A Meta-Model for Knowledge Representation Integrating Maturity for Decision Making in Engineering Design

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Abstract. Computer Aided Design (CAD) and Computer Aided Engineering (CAE) models are often used during product design. Various interactions between the different models must be managed in a PLM approach for the designed system to be robust and in accordance with defined specifications. To effectively manage engineering changes on the system definition, the dependencies between the different models must be known and managed in a PLM system. A lot of data are exchanged in collaborative design and different problems must be managed in terms of data consistency. We propose a meta-model for knowledge representation integrating maturity concept to support decision making in preliminary collaborative design. A literature survey about existing knowledge models is done before presenting the proposed meta-model of knowledge.

Keywords: preliminary collaborative design, maturity, PLM, decision making, uncertainties.

1 Introduction

The design process is complex and dynamic due in part to the volume of handled data and models, the number of exchanges between the different design teams and businesses interacting. The design teams, organized in Concurrent Engineering (CE) do not wait to get the result of the later phases of the design life cycle; they anticipate them by making assumptions and by taking into consideration previous experiences and know how. In that framework, quality approaches for the control of product performance, and collaborative engineering tools to support CE and collective decision making are required.

Product development cycles, and more generally product life cycles are becoming increasingly complex. This complexity is due to several aspects. One of them is related to the different levels of representation and modeling due to the organizational and technical decomposition of the technical system, the inter-relations between different kinds of knowledge involved to anticipate the product's behavior. Another one can be associated to with the necessity to integrate different viewpoints, creating problems related to the data consistency and considering the impact of engineering change. It is therefore necessary to be able to qualify and quantify the data in the upstream phases of product design [1] and throughout the design process in order to help to the next step decision making [2].

In order to support decision making in early design and product's performance management, this paper proposes a meta-model for knowledge representation integrating maturity to support decision making in preliminary collaborative design. Section 2 presents an overview of the problematic of decision making in preliminary collaborative design. Section 3 presents a literature survey about knowledge meta-modeling approaches. Finally, Section 4 describes the different elements of the proposed meta-model

2 The decision making in preliminary collaborative design

Ullman [2] defines the decision pyramid in several levels (Data, Models, Knowledge and Decision). Decision making requires the management of data, models and knowledge, and the associated judgment on which decisions are based. In other words, data are the pyramid basis and also the basis of decision making in design (section 2.1). Moreover the collaborative aspect includes different representations of a same mechanical system, oriented with respect to the expertise domain considered. These representations are supported by knowledge and product models.

2.1 Decision making and lack of knowledge

Decision making in preliminary collaborative design involves the selection of an alternative design in order to go towards the next design iteration. Several factors are considered in order to make a decision, such as market demand, design alternatives, designer's preferences and uncertainties [2]. We focus on the "uncertainties" factor because it can represent the lack of knowledge in the decision making (for epistemic uncertainties). The decision making enables us to get a new definition of the mechanical system and we assume that maturity level and uncertainties on the product design data facilitate the next design decision. Maturity level is a characteristic often used to qualify information in design [3]. It can be defined as the improvement degree through a predefined set of process domains in which all objectives of the set are completed [4].

To design a mechanical system means to integrate several technologies with strong interactions and to take into consideration different aspects such as mechanical, electronic, etc. Moreover, in a collaborative or an extended enterprise context, several people must work together in order to design efficiently a mechanical system [2]. This collaborative aspect is very important because each person has a specific point of view and way to thinking but these people must take decisions together in order to meet compromises and to be able to go to the next design iterations repeatedly until the design objectives and technical specifications are achieved.

The preliminary design in collaborative design of mechanical system provides still more difficulties because the mechanical system is being defined [3] [5] [1]. It means that uncertainties about design data and unknown data have to be considered.

2.2 Product and knowledge representation

Design can generate many models (geometric and simulation for example 3D geometric representations, FEA models, etc.), with respect to the behavior which is to be studied, the component and configuration of the product, as illustrated by Scheidl and Winlker [6] on a beam, where the different models are clearly in the conceptual design phase. Another reason for the model diversity is related to the complexity of actual systems being developed [7]. These systems are characterized by independent functionalities that, together, compose the product (systems of systems). Complex systems are an association of several functionalities using diverse technologies to achieve the required operation of the product. During the design phases, the models that are used aim at providing a representation of the product in terms of its physical description (geometric model) as well as behavioral description (simulation model).

Thus, the design of complex systems can necessitate a significant number of models, specific for each discipline and that require a multiple views approach. Different engineering domains require different viewpoints on the product with different levels of granularity. For instance, within an electro-mechanical product, the structural decomposition depends on the engineering domain of the expert analyzing the product: an electrical model considers the gaps between parts while mechanical analyst does not mind about these, and typically they will not use the same product decomposition [8]. In terms of data and process modeling, several product models exist to support the multiple view representation of the system and will be described Section 3, in order to support product lifecycle management and the collaborative decision making process. Moreover, in order to support knowledge mapping and to ensure consistency between different models, meta-models can be proposed using generic semantic and rich representation of concepts and relationships between them. The goal is to propose a conceptual framework that facilitates the definition of heterogeneous knowledge models integrating the maturity in order to help to the decision making.

3 Maturity, data qualification and knowledge models

3.1 Definitions

We define maturity based on the work of Beth [4], as the association of the knowledge and performance. This means that there is the judgment of an actor on information (transmitter and receiver) and the state of information from actor user of information must be taken in consideration.

Performance is the link between specification of the product and the specification achieved in the current design iteration [9]. If no specification is respected then the performance is null and if they are all achieved then the level is of 100%.

We define knowledge as a cognitive structure allowing interpreting a set of information in order to follow a reasoning in a particular situation (or context of use) and for a stated purpose [10]. The lack of knowledge, in this case, is represented by the uncertainty on parameters of the product, for example the uncertainty of the part diameter, more or less 10 millimeters. Designers and user of the parameters define this uncertainty. A type of uncertainties is interesting in this context: Epistemic: uncertainty related to a lack of knowledge or information in any phase or activity of the design process [11].

Consequently, in order to improve Computer Aided Design Software (CAD, PDM and PLM essentially), the following question addressed in this paper, is then: "How to model product information and uncertainties in collaborative preliminary design?"

To answer the question a state of the art is built on uncertainty modeling and product/knowledge models to analyze how the product models support decision making taking into account uncertainties.

3.2 Literature survey

Table 1 is a synthesis of different qualitative and quantitative approaches allowing to qualify and quantify data uncertainty and to answer the questions identified in Section 3.1. The keypoints such as sustainability, sensitivity or collaborative dimension are presented in more detail in the following paragraphs. The product and knowledge models identified allow us to decompose, structure and take into account the different design activities of mechanical systems in order to support the product lifecycle management. However, it should be underlined that none of them considered uncertainties.

Table 1. State of art of the approaches

Uncertainties modeling		Product and knowledge models
Qualitative approaches	Quantitative app.	
Sustainability [12] Variation[13] Sensitivity[14] Completeness [15] PEPS: Precision, Accurancy, Parsimony, Specialisation [16]	Probability theory Fuzzy sets [17] Possibility theory[18] [19] Evidence theory [20] [21]	PPO: Product Process Organisation [22] KCM: Knowledge Configuration [23] CPM: Core Product Model [24] MOKA: Methods and tools Oriented to Knowledge Acquisition [25]

Qualitative approaches are based on the preliminary information concept introduced by Clark and Fujimoto [26] to allow the parallel execution of activities in the product development processes. Eppinger [27] defined the concept of preliminary information as a parameter that is in continual evolution before it achieves its final value. The status of the parameter in its evolution refers to its maturity [28].

The qualification and characterization of the model and information include several aspects: sustainability, variation, sensitivity and completeness. Information within a design office can be classified with respect to the level of sustainability [12] that is to say, the longevity of the information. A scale from "1" (Information not sustainable) to "5" (valid information for the currently used technologies) is used and refers to the information validity degree.

Sensitivity levels define the impact of change on information, according to [14] are classified along a scale from "0" corresponding to not sensitive, to "3" corresponding to sensitive.

Generally, three main categories of knowledge are distinguished in a development process: product engineering knowledge, manufacturing process knowledge and organizational knowledge. Another kind of knowledge concerns the capitalization of decision justification during the development project.

In the literature, several recent works exist, dealing with models in order to represent product, process and organization knowledge. These works are principally developed in three scientific fields: development of domain ontology in order to identify the mains concepts of a domain and the relationships between these concepts [29]; the development of projects memory that aims at achieving the traceability of the project evolution for reuse perspective [30] and finally, the development of business tools such as PDM and CAX tools in order to support the technical activities of designers [26].

The commonly accepted approach for structuring product knowledge has been through the construction of Product Models. As an example of such models, [31] translated NIST's core product model [24] and proposed an ontology for the Open Assembly Model (OAM) implementing several OWL (Ontology Web Language) capabilities. Lee [32] has developed a model for sharing product knowledge of the Beginning Of Life (BOL) on the web. Terzi [33] has proposed to use the concept of Holon for the description of product knowledge. The Holon is defined as a composition of a physical entity and all of its related information.

In parallel, the process knowledge definition is based on activity models: activities allow creation of the link between products, resources (facilities, humans...) and their characteristics (behavior, task, properties…), they structure and define the behaviour of the processes. An activity aggregates several kinds of knowledge such as sequences, functions, rules, states [34]. It concerns the process scheduling, the set of resources (human resources, machines, tools and tooling), the organization of the production unit (work centres) and the manufacturing know-how [35].

Other categories of models are developed with generic perspective in order to cover heterogeneous knowledge fields [25]. For instance, Nowak [35] have presented the architecture of a collaborative aided design framework integrating Product, Process and Organization (PPO) models for engineering improvement. The PPO information kernel stores persistent data on the interoperable files that might be reached by several external applications on the collaborative PLM system among the whole product life cycle [22]. Danesi [36] have proposed the P4LM methodology, which allows the management of Projects, Products, Processes, and Proceeds in collaborative design. It aims at allowing the integration of information coming from different partners which are involved in a PLM application. The KCM (Knowledge Configuration Model) is another example of knowledge model, which is developed with the aim to manage knowledge using configurations synchronized with expert models that enable designers to use parameters consistently in a collaborative design process [23]. The KCM approach is based on the concept of “knowledge configuration”, which is a virtual object composed by a set of parameters and rules instantiated from the generic baseline and contextualized into an expert model for a specific milestone of the project in order to ensure consistency and decision making supported by all expert knowledge.

All of these models allow us to represent product or knowledge and ensure the data consistency but no one of them take in consideration uncertainties and maturity of data and mechanical systems, in order to help the decision making.

4 A meta-model for knowledge representation integrating maturity

4.1 The key factors and the metric allowing to define maturity

The presented metric allows us to evaluate the maturity of a mechanical system by calculating the maturity of each components to each iteration of design. The equation (1) presents how the maturity of a component (Ci) is defined, where ‘i’ is the number associated to the component. The metric evolves with each design iteration, and as a consequence each parameter is constantly updated until it meets the full technical specification of the need.

$$C_i = \frac{1}{Co_i} \times \frac{\frac{\sum_{x=1}^{n}\left[1-\left(\frac{tolerance}{value}\right)\times SusSen\right]}{n} + Per_J}{2} \qquad (1)$$

The factors are “n”, “value”, “tolerance”, “SusSen”, “Perf” and “Coi”.

- “n” is the number of design parameters of a part (diameter, length, …)
- “value” is the nominal value of the design parameter, (diameter=25mm).
- “tolerance” is the domain of variation of the value, (diameter=25 ±5mm).
- “SusSen” represents the association of Sensitivity and Sensibility of the information. A first designer which has created this information (design parameter and tolerance) characterizes it using a sustainability level based on qualitative scale like described by Gaudin [12]. The level of sustainability is the time during which information may be considered as valid. The level of sensitivity is the impact importance of the data on the assembly. The designer qualifies the result due to a sensitivity level based on qualitative scale like described by Krishnan [14].
- “Perf” is the level of performance is defined by the percent of requirement number achieved by the end of the design iteration in comparison with the number of total requirements of the part in question. For example, if a part has three requirements and only two are achieved by the end of the design iteration, then the level of performance for this part is 66%. When 100% is achieved it means that all technical specifications of the need are completed.
- “Coi” is the level of maturity that we wish to achieve at the end of the design iteration. This is a constant that allows the adjustment of the level of maturity.

4.2 Methodology to use the metric

The result of the metric (level of maturity) is actualized at the end of each design iteration in order to help the decision making for the next design iteration.

The first step to build and use the metric is done by the first designer by defining the design parameters in CAD software such as CREO ® or CATIA ® More than the nominal value of the parameter, he is defining the interval of possible values ("tolerance") and the level of sustainability based on qualitative scale like the one described by Gaudin [12].

The part (with parameters, values, tolerances and level of sustainability) is integrated in a PDM system, as metadata, in order to capitalize knowledge. This will also allow us to share the information and to trace the previous information in the next design iteration.

The second point of the methodology is the definition of the level of performance for the different parts composing the system.

The third step of the proposed methodology is the simulation of the assembly behavior of parts comprising the system. The simulation of the assembly behavior allows its approval. This study is done using simulation software such as NASTRAN, SIMULIA, etc. The designer does not only simulate the behavior of the assembly but does three points:

- Adjusts the tolerances using the results of the simulation.
- Checks if the requirements are met.
- Defines the level of sensitivity of the results of calculation (design parameters including tolerances).

The level of sensitivity is the impact importance of the data on the assembly. The designer is able to qualify this result using a sensitivity level based on qualitative scale like described by Krishnan [14].

At this step, all necessary factors are defined to calculate the level of system maturity. These factors are levels of sensitivity and sustainability of information, importance of tolerances in function of the value and the level of performance. The maturity is translated as a percent of the association of these three factors taking into consideration the goals to achieve, the user experience and knowledge, and the precision of the tolerances.

This metric helps the decision making for the next design iteration by highlighting the parameters where the unknown is the most important. For example, designer could have devoted more effort to a design parameter with a low level of sustainability and a high sensitivity instead of focusing on a parameter having a high level of sustainability and lower level of sensitivity; this way it may be easier to make decision between different point of views and design activities.

4.3 Proposed meta-models and models integrating maturity

The goal of the proposed meta-models is to provide a tool able to federate data, ensure consistency and integrate maturity in order to help to the decision making. The Data Meta-Model (DMM) generates a Data Model (DM) and the Collaboration Meta-Model (CMM) generates a Collaboration Model (CM). These Meta-Models are instances of the so-called Knowledge Meta-Model (KMM). They are described as follows:

Data's meta-modeling: the Data Meta-Model (DMM) puts the concepts allowing the representation of the business knowledge within a common and simplified semantic. In particular, it includes the parameters, their relationships and the maturity information.

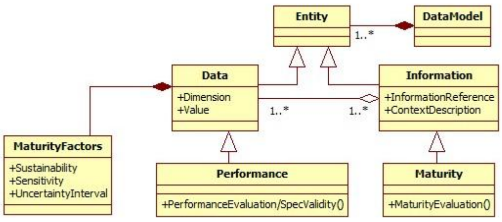

Fig 1. DMM package description

Figure 1 details how the DMM package works. The content of the Entity class will be described later. The Data and Information classes inherit from the Entity class. For a given context of use, parameters and their values are enclosed in the Data class. MaturityFactors class composes Data class and allow the definition of the level of maturity (Maturity class). Performance class allows us to determine the level of performance based upon the SpecValidity relation. The Information class defines the knowledge configuration structure and the level of Maturity.

Collaboration meta-modelling: the Collaboration Meta-Model (CMM) (Figure 2) proposes the concepts representing the collaboration between business models in the sense of flipping from one to another, and the Specification Model. This includes inter-business parametric relationships and model transformations. The Constraint class holds the business rules. The Transformation class outlines the transformation rules, that is to say the identification elements of equivalence relationships. The SpecValidity class checks the validation of the necessary technical specifications.

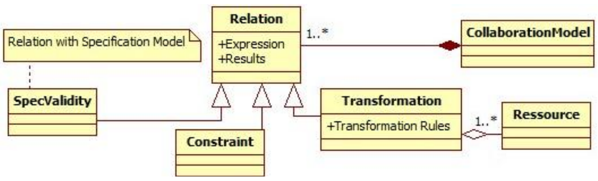

Fig 2. CMM package description

Knowledge meta-modelling: the Knowledge Meta-Model, named KMM, is a conceptual framework allowing the creation of Knowledge Models (KM) through instantiation of the KMM. This way, the collaboration between KMM is supported. As pointed out in the previous section, there are numerous Knowledge models. Therefore, the KMM must be user-friendly and generic for the purpose of bringing consistency within one conceptual representation in order to open the possibility of combining different models and then building the most appropriate one.

The MMCore package (Meta Model Core) is the heart of the modelling approach. It contains all generic classes that are common for the different meta-models. The specific meta-model classes are then obtained by means of specification relations from the MMCore classes.

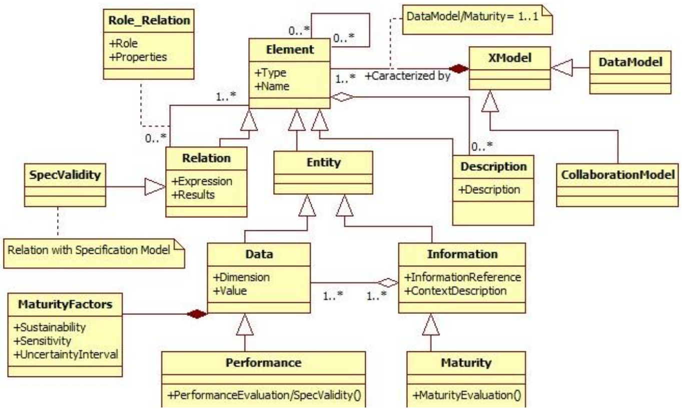

Fig 3. MMCore package description

Figure 3 presents the UML diagram of the MMCore package. The MMCore includes six main classes:

- The Element class is the most generic level of the MMKM.
- XModel class defines the type of model (data, collaboration) linked to an element
- Description class enables the formulation of a specification as any of the quantifiable properties
- Entity class capitalizes and structures on the main data extracted from business models or from experts.
- Relation class provides a link between the components of the Entity class.
- RoleRelation class manages the relations, namely to give a direction to the relation, to handle the spread of the modifications using a tree approach instead of CSP.

5 Conclusion

In the product development project, the large variety of knowledge models identified in the literature survey pointed out the importance of robust meta-modelling approach to guarantee the coherence of the elements of heterogeneous knowledge produced during the collaborative design project. Indeed, this knowledge is generally coming from various sources, expressed with different semantics and supported in large numbers of business models.

Based on the analysis of the literature survey and the industrial experience, we have proposed in this paper a new meta-modelling approach integrating maturity that aims to help take into account the lack of knowledge (uncertainties and maturity) in decision making during preliminary design in a collaborative environment, but also to support the integration of multi-knowledge models and guarantee data consistency.

Current work consists to validate this proposal by doing an implementation of the MMK in the KCM (Knowledge Configuration Model) and by this way to validate its feasibility. Another level of validation also being established is to implement the

MMK on a use case defines in partnerships with industrials in the case of the national project ADN.

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