies substantially on existing knowledge sources, the source level is characterized by a variety of knowledge and information sources, heterogeneous with respect to several dimensions concerning form and content properties. The framework should perform the mapping from the application-specific knowledge needs to these heterogeneous source-level sources via a uniform access and utilization method on the basis of an ontology-based, knowledge-rich knowledge description level. When a designer recognizes a knowledge need within the actual flow of work on application layer, a query to the knowledge description layer must be derived. This query is instantiated and constrained as specifically as possible on the basis of *Design Ontology* content. In the opposite way, the knowledge description layer can also store new knowledge created within a given working situation in a contextually enriched form on the basis of *Design Ontology* content.

6. Implications

In the product development domain, ontology is needed to solve many heterogeneity problems. Using the formal ontology structures has advantages over the standardized approaches (i.e. STEP schemes), because standardized approaches need a pre-agreement about everything, and in an ontology approach we need just to agree about common terminology. The main contribution of this research can be summarize in merging existing methodologies of building ontologies in experiment of building ontologies in a product development domain. The major findings encounted in building the *Design Ontology* are as follows:

1. Formalization of the ontology depends mainly upon background theories. The many statements that we are using every day for describing situation in domain of discourse (product development) are not understandable without recognizing and respecting the background theories where they are originated and which brings concepts together.
2. Formalization of the *Design Ontology* requires much more detailed specification and explanation of the concepts and associations between them than is provided by current theoretical models in order to provide the framework for useful reasoning about design/product domain.
3. Differentiation between the six different kinds of ontology terms extracted during the domain knowledge description phase is based upon the high level ontology ensuring backward compatibility between this proposal and more general ontology that is reusable for building ontologies for different domains.
4. It is necessary that the *Design Ontology* exists both in the form of a comprehensive, carefully prepared natural language and in a formal language in order to be accessible and understandable to the all subjects in product development process.

It should be clear that the *Design Ontology* is a working research. Since presented work was built upon predefined theoretical background, the future work is to define complex rules composed of two or more simple rules that will enable us to enforce more constrains on defined structures. Besides, as a necessary prerequisite for the proposed implementation framework realization, besides the proposed part of the ontology related to the design/product, the design process oriented part of ontology based on the same background should be defined. On that base will be possible to reach the final goal: develop more knowledgeable information systems that will provide intelligent support to the end users that are related but from different groups, thus facilitating knowledge transfer between different communities.

7. Conclusion

In this document a description of the *Design Ontology* research project that was aimed at the achievement of the formal description of the Genetic Design Model System structure is given. This document has established the problem being studied, laid out the methods being used, indicated the possible problems, and benefits that may be achieved. From the research results autor have learned how existing general upper level ontologies can be used to derive, organize and categorize terms and their definitions in specific domain ontology in order to gradually develop it in a structured fashion. By the results of the research, background theories have been extended with new understanding and knowledge, especially in the understanding of associations between domain concepts. The differentiation of the terms between physical and abstract word is contribution to better understanding of the existing product/design knowledge nature. As the main contribution, the understandable and uniform formal language for product/design description has been proposed, that should be useful contribution for the different development projects. Authore believe that such collected research experience can be generalized and utilized for the building future ontologies in product development domain. Therefore, as the next step, research will be aimed to the building of the Design Process Ontology, as well as extending the *Design Ontology* proposal for specific purposes at the application level (modular design, design for assembling, feature based design, etc.) as the building blocks for defining the "general product development ontology".

Literature

Abecker, A., Bernardi, A., Hinkelmann, K., Kuhn, O., Sintek, M.: "Toward a technology for organizational memories", IEEE Intelligent Systems, IEEE computer Society, IEEE Inc., 1998.

Ahmed, S., Kim, S., Wallace, K.: "A methodology for creating ontologies for engineering design"; Proceedings of DTM 2005; ASME 2005 Design, Theory and Methodology Conference; Long Beach, California, USA; 2005.

Ahmed, S.: "Encouraging reuse of design knowledge: a method to index knowledge"; article in press, Design Studies, Elsevier Ltd., UK, 2005.

Alberts, M.: "YMIR: an Ontology for Engineering Design"; PhD thesis; University of Twente, Netherlands; ISBN: 90-9006128-2; 1993.

Allen, J.: "Towards a general theory of action and time"; Artificial Intelligence 23; pp. 123-154; 1984.

Anderl, R., Grabowski, H.; Pratt, M.: "Advanced Modelling for CAD/CAM systems"; Research Report ESPRIT Project 322, Vol.7; Springer-Verlag; Berlin-Heidelberg-New York; 1991.

Andersson, C., Pettersson, R.: "How can a design process and a scientific process in information design collaborate?"; Proceedings of the 4th International Seminar and Workshop EDIProD; Zielona Gora; Poland; pp. 87-96; 2004.

Andersson, F.: "The dynamics of requirements and product concept management – a product modelling approach"; PhD thesis; Engineering and Industrial Design; Division of Product and Production Development; Chalmers University of Technology; Sweden; ISBN 91-7291-385-5; 2003.

Andreasen, M.M., Hein, L.: "Integrated product development"; IPD; Lyngby; Denmark; 2000.

Andreasen, M.M.: "Machine design methods based on systematic approach – contribution to the design theory"; Dissertation; Department of Machine Design, Lind Institute of Technology, Sweden; 1980.

Andreasen, M.M.:"Conceptual Design Capture"; Proceedings of EDC'98-Design Reuse; Brunel Universit; pp. 21-30; 1998.

Anić, V., Goldstein, I.: "Rječnik stranih riječi"; NOVI LIBER; Zagreb; 2002.

Baader, F., Calvanese, D., McGuinness, D., Nardi, D., Patel-Schneider, P.: "The description logic handbook – Theory, Implementation and Applications"; Cambridge University Press; UK; 2003.

Bakemann, R., Gottam, J.M.: "Observing interaction: an introduction to Sequential Analysis"; Cambridge University Press, Cambridge, UK; 1997.

Benyon, D.: "Information and data modelling"; Henley-on-Thames; UK: Alfred Waller Ltd.; 1990.

Blessing, L.: "A process Based Approach to Computer Supported Engineering Design"; dissertation, University of Twente, the Netherlands; 1994.

Blessing, L.: "What is thing called Design Research"; Annals of 2002 Int'I CIRP Design Seminar; Hong Kong; 2002.

Blessing, L.T.M., Chakrabarti, A., Wallace, K.M.: "An Overview of Descriptive Studies in Relation to a General Design Research Methodology"; Designers: the Key to sucessful Product Development; E. Frankeberger, P- Badtke-Schaub and H. Birkohofer; 1998.

Blessing, L.T.M., Chakrabarti, A., Wallacw, K.M.: "An overview of descriptive studies in relation to a general design research methodology"; in Frankerberger, E., Badke-Scahub, P., Birkhofer, H. (editors): The Key to successful product development; pp. 42-56; Springer-Verlag; Berlin; 1998.

Borgo, S.; Guarino, N., Masolo, C.: "An Ontological Theory of Physical Objects"; in L. Ironi (ed.), Proceedings of Eleventh International workshop on Qualitative Reasoning QR'97; Cortona; Italy; pp. 223-231; 1996.

Borst, W.N.: "Construction of engineering ontologies for knowledge sharing and reuse"; PhD thesis, Centre for Telematics and Information Theory; Enschelde; Netherlands; 1997.

Brachman, R.J., Pigman Gilbert, V., Levesque, H.J.: "KRYPTON: Integrating terminology and assertion"; Proc. of the 9th International Joint Conferecne on Artificial Intelligence (IJCAI'85); pp. 532-539; 1985.

BSO: "Broad system of Ordering: schedule an index"; St. Albans; BSO Panel; 1993.

Burgess, J.D.G., Shahin, T.M.M., Sivaloganathan, S.: "Design reuse for detailed component design"; Engineering Design Conference 1998; UK: Professional Engineering Publishing Limited; pp. 271-280; 1998.

Burkett, W.C.: "Product markup language: a new paradigm for product data exchange and integration"; Computer-Aided Design 33; Elsevier Science; pp. 489-500; 2001.

Casati, R., Varzi, A.: "Wholes and Other Superficialities"; MIT Press, Cambridge; MA; USA; 1995.

Chaplan, M.A.: "Mapping Laborline Thesaurus to Library of Congress Subject Headings", Implications for vocabulary switching; Library Quartely; Vol. 65; No. 1; pp. 39-61; 1995.

Checkland, P.B.: "System thinking"; UK: Wiley; 1981.

Chesnut, H.: "Systems engineering methods"; New York: Wiley; 1967.

Clark, K.B., Wheelwright, S.C.: "Managing new product and process development"; The Free Press; New York; USA; 1993.

Cochrane, P.A.: "Indexing and searching thesauri"; in Williamson, N.J., and M. Hudon, Editors; Classification Research for Knowledge Representation and Organization; Amsterdam; Elsevier Science; 1992.

Comte, A.:"A General View of Positivism" London: Routledge and Sons; 1907.

Corcho, O., Fernandez-Lopez, M., Gomez-Perez, A.: "Methodologies, tool and languages *for building ontologies. Where is their meeting point?"; Data & Knowledge Engineering 24; Elsevier Science; pp. 41-64; 2003.*

Court, A.W.: "Modelling and classification of information for engineering design"; Ph.D. thesis, University of Bath, UK; 1997.

Cross, N.: "Editorial"; Design Studies 16(1); pp. 2-3; 1995.

Culley,S.J.; Allem, R.D.: "Informal information – definitions and examples with reference to the electronic catalogue"; ICED 99, pp. 1961-1964; 1999.

Darlington, M., Culley, S.: "Investigating Ontology Development for Engineering Design Support"; accepted for publication in Advanced Engineering Informatics; Elsevier Science; 2005

Davenport, T.H., Jarvenpaa, S.L., Beers, M.C.: "Improving Knowledge Work Processes", Sloan Management Review, Vol. 37, No. 4, pp. 53-65, 1997.

Davenport, T.H.: "Some principles of Knowledge Management", http://www.bus. Utexas.edu/kman, 1996.

Dean, M., Connolly, D., van Harmelen, F., Hendler, J., Horrocks, I., McGuinness, D.L., Patel-Schneider, P.F., Stein, L.A.: "OWL Web Ontology Language 1.0 Reference"; W3C Working Draft; Available from <http:// www.w3.org/TR/owl-ref/>; 2002.

Devine, D.J., Kozlowski, S.W.J.: "Domain-specific knowledge and task characteristics in decision making"; Organizational Behaviour and human Decision Process, 64(3); pp. 294-306; 1995.

Dextre Clarke, S.: "Integrating thesauri in the agricultural sciences"; in Compability and integration of order systems; TIP/ISKO Meeting; Warsaw; pp. 111-122; 1996.

Duffy, A., Andreasen, M.M.: "Enhancing the evolution of Design Science"; Proceedings of the 10th International Conference on Engineering Design ICED'95; Praha; WDK; pp. 29-35; 1995.

Duhovnik, J.: "Concept generation, selection and testing"; Presentation for European Global Product Realization; University of Ljubljana; Slovenia; 2005.

Eekels, J.: "On the fundamentals of engineering design science: The geography of engineering design science. Part 1"; Journal of Engineering Design; Vol 11, No. 4; pp. 377-397; 2000.

Elmagarmid, A., Rusinkiewicz, M., Sheth, A. (editors): "Management of Heterogeneous and Autonomous Database Systems"; Morgan-Kaufmann; San Francisco; 1999.

Farquhar, A. Fikes, R., Rice, J.: "The Ontolingua Server: A Tool for Collaborative Ontology Construction"; Knowledge Systems Laboratory,Stanford University; 1996.

Farquhar, A., Fikes, R., Pratt, W., Rice, J.: "Collaborative ontology construction for informative integration"; Technical Report KSL-95-63; Stanford University Knowledge Systems Laboratory; 1995.

Farquhar, A., Fikes, R., Rice, J.: "The Ontolingua Server: A Tool for Collaborative Ontology Construction"; in: Proc. 10th Knowledge Acquisition for Knowledge-Based Systems Workshop (KAW96); pp. 44.1– 44.19; 1996.

Feigenbaum, B., Forbus, K.D.: "Compositional Modeling: finding the righet model for the job"; Artificial Intelligence; pp 95-143; 1991.

Fernandez-Lopez, M., Gomez-Perez, A., Pazos-Sierra, A., Pazos-Sierra, J.: "Building a chemical ontology using MENTHODOLOGY and the ontology design environment"; IEEE Intelligent Systems & their applications 4 (I); pp.37-46; 1999.

Finger, S.: "Design reuse and design approach"; Engineering Design Conference 1998; UK: Professional Engineering Publishing Limited; 1998.

Frankfort-Nachmians, C., NAchmians, D.: "Research methods in the social science", Arnold, London, 1996.

Fuchs, J., Wheadon, J.: "Prospective applications of ontologies for future space missions"; The impact of Ontologies for Reuse, Interoperability and distributed Processing; Unicom Seminars; London; pp.83-96; 1995.

Garson, J.: "Modal Logic"; The Stanford encyclopaedia of Philosophy; Zalta, E.N. (editor), http://plato.stanford.edu/archives/win2003/entries/logic-modal/; 2001.

Genesereth, M., Fikes, R.: "Knowledge interchange format"; Technical Report Logic-92-1; Computer Science Department; Stanford University; USA; 1992.

Genesereth, M., Nilsson, N.: "Logical foundations of Artificial Intelligence"; Morgan Kaufmann; San Mateo; CA; 1987.

Gilchrist, A.: "Thesauri, Taxonomies and Ontologies – an etymological note"; Journal of Documentation; London; Vol. 59; No. 2; pp. 131-142; 2003.

Gruber, T.R.: "ONTOLINGUA: A Mechanism to Support Portable Ontologies"; technical report; Knowledge Systems Laboratory; Stanford University; 1992.

Gruber, T.R.: "Towards principles for the design of ontologies used for knowledge sharing"; in Guarino, N. and Poli, R. (editors): Formal Ontology in Conceptual Analaysis and Knowledge Representation; Kluwer; 1994.

Gruninger, M., Fox, M.S.: "Methodology for the design and evaluation of ontologies"; Workshop on Basic Ontological Issues in Knowledge Sharing; Montreal; 1995.

Guha, R.V.: "Contexts: A Formalization and some Applications"; PhD thesis; Stanford University, 1991.

Hall, A.D.: "A methodology for systems engineering;, Princeton: Van Nostrand; 1962.

Hamilton, V.L., Beeby, M.L.: "Issues of traceability in integrating tools"; Proceedings Colloquium IEE Professional Group C1; London; 1991.

Hansen, C.T., Andreasen, M.M.: "Basic thinking patterns of decision-making in engineering design"; International Workshop on Multi-criteria Evaluation; MCE 2000; Neukirchen; pp 1-8; 2000.

Hansen, C.T., Andreasen, M.M.: "Two approaches to synthesis based on the domain theory"; in Chakrabarti, A. (editor): Engineering Design Synthesis-Understanding, Approaches and Tools, Springer-Verlag; London; pp. 93-108; 2002.

Hayes, P.J.: "The logic of frames"; Frame conceptions and Text Understandning; Walter *de Grutyer and Co.; 1979.*

Heflin, J.D.: "Towards the semantic web: knowledge representation in a dynamic, distributed environment"; PhD thesis; University of Meryland; 2001.

Hicks, B.J., Culley, S.J., Allen, R.D., Mullineux, G.: "A framework for the requirements of capturing, storing and reusing information and knowledge in engineering design"; International Journal of Information Management 22; Pergamon; pp. 263-280; 2002.

Hodges,W.: "Tarski's Truth Definition"; The Stanford encyclopaedia of Philosophy; Zalta, E.N. (editor), http://plato.stanford.edu/archives/win2001/ entries/tarski-truth/; 2001.

Hollingum, J.: "Implementing an Information Strategy in Manfacture"; ISBN 0 94850747 0; Bedford; UK; 1987.

Horrocks, I., Fensel, D., Harmelen, F., Decker, S., Erdmann, M., Klein, M.,: "OIL in a Nutshell"; in: ECAI_00 Workshop on Application of Ontologies and PSMs; Berlin; 2000.

Horrocks, I., van Harmelen, F.: "Reference Description of the DAML-OIL Ontology Markup Language"; technical report; http://www.daml.org/2001/ 03/reference.html; 2001.

Hubka V.: "Theorie der Konstruktionsprozesse"; Springer-Verlag; Berlin; 1976.

Hubka, V., Andreasen, M.M., Eder, W.E.: "Practila Studies in Systematic Design", Butterworth & Co. Ltd, UK, 1988.

Hubka, V., Eder, W.E.: "Einfuhrung in die Konstruktionswissenschaft"; Springer; Berlin; 1992.

Hubka, V., Eder, W.E.:"A scinetific approach to engineering design"; Design Studies; Vol. 8, No. 3, pp. 123-137, 1987.

Hubka, V., Eder. W.E.: "Theory of technical systems – A total Concept Theory for Engineering Design"; Berlin Heidelburg: Springer-Verlag; 1988.

Hubka, V.: "Practical studies in systematic design"; ButterWorth Scientific Co.; UK; 1988.

Hubka, V.: "Principles oh Engineering Design"; Springer; New York; 1989.

ISO TC184/SC4: "External representation of product data model"; ISO 10303; 1997.

Jensen, T.A.: "Functional modelling in a design support system – contribution to design workbench"; Dissertation; IKS, Technical University of Denmark, 1999.

Jones, M., Wheadon, J.; Whitgift, D., Niezzate, M., Timmeramans, R., Rodriguez, I., Romero, R.: "An agent based approach to spacecraft mission operations"; Towards very Large Knowledge Bases - Knowledge building and Knowledge Sharing; IOS Press Amsterdam; pp. 259-269; 1995.

Kalay, Y.E.: "Performance-based Design"; Automatization in Construction 8 (4); pp. 395-409; 1999.

Kayed, A., Colomb, R.M.: "Extracting ontological concepts for tendering conceptual structures"; Data & Knowledge Engineering 40; Elsevier Science; pp. 71-89; 2002.

Kifer, M., Lausen, G., Wu, J.: "Logical foundations of object-oriented and frame-based languages"; Journal of the ACM 42 (4); pp. 741–843; 1995.

Kitamura Y., Mitzoguchi R: "Ontology-based systematization of functional knowledge"; Journal of Engineering Design, Vol 15, Issue 4; Taylor and Francis Group; 2004

Klaus, G: "Worterbuch der Kybernetik"; Ditz Verlag; Berlin; 1968.

Klir, J., Valach, M.: "Cybernetic modelling"; London: Illiffe Books; 1967.

Knowledge Base Systems: "IDEF 05 Method Report"; 1994.

Knowledge Based Systems, Inc.: "IDEF5 Method Report"; 1994.

Krause, F.L.: "Knowledge integrated product modelling for design and manufacture"; The second Toyota conference; Aichi; Japan; 1988.

Lassila, O., Swick, R.: "Resource description framework (RDF) model and syntax specification "; W3C Recommendation, http://www.w3.org/TR/REC-rdf-syntax/; 1999.

Lenat, D.B., Guha, R.V.: "Building Large Knowledge-Base Systems: Representation and Interfence in the Cyc Project"; Addison-Wesley; Boston; 1990.

Lloyd, J.W.: "Foundations of Logic Programming"; Springer-Verlag; Berlin; 1987.

Luke, S., Hefin, J.: "SHOE 1.01. Proposed Specification"; SHOE Project technical report; University of Maryland; http://www.cs.umd.edu/ projects/plus/SHOE/spec1.01.htm; 2000.

MacGregor, R.; "Inside the LOOM clasifier"; SIGART bulletin 2 (3); pp.70–76; 1991.

McCarthy, J.: "Notes on formalizing context"; Proc. of 13th International Conference on Artificial Intelligence (IJCAI-93); Morgan-Kaufmann; Los Altos; pp. 555-560; 1993.

McKay, A.; Hagger, D.N.H.; Dement, C.W.; de Pennington, A.; Simons, P.: "Relationships in product structures"; Proceedings of the 7th Workshop on Product Structuring – Product Platform Development; Chalmers University of Technology; Goteborg; pp. 111-121; 2004.

McMahon, C.A., Pitt, D.J., Yang, Y., Sims Williams, J.H.: "An information management system for informal design data"; Engineering with computers, 11; pp. 123-135; 1995.

Mehkilef, M., Bourey, J.P., Bigand, M.: "An UML modelling of an architecture for knowledge documentation"; 14th International Conference on Engineering Design, ICED 03, Stockholm, Sweden, 2003.

Merkamm, H.: "Product modelling: A prerequisite for effective product development"; Proceedings of Produktmodeller95; Linkoping University of technology; Sweden; 1995.

Milstead, J.: "Invisible tresauri"; Online & CDROM Review; Vol. 19; No. 2; pp. 93-94; 1995.

Minker, J., editor: "Foundations of Deductive databases and Logic Programming"; Morgan-Kaufmann; Los Altos; CA; 1988.

Minsky, M.: "A framework for representing knowledge"; in Patrick-Henry Winston (editoe), The Psychology of Computer Vision; McGraw-Hill; New York, 1975.

Monk, J.D.: "Mathematical Logic"; Springer-Verlag; 1976.

Mortensen, N.H.: "Design modelling in a Designer's Workbench – contribution to design *language"; Dissertation; IKS, Technical University of Denmark, 1999.*

Neches, R., Fikes, R.E, Finn, T., Gruber, T.R, Senator, T., Swartout, W.R.: "Enabling technology for knowledge sharing"; AI Magazine 12 (3); pp. 35-56; 1991.

Niles, I., Pease, A.: "Origins of the IEEE Standard Upper Ontology"; Working Notes of the IJCAI-2001 Workshop on the IEEE Standard Upper Ontology; Seattle; pp. 37-42; 2001.

NIST Special Publication 939: "STEP The Grand Experience"; Manufacturing Engineering Laboratory; ed. Sharon J. Kemmerer; 1999.

Nonaka, I: "A Dynamic Theory of Organizationala Knowledge Creation"; Organization Science, Volume 5; pp 14-37; 1994.

O'Leary, D.: "Enterprise Knowledge Management", Computer, Vol. 31, No. 3, pp. 54-61, 1998.

Olesen, J.: "Concurrent Development in Manufacturing – based on dispoditional mechanisms", PhD thesis, Department of control and Engineering Design, TUD, 1992.

Ontoprise GmbH: "How to work with OntoEdit Version 2.6", Ontoprise GmbH, Karsruhe, Germany, www.ontoprise.de, 2002.

Orne, M.T.: "Demand characteristics and the concept of quasicontrols", in Rosenthal, Rosnow (editors): Artefact in behavioural research, Academic Press, New York, pp143-179, 1969.

Otto, K.N.; Wood, K.L.: "Product Design: Techniques in Reverse Engineering and New Product Development"; Prentice Hall USA; 2001.

Ottoson, S.: "When time matters"; Key note speech, Tools and Methods in Competitive Engineering – TMCE 2004; Lausanne; 2004.

Pahl, G., Beitz, W.: "Engineering Design"; The Design Coucil; London; 1988.

Palmer, J.D.: "Traceability"; Software Requirements engineering; 2nd Edition; IEEE computer Society; pp.412-422; 2000.

Pascal, B.: "Pensees"; The Franklin Library; Pennsylvania; p.22; 1670/1979.

Pavković, N., Bojčetić, N., Marjanović. D.: "Modelling the relation network in the integrated product and design process model"; Proceedings of the 7th International Design Conference – DESIGN 2002, Dubrovnik, Croatia; Marjanović, D. (editor), University of Zagreb, The Design Society, pp. 391-396, 2002

Peirce, C. S.: "Note B: The Logic of Relatives"; In Studies in Logic by Members of the Johns Hopkins University Boston; Little Brown and Co.; Reprinted in Peirce (1933), 1883.

Perakath C. B., Menzel, C.P., Mayer, R. J., Fillion, F., Futrell, M. T., deWitte, P.S., Lingineni, M.: "IDEF5 Method Report"; Knowledge Based System Inc., CN F33615-C-90-0012, Texas, USA; Armstrong Laboratory, Wright-Patterson Air Force Base, Ohio, USA; 1994

Pollock, J.T.: "The Big Issue: Interoperability vs. Integration"; eAI Journal October 2001; http://www.modulant.com/ResourceLibrary/Library_WhtPapers .htm; 2001.

Pollock, J.T.: "Integration's Dirty Little Secret: It's a Matter of Semantics"; A Modulant

White Paper; http://www.modulant.com/ResourceLibrary/ Library_Wht Papers.htm; 2002.

Pollock, J.T.: ”IT Systems Interoperability and the Revolution in Semantic Computing: Same Problem, Better Solutions”; A Modulant White Paper; http://www.modulant.com/ResourceLibrary/Library_WhtPapers.htm; 2001.

Quilian, M.R.: "Word concept: A theory and simulation of some basic semantic capabilities"; Behavioral Science 12; pp. 410-430; 1967.

Ramesh, B., Jarke, M.: "Toward reference models for requirements traceability"; Software engineering; 27(1); pp. 58-93; 2001.

Ranta, M., Mäntylä, M., Smeds, R., Haho, P., Alvesalo, J.: "Improving product development: Towards a framework for integrating artefact and process models"; Proc. of the Advances in Production Management Systems Conference APMS '99; Berlin; Germany; 1999.

Riddle, S., Arkney, P., Mason, P.: "Position paper: Enabling Traceability", First International Workshop on Traceability in Emerging Forms of Software Engineering; Edinburgh; 2002.

Roget, P.M.: "Thesaurus of English Words and Phrases"; Longman and Harlow; London; 1852.

Ropohol, G.: "Flexibile Fertigungssysteme"; Krausskopf Verlag; Mainz; 1971.

Rosenman, M.A., Gero,J.S.: "Purpose and function in design from the socio-cultural and the tchno-physical"; Design Studieas Vol. 19 No.2; 1998.

Rosenthal, R. "Experimenter effects in behavioural research", Appleton Century Crofts, New York, 1966.

Roth, K.: "Konstruiren mit Konstuktionskatalogen"; Springer; 1980.

Rubenstein-Montano, B. Liebowitz, J., Buchwalter, J., McCaw, D., Newman, B., Rebeck, K.: "A systems thinking framework for knowledge management"; Decision Support Syystems, volume 31; pp 5-16; 2001.

Russell, S., Norvig, P.: "Artificial Intelligence: A Modern Approach"; 1995.

Salminen, V., Verho, A.: "Experiences of using meta modelling in systematic design of mechatronics"; Proceedings of ICED ’91; Zurich; Heurista; 1991.

Salustri, F.A.: "Mereotopology for product modelling"; Journal of Design Research, 2(1), 2002.

Shooter, S.B., Keirouz, W.T., Szykman, S., Fenves, S.J.: "A model of flow of design information in product development"; Engineering with Computers; Springer-Verlag London; 1999.

Sim, S.K., Duffy, A.H.B: “Towards an ontology of generic engineering design activities”; Research in Engineering Design; Vol. 14, No. 4; Springer London; 2003

Smith, B.: "Mereotopology: A Theory of Parts and boundaries"; Data and Knowledge Engineering; 20; pp. 287-303; 1996.

Smith, B.: "Mereotopology: a theory of parts and boundaries"; Data and knowledge Engineering; 20; pp. 287-303; 1996.

Sowa, J.: "Knowledge representation"; Brooks/Cole, Pacific Grove, CA, USA; 2001.

Sowa, J.F.: "Conceptual structures: Information processing in minds and machines"; Addison-Wesley; Reading, MA; 1984.

Staab, S., Schnurr, H.P., Studer, R., Sure, Y.: "Knowledge process and ontologies"; IEEE Intelligent Systems 16 (I), pp. 26-34; 2001.

Studler, R., Benjamins, V.R., Fensel, D.: "Knowledge engineering: principle and methods"; Data and Knowledge Engineering 25; pp. 161-197; 1998

Suguman, V., Storey, V.C.: "Ontologies for conceptual modelling: their creation, use, and management"; Data & Knowledge Engineering 42; Elsevier Science; pp. 251-271; 2002.

Sure, Y., Angele, J., Staab, S.: "OntoEdit: Guiding Ontology Development by Methodology and Inferencing" Proceedings of the International Conference on Ontologies, Databases and Applications of Semantics (ODBASE 2002), Irvine, California, USA, 2002.

Sure, Y., Erdmann, M., Angele, J., Staab, S., Studer, R., Wenke, D.: "OntoEdit: Collaborative Ontology Development for the Semantic Web", Proceedings of the first International Semantic Web Conference 2002 (ISWC 2002), Sardinia, Italia, 2002.

Swartout, B., Ramsh, P., Knight, K., Russ, T.: "Toward Distributed Use of Large-Scale Ontologies"; AAAI Symposium on Ontological Engineering, Stanford; 1997.

Szykman, S.; Fenves, S.J.; Keirouz, W. Shooter, S.B.: "A foundation for interoperability in next-generation product development systems"; Computer-Aided Design 33; pp. 545-559; 2001.

Szykman, S.; Fenves, S.J.; Keirouz, W. Shooter, S.B.: "A foundation for interoperability in next-generation product development systems"; Computer-Aided Design 33; 545-559; 2001.

Štorga, M., Andreasen, M.M.: "Complexity of the product development context"; 4th International Seminar and Workshop EDIProD 2004; Poland, 2004

Štorga, M., Marjanović, D., Bojčetić, N.: "Consideration on IT systems interoperability in product development"; Proceedings of the TMCE 2004; Millpress; Rotterdam; pp. 787-796.; 2004.

Štorga, M.: "Traceability in product development"; Proceedings of the DESIGN 2004; FSB; The Design Society; Zagreb; 2004.

Tarski, A.: "The semantic conception of truth and the foundations of semantic"; Philosophy and Phenomenological Research 4; 1944.

Tarski, J.: "A decision method for elementary algebra and geometry"; 1948.

Tomiyama, T.: "A design process model that unifies general design theory and empirical findings"; ASME Design Engineering, 83(2); pp. 329-340; 1995.

Tomiyama, T.: "Metamodel: A Key to Intelligent CAD Systems"; Research in Engineering Design; Springer- Verlag; New York; 1989.

TopQuadrant Tehnology Briefing: "Semantic Integration – Strategies and Tools", USA, 2003.

Ullman, D.G.: "The Mechanical Design Process"; McGraw-Hill; 1992.

Ulrich K.T, Epinger, S.D.: "Product design and development (2nd edition)"; McGraw-Hill; Boston; USA; 2000.

Uschold, M., Gruninger, M.: "Ontologies: Principles, Methods and Applications"; Knowledge Engineering Review Vol 11 No.2; 1996.

Uschold, M., Jesper, R.: "A framework for Understanding and Classifying Ontology Application"; Proceedings IJCAI99 Workshop on Ontologies and Problem solving Methods; Stockholm; 1999.

Uschold, M., King, M.: "Towards a Methodology for Building Ontologies"; IJCAI95 Workshop on Basic Ontological Issues in Knowledge Sharing; Montreal; 1995.

VDI 2221:"Methodik zum Entwickeln und Konstruiren technischer Systeme und Produkte"; Berlin; Beuth Verlag; 1993.

Vickerty, V.C. "Thesaurus – a new word in documentation"; Journal of Documentation; Vol 16; pp. 181-189; 1960.

Vickery, B.C.: "Ontologies"; Journal of Information Science; Vol 23; No. 4; pp. 277-286; 1997.

Von Wright, G.H.: "Explanation and Understanding"; London: Routledge & Kegan Paul; 1971.

Wall, R.A.: "Finding and using product information"; UK Gower; 1986.

Wiig, K.M. De Hoog, R., Can Der Spek, R.: "Supporting Knowledge management: A section of Methods and Techniques"; Expert Systems with application, volume 13, Numero 1,; pp 15-27; 1997.

Wilson, P.: "Information Modelling"; IEEE computer Graphic and Applications; pp. 65-67; 1987.

Yoshikava, H.: "General Design Theory as a Formal Theory of Design"; Intelligent CAD I; ed. Yoshikawa; Gossard; Procc. of IFIP TC5/WG5.2; North Holland; Boston; 1987.

BIOGRAPHY

Mario Štorga was born on February 24th 1974 in Varaždin where he completed his secondary school education (technical high school). In 1997, he graduated in mechanical design from the Faculty of Mechanical Engineering and Naval Architecture of the University of Zagreb. Since 1997 he has been a science novice at the Design Department of the Faculty of Mechanical Engineering and Naval Architecture of the University of Zagreb, at the research projects no. 120-015 "Model of intelligent CAD system" and no. 0120017 "Models and methods for improving the computer support of product development".

In 2002 Mario Štorga acquired the M. Sc. degree at the Faculty of Mechanical Engineering and Naval Architecture of Zagreb University with the thesis "Web Service for the Product Data Exchange and Management". Besides teaching activities at the home faculty, he has been involved in the teching at the Study of Design on Faculty of Architecture in Zagreb and at the Study of Mechanical Engineering and the Study of Computer Science (Informatics) at the Polytechnics of Zagreb.

During the summer 2000, Mario Štorga has participated the "Ph.D. Course - Design Methodology" organized by the Technical University of Denmark, Technical University of Berlin and Technical University of Saarland. He also took the part in the organization of the international design conferences DESIGN '98, DESIGN 2000, DESIGN 2002, DESIGN 2004 held in Dubrovnik. Since 2004 he is the member of Scientific Advisory Board of the DESIGN and ICED conferences organized by international research community - the Design Society.

In academic year 2003/04 by foundation of Croatian Ministry of Science, Education and Sports, Mario Storga has spent six months as a guest researcher at the Technical University of Denmark working on the research related to his dissertation. As the author or co-author he has published 21 scientific papers and 13 technical reports in Croatia and abroad. He is member of "The Croatian Society for Machine Elements and Design" as well as an international association "The Design Society". He has a good command of English and can read German well.