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EXTENDED EDITORIAL

Ontological engineering for supporting semantic reasoning in design: Deriving models based on ontologies for supporting engineering design

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1. Research issues on ontology development and utilisation in engineering design

The aim of this section is to provide an overview on the state of the current research, the exposition of the challenges faced in various fields of knowledge formalisation and representation (KFR), and to cast light on the relationship between ontology development and semantic reasoning in engineering design.

1.1. Knowledge formalization and representation

KFR have received much attention in the last decades, especially in the context of knowledge-intensive systems engineering, product design, life-cycle management, and artificial intelligence-based solutions. The opportunities offered by the related technologies are far from being completely exploited. Actually, new technological affordances and new application demands appear on a daily basis. This makes KFR a strategic strand of both scientific inquiry and engineering utilisation, which is critical to aligning, interpreting, and overlapping design and engineering models as interoperable, and facilitating reasoning over their contents. The first studies addressed the latter issues at a high abstraction level. However, time has come to address these issues at a specific abstraction level (i.e., to operationalise knowledge formalisation and representation for design and engineering, and to bring it into synergy with other lifecycle aspects) and in a context-dependent manner. The industry is waiting for testable and utilisable implementations. Many intellectual challenges and practical limitations have been realised in this context. Some of the main barriers are:

1) acceptance (i.e., the difficulty of reasoning with semantics and logics for non-logicians and non-philosophers);
2) orthogonality (i.e., ontology engineering is seen as a cross-design activity and time-consuming effort), and
3) implementation (i.e., interoperability of ontology models and computer aided design systems seem to be an unsolved issue).

Not only the ontology scientists, but also the engineering design community has made steps to achieve the above goals and to overcome the aforementioned and other barriers. The efforts have led to more knowledge intensive approaches and solutions. However, there is still a long road ahead. Contrary to the facts that the efficiency of industrial product development processes has been significantly increased by integrating lifecycle aspects, and that the diversity of the developed products/systems (including electromechanical, mechatronics, cyber-physical systems, and so on) has been successfully addressed, cognitive engineering of smart products is lagging behind. At the same time, closed-loop processes built upon Internet of Things technologies have increased the awareness in manufacturing. It has been recognised that engineering design can have cognitive support from various ontology engineering approaches and application of machine/deep learning methods. In this context, data-driven reasoning, ontology-based construction of models, and dynamic capturing and exploitation of context information are the major competing paradigms. In addition, increasing the semantic context of engineering design models, and creating opportunities for direct inferring or predictive reasoning are also at stake. In the coming years, various ontologies can play a crucial role with regards to capturing knowledge for semantic-rich design and engineering modelling, and to complementing design reasoning and engineering problem solving with semantic knowledge. Ontology technologies are becoming more and more advanced (e.g., integrated and interconnected), as well as the systems and supporting processes where they are used.

Considering all of these developments, the objective of this Special Issue has been to present those research approaches and results that have made significant contribution to understanding and operationalising the phenomenon of deriving models based on ontologies for supporting design and engineering processes. The highlighted papers address not only the knowledge formalisation and representation problem, but also offer tested solutions to engineering modelling based on ontologies. In this sense, many of them open up future perspectives in delivering semantic models for engineering design. They also brought into the limelight that further support of semantic reasoning in design and engineering requires 1) dedicated ontological engineering approaches (i.e. procedures, framework, methodology, methods, tools, theories, etc.) to 2) support/improve/extend semantic reasoning mechanisms (by using some sort of semantic reasoners such as inference engines, rule-based mechanisms, semantic algebras, ontological languages, representational logics, etc.) for 3) inferring logical/semantic/pragmatic consequences to support engineering design issues (e.g., creative combination, control design, etc.). The rest of this Extended Editorial is structured as follows. The next subsections in Section 1 further elaborate on the research issues concerning KFR, ontology development, and semantic reasoning in engineering design. In Section 2, front-line research works in using ontological knowledge in model construction in engineering design is introduced. In Section 3, we present the synopsis of the contributions to the Special Issue and arrange the contributed papers and their interrelationships. Finally, the remaining challenges are introduced in this extended editorial.

1.2. Ontology development strategies

Ontology has originally received much attention from philosophers and mathematicians over centuries, dealing firstly with the conceptualisation of the reality and then the multiple perceptions of the physical phenomenon. This has generated abundant research works in the field of knowledge engineering and surrounding engineering domains that leverage knowledge and knowledge-based techniques. In such a context that is time- and domain-dependent, one can identify two different strategies of developing ontologies in the literature. These are the *top-down* and *bottom-up* strategies. On the one hand, the top-down strategy promotes a higher abstraction-level ontology development by putting the emphasis on the underpinning theories or philosophical stances/assumptions. Such development direction is represented by foundational ontologies – which are either built upon an endurantist vision or a perdurantist one (Sider 2001) – to describe general concepts and relationships independent of any domains. The first addresses a three-dimensional perception of the physical objects, which persist over time. The latter promotes a four-dimensionalist stance by considering the fact that physical objects have distinct temporal parts through their existence. Hence, it is beforehand required to adopt one of the mentioned stances in order to develop an axioms-based and stable machine-interpretable structures like those foundational ontologies already well-established: DOLCE – Descriptive Ontology for Linguistic and Cognitive Engineering (Gangemi *et al*. 2002), SUMO –

Suggested Upper Merged Ontology (Pease *et al*. 2002), and BFO – Basic Formal Ontology (Arp *et al*. 2015) ontologies, just to name a few.

From another perspective, the bottom-up strategy of ontology development received much more attention from non-logicians and non-philosophers over the last two decades, due to the fact that bottom-up ontologies may structure knowledge belonging to a specific domain. In a sense, this development direction is represented by domain ontologies, which describe concepts for a specific domain, and application ontologies, which include concepts for a particular application (de Bruijn 2003). To do so, the lack of tools to support knowledge acquisition or reuse through natural language interfaces and diagrams is still an issue, albeit some promising efforts show that learning techniques can facilitate the mass knowledge acquisition in an automatic manner. This is actually addressed by techniques like natural language processing and machine learning (Keet 2018).

Another research issue in this particular research field is about the organisation and alignment of ontologies from an abstraction hierarchy point of view along the level of expressiveness (Chandrasekaran *et al*. 1999; Ye *et al*. 2007). The level of expressiveness is ranged from concepts, taxonomies, and relationships between concepts and properties (i.e., lightweight ontologies) to formal axioms and constraints, the latter ensuring the semantic interpretation (i.e., heavyweight ontologies) (Ye *et al*. 2007). In the space of twenty years, we have shift from 'monolith' ontology describing single perception to ontology supporting multiple viewpoints, representations and different levels of granularity, which were inspired by the recent software development methodologies featured by collaborative modelling and agile development to name a few. It is relevant to consider the development of ontology as a whole in order to deliver formal and explicit contributions to the generic ontologies and therefore enriching and structuring the body of knowledge of the physical world, where technologies are increasingly developed as knowledge and information intensive consumers.

In the context of engineering design where lifecycle concerns and their specific point of view have to be articulated in a modular fashion to deliver well-balanced systems, the aforementioned issues remain true. To prevent information inconsistencies entailed by the multiple conceptualisations and the related interoperability issues, Arp *et al*. (2015) focused their attention on ontological realism that considers perspectivism in a way that multiple conceptualisations can exist as long as each of them is true. Even if this latter seems to be promising, ontology development strategy has to initially consider the purpose of using ontology as well as its dedicated reasoning layers. In such a way, it is needed to enhance current developments by operating the intrinsic forces of a formal and explicit knowledge systems. As an example, with the growing demand of artificial intelligence-based techniques in engineering design, ontology has also a tremendous role to play, especially by coupling reasoning and learning capabilities (Baclawski *et al*. 2017).

1.3. Semantic reasoning in engineering design

The primary intention of developing ontology for engineering design is to assist designers in knowledge sharing and reuse in a collaborative manner. In a sense, ontologies provide a support for the design process, by capturing and reusing engineering contents like technical information and knowledge from requirements modelling to CAD modelling and simulation/optimisation phases. Although significant progress has been done in eliciting design knowledge, it remains important to represent knowledge covering design and manufacturing across disciplines. In addition to the capture of inert knowledge, another key point is about the activation of the ontology structure to a specific context. In such a way, the knowledge sharing reuse becomes efficient as their instantiation is made in an appropriate way. At an information system level, ontology has played a great role in ensuring the interoperation between product design systems. This has enabled information exchange and information interpretation in two-ways (Szejka *et al*. 2017). On the other hand, ontology has introduced the opportunity to provide more rigorous reasoning procedures based on semantics and logics about the construction of engineering models and related processes. Consequently, the ontology is also used to provide verification means of the integrity, completeness and coherence of engineering design models.

2. A glimpse on the front-line research in using ontological knowledge for model construction in engineering design

2.1. The reasoning model used in the brief survey

Not long ago, Lim *et al*. (2015) surveyed the status of using ontologies in engineering design and casted light on some important challenges that are aligned with one of the objectives of this Special Issue to sketch up the current state of progress in research in the field of ontological engineering to support semantic reasoning in engineering design. However, as a consequence of the broadness of the field, we have restricted the scope of review to the approaches and results of deriving models based on ontologies for supporting engineering design. In our review, we used a reasoning model to identify the most relevant subfields of interests and their interrelationship. From the large number of related research frontiers, we selected the four subfields shown in Figure 1 with a view to the specific contribution of the selected papers included in Section 3. There have been rapid developments in each of these fields, all of which obviously cannot be incorporated in this concise overview. Putting the focus on the indicated subfields also provides a unique character for this Special Issue in comparison with other similar ones such as the Special Issue on *Modeling, Extraction, and Transformation of Semantics in Computer Aided Engineering Systems*, recently published in Advanced Engineering Informatics Journal (Zeng *et al*. 2013).

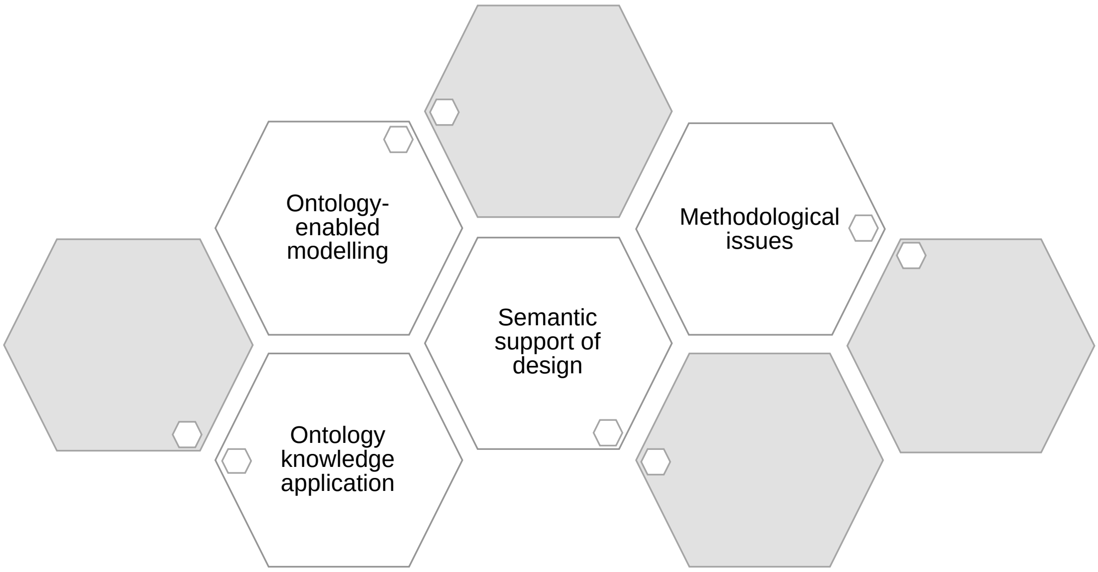

Figure 1 *– Conceptual model of the survey*

2.2. Examples of typical front-end contributions in the related literature

2.2.1. Ontology-enabled modelling

The objective of ontology-enabled modelling is to use the knowledge residing in engineering-orientated and/or generic ontologies to make the modelling more knowledge-intensive and to lift the related information reasoning from the syntactic to semantic level. The means and processes of enabling are rather varied. As reflected by the literature ontological underpinning has been considered in both engineering content modelling and engineering context modelling. Bellatreche *et al*. (2006) analysed the role of ontology-based data modelling in the context of automatic integration of electronic catalogues within engineering databases. Blobel *et al*. (2018) discussed the challenges of data modelling with regards to advanced interoperability. Sarder *et al.* (2007) proposed a methodology for design ontology modelling.

The implementation of Industry 4.0 emphasises the need for increasing knowledge-intensiveness, providing semantics-sensitive knowledge platforms, and developing smart systems with advanced reasoning capabilities. In this respect, Giustozzi *et al*. (2018) addressed the issues of ontology-based context modelling. Gu *et al*. (2004) addressed the issue of ontology-based context modelling from the perspective of intelligent environments. HameurLaine *et al*. (2015) proposed a combined ontology and rule-based model to reason out the contextual information. Their intention was to support providing context sensitive services in healthcare systems. Ye *et al*. (2007) proposed the use of ontology-based models in pervasive computing systems.

2.2.2. Semantic support of engineering design

It seems that the research in semantic support of engineering design has two distinct objectives: 1) capturing and representation semantics and 2) using semantic information in design reasoning and decision making. In connection with the first topic, Lu *et al*. (2015) proposed an approach for enriching the semantics of variational geometric constraint data by ontology-contained information. The work of Choi *et al*. (2013) focused on the management semantic assembly design rules and proposed a disparate attributes algorithm for semantic rule complexity reduction. Premkumar *et al*. (2014) discussed the issues and proposed a semantic knowledge management system for laminated composites.

There are many useful contributions to the topic of using semantic information in design reasoning and decision making. For instance, Zeng *et al*. (2013) addressed the issue of modelling, extraction, and transformation of semantics in the context of computer aided engineering systems. Zhu *et al*. (2012) used product assembly ontologies to enable reasoning in semantics-dependent applications. De Bruijn (2003) suggested to employ ontologies for knowledge sharing and reuse on the semantic web. Nuñez and Borsato (2018) developed an ontology-based model for implementing prognostic health management in mechanical machines.

2.2.3. Ontology knowledge application

Ontology knowledge means, on the one hand, the knowledge encapsulated and implied by formal ontologies (‘what’ type of knowledge), and on the other hand, the know-how and best practices of utilizing ontology-provided knowledge (‘how’ type knowledge). Among the pioneering works that intended to use what-type ontology knowledge was the project of Horváth *et al*. (1998), which had a dual focus. It proposed an approach to the development and application of design concept ontologies, and presented an application case study concerning the use of this ontology knowledge for design conceptualization in context. Van der Vegte *et al*. (2002) used ontology for modelling product functionality and use in the case of intended and unintended use and behaviour. Dual focus was the characteristics also of the paper of Yoshioka *et al*. (2004), which proposed a physical concept ontology, and showed how it could be applied as a content for a knowledge-intensive engineering framework. In the field of collaborative design, Kim *et al*. (2006) presented ontology-based formalism that supports semantic reasoning of product assembly with joints. This formalism has been extended to mereotopological semantic reasoning for assembly modelling (Kim *et al*. 2009; Gruhier *et al*. 2016) and process design (Gruhier *et al*. 2015).

To enable integrated product design and assembly sequence planning, Gruhier *et al*. (2015) proposed the use of a spatiotemporal mereotopology-induced formal ontology knowledge. Sun *et al*. (2010) discussed many lately recognised issues of knowledge-intensive support for product design using how-type ontology knowledge. In a study focusing on the construction industry, Zhou *et al*. (2016) provided an overview and analysis of ontology studies supporting the methodological developments in this sector. Ahmed and Štorga (2009) compared the empirical and theoretical approaches to develop engineering ontologies and investigated how a merged ontology could support engineering design. Guo & Goh (2017) showed how design of active fall protection systems can benefit from the use of ontology knowledge.

2.2.4. Methodological issues of ontology-based model construction

Our observation is that three significant strands of research seem to be formed concerning the use of ontological knowledge in model construction in engineering design. These are: 1) abstractions imposed on ontology contents; 2) frameworks for exploitation of ontology knowledge in modelling; and 3) increasing the efficiency of knowledge-intensive modelling. A typical example of abstraction-orientated studies is the work of Cho *et al*. (2006), who proposed a meta-ontology for automated information integration concerning parts libraries. Soininen *et al*. (1998) investigated the need and opportunity of establishing a general ontology of configuration. Li *et al*. (2009) proposed a methodology for acquisition and validation of engineering ontologies for the practice.

Largely different frameworks were proposed for exploitation of ontology knowledge in modelling with regards to engineering design. For instance, Li *et al*. (2018) have developed an ontology-based product design framework for verification of manufacturability and knowledge reuse. Maleki *et al*. (2018) elaborated on an ontology-based framework enabling smart product-service systems development in particular for machine health monitoring. Gregor *et al*. (2016) proposed a methodology for construction of a structured ontology dedicated to designing intelligent transportation systems.

As far as the performance and efficiency increasing efforts are concerned, Vijaykumar and Chakrabarti (2008) investigated the actual knowledge needs of industrial designers during product design processes. Abadi *et al*. (2018) proposed to consider using SWRL (Semantic Web Rule Language) rules expression and ontology-based reasoning in combination in order to improve integrated product design. Several issues of effective ontology engineering have been discussed by Hildebrandt *et al*. (2018) in the context of processing requirements for collaborative embedded systems. Though each of the cited works has reasonable contribution to the corresponding domains, we should regard them as purposefully chosen examples, rather than the sole representative of those domains.

2.3. Implications and conclusions

The above concise literature analysis casts light on two important facts. First, no matter how we focus the scope of our investigation a large number and very diverse studies can be found, which are difficult to be placed in a systematic taxonomy or classification. Second, though many research phenomena have already been addressed, many of the even from several aspects, there is still a need for an intense research to fill in the white spots and to resolve the open issues. There is an intrinsic research challenge not only due to the wide range of the possible topics waiting for research, but also from the enormous variety of engineering design applications and issues that are waiting for solutions. It can also be observed that the traditional reductionist approach and the doctrine of 'divide and conquer' do not lead to proper solutions always. However, there is a lack of holistic and integrative research approaches. While research is getting more and more interdisciplinary, multi-disciplinary, and even transdisciplinary, the collaborative efforts of the best representatives of the various research domains would provide more opportunities to realise more holistic way to derive semantically processible ontology models and integration to various product design systems; however, it does not seem to be an immediate trend. Next section will introduce the contributions of the Special Issue and their place regarding the proposed reasoning model.

3. Synopsis of the contributions to the Special Issue

3.1. Overview of the contribution

This special issue has received 25 full-paper submissions. Among the great number of received papers, 10 articles survived the review process to be published, leading to an acceptance ration of 0.4. Based on the accepted papers, the Guest Editors have carefully considered their scope and have unfortunately made decisions to rule out high-quality articles in order to ensure cohesion and articulation between the selected papers. As a consequence, eight research orientated papers and two application orientated papers are selected and briefly presented hereafter.

The first article – proposed by Madhusudanan *et al*. and entitled *From natural language text to rules: Knowledge acquisition from formal documents for aircraft assembly* – introduces a procedure for semantic knowledge discovery and acquisition from design documents by considering natural language understanding and processing. The purpose of their knowledge extraction was to support the decision making in the context of smart manufacturing systems, especially through the application domain of aircraft assembly. Then, Li *et al*. in their article entitled *Supporting the construction of affective product taxonomies from online customer reviews: an affective-semantic approach*, have incorporated affective engineering and semantic analysis to extract product features and affective attributes from online product information.

At a higher abstraction level, Bock and Galey have considered ontology in their article *Integrating four-dimensional ontology and systems requirements modeling*. The authors proposed to incorporate the temporal dimension to enable a more realistic modelling and analysis in engineering, especially in the modelling of four-dimensional requirements. In a sense, this article introduces engineering-accessible extensions to logical system modelling in order to cover the changeable design requirements on action orientated-system behaviour occurring in both space and time. Similarly, the third article, introduced by Liu *et al*., entitled *Ontology-based model-driven design of distributed control applications in manufacturing systems,* addresses integration and automation issues at the system design level via SysML and IEC 61499 where a manufacturing ontology and a distributed control ontology construction are proposed within a systematic approach enabling the correlation of system and control application design knowledge.

Pavkovic *et al*. in their article *Patterns of Engineering Design Collaboration and Reasoning Activities Modeled with Coloured Petri Nets* – introduces Coloured Petri Nets to model engineering design collaboration activities. In such a way, the article covers the process knowledge formalisation issues in the context of collaborative engineering by simultaneously and dynamically conceptualising the associated rules and relationships. This result in the instantiation of engineering activities taxonomy supports the development of the ontology definitions, suitable to address semantic integration between decision support systems and ontology models. Considering knowledge reuse in conceptual design, Jia *et al*., through their article *Analogical Stimuli Retrieval Approach Based on R-SBF Ontology Model*, have proposed a retrieval approach with the structure-behaviour-function model while promoting analogy-aided design innovation by associating knowledge description and analogy-based retrieval method.

Furthermore, Hagedorn *et al*. through their article *Interoperability of disparate engineering domain ontologies using Basic Formal Ontology* have developed an integrated framework for additively manufactured products and design with additive manufacturing that allows simultaneous capture, reasoning over, and querying of information relating to design, additive manufacturing, product contact, market factors, regulations, and external domain information. Built on this, their also proposed a novel design method that uses the interconnectedness of the multidisciplinary knowledge availed by the upper ontology framework based in BFO. Cheong and Butscher, in *Physics-based simulation ontology: an ontology to support modeling and reuse of data for physics-based simulation*, aim to model physical phenomenon of interests independent of computer aided engineering solver-specific interpretations. To do this, their developed a physics-based simulation ontology built upon the BFO ontology to support the modelling and reuse of data for physics-based simulation. In such a way, this ontology is intended to provide a shared viewpoint generic enough to be instantiated in multiple simulation solvers.

The last two articles present application contributions. In the field of computer aided design and engineering, Boussuge *et al.*, with their article entitled *Capturing simulation intent in a ontology: CAD and CAE integration application*, have introduced a simulation intent ontology to formalise and structure analysis parameter, the cellular modelling and idealisation decisions in order to construct knowledge-based CAE models for multiple simulation domains. Finally, Wang *et al.*, in their article *Design for robust decision workflows using a template-based ontological method*, have developed an ontology for robust design and a template-based ontological method that supports the design of decision workflows ensuring a decision with the features of robustness, feasibility and comprehensiveness. Both articles presented detailed ontology-based application cases in their works.

3.2. Reflection on scientific contribution

This set of relevant contributions clearly demonstrates a joint interest towards the need of ontology-based engineering models for supporting engineering design. Covering multiple purposes in various engineering design fields (e.g., system engineering, assembly design, simulation to name a few), the selected authors have developed different kinds of ontology ranged from endurantist to perdurantist stances, having various levels of expressiveness and granularity. This provides hence representative materials of the latest efforts done in this particular research field, where operational expectations remains flawless. Although these research efforts have introduced an interesting spectrum of ontology engineering approaches and some reasoning mechanisms, its remains important to cover the generative aspect, that is the way ontologies are computing, therefore inferring logical/semantic/pragmatic consequences to support engineering design issues (e.g., creative combination, control design, etc.).

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