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A Transdisciplinary Method for Requirements and BOMs Engineering and Their Chaining Toward CAD Models

Alain-Jérôme FOUGÈRES[a,1], Egon OSTROSI[b] and Josip STJEPANDIĆ[c]
[a] *ECAM Rennes, Campus de Ker Lann – Bruz, Rennes 35091, France*
[b] *University of Bourgogne Franche-Comté, UTBM, ERCOS/ELLIAD EA4661, Belfort 90010, France*
[c] *PROSTEP AG, Dolivostr.11, 64293 Darmstadt, Germany*

Abstract. The interconnectedness of knowledge implies the need for a transdisciplinary attitude between humans and computers. This paper proposes a method for requirements and BOMs engineering and their chaining toward CAD models. Agents and multi-agent systems are considered and modelled as transdisciplinary concepts. The cooperative and agent-based platform *F-EGEON* (Fuzzy Engineering desiGn sEmantics elabOration and applicatioN) is developed for requirements and BOMs engineering. *F-EGEON* agents structure data into fuzzy BOMs: Fuzzy Requirement BOM (*r-BOM*), Fuzzy Function BOM (*f-BOM*), Fuzzy Component (*c-BOM*) and Fuzzy Parameters BOM (*t-BOM*). Then, a specific F-EGEON agent generates the Fuzzy *cad-BOM* to be transmitted to the *CAD* models. The prospect of equipping intelligent requirements engineering with systems like *F-EGEON* should not only aim to represent designer proposals, but also to support positive actions or behaviors in the design environment. An intelligent requirement engineering system must be capable of identifying (and even analyzing) false (even imprecise, incomplete, contradictory) statements and biased representations.

Keywords. Collaborative design, natural language processing, fuzzy requirement engineering, engineering design platform, transdisciplinary engineering, multiagent

Introduction

To produce a *CAD* representation of a product from its conceptualization, designers use a variety of knowledge that they express in a linguistic form. This process of linguistic modelling of a product follows a path that starts from the cognitive modelling of the product envisaged and ends with the formulation of a sequence of words belonging to the natural language used by the designer.

Much of design is about creating meaning. Words have definitions but, at the same time, do not have clear boundaries to their meanings. When asked, designers can of course explain the meaning of a word or sentence they have used [1], however, many words do not have a strict meaning. Therefore, the meaning that seems clear and unambiguous to one designer may seem fuzzy to another, even if those designers have shared design experience in a particular field. Although the mathematician Thom discussed the possibility of reaching hard conceptual delimitations in a mathematical

[1] Corresponding Author, Mail: alain-jerome.fougeres@ecam-rennes.fr.

language (geometric and topological representation) [2], natural language inherently generates many possible meanings with fuzzy, imprecise and uncertain limits.

The cognitive modelling performed by a designer is outsourced into an engineering object (a drawing, schematic, plan, 3D model or prototype). Thus, the designer demonstrates his skills to model a technical design, but the language of design also conditions the expression of his creativity. In addition, designers use intermediate models to facilitate their reflections, their discussions, and to support their decision-making, as well as the means of evaluating the reliability and the relevance of these decisions.

Assisting *CAD* actors with automatic processing on their own language raises a set of preliminary questions such as: how to facilitate the process of formalizing product specifications from their expressions in natural language? How to facilitate the extraction of linguistic information contained in the expression of these specifications in order to develop conceptual, schematic, or even formal models? How to define a specification language specific to *CAD* modelling?

These are all questions that researchers in requirements engineering and automatic natural language processing (*NLP*) ask each other [3]. Different approaches have thus been proposed over the last thirty years [4, 5]. Among the most recent works on the application of *NLP* to design specifications, we find in particular: an approach to facilitate the use of *CAD/CAM* systems and improve the efficiency of their design [6]; automatic generation of parametric requirements from unstructured and semi-structured specifications [7]; an approach to identify, then classify, ambiguous terms between different domains [8]; automation of change management in construction models [9].

Defining a process of semantic analysis and representation of the verbalizations carried out by the designers (process of assistance with the conceptualization which would use the linguistic and conceptual knowledge acquired beforehand) remains a good perspective to assist the design.

We assume that this process can be fully inscribed in transdisciplinarity where linguistics, design science and artificial intelligence bring out a form of human-artificial co-design. An intelligent system should be able to understand the conceptual model that a designer is trying to define with his language, and then automatically build successive formal representations that are more or less dependent on the set of propositions produced by the designer. These formal representations can then be provided for computational processing. Also, for reasons of efficiency and readability for the designers who follow the process, these design briefs must be: concise, precise, coherent and unambiguous.

Nonetheless, while there has been much research on the application of requirements engineering, none has focused specifically on fuzzy requirements engineering from natural language to CAD and PDM modelling. Therefore, the main goal of this article is to propose an intelligent method of requirements engineering from natural language, as well as its chaining to *CAD* models and PDM.

This article is organized as follows: following this introduction, section 1 presents a transdisciplinary modelling approach for requirements and BOMs engineering; section 2 illustrates the proposed method by presenting a case study on the design of a car door hinge using the cooperative and agent-based platform for product requirements and BOMs engineering *F-EGEON* (Fuzzy Engineering desiGn sEmantics elabOration and applicatioN); and section 4 provides some discussions and conclusions on this research and considerations for future research.

1. Transdisciplinary modelling approach for requirements and BOMs engineering

The actors involved in the cooperative development of the requirements are the team of designers who produce the product requirements, as well as the architect who defines the structure of the product (embodiment design).

To build the product requirements and BOMs, the designers will exchange verbally in order to define the functions of the product *(F)*, these requirements *(R)*, components *(C)* and component characteristics *(T)*, which will be grouped into the respective sets *F*, *R*, *C*, and *T*.

Figure 1 illustrates the standard scenario, or more accurately, the current situation of product specification and BOMs development: a) the designers exchange with each other to define the specifications of the product and establish the structuring of the specification data which will be stored in files managed by various IT and/or office automation tools; b) they also exchange with the architect in charge of defining the structure of the product and who ensures the storage of product and *CAD* data in the *PDM* in the form of *BOMs*; c) this last exchange with the *CAD* draftsman to give him the instructions for modelling the product on the *CAD* (for instance, geometric and mechanical model).

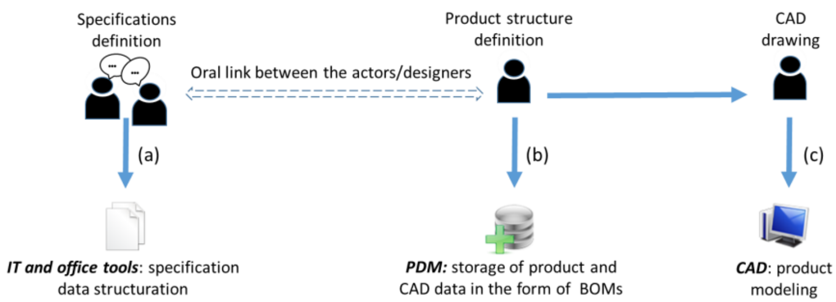

Figure 1. Actual situation

In this scenario, multidisciplinary stakeholders must acknowledge the uncertainty and fuzziness in order to ultimately achieve relevant communication and chaining of engineering requirements. Any soft computational procedure facilitating building design requirements contributes to reducing the time taken to realize not only the requirements' elaboration, but also the other design phases. Thus, it is important to gain a coherent and more complete picture of requirement engineering and BOMs engineering and their changes by considering the possibilistic nature of design formalized by fuzzy set theory.

The dynamics of computational processes from fuzzy linguistic modelling, and fuzzy cognitive modelling to fuzzy design modelling constitute in themselves a difficult and not fully explored domain. Moreover, the interconnectedness of knowledge implies the need for a transdisciplinary attitude between humans and computers. Transdisciplinary appear to point to the need for transcendent concepts [10]. The soft computational system should be transcendent because it should resolve an engineering design problem, communicate and collaborate with designers. This transdisciplinary system should be synthetic because its knowledge should be linguistic, mathematical, computational, and engineering in nature.

Agents and multi-agent systems can be considered as transdisciplinary concepts [11]. They are synthetic and can be modelled to have a transdisciplinary attitude between humans and computers. Figure 2 shows the proposed agent-based scenario, for product requirements and BOMs engineering.

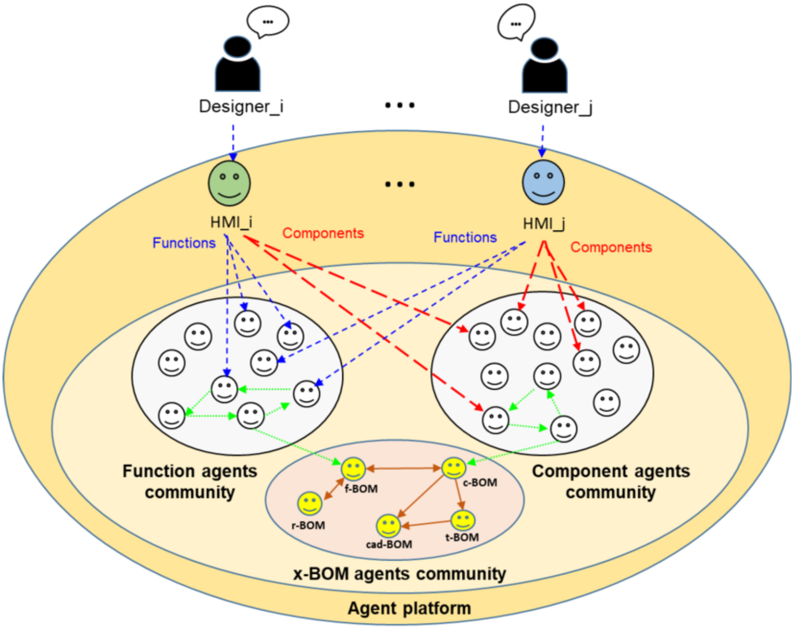

Figure 2. Proposed agent based-scenario

The product data structuration is performed by a multi-agent system composed of agents *r-BOM* (requirements-BOM), *f-BOM* (functions-BOM), *c-BOM* (components-BOM), *t-BOM* (characteristics-BOM), and *cad-BOM* (see Figure 2). These agents, generically called *x-BOM*, interact with each other by exchanging messages to share the update of their knowledge (construction of their specific lists, for example). Thus the *r-BOM* and *f-BOM* agents communicate and establish the link between requirements and product functions; *f-BOM* and *c-BOM* agents communicate and establish the link between product functions and components; the *t-BOM*, *c-BOM* and *cad-BOM* agents communicate and establish the link between product components and their attributes, and the *cad-BOM* which will be linked to the *CAD*.

Transdisciplinary modelling (linguistic, cognitive and engineering) is within the range of possibility in the world of human and agents. This principle becomes even stronger when considering requirement engineering in a cooperative context where each human and agent will have a personal perception of the different formulated language elements. These requirements from natural language should be refined to obtain formal design requirements. Indeed, the proposals set out by designers for product design are essentially descriptions of objects, elements of objects, functionalities, characterization of these functionalities, but also contexts, situations, actions or events. To interpret and then represent them, the linguistic universals: the distinctions between noun and verb, between objects, and between action and relation is an important issue. It is then a question of identifying the structural, functional and dynamic elements contained in the sentences expressing the engineering requirements, and then representing them. For this type of processing, the case grammar can be successfully used. It makes it possible to determine the category of a proposition (action, event, state) and the arguments of the predicate (agent, object, source, etc.) is an appropriate tool [12].

Moreover, the move from the informal requirements to the formal ones needs an intermediate representation. This intermediate representation might be in the form of conceptual graphs. The formal intermediate representation of fuzzy requirements serves as a pivot for translation into different design requirement languages. The identified syntactic-semantic structures can then be translated into the form of fuzzy conceptual graphs, which are the basic formal representations of product specifications for subsequent computer processing. It is then possible to translate the logical description's content into the target formal design language.

Figure 3. The method for building fuzzy engineering specifications [13, 14].

As a result, building fuzzy engineering specifications by agents which can then be chained to *CAD* models follows the six phases presented in Figure 3:

Fuzzy Engineering Language. From natural language to the fuzzy engineering language; this phase performs the extraction of words with the highest density. This density is interpreted as membership function.

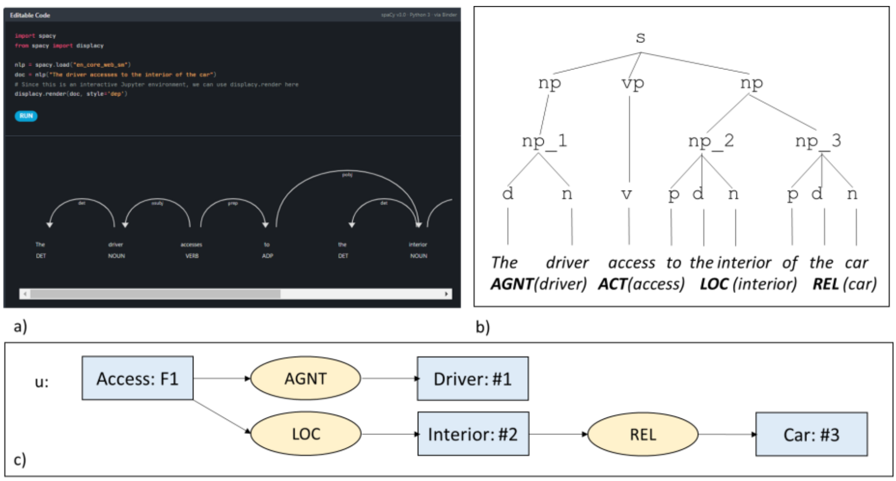

Figure 4. Fuzzy linguistic analysis and fuzzy conceptual graphs phases apply to the sentence "The driver access to the interior of the car": a) result of syntactic dependencies visualized with the *spaCy* parser. (https://spacy.io/usage/spacy-101), b) syntactic tree obtained with semantic (case) relations c) the building of the conceptual graph

Fuzzy Linguistic Analysis. This phase produces three fuzzy plans: 1) a syntactic plan using a dependency parser like *spaCy* [15], a semantic plan using case grammar [16], and a conceptual plan using conceptual graphs [17] (see an example in Figure 4.a, Figure 4.b and Figure4.c).

Fuzzy Conceptual Graphs. This phase formalizes the previous linguistic representation in fuzzy conceptual graphs which can represent the uncertainty/probability and the imprecision/subjectivity of the proposals made by cooperative designers [18].

Fuzzy Engineering Ontology. This phase builds a fuzzy ontological representation from fuzzy conceptual graphs and acquired ontology.

Fuzzy Specification Language. This phase transforms fuzzy conceptual graphs and fuzzy engineering ontology into specification language based on the logic of the first order (including fuzzy values). A logical interpretation of the conceptual graph model has been made by Sowa [18], then extended to fuzzy values in [19].

Fuzzy CAD Models. This is the final phase: the chaining of fuzzy specification language toward fuzzy CAD models.

2. Application with F-EGEON

F-EGEON (Fuzzy Engineering desiGn sEmantics elabOration and applicatioN) is a cooperative and fuzzy agent-based platform for product requirements and BOMs engineering (Figure 5). The fuzzy agent-based system $\widetilde{M}_\alpha$ of *F-EGEON* is defined by the following quadruplet [11]:

$$\widetilde{M}_\alpha = < \tilde{A}, \tilde{I}, \tilde{P}, \tilde{O} > \quad (1)$$

The set of fuzzy agents $\tilde{A}$ playing a set of fuzzy roles $\tilde{P}$ are organized in a set of fuzzy communities $\tilde{O}$ (see Figure: interface agent fuzzy community, design agent fuzzy community) are characterized by a set of fuzzy interactions $\tilde{I}$.

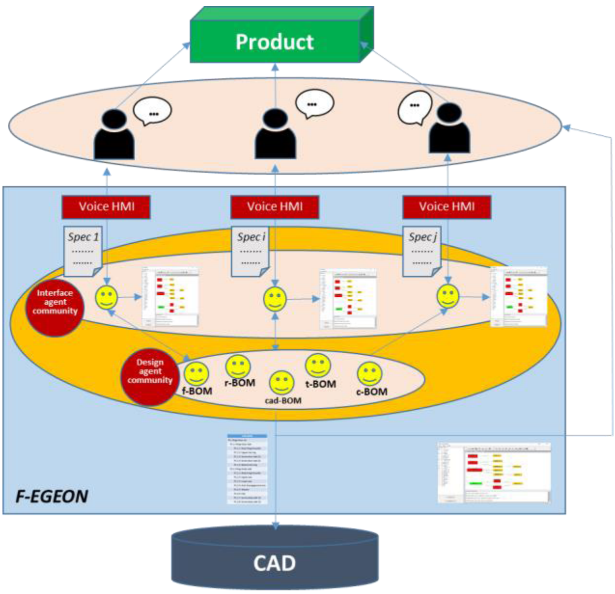

Figure 5. Cooperative and fuzzy agent-based platform *F-EGEON*.

Each time a function or a component is described by a designer, an agent respectively function agent or component agent is created. Thus, each agent function *f* of the set $F = \{f_1, f_2, \ldots, f_n\}$ is transformed into a fuzzy agent $\tilde{f}_{[1..n]} \in \tilde{A}_F$, and each agent component *c* of the set $C = \{c_1, c_2, \ldots, c_n\}$ is transformed into a fuzzy agent $\tilde{c}_{[1..n]} \in \tilde{A}_C$. Then, for making the *r-BOM*, *f-BOM*, *c-BOM*, *t-BOM* and *cad-BOM*, new agents *x-BOM* of the set $X = \{r-BOM, f-BOM, c-BOM, t-BOM, cad-BOM\}$ are created. These agents are also fuzzy agentified (eq. 2):

$$F,\ C,\ X\ \rightarrow\ \tilde{A}_F, \tilde{A}_C, \tilde{A}_X \quad (2)$$

The product functions formulated by the designers are structured in the form of a list of functions that the *f-BOM* agent keeps up to date throughout the exchanges. When the exchanges relate to the characterization of functions, it is the turn of the *r-BOM* agent to structure and update these characterizations. The designers also discuss the components of the product. These are also structured in the form of a list kept up to date by the *c-BOM* agent. When the exchanges relate to the characterization of components, it is the *t-BOM* agent that structures and updates these characterizations.

The application to illustrate our approach concerns the design of a car hinge. The scenario that we propose in this illustration connects two designers who begin to discuss the first function of the hinge, namely to easier "access to the interior of the car for the driver". The statement of this primary functionality will be accompanied by the formulation of three other secondary functions, as indicated in Table 1.

Table 1. Product functions exchanged by the two designers.

Actor	Function	Structuration
Designer 1	Facilitate access to the interior of the car	<F1> <Access><Driver><Interior Car>
Designer 2	Rotate the door relatively to the car body	<F1.1> <Rotate><Door><Car, Body>
Designer 2	Ensure solidarity between the door and the car body	<F1.2> <Solidarize><Door><Car, Body>
Designer 1	Facilitate the opening and closing of the door for the driver	<F1.3> <Open><Door><Driver> <F1.4> <Close><Door><Driver>

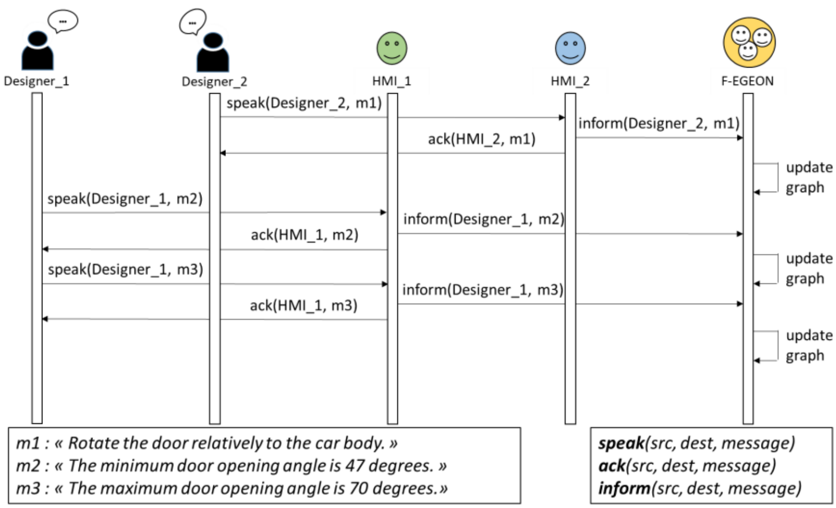

Figure 6. Specifications scenario dynamics modelling

These exchanges between the two designers are captured by the *HMI*s of each (see Figure 5), then once interpreted, transmitted to the agents of the *F-EGEON* platform. It should be noted that the design of such HMIs is relatively well mastered nowadays [20]. Figure 6 illustrates this dynamic: the *Designer_2* formulates the message *m1*, which corresponds to the product function *F.1.1*, then the *Designer_1* formulates the two messages *m2* and *m3* which correspond to two characterizations of the product function *F.1.1*.

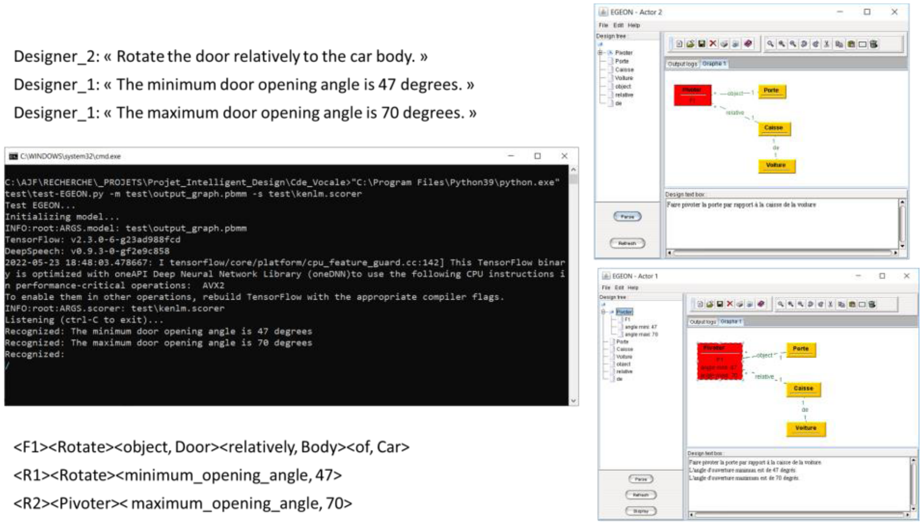

Figure 7. Scenario dynamics modelling

The different stages of the processing corresponding to the scenario of Figure 6 are represented in Figure 7: 1) the formulation by the two designers of a function of the product and of two characterizations of this function; 2) voice recognition by designers' *HMIs* (here the voice interface of *Designer_1*); 3) interpretation and structuring of recognized messages; then 4) graphical representation in *F-EGEON* in the form of semantic graphs.

f-BOM
F1 Facilitate access to the interior of the car for the driver
F1.1 Rotate the door relatively to the car body
F1.2 Ensure solidarity between the door and the car body
F1.3 Facilitate the opening and closing of the door for the driver
c-BOM
C1 : Hinge door car
C1.1 : Hinge door side
C1.1.1 : Door hinge knuckle
C1.1.2 : Upper hat ring
C1.1.3 : Screw door side
C1.1.4 : Bottom hat ring
C1.2 : Hinge body side
C1.2.1 : Body hinge knuckle
C1.2.2 : Upper axis
C1.2.3 : Lower axis
C1.2.4 : Anti-disengagement axis
C1.2.5 : Washer
C1.2.6 : Clip
C1.2.7 : Screw body side

cad-BOM
P1: Hinge door car
P1.1: Hinge door side
P1.1.1: Door hinge knuckle
P1.1.2: Upper hat ring
P1.1.3: Screw door side (1)
P1.1.4: Screw door side (2)
P1.1.5: Bottom hat ring
P1.2: Hinge body side
P1.2.1: Body hinge knuckle
P1.2.2: Upper axis
P1.2.3: Lower axis
P1.2.4: Anti-disengagement axis
P1.2.5: Washer
P1.2.6: Clip
P1.2.7: Screw body side (1)
P1.2.8: Screw body side (2)

Figure 8. Data structuration in BOMs made by agents of F-EGEON

In parallel with the graphic representation, the agents of the platform build the *x-BOMs* and update them with each intervention of a designer (see Figure 8). As standard, the *cad-BOM*, representing the file structure of the model, is generated from the *CAD* model. This same operation can be performed in *F-EGEON* by the *cad-BOM* agent in interaction with the *c-BOM* and *t-BOM* agents. The *x-BOM* agents exchange with each other in order to build the *cad-BOM* which will be transmitted to the *CAD* (see Figure 9).

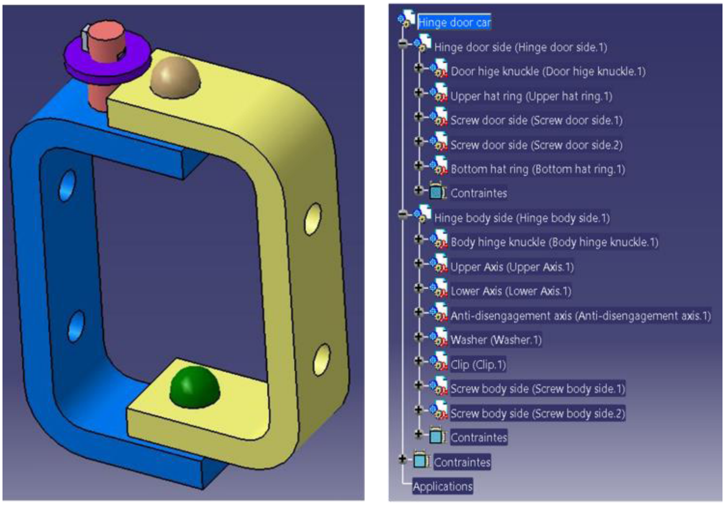

Figure 9. Generation of the CAD-BOM from the CAD

3. Discussion and Conclusions

This paper proposes a method and an agent-based collaborative platform for product requirement and BOMs engineering. Product requirement and BOMs engineering are transdisciplinary problems. Because knowledge is interconnected, a transdisciplinary approach between humans and computers is required. The proposed agent-based collaborative platform *F-EGEON* (Fuzzy Engineering desiGn sEmantics elabOration and applicatioN) is a transdisciplinary tool. Agents of *F-EGEON* are synthetic and are modelled to have a transdisciplinary attitude between humans and computers for the development of product specifications and BOMs.

The proposed method focuses on the design team discussion, what we call the social process of design through discussion. This tool makes it possible to visualize the progressive construction of the semantic network of the engineering requirements stated by the designers, as well as the systemic and functional structuring elements of the product. This allows designers to explain the causality and inferences made throughout the process from stating specifications to linking to *CAD* models. Thus, the method allows a design team to use *F-EGEON* in a dialectical, exploratory and open way.

Transdisciplinary co-design combining human designers and artificial designers is a perspective opened up by this work. The development of requirements by collectives of specialists, intelligently assisted in their collaboration, allows the development of better design proposals. However, the prospect of equipping intelligent requirements engineering with systems like *F-EGEON* should not only aim to represent the proposals made by designers, but should also aim to support positive actions or behaviors in the design environment. An intelligent requirement engineering system must make it possible to identify (even analyze) false (even imprecise, incomplete, contradictory) statements and biased representations. These defects in the generated representation, individually or cumulatively, can only have a negative impact on the development of a design. This therefore generates a negative impact on the social design process. Thus, future developments of the *F-EGEON* tool concern the artificial intelligence component of the platform. *F-EGEON* agents must improve their skills to become real design co-actors. AI has already shown great aptitude for meeting this challenge.

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