An ontology-based support for knowledge modeling and Decision-Making in Collaborative Product Design

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Abstract
In order to reduce product costs and time-to-market while improving product quality, industrial companies are forced to adopt an effective collaborative product development approach. Greater efficiency can be achieved if this collaboration is realized at the earlier phases of the product lifecycle, particularly, at the design phase. Yet, to achieve such an agile and flexible approach, two major issues need to be solved. First, the exchange and management of product, process and logistic information among many actors (and then semantic interoperability between the different information systems involved) and second, the reactivity of the decision making process. With the emergence of ontologies as a new modeling paradigm in industry during the last decades, efficient integration and semantic interoperability among all the involved inter-actors of the virtual enterprise have become attainable. In fact, in addition to their great expressiveness, ontologies can afford many reasoning capabilities. Therefore, our aim in this paper is to exploit the different potentialities of ontologies in order to support the collaborative product design process. First, we will exploit their expressivity to support the design information and knowledge management and second we will exploit their inference abilities to support the decision-making process within the design phase. To do so, we propose a new collaborative design domain ontology, general enough to model simultaneously the product, process and logistic data and specific enough to support the decision making process. Then, in a second part, we extend our proposed ontology into a fuzzy ontological model and exploit its potentialities through the proposition of a new fuzzy-ontology based approach to handle the vagueness and subjectivity inherent to the different stages of the design phase and to support the decision making process at this phase. An industrial case of study is given to validate and demonstrate the competency of the proposed ontology (CPD-Onto) and our proposed fuzzy-ontology-based approach.

Keywords: Ontologies; Fuzzy Ontologies; Collaborative product design; Semantic interoperability; Knowledge Representation; Multi-Criteria Decision-Making; Design alternatives selection; Fuzzy Ontology Reasoner.

INTRODUCTION
Nowadays, manufacturing companies have become aware that working independent of one another and making local efforts to improve their own production and business processes aren’t enough to evolve in the actual very dynamic and competitive environment[1]. In fact, strong collaboration and integration of the different inter-actors of the virtual enterprise have become a must to the achievement of cost, quality and deadlines goals.

Research studies showed that greater efficiency can be achieved if this integration is realized at the earlier phases of the product lifecycle, particularly, at the design phase ([2], [3]). In fact, the design phase is the strategic stage of the product lifecycle which consumes only 5 to 10% of the whole product’s cost[4], yet it determinates over 70% of it [5] and commits over 85% of logistic costs [6]. For all these reasons, the design of today new products has become a collaborative process conducted by a set of multidisciplinary teams who coordinate between them.

Product development process becomes then more and more complex and knowledge intensive for delivering lifecycle friendly products (i.e. assembly friendly products, green products, services oriented products, etc.), which generates design mistakes and misunderstanding [7]. In fact, in addition to the complexity of today’s products, each inter-actor contributing to the development of the new product has his own domain of expertise, speaks his own language and needs to accede to a set of information and knowledge distributed in several information systems (internal or external to his own organization) in order to effectively make his choices and take into account all the constraints required.

Thus, the realization of an effective Collaborative Product Development approach requires the resolution of two major issues. First, the exchange and management of product, process and logistic information among many actors (and then semantic interoperability between the different information systems involved in the process) and second, the reactivity of the decision making process.

To deal with these different issues related to the management of the complexity of the collaborative product design process, we propose in this work to exploit the power of the recent modeling paradigm in industry which is Ontologies. In fact, in addition to their wide expressivity, ontologies provide many reasoning abilities[8]. Therefore, ontologies have been widely used in the recent literature to deal with different issues all throughout the product lifecycle [9]. Yet, these industrial applications of ontologies present many deficiencies that we will identify later on in our paper.
The first contribution of this work addresses the research gap by developing and evaluating a consistent ontology (CPD-Onto) for the domain of collaborative product design. The ontology is aimed at providing a formal and explicit specification of a shared conceptualization of the collaborative product design domain in order to provide to designers and industrial enterprises in general, a consistent domain ontology able to support them in the information management, the enhancement of collaboration and the decision making all throughout the collaborative design process. Then, in the second contribution of our work, we proposed to go further and to extend our ontological model into a fuzzy ontology in order to improve its expressiveness and its capacities and in order to take into account all the particularities of the design phase. Therefore, we proposed a fuzzy ontology-based approach exploiting the different potentialities of fuzzy ontologies in a complete methodology to support the designers particularly in the decision making process.

So, the remainder of this paper is organized as follows. Section 2 provides a review and analysis of papers related to the applications of ontologies for the product design. Section 3 presents the first main contribution of our work consisting in the development and evaluation of our new Collaborative Product Design ontology (CPD-Onto). Next, section 4 presents the fuzzy extension of the CPD-Onto and proposes a fuzzy ontology-based approach for multi-criteria decision-making in the design process which is the second main contribution of our work. Then, a complete industrial case of study is developed in section 5 in order to demonstrate the potentialities of our proposed ontology and approach. Finally, section 6 set out some conclusions and ideas as perspectives of our work.

RELATED WORK: ONTOLOGIES AS A NEW MODELING PARADIGM TO SUPPORT PRODUCT DESIGN

According to [10], an ontology is an explicit and formal specification of the concepts, individuals and relationships that exist in some area of interest, created by defining axioms that describe the properties of these entities. In the last decade, ontologies have widely been used for knowledge representation and for many other industrial applications [11]. Fortineau and al. [9] have explained that the expected benefits from using inference ontologies can be classified into three categories that refer to the capabilities offered by the ontological models: (i) Integration and completeness provided by language expressivity, (ii) Embedded intelligence due to their reasoning capabilities and (iii) Dynamism and flexibility which they afford through queries and web services.

In the literature, the industrial applications of ontologies for the resolution of integration and semantic interoperability paradigms within the extended enterprise can be divided into three main categories: (i) Product ontologies which are centered on the product itself and dedicated only to the representation of product information (even in a Product Lifecycle Management perspective) ([12], [8]);(ii) Supply chain ontologies which are dedicated to the modeling of information and knowledge relating to the different supply chain members [13];And (iii) Collaborative Product Development and Simultaneous Engineering Ontologies which are contributing to the achievement of the collaborative approaches by integrating both of product and supply chain information and knowledge at the same time.

In our work, we join the third category of ontologies applications and we focus on the collaborative product design process. Therefore, reviewing the literature relating to this category of applications, we noticed that the most relevant works, especially those focusing on the design process are: The Product Design ontology (PDO) proposed in [12] in order to support collaboration between designers; The ontology-based model proposed by Zhang and al. [14] aiming to capitalize the knowledge of the previous projects and to ensure understanding and semantic interoperability between the different partners in the context of collaborative products development; The attempt of Bock and al. in [15] to propose a product modeling language for collaborative design that has the benefits of ontologies; The proposed ontology of Mostefai and al. [16]standing on three basic points of view in Collaborative Product Development: The design of the components, the assembly and the production plan; The ontology developed in [17] trying to exploit the reasoning capacities for the optimization of the assembly process; The attempt in [18] to propose a meta-ontology for products’ design, based on five root concepts: property, attribute, behavior, entity and object relationship; The efforts of Assouroko and al. in [19] to exploit ontologies in a semantic relationship management-based approach in order to support knowledge management and reuse in collaborative product development; The attempt of Chang and al. in [20] to propose an ontology-based approach to support data integration and decision making during the collaborative design of products; and finally, the product design and manufacturing process based ontology proposed by Chhim and al. in [21] in order to support manufacturing knowledge reuse.

We conclude that a wide number of different industrial applications of inference ontologies for Collaborative Product Development has been proposed in the recent years in literature. Although, despite their diversity and big number, all these works present many limitations. In fact, on one hand, few of them have succeeded to take into consideration both the product and logistic information in a clear and generic way because the majority of them propose either an ontological model centered on the product information, or ontology centered on logistic information. Although, to effectively manage the complexity of today collaborative product development projects, it is an indispensable issue to take into account the three basic aspects of the product lifecycle gathered in the product, manufacturing process and logistic information and knowledge. It is a must also to consider the interactions and dependencies between all of them in our information model. On the other hand, almost all the proposed ontological based models focused on exploiting only the expressivity of ontologies and neglected a fundamental capacity that ontologies offer which is their ability to infer new information: Reasoning. Moreover, no one of these works has taken into consideration the specific particularity of the
information manipulated at the design phase consisting on their imprecision and uncertainty.

Furthermore, beside all these deficiencies concerning the incomplete exploitation of the different abilities of ontologies, the majority of works aiming to support the design phase and to integrate the logistic constraints since the earlier phases of the product lifecycle are based on analytical modeling approaches (analytical models, stochastic analytical models ...). However, according to [22], mathematical models, alone, are no longer sufficient to realize an effective product design and supply chain optimization.

Thus, our first aim in this work is to address all these limitations by developing a formal collaborative product design ontology, exploiting simultaneously the different potentialities of ontologies. First, their wide expressivity to model and manage at the same time the product, manufacturing and logistic information and second their inference abilities to support the decision making process all throughout the design phase.

PROPOSITION OF A NEW DESIGN ONTOLOGY TO SUPPORT COLLABORATIVE PRODUCT DESIGN: THE CPD-ONTO

In order to overcome the drawbacks of the existing ontological models that we have highlighted before, we propose in this section a new design ontology aiming to support the collaborative product design process. The developed ontology takes into consideration the multidisciplinary and collaborative aspects of today’s product design projects. Moreover, it takes into account the early integration of manufacturing process and logistic constraints since the earliest phases of the product lifecycle. In fact, the particularity and the originality in the new developed ontology that we propose in this work is the fact that it supports the simultaneous design of the product, its manufacturing process and the whole of its associated supply chain. In what follows, we will present the adopted methodology and then we will describe on details the development process of our design ontology.

In the literature, a multitude of ontology design methodologies were proposed. Among the most known ones, it is possible to mention METHONTOLOGY [23], SENSUS [24], TOVE [25], and UPON [26]. A more complete state of art overview of methodologies for ontology engineering can be found in [27]. According to [28], even if the existing works report different principles, design criteria, and stages for ontology development, all of them involve at least the three stages proposed by the Enterprise ontology methodology [29]: (i) to identify the purpose and scope, (ii) to capture the concepts and relationships among these concepts and (iii) to codify the ontology.

For the development of CPD-Onto, we adopt the generic methodology based on well accepted principles. The adopted methodology has already been adopted by [28] and it has the following four stages:

1. Requirements specification: this stage identifies the scope and purpose of the ontology.

2. Conceptualization stage, which organizes and converts an informally perceived view of the domain into a semi-formal specification using diagrams.

3. Implementation stage, which implies the codification of the ontology using a formal language.

4. Evaluation stage, which allows making a technical judgment of the ontology quality and usefulness with respect to the requirements specification, competency questions and/or the real world.

Requirements specification

The specification of the scope and the different ontology requirements is the first step in the development process of CPD-Onto. At this stage, an analysis of the needs of today’s products design projects, the demands for different types of industries and the drawbacks of the existing models was carried out through an extended bibliographical research. An overview of these analyses was presented in section 1 and 2. In addition, a set of competency questions, that were proposed by [8] in their methodology, has served as a guideline at this stage. These questions include, but are not limited to. “What are the purposes of the ontology?”; “Who are its end-users?”, “What information should be captured in the ontology?”; and “What design criteria should be followed?”.

By answering all the competency questions and based on the knowledge gathered during this stage, we were able to identify the following requirements, which guided the design of CPD-Onto as a domain ontology:

1. Model in a consistent and generic way the collaborative product design domain by identifying its relevant concepts and the relationships among them.

2. Support the early integration of manufacturing and logistic constraints in a concurrent design perspective. Therefore, the ontology should allow:

   a. Modeling of the information and knowledge relating, at the same time, to the design of the product, its manufacturing process and its associated supply chain;

   b. The representation and management of the different constraints and requirements within the design project;

   c. Providing mechanisms to verify constraint satisfaction during the progress of the design project.

3. Enable a common understanding of the ontology content by using semantics and by providing a common vocabulary and this in order to solve the problem of semantic interoperability between the different inter-actors and also between the different information systems involved in the design project.
4. Support the decision making process, particularly in concepts design’ selection by exploiting the inference capacities of the ontology.
5. Enable the designers to reuse the knowledge of the previous similar design projects.
6. Take into account the existence of various product versions and production routes.
7. Capitalize all the design project data.

In addition to the requirements that we have specified previously, the purpose and the scope of the ontology were clearly defined. In fact, the objective is to design a general ontology able to model and manage the information of the collaborative design process and at the same time able to support its decision making stages. In addition, the scope of the proposed ontology is to support various collaborative design processes belonging to various industries and application domains. Therefore, we have decided that the ontology should represent only the concepts and relations that are common among different industries, leaving aside the details of particular domains. To do so, the axiomatization of the ontological terms was kept to a minimum [28] in order to allow for different extensions and to improve its reusability.

Ontology conceptualization

A generic conceptual model

The ontology (i.e. CPD-Onto) developed in this paper represents an effort to build a generic domain ontology able to support the whole process of collaborative product development by meeting the different requirements that we have identified before. Therefore, the next stage of CPD-Onto’s development process was the definition of the conceptual model of the ontology in order to capture the whole domain knowledge. According to ([27], [28]), the conceptualization activity “organizes and converts the informally perceived view of a domain into a semi-formal specification”. Therefore, to develop the ontology, an iterative approach was adopted and an intermediate semi-formal model was developed. In fact, we started by identifying the main concepts and relationships relevant to describe in a generic and optimal way nowadays complex product design projects. This has been done on the basis of our own experiences, of the knowledge available in literature about today’s collaborative design projects, of the existing models and their drawbacks.
that we want to overcome throughout our ontology and finally, on the basis of the different requirements that we have set before. Then, in a second iterative pass, the concepts and relationships were re-evaluated to ensure the consistency of the model and its meeting to the different ontology requirements. Figure 1 represents the global conceptual model developed to describe the main concepts and relationships, among them, of our ontology CPD-Onto. In what follows, we will describe on details all these constructs.

The main concepts and semantic relationships among them

1. **DesignProject**: The first main concept in CPD-Onto is the concept “Design project”. It models the different information relating to the design project itself. This concept has as sub-concepts: “ProductDesign”, “ManufacturingProcessDesign” and “SupplyChainDesign” in order to support the simultaneous design of the product, its manufacturing process and the whole of its associated supply chain and also to support the early integration of manufacturing and logistic constraints from the early phases of the product lifecycle. Thus, as represented in figure 2, a “DesignProject” is associated to a “Product”, a “ManufacturingProcess” and a “SupplyChain”. Each design project does have many phases. This has been modeled by the object property `hasPhase` linking the two concepts “Phase” and “DesignProject”. In addition, it has a set of resources and must meet a set of requirements. The object properties `hasResource` and `hasRequirement` have been then defined and used. Finally, in a design project, the design team members often use the different archived data and knowledge in order to benefit from the previous similar design project that they have accomplished before. We have then modeled this using the object property `usesKnowledgeAndData` between the two concepts “DesignDataAndKnowledge” and “DesignProject”.

2. **Product**: This concept models the set of data and knowledge relating to the product. We have taken into consideration all its statuses (idea, virtual product and physical product) and we have defined as sub-concepts of a “Product” the concepts: “Assembly”, “ConceptDesignAlternative”, “ProductVariant” and “ProductVersion”. In fact, a product can be a subpart of an assembly. The reflexive object property `hasComponent` has been used to model this. In addition, in the different phases of the design project, many design alternatives, versions and variants can be proposed by the designers for a specific product. For this reason, we have defined the object properties: `hasProductVersion` and `hasVariant`. In addition, as represented in figure 3, the “Product” has a set of characteristic documents where are stored all the data and knowledge relating to its functions, behavior, structure, geometry, features, tolerances, and development process. Therefore, in CPD-Onto the product is linked to its “BillOfMaterials”, “ProductModel”, “AnalysisStudy”, “ProductCharacteristicDocument” and “DevelopmentPlan”. Finally, the product satisfies to a set of Functional Specifications and “Requirements” and it is associated to the “Costumer” who demands it.

![Figure 2: Classes and sub-classes related to the main concept “DesignProject” of the domain-ontology (CPD-Onto).](image-url)
3. SupplyChain: It represents all the information relating to the extended enterprise and its different inter-actors involved in the value chain and in the whole product’s lifecycle. We consider that the virtual enterprise is composed by a supplier, a production company, a transport, a warehouse and a customer. Each one of these supply chain members has a set of characteristics that we have modeled in our ontology using the relationship hasSupplyChainMember-CharacteristicDocument.

4. ManufacturingProcess: This concept models the process of transforming raw materials, components and sub-products into a finished product that meets the entire customer’s and designers’ requirements and specifications. In CPD-Onto, we are handling the design phase, therefore we have taken into account both the virtual (simulation) and real (physical) manufacturing process.

5. Phase: This concept represents the different stages of the design project. It includes the “functionalSpecifications Definition”, the “CoceptualDesign”, the “ConceptSelection Process”, the “DetailedDesign” and the “DesignValidation”. In CPD-Onto (figure 4), each design “phase” uses and generates a set of “DesignDataAndKnowledge” and uses a set of “Resources”.

6. Requirement: It models the functional specifications and the different constraints, which are imposed by the customer, the design team members and the supply chain inter-actors, and which the final product must satisfy.

7. Resource: This concept models all the resources allocated to accomplish the design project. In our ontological model, the three main categories of the design project’ resources were modeled. In fact, in CPD-Onto the concept “Resource” has as sub-concepts: “MaterialResource” which represents the documentation, the equipment, the hardware and the software resources; “FinancialResource”; and finally “People” which refers essentially to the different “DesignTeamMember”.

8. Task: It models the elementary piece of a work, executed by a specific design project’s resource in order to contribute in the achievement of the design project goals.

9. DesignDataAndKnowledge: It constitutes one of the main concepts of CPD-Onto because it gathers all the data and knowledge generated and used all throughout the design phase (figure 5). This concept has as a role to facilitate the access to the different information relating to precedent design projects in order to reuse it for the design of the new product. And also, it will facilitates the real
time and simultaneous access of the different information relating to the design project’s advancement, among the different design team’s members. Finally, it will enable us to achieve all the knowledge and information generated within the design phase in a structured way.

**Ontology implementation**

After the accomplishment of the requirements specification and the conceptualization phases, the next step in the ontology development process is its implementation. This phase consists in transforming the ontology into a formal model by representing it in a formal ontology implementation languages so as to become interpretable. Since the Ontology Web

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**Figure 4**: Classes and sub-classes related to the main concept “Phase” of the domain-ontology (CPD-Onto).

**Figure 5**: Classes and sub-classes related to the concept “DesignDataAndKnowledge” of the domain-ontology (CPD-Onto).
Language (OWL) is the standard ontology language that has been recommended by the World Wide Web Consortium (W3C) working group since 2004[8] and in order to allow the wide reusability of CPD-Onto, we have developed our ontology using Protégé 5.0. Protégé is a free, open-source ontology editor and framework for building intelligent systems [30] and for developing OWL ontologies. The main strength of Protégé compared to other similar systems are: its user interface, the extendibility using plug-ins, the functionality that the plug-ins provide as well as the different formats that can be imported and exported ([7], [31]).

Therefore the conceptual model developed previously has been converted to a formal ontology where concepts, relations, and attributes were modeled as “classes”, “object properties” and “data properties”, respectively. For the ontology axioms, they have been represented in Protégé through the use of OWL restrictions, characteristics of object property and data type restrictions. The restrictions will be detailed later in the paper. Figure 6 gathers the different classes, object properties and data properties of the developed ontology (CPD-Onto) using Protégé 5.0.

![Figure 6: The different classes, object properties and data properties of the developed ontology (CPD-Onto) using Protégé 5.0](image-url)
Ontology evaluation

The last step in the development process of CPD-Onto is its evaluation. Ontology evaluation is a very important step which represents “the assessment of the quality and the adequacy of an ontology or parts of it according specific aim, goal or context”[32]. According to [33] and [32], several ontology evaluation approaches have been proposed in the literature in order to assist the ontologies’ designers in the evaluation process of their ontologies. Some of the most known and powerful ones of these approaches are: gold standard evaluation, automated consistency checking, data driven evaluation, criteria-based evaluation, assessment by humans, application-based evaluation and task-based evaluation ([33],[34]).

Some of these approaches may not fit well to the ontology and its application, therefore we have taken into consideration the limitations of each approach and we have then adopted a combination of automated consistency checking, criteria-based evaluation, and task-based evaluation in order to evaluate in an effective way the CPD-Onto.

Automated consistency checking

An essential aspect of ontology evaluation is to check the consistency of the ontology. By definition, a consistent ontology is a one that has no conflicts [35]. If an ontology is inconsistent, then the reasoning can’t be processed and any conclusion may be deduced[36]. In our work, the consistency of CPD-Onto was evaluated by using the Description Logic reasoner: Pellet[37]. Pellet is an integrated open source DL reasoner in Protégé 5.0 which has many competitive advantages in terms of the time it takes to check the consistency of the data and the standard and extended reasoning services that it provides.

The consistency checking of CPD-Onto has been done in an iterative way all throughout the construction and editing of the ontology. In fact, during the processing of each automated consistency checking, the inconsistent classes were marked in red and we corrected them until we had a consistent checked ontology. Figure 7 represents the final result of consistency checking of CPD-Onto within Protégé using Pellet.

Criteria-based evaluation

Criteria-based evaluation takes the ontology and evaluates it based on proposed criteria [38]. For the evaluation of CPD-Onto, we have selected five main criteria which match to the objectives of our ontology and which were proposed by past literature ([39],[40],[41]). These criteria include clarity, conciseness, extendibility, completeness and coverage.

- Clarity — Gruber [39] states three requirements for clarity that include the following: i) the ontology terms should be defined formally without subjectivity; ii) the ontology needs to be documented with natural language, and iii) the terms must convey ‘the intended meaning’ with regard to the requirements of social situations and computation rather than their context. In our work, we have considered this criterion since the conceptualization phase. In fact, to ensure the clarity of CPD-Onto, most concepts related to the design phase were inspired from the existing projects and models and most concepts relating to the product, supply chain and manufacturing process were inspired from three main standards: STEP (which is the Standard for Exchange of Product model data), SCOR (which is the Supply Chain Operations Reference) and PSL (Process Specification Language which is a standard of manufacturing activities). In addition, the ontology concepts were deemed to be defined formally and clearly. In fact, we have enriched our ontology with comments’ annotations. For example, we have defined a task as “the elementary piece of a work, executed by a specific design project’s resource in order to contribute in the achievement of the design project goals” and so on especially for all the other key concepts.

- Conciseness — The conciseness criterion means that an ontology should not include unnecessary concepts or redundancies [42]. This aspect has been carefully considered during our ontology development and validation. In fact, the last version of CPD-Onto doesn’t contain any redundant concepts or terms.

- Expandability/extendibility — It refers to an ontology’s ability to expand itself to “describe specific application domains in a way that does not change the current definitions within the ontology” ([33],[40]). The CPD-Onto was built to support various collaborative design applications.

Figure 7: The final result of consistency checking of CPD-Onto within Protégé using Pellet.
processes belonging to various industries and application domains. Therefore, it contains only the concepts and relations that are elementary and common among different industries, leaving aside the details of particular domains in order to allow for different extensions and to improve its reusability. The extensions can be made based on the generic ontological model of CPD-Onto, without changing the current definitions of concepts in the ontology.

- Completeness —This criterion refers to the fact that all the knowledge that is expected to be in the ontology is either explicitly stated or can be inferred from the ontology [43]. Checking this criterion is a difficult task because it is not possible to prove both the completeness and incompleteness of an ontology. However, an ontology is considered semantically complete if it meets the two requirements: (i) each definition is complete and (ii) the ontology explicitly includes all that is supposed to be included[33]. In our work, in order to check the completeness of our proposed ontology, we have first checked the completeness of the classes. Then we have verified the completeness of the domains and ranges of the object properties of our ontology and that they are properly defined in the ontology. Finally, we have checked the completeness of the class hierarchy. In fact, for example a “Costumer” is at the same time a sub-concept of “Supply Chain Member” and “Design Team member” because we had to model the voice of costumer in our collaborative design ontology. So, CPD-Onto wouldn’t be complete if such definitions were missing.

- Coverage — This criterion can be defined as the completeness and coverage of terms and concepts to represent an information domain [40]. In order to ensure the coverage of our ontology, the concepts, object properties and data properties of the CPD-Onto were mainly extracted and inspired from the current publications on Collaborative Product Design and on the different standards that we have cited before. These elements have been manually organized then we have checked if the ontology meets its different requirements and its scope and if it overcomes the drawbacks, that we have identified before, of the existing models. Thus, the coverage of our ontology was improved by adding missing core concepts, object properties and data properties to the CPD-Onto.

Task-based evaluation

The task-based evaluation assesses the ontology according to its competency in achieving target tasks by measuring its performance within the context of the application[42]. To evaluate the competency of the CPD-Onto, we have used it as a centric element and a core support of a complete collaborative product design project. In fact, in the industrial case study, the relevant concepts, relations and attributes of our ontology have been used to describe, model and manage all the data and knowledge of the design phase. Thus, the usefulness and coverage of our ontology were further proved by the industrial case study because we have demonstrated that the CPD-Onto can capture all essential elements and ensure the semantic interoperability between the different inter-actors of the collaborative product design process as we will see in section 5 of our paper. In addition, the CPD-Onto was extended into a fuzzy ontology, without having to change its current structure or elements but just by adding some new fuzzy extensions, in order to handle the subjectivity, uncertainty and fuzziness inherent to the different activities and information manipulated in the design phase. This has demonstrated the flexibility and easy extendibility of our ontology. Finally, the CPD-Onto has been used as a support for the decision making within the design phase thanks to the different reasoning abilities of the ontology. The details of all these tasks and applications are given in the next sections of our paper.

PROPOSITION OF A NEW FUZZY ONTOLOGY-BASED APPROACH TO SUPPORT THE DECISION-MAKING PROCESS IN CPD

Motivation

After developing a generic domain ontology for Collaborative Product Design (i.e. the CPD-Onto), we propose in this section to exploit in an effective way its different potentialities, in an ontology-based approach aiming to support the semantic interoperability and the decision making process within the design phase.

In fact, collaborative product design is a crucial process which encloses many critical decision points, such as the design concept evaluation. In this critical stage, the designers should determinate the best conceptual design of the new product among a set of available alternatives. In general, this critical decision point can be considered as a Multi-Criteria and Multi-Experts decision making problem because many decision makers are involved and many factors must be taken into consideration while implementing the performance evaluation [44]. Moreover, what increases the complexity of this stage is the amount and the nature of data manipulated. In fact, information managed at this stage is generally incomplete, imprecise and uncertain because only rough sketch or idea of concept exist [45] and because decision makers judgments are often based only on their own experiences so they are vague and uncertain [46]. All these issues have pushes us to think about the enhancement of the different abilities of crisp ontologies with the specificities of fuzzy ontologies, particularly their different potentialities in dealing with impreciseness and uncertainties. Our aim then in this section is twofold. First, we want to use the expressivity of the fuzzy extension of our ontology, the CPD-Onto, to ensure the semantic interoperability among the different inter-actors of the design team. And second, we want to exploit the inference capacities of the ontology in order to support the decision making process (figure 8).

In fact, crisp ontologies which are based on description logics [47] aren’t enough for dealing with imprecise information [48] as in our context of product design. To handle these types of problems, Fuzzy Ontologies were developed. A Fuzzy Ontology is an extension of crisp ontology which can be
Fuzzy ontologies offer, in addition to all the potentialities of crisp ontologies, the possibility to express fuzzy relations $F$. These relations allow to each individual to be related to a concept to a certain degree described by what is called ‘membership degree’ that is usually defined over the interval $[0,1]$ [47].

Recently, fuzzy ontologies have emerged as a promoting new modeling paradigm in several domains and for different applications, such as information retrieval [51], ambient intelligence [52], image interpretation [53], robotics [54], and of course decision making [55]. Our work joins the last category of applications and aims to propose a fuzzy ontology-based approach exploiting the potentialities of fuzzy ontologies to take into consideration the particularities of the information manipulated at the design phase and also to support the decision making process in one of the most crucial stages of the product lifecycle which is the conceptual design.

The proposed fuzzy-ontology based approach for MCDM within the CPD process

The fuzzy extension of the CPD-Onto constitutes the center of the proposed approach. In fact, it is around it that all the different stages of the collaborative product design are made. In the fuzzy-ontology based approach, the collaborative product design, and also the design of its associated manufacturing process and supply chain, will be handled by combining the following:

- Collaboration of multi-disciplinary design team members (including product designers, supply chain designers, manufacturing process designers, customer and others)
- Integration of manufacturing and supply chain constraints at the product design
- Management of all the design data and knowledge using the fuzzy ontology
- Combining the multi-criteria decision-making mathematical models with fuzzy ontologies inference capacities in order to improve the decision-making process, for instance in the concept design evaluation stage.

In this paper, we assume that the market research, the product demand and the marketing studies and estimations have a priori been done out of the scope of this paper.

We present in figure 9 the flowchart of our fuzzy-ontology based approach. We suppose that we are dealing with the general case of the collaborative design of a new industrial product and its associated manufacturing process and supply chain. The product may be composed of new components that have never been developed or existed in the old products and it may also combine old components and common ones.

According to the different tools of requirements engineering will be used by the design team members in order to gather all the requirements of the customer about the product, its functions, uses and esthetic. Thus, they will have a preliminary idea about the different specifications and preferences of the customer and also about the elementary functions that the final product must ensure. This information will be then encoded in the fuzzy extension of our ontology (i.e. the CPD-Onto), particularly as sub-concepts of the concepts “ProductRequirement” and “CustomerPreferences”. This step will give us the possibility to query and question the ontology about the archived similar products, components or old design projects using key words relating to the current product that we want to design. So, the design team members will have the possibility to reduce considerably the time and effort in the conceptual design stage by checking and reusing the archived knowledge relating to the old design projects that have already been treated previously and by exploiting their similarities with the current new design project.

After performing the matchmaking step, the designers will develop a set of design solution alternatives which satisfies the different functional specifications of the targeted product. In fact, using the different combinations of the technical solutions for each elementary function of the different subparts of the product, a large set of possible designs will be generated and developed by the design team which enhances the difficulty and complexity of the knowledge management and decision making process at this step because a huge number of alternatives must be handled and evaluated.

To overcome these issues, we will use the different potentialities of our ontology. On one hand, we will deal with the information management problem essentially by introducing each design solution as a sub-concept of the root class “Concept Design Alternative” and its sub-concept “Design Solution” and by associating to each of them its relating characteristics and documents on the CPD-Onto. On the other hand, we will take into consideration the different logistical constraints of the inter-actors of the supply chain in order to reduce the number of alternatives that we will evaluate.
further in the decision making process. This will enable the decision making team to focus only on the feasible and pertinent alternatives. This step will be performed by modeling the logistical constraints as axioms in our ontology using the expressivity of the OWL. Then, using the inference abilities of the ontology, the set of concept design alternatives to evaluate will be reduced and only the alternatives that satisfies both the costumer and logistical constraints will be taken into consideration by the decision making team later on.

Next, we will proceed to the fuzzy multi-criteria decision-making process in order to evaluate the design alternatives and to choose the optimal one among them. To do so, we propose in this work to exploit the different facilities provided in ([56], [55]) and to adopt them to our context of concept design selection.

The decision making stage using our fuzzy ontology will be described in details in the next section of our paper. This stage will has as an output the final best conceptual design alternative that will be extended further by the design team in the detailed conception phase. Finally, all the manipulated and generated design information and knowledge will be stored and archived in our ontology (i.e. the CPD-Onto).

The Fuzzy Multi-Criteria Decision-Making process

In our fuzzy ontology-based approach, we propose to combine the Multi-Criteria Decision-Making (MCDM) mathematical methods with the potentialities of fuzzy ontologies, particularly their inference abilities, in order to support the concept design evaluation process.

In fact, all the inputs of the decision making process are already stored in the fuzzy ontology, since it is the centric element of our approach which gathers all the data relating to the design phase. Thus, our idea is to encode a fuzzy MCDM method and to introduce its elements as axioms in the fuzzy ontology in order to provide not only a support for the information management issue but also for the decision making process throughout the use of just one centric and potential tool, i.e. the fuzzy extension of our ontology: the CPD-Onto.

In this work, we propose to use one of the common MCDM models which is the Weighted Sum Model (WSM). However, the information manipulated in the design phase is mainly imprecise and subjective. Therefore, we propose to use the fuzzy extension of WSM in our case. In fact, the fuzzy decision making theory, which is an application of the founding work of Zadeh[57], uses membership functions and fuzzy set operations which give the possibility to handle ambiguities and uncertainties[58].

We consider that $A = \{A_1, ..., A_n\}$ is the set of the conceptual design alternatives and $C = \{C_1, ..., C_m\}$ is the set of the evaluation criteria according to which the performance of each alternative is judged. The best alternative $A^*$ is the one which has the performance satisfying the following relation:

$$P = \max_i \sum_j \tilde{a}_{ij} W_j$$

for $i = 1, ..., m$

In this relation, $\tilde{a}_{ij}$ is the fuzzy triangular number representing the performance of the $i$th alternative in terms of the $j$th criteria and $W_j$ is the weight of importance of the $j$th criterion. We assume that the sum of the weights satisfies: $\sum_j W_j = 1$ and that the decision makers' team is composed of a set of K experts $DM = \{DM_1, ..., DM_k\}$, therefore the final
rank value of each alternative will be calculated using a weighted sum taking into consideration the weight of each decision maker in this team. The computation of these rank values will be processed throughout the use of the expressivity and the reasoning abilities of our fuzzy ontology.

In fact, the fuzzy Multi-Criteria Decision-Making process proposed in this study is divided into the following steps:

- **Step 1:** Selecting the design alternatives’ evaluation criteria and assigning weighting values to take into account the relative importance of each decision maker.
- **Step 2:** Determining the decision makers’ performance for each design alternative with respect to each criterion using linguistic variables.
- **Step 3:** Encoding the different membership functions of linguistic values, used by the decision makers while judging the alternatives, in the fuzzy ontology using data types annotated as in the case study that we will develop later on in this paper.
- **Step 4:** Assigning a degree of truth to each one of them.
- **Step 5:** Calculating the relative ranking value of each conceptual design alternative according to each decision maker by developing a set of weighted sum concepts and by using the fuzzy DL reasoner.
- **Step 6:** Calculating the final ranking value of each design alternative as in the fifth step.
- **Step 7:** Querying the fuzzy ontology to deduce the best conceptual design alternative (the one who maximizes the satisfiability degree of the fuzzy concept FinalValue-i).

### Fuzzification of the CPD-Onto

To enable our developed collaborative product design ontology, the CPD-Onto, to deal with the uncertainty and subjectivity inherent to the information and knowledge manipulated at the design phase, we propose as we have said before to extend it into a fuzzy ontological model. In this section we will present the different fuzzy elements that we have defined in the CPD-onto in order to enhance the expressivity of OWL with the potentialities of fuzzy logic. These fuzzifications have been done as follows:

- **Fuzzy data types (data properties):** The definition of the fuzzy data types is made throughout the expression of their ranges as data range expressions. For instance, for the data property hasCost, it may have as a range an expression such as \(\text{double \{\geq 50.0\}}\) and \(\text{double \{\leq 150.0\}}\). We use as range the referential set over which the fuzzy membership functions associated are defined[52]. Similarly, fuzzy concrete roles can be defined in the fuzzy ontology by specifying their membership functions. For example, in our case the decision makers usually use linguistic variables to express their opinions about a design alternative with respect to a specific decision criterion (such as poor, good, excellent…). To encode this knowledge, we will define first the membership values associated to these linguistic variables. For instance, we will define Good as a data type with a fuzzy annotation property defining Good the triangular fuzzy number \((a = 3, b = 4, c = 5)\). Practical examples of these annotation properties will be presented on details later on in this paper in the industrial case of study.

- **Fuzzy Object Properties:** The crisp objet properties can be transformed into fuzzy object properties by means of the assignment of a fuzzy membership value [52]. Examples in our ontology are: “Requirement-is SatisfiedBy-ConceptDesignSolution” which will enable us to characterize the degree of satisfiability of each requirement by each proposed design solution. We have also: “Costumer-demandsProduct-Product” through which we can characterize the degree of our confidence on a costumer with respect to his demand.

- **Fuzzy Modifiers and Fuzzy Modified Data Types:** These fuzzy elements enable us to specify the degree of membership of fuzzy data types. In fact, a fuzzy modifier is a function \(f_{\text{mod}} : [0;1] \rightarrow [0;1]\) which applies to a fuzzy set to change its membership function, which can be linear or triangular \((a, b, c)\) [59].

### Fuzzy reasoning

In the proposed fuzzy ontology-based approach, all the operations of the design phase are made around the fuzzy extension of the CPD-Onto. In fact, throughout our approach, the three main features of ontologies are exploited: their expressiveness, their storage abilities and their inference potentialities.

Exploiting the reasoning and inference abilities of our ontology to support the different operations of the design phase is one of the major contributions of our work. In fact, as we have seen, in the big majority of the existing works of the previous literature, authors focus only on exploiting the expressivity of...
ontologies and forget about one of their main potentialities which is reasoning.

In this work, we propose to exploit the inference capacities of the fuzzy ontology in several stages of the proposed approach and of the design phase in general. First we will exploit them for knowledge retrieval. In fact, by modeling costumers’ requirements and preferences in OWL2, we will be able to query the fuzzy ontology and to benefit from the previous similar projects. Second, the reasoning abilities of our ontology can be used by the product designers to deduce new conceptual design alternatives by combining different technical solutions of the different sub-parts of the product. Moreover, if we take into account the logistical constraints already encode in the ontology, these design alternatives would be restricted by the fuzzy DL reasoner into a pertinent consistent group of suitable alternatives to evaluate which will considerably ease the criteria decision-making process and save much time and effort. Finally, the inference capacities of the fuzzy ontology will be used to compute the different relative and final ranks of the design alternative in a correct and automatic way.

To perform the different fuzzy reasoning tasks, we propose to use, in this part of our work, the fuzzy Description Logic reasoner FuzzyDL[56] because it represents many advantages comparing to other fuzzy DL reasoner and because the fuzzy extension of our ontology, the CPD-Onto, is mainly characterized by the presence of many fuzzy data types, which are especially tackled by this reasoner. In fact, FuzzyDL is the most popular fuzzy ontology reasoner supporting fuzzy logic reasoning [56] and several applications have proved its different reasoning potentialities, including matchmaking applications and fuzzy control systems. This is why we have thought to use it in our work too.

FuzzyDL extends the classical DL SHIF (D) to the fuzzy case and it allows some new concepts constructs that we need in our case and that are not supported by other DL reasoners such as new concept constructs (like weighted sum concepts), explicit definitions of fuzzy concepts (by means of crisp intervals, trapezoidal or several other types of membership functions), concept modifiers and concrete features or datatypes [60].

In the next section, we will develop a complete industrial case of study in order to evaluate the competency of the CPD-Onto and to show the applicability and the potential of our proposed fuzzy ontology-based approach.

CASE OF STUDY

In this industrial case of study, we consider a manufacturing enterprise specialized in the production and assembly of different types of bikes. The factory has a new design project of a new product consisting in an “electric bike” and our role is to assist the designers all throughout the design phase using our ontology, the CPD-Onto, and our proposed fuzzy ontology-based approach. In fact, our aim is to validate and demonstrate the potentialities of our proposals in the support of the designers in the formulation of the technical specifications, the reuse of the precedent similar projects, the generation of different conceptual design alternatives, the decision making process and of course the enhancement of the collaboration among the collaborators and the information management in the whole of the collaborative design process.

The first step in our proposed methodology is to gather the different specifications of the costumer, to reformulate them as functional specifications and to introduce them in our ontology. In our case, the costumer is demanding a set of 120 electric city bikes destined essentially to men and women who will use the bike as a mean of transport to go to their works and to circulate within a Moroccan city. The electric bike should be comfortable and should remove or at least reduce considerably the effort from riding a conventional bike. It should be an ecologic product and must respect the electric bike norms. In addition, the costumer specifies that the autonomy of the battery of the new product should be between 35 and 60 Km and its full charging time shouldn’t be more than 3 hours but it may go up to 4 hours to a lesser degree of satisfaction. Finally, the costumer suggests that the price of the electric bike should be between 1500 and 3500 € and he prefers to equip it with a set of traditional equipments consisting basically ina frame lock, sidelights and reflectors, a headset and a waterproof bag. The due time that the costumer suggests to receive its full command is 12 weeks.

Let us show now how we have introduced all these relevant information as functional specifications in our ontology. The concept “CostumerSpecifications” gathers all the costumer’s requirements and preferences in such a way that the higher the maximal degree of satisfiability of this concept, the more the costumer is satisfied. The information was then encoded as follows:

| CostumerSpecifications ≥ CostumerRequirements ∧ CostumerPreferences |
|-------------------------|------------------|
| CostumerRequirements = R1 ∨ R2 ∨ R3 ∨ R4 ∨ R5 ∨ R6 |
| R1 = Bike ∨ HasTypeElectric |
| R2 = HasUse.City ∧ HasUser(Men ∨ Woman) |
| R3 = Respect.Norms(E-BikeNorms ∨ BikeNorms ∨ EcoNorms) |
| R4 = HasAutonomy.tui = 4.7-60 |
| R5 = HasRechargingTime.k = 3-4 |
| R6 = HasDemand.Quantity = 120 |
| CostumerPreferences = P1 ∧ P2 ∧ P3 |
| P1 = HasContr.tui = 500.2500.3500 |
| P2 = HAS.Accessories.(FrameLock ∨ Sidelights ∨ Reflector) ∧ (Helmet ∨ WBag) |
| P3 = HasDueTime = 11-12 |

We note that “tri” and “ls” refer to the triangular and left-sidehoulder membership functions [61]. Once we have introduced all the functional specifications of the new targeted product to the ontology, it is time to take advantage of the previous similar design projects that the design team has treated before. To do so, we exploit the inference abilities of the ontology.

In fact, the designers can use queries to look for information about all the previous similar design projects using either some
simple DL queries or some more complex queries expressed in SQWRL (Semantic Query-enhanced Web Rule Language) [62] to obtain more details.

The reasoner query the knowledge base of the ontology and gives designers suggestions about the bill of materials, characteristics, components, manufacturing plans and so on, of the archived similar products, i.e. city bikes. An electric city bike is before all a city bike so this querying stage will help considerably the designers in the generation of the different conceptual design solutions of the electric city bike that they want to design. Some examples of these queries are detailed next:

- **Query 1**: Show all the city bikes in our case of study.
- **Query 2**: Show only the city bikes which have a cost between 1000 and 3000 €.
- **Query 3**: Show the bill of materials and characteristics document of each city bike.
- **Query 4**: Show the related product models and their categories (is it a Sketch, a CAO model..) of each city bike.
- **Query 5**: Show the related CAO models and characteristics documents of each component of each bike.
- **Query 6**: Show the manufacturing plan and manufacturing rules of each component.

For instance, we present in figure 10 the third query and its related answers that we have obtained from our ontology, the CPD-Onto using the reasoner Pellet.

Based on the results of the knowledge reuse phase and on their own expertise, the designers propose a set of several conceptual design solutions. In this case of study, some solutions were inspired from the generic solutions existing in the web and in the previous literature [63]. We present in figure 11 the generic bill of materials of the new product, i.e. the electric city bike. By combining the different alternatives of each component, a huge number of concept design alternatives are generated. As we have explained before in our methodology, to overcome this difficulty we propose to take into consideration the manufacturing and logistic constraints and to introduce them in the CPD-Onto. Some examples of the constraints that we have taken into consideration at this stage are in the following:

- While choosing the type of the fork, either rigid or suspension, the absence of maintenance, the robustness and the simple design of the rigid fork have been considered. In fact, the electric bike is destined to a quotidian use so its elements should allow a certain robustness with a minimum maintenance; therefore the designers choose a rigid fork.
- The rigid fork imposes to do an extra work in the frame of the electric bike in order to make it more flexible in some points. Therefore, the designers opted for a frame made from aluminum for its easy manufacturability and also for its lightweight.

![Figure 10](http://www.ripublication.com)
The easy insertion and removing of the battery must be considered while specifying the form of the frame.

- The designers choose to subcontract the frame of the bicycle instead of buying the machines and the resources needed for producing it locally in order to reduce its cost.
- The electric bike should have as much standard components as possible.
- The position of the motor at the level of the crank set (pedals) or on the front wheel influence considerably on the stability and balance of the bike. Therefore, the designers opt for a crank set motor for a better distribution of masses within the bike and also to facilitate the assembly of the wheels.
- The electric bikes’ norms impose that electric motor must have a maximum continuous rated power of 250W, of which the output is progressively reduced and finally cut off as the vehicle reaches a speed of 25 km/h, or sooner, if the cyclist stops pedaling. Thus, the electric bike has been equipped with a pedaling sensor. In addition, the choice of the motor and the configuration of the speed controller have been done in a way to meet these requirements too.

At the end of this first selection stage and considering all the costumer, manufacturing and logistic constraints, the design team retains the most three pertinent conceptual design alternatives among all the generated solutions. It’s the ones which maximize the degree of satisfiability of the conjunction “CostumerSpecifications ∩ ManufacturingConstraint ∩ LogisticConstraint”. The three alternatives that will be evaluated further throughout our fuzzy ontology-based approach are represented in figure 12.

Let’s proceed now to the final decision making stage in order to select the best electric bike design alternative among the three ones as described before in our approach. The decision making team is composed of five experts (DM1, DM2, DM3, DM4 and DM5) including a product designer, a manufacturing process designer, a supply chain designer, the costumer and another decision maker. Four common criteria are considered by the decision making team:

- C1: Robustness,
- C2: Comfort,
- C3: Manufacturability,
- C4: Development Cost.

We represent in table 1 the importance degree of each decision maker and we summarize in table 2 the weight that each of them has associated to each criterion.

**Figure 12:** The three conceptual design alternatives of the electric bike that will be evaluated.
The next step in our methodology is to collect the different performances that the decision makers assign to each electric bike design alternative with respect to each criterion. To do so, the experts have used the six linguistic variables described in figure 13. These linguistic variables are then directly converted into fuzzy numbers. In fact, we have defined in the fuzzy extension of the CPD-Onto six datatypes, each one with an annotation property specifying the parameters of the fuzzy membership function of her associated linguistic variable. For instance, we present in figure 14 the annotation properties that we have encoded to define the linguistic variables “Good” and “Excellent” in the fuzzy extension of the CPD-Onto with the editor Protégé 5.

Table 1: The importance degree of decision makers.

<table>
<thead>
<tr>
<th>Decision Maker</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM₁</td>
<td>0.3</td>
</tr>
<tr>
<td>DM₂</td>
<td>0.17</td>
</tr>
<tr>
<td>DM₃</td>
<td>0.15</td>
</tr>
<tr>
<td>DM₄</td>
<td>0.2</td>
</tr>
<tr>
<td>DM₅</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Table 2: The weight of each criterion according to each decision maker.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>DM₁</th>
<th>DM₂</th>
<th>DM₃</th>
<th>DM₄</th>
<th>DM₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₁</td>
<td>0.35</td>
<td>0.25</td>
<td>0.25</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>C₂</td>
<td>0.25</td>
<td>0.15</td>
<td>0.4</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>C₃</td>
<td>0.2</td>
<td>0.3</td>
<td>0.2</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>C₄</td>
<td>0.25</td>
<td>0.25</td>
<td>0.17</td>
<td>0.33</td>
<td></td>
</tr>
</tbody>
</table>

Once all the needed datatypes encoded and the performance of each decision maker DMᵢ for each electric bike’s design alternative Dᵢ with respect to each criterion Cⱼ collected, we proceed to encoding this relevant knowledge. To do so, we first add a new data property “hasPerformance” in the fuzzy CPD-Onto. Then, for instance, DM 4 has given to the alternative 3 with respect to criterion 1 an ‘Excellent’ performance. Therefore, we have created a concept Performance 431 defined as: Performance 431= hasPerformance Excellent, where Excellent is the datatype that we have defined before and which encodes the linguistic variable ‘Excellent’ as the right shoulder fuzzy number (5, 6). All the other performances are encoded using the same methodology.

Table 3: Decision makers’ performances.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Decision alternative</th>
<th>DM₁</th>
<th>DM₂</th>
<th>DM₃</th>
<th>DM₄</th>
<th>DM₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₁</td>
<td>D₁</td>
<td>P</td>
<td>VP</td>
<td>F</td>
<td>VP</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>D₂</td>
<td>F</td>
<td>F</td>
<td>G</td>
<td>G</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>D₃</td>
<td>VG</td>
<td>E</td>
<td>VG</td>
<td>E</td>
<td>G</td>
</tr>
<tr>
<td>C₂</td>
<td>D₁</td>
<td>VP</td>
<td>P</td>
<td>VP</td>
<td>VP</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>D₂</td>
<td>F</td>
<td>F</td>
<td>P</td>
<td>G</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>D₃</td>
<td>G</td>
<td>VG</td>
<td>F</td>
<td>VG</td>
<td>F</td>
</tr>
<tr>
<td>C₃</td>
<td>D₁</td>
<td>VG</td>
<td>VG</td>
<td>VG</td>
<td>G</td>
<td>VG</td>
</tr>
<tr>
<td></td>
<td>D₂</td>
<td>P</td>
<td>F</td>
<td>F</td>
<td>F</td>
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</tr>
<tr>
<td></td>
<td>D₃</td>
<td>G</td>
<td>G</td>
<td>E</td>
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<td>G</td>
</tr>
<tr>
<td>C₄</td>
<td>D₁</td>
<td>G</td>
<td>P</td>
<td>F</td>
<td>F</td>
<td>E</td>
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<tr>
<td></td>
<td>D₂</td>
<td>F</td>
<td>VP</td>
<td>G</td>
<td>G</td>
<td>VG</td>
</tr>
<tr>
<td></td>
<td>D₃</td>
<td>E</td>
<td>G</td>
<td>VG</td>
<td>VG</td>
<td>G</td>
</tr>
</tbody>
</table>

Figure 13: Membership functions of linguistic values used for design alternatives rating.

Figure 14: The annotation property defining the fuzzy data types “Excellent” and Good.
Let’s show now how the computation of the relative rates of the design alternatives according to the decision makers has been performed. In fact, we defined a concept denoted RelativeScore. Then, we have developed for each electric bike’s design alternative Di and for each decision maker DMk, a sub concept RelativeScore-k and we have annotated it as a weighted sum concept as in figure 15.

The last stage in our approach is to use the same encoding methodology to compute the final rank value of each design alternative. Therefore, similarly we defined three weighted sum concepts denoted “FinalScore-i”, each one associated to a specific electric bike’s design alternative Di and we have taken into account the importance degree of each decision maker and the different relative rates computed before.

We present in figure 16 an example demonstrating the fuzzy annotation that we have encoded to characterize the final rank of the conceptual design alternative 3. Finally, using the fuzzy DL reasoner FuzzyDL [56] we deduced the best design alternative to choose. It is the one which maximizes the satiability degree of the fuzzy concept “FinalScore-i”. Table 4 represents the final rank value of each design alternative.

Table 4: The final rank values of the design alternatives.

<table>
<thead>
<tr>
<th>Design alternative</th>
<th>Final score</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>2,876</td>
</tr>
<tr>
<td>D2</td>
<td>3,128</td>
</tr>
<tr>
<td>D3</td>
<td>4,573</td>
</tr>
</tbody>
</table>

Thus, the ranking of the three conceptual design alternatives is: D3 > D2 > D1 and the optimal electric bike’s design alternative that designers will choose and extend in the detailed design phase is D* = D3.

Throughout this industrial case of study, we have demonstrated the potentialities of the different proposals that we have developed in this work, i.e. the CPD-Onto and the fuzzy ontology-based approach, in the support of the designers all throughout the collaborative design process. First the competency of the CPD-Onto was evaluated and demonstrated since we have used it as a centric element and a core support of a complete collaborative product design project. In fact, its different concepts, relations and attributes have been used to describe, model and manage all the data and knowledge of the design phase. Second, the coverage of the ontology was further proved by the industrial case of study because we have demonstrated that the CPD-Onto can capture all essential elements and ensure the semantic interoperability between the different inter-actors of the collaborative product design process. Third, the flexibility and easy extendibility of our ontology was proved because we have extended it into a fuzzy ontology, without having to change its structure or elements but just by adding some new fuzzy extensions.

This fuzzy extension has even added more potentialities to the ontology in term of handling the subjectivity, uncertainty and fuzziness inherent to the different activities and information manipulated in the design phase. In addition to all these details concerning the competency of the CPD-Onto, throughout the developed case of study we were able to validate and demonstrate the applicability and potential of our proposed fuzzy ontology-based approach. In fact, by pursuing the different steps of our methodology and thanks to the two main characteristics of ontologies, i.e. their expressivity and inference abilities, we have been able to support the technical specifications, the reuse of the precedent similar projects, the generation of different conceptual design alternatives, the
decision making process and of course the collaboration among the collaborators and the information management in the whole of the collaborative design process.

CONCLUSION

In order to manage the complexity, multidisciplinary and collaborative aspects of today’s products design processes, we proposed in this paper to exploit the different potentialities of ontologies. In fact, in the recent years they have emerged as a new promising information modeling paradigm thanks to their wide expressivity and to their inference abilities.

Although, this paper goes beyond the traditional industrial application of ontologies consisting basically on using only their expressivity to solve semantic interoperability problems. Indeed, the first contribution of our work consists on the development and evaluation of a new domain ontology, i.e. the CPD-Onto, overcoming the identified drawbacks of the existing ontological models and supporting both the information modeling and the decision making in the collaborative design process. The originality of the proposed ontology consists on the fact that it takes into consideration the early integration of manufacturing and logistic constraints since the earliest phases of the product lifecycle. Three ontology evaluation methods consisting on automated consistency checking, criteria-based evaluation, and task-based evaluation have been then used to evaluate and demonstrate in an effective way the competency of our ontology.

Then, the second contribution of our work constituted in extending the CPD-Onto into a fuzzy ontology in order to handle the subjectivity, uncertainty and fuzziness inherent to the different activities and information manipulated in the design phase. A new fuzzy ontology-based approach combining the Multi-Criteria Decision-Making (MCMD) mathematical methods with the potentialities of fuzzy ontologies, particularly their inference abilities, was then proposed in order to provide not only a support for the information management issue but also for the decision making process, particularly in the concept design evaluation stage. Finally, a complete industrial case of study consisting on the design of a new electric city bike was developed in the last section of our paper in order to validate and demonstrate the potential of the proposed ontology (CPD-Onto) and our proposed fuzzy ontology-based approach.

In our future work, we plan to extend the CPD-Onto and our proposed approach to cover the next stages of the product lifecycle. We also intend to complete the work done by exploiting the potentialities of ontologies for the resolution and automation of other relevant issues in other stages of the product lifecycle.

REFERENCES


