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A METRIC TO EVALUATE DATA MATURITY TO HELP DECISION MAKING: APPLICATION IN PRELIMINARY COLLABORATIVE DESIGN OF MECHANICAL SYSTEMS.

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ABSTRACT

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 during the. The design teams, organized in Concurrent Engineering (CE) don’t 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 their 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.

In order to support decision making in early design and product’s performances management, this paper proposes a metric. It will enable to measure maturity in order to take into account the impact of lack of knowledge in decision making during preliminary collaborative design.

Keywords: decision making, maturity, preliminary collaborative design,

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1 INTRODUCTION

Today, collaboration, integration and simultaneous engineering are the focus of significant research effort in product design (for example (Mtopi-Fotso et al., 2007) (Chen and al, 2012) (Grebici and al, 2005)). 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 activities. The design teams, organized in Concurrent Engineering (CE) don't 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 their 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 partly due 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. These businesses operate simultaneously and must integrate different viewpoints, creating problems relating 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 (Pahl and Beitz, 1984) and throughout the design process to support decision making in later stages (Ullman, 2001).

A metric is proposed to support decision making in early design and product performance management. The metric measures maturity in order to take into account the impact of lack of knowledge in decision making during preliminary collaborative design. In the next section, the context of decision making in preliminary collaborative design is presented in order to show the importance of the problem of decision making in this context.

2 THE DECISION MAKING IN PRELIMINARY COLLABORATIVE DESIGN

2.1 Lack of knowledge

To design a product means to integrate several technologies with strong interactions and to take into consideration different aspects such as mechanical or electronic for example. Moreover, in a collaborative or an extended enterprise context, several people must work together in order to design efficiently a mechanical system (Ullman, 2001) (Kvan, 2000). This collaborative aspect is very important because each person has a specific point of view and way to think, but these people must take decisions together in order to make compromises and to be able to go to the next design iteration until the achievement of the design objectives and technical specifications.

The preliminary design in collaborative design of mechanical system provides still more difficulties because the mechanical system is under definition (Grebici and al, 2005) (Blessing, 1996) (Pahl and Beitz, 1984), meaning that uncertainties about design data and unknown data have to be considered.

2.2 Decision making

Decision making in preliminary collaborative design involves the selection of a design concept before proceeding towards the next design iteration. Several factors are considered in order to make these decisions such as: market demand; design alternatives; designer's preferences; and, uncertainties (Besharatia and al, 2006) (Antonsson and al, 1995) (Ullman, 2001). We focus on the "uncertainties" factor since it represents the lack of knowledge in the decision making (for epistemic uncertainties). The decision making supports the iteration and evolutionof the mechanical system. We also assume that the maturity level and uncertainties on the product design data facilitates the next design decision. The maturity level is a characteristic often used to qualify information in design (Grebici and al. 2005). It can be defined as the improvement degree through a predefined set of process domains in which all objectives of the set are completed (Beth et al., 2007).

Moreover the collaborative aspect includes different representations of the mechanical system, oriented with respect to the expertise domain considered. These representations are supported by knowledge and product models such as KCM, PPO, CPM...

2.3 Product representation

Design can generate many models (geometric, simulation, FEA), with respect to the behaviour to study, the component and configuration of the product, as illustrated by Scheidl and Winlker (2010) on a beam, where the different models are clearly in the preliminary design phases.

Another reason for the model diversity is related to the complexity of actual systems being developed (Mtopi-Fotso et al., 2007). 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) as well as behavioral description (simulation). The design of complex systems can necessitate a significant number of models, specific for each discipline and that require a multiple views approach, for example Finite Element Analysis (FEA) or Computional Fluid Dynamics (CFD). 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 analysing the product: an electrical model considers the gaps between parts while the mechanical analyst does not mind about these, and typically they will not use the same product decomposition (Noel et al., 2005). In terms of data and process modeling, several product models exists to support the multiple view representation of the system and will be described in Section 3, in order to support product lifecycle management and the collaborative decision making process.

2.4 Methodology

The evaluation and validation of the design parameters (data) during the preliminary design phases in a collaborative context plays a significant role in decision making in support of the progression to the next design iteration. We made the hypothesis that the qualification of product definition information supports the system evolution and subsequently facilitates decision making. In innovative design, the lack of knowledge is offset in industrial sector, by experience and intuition of the designer during the first design parameter definitions and decision making. In other words, the main question that may be asked is: "How to take into account the lack of knowledge (epistemic uncertainties (Thunisen, 2005) and maturity (Skyrme, 1994) (Ganascia, 1996) (Prax, 2000) in decision making during preliminary design in a collaborative environment?"

The research methodology adopted to answer these questions is based upon a literature survey to propose a metric to integrate uncertainty and maturity modeling in product models in order to support collaborative decision making. The proposal is then illustrated on a case study to show how it is used and to evaluate its interests for decision making in an academic context. The use case presented in this paper had been built with industrial partners to be representative of the industrial problem of collaborative decision making process.

3 MODEL AND DATA QUALIFICATION

3.1 Definitions

We define maturity based on the work of Beth et al. (2007), as the association of knowledge and performance. This means that there is a judgment by both a transmitter and receiver of the state of information which must be taken in consideration.

Performance is the link between specification of the product and the specification achieved in the current design iteration (Boucher, 2003). If no specification is achieved then the performance is "0%" and in the opposite case, if they are all achieved then the level is of "100%".

We define knowledge as a cognitive structure allowing interpreting of a set of information in order to follow a rationale in a particular situation (or context of use) and for a stated purpose (Skyrme, 1994) (Ganascia, 1996) (Prax, 2000). 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 which could be quantified as ± 10 mm. Designers and users of the information define this uncertainty. Two types of uncertainties are identified in this context:

- Epistemic: uncertainty related to a lack of knowledge or information in any phase or activity of the design process. (Thunisen, 2005)
- Aleatory: uncertainty related to the variation inherent in a physical system or environment in

question (Thunisen, 2005).

Aleatory uncertainties require knowledge, an appropriate population size and are achieved by probability, which is opposite to epistemic, where the population size is limited and the lack of knowledge very important. In the context of preliminary design, we focus our research on epistemic uncertainties. The link between both uncertainties in a context of preliminary collaborative design (where the lack of knowledge is very high) is also particularly interesting because it allows the use of past knowledge through probabilities and knowledge of the information transmitter/receiver (that represents the collaborative dimension).

Two questions have been identified in order to answer the problem of how to take into account the lack of knowledge in preliminary collaborative design :

- What is data maturity and uncertainity and how maturity of data in design is represented?
- What information is needed to take decisions in collaborative design?

This challenge is not only a scientific one but it is also an industrial problem that is underlined today by the competitivity and the need to decrease more and more the design duration.

Consequently, in order to improve Computer Aided Design software (CAD and PDM essentially), the third question, obtained by an informational approach, is then: “How to model product information and uncertainties in collaborative preliminary design?”

To answer the question a literature survey is built on both uncertainty modeling and product models in order to analyze how the product models that support decision making take account of uncertainties.

3.2 Literature survey

Table 1 is a synthesis of different qualitative and quantitative approaches 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.

The product and knowledge models identified allow the decompositionand structuring as well as taking into account the different design activities of mechanical systems in order to support Product Lifecycle Management (PLM). However, it should be underlined that none of these product and knowledge models considered uncertainties today.

Table 1. State of art of the approaches

Uncertainties modeling								Product and knowledge models
Qualitative approaches					Quantitative approaches			
Sustainability (Gaudin, 2001)	Variation (Grebici et al., 2006)	Sensitivity (Krishnan, 1996)	Completeness (Yassine et al., 1999)	PEPS: Precision, Accurancy, Parsimony, Specialisation (Sebastian et al., 2005)	Fuzzy sets (Zadeh,1965)	Possibility theory (Zadeh,1978) (Du and Choi, 2006)	Evidence theory (Dempster, 1967) (Shafer, 1976) (Shafer, 1978) (Shafer, 1986)	PPO: Product Process Organisation (Noel et al., 2004) KCM: Knowledge Configuration Model (Badin, 2011) CPM: Core Product Model (Sudarsan et al., 2005) MOKA: Methods and tools Oriented to Knowledge Acquisition (Moka) PPR: Product Process Ressource

Qualitative approaches are based on the preliminary information concept introduced by Clark and Fujimoto (1991) to allow the parallel execution of activities in the product development processes. Eppinger et al. (1997) 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 (Hanssen, 1997).

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 (Gaudin, 2001) that is to say, the longevity of the information. A scale from 1 to 5 is used and refers to the information validity degree. The ranking shown in Table 2 represents the sustainability level and corresponding qualification.

Table 2. Sustainability levels (Gaudin, 2001)

Levels	Qualification
1	Information not sustainable.
2	Valid information about a week until the next change.
3	Valid information for the duration of the study, about six months.
4	Valid information on several programs.
5	Valid information for the currently used technologies.

Sensitivity levels define the impact of change on information, according to Krishnan (1996) are classified along a scale from 0 corresponding to not sensitive, to 3 corresponding to sensitive - Table 3.

Table 3. Sensitivity levels of information (adapted from (Krishnan, 1996))

Levels	Level description of the attribute
0	Not sensitive: The activity is insensitive to any change in the incoming object.
1	Weakly sensitive: The activity is very sensitive to any change in the incoming object.
2	Moderate Sensitivity: The activity is moderately sensitive to the slightest change in the incoming object.
3	Sensitive: The activity is very sensitive to the slightest change in the incoming object.

The schema below (Figure 1) from Grebici et al. (2005) shows the characterization process and qualification of data/information from the transmitter to the receiver or user.

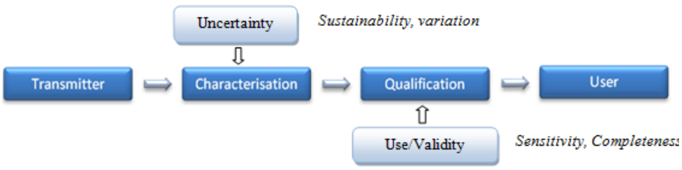

Figure 1. Uncertainty of information from transmitter to receiver (Grebici et al. 2005)

The first stage within Figure 1 is the characterization of information uncertainty by the transmitter. The uncertainty characterization supports the development of answers to the following questions: what is the nature of the change; what is the expected frequency change; and, what is the rate of change? The answers to these three questions are associated to the instability or degree of evolution of information (Terwiesch, and Loch, 1999) (Yassine et al. 1999). Additional questions relate to: what are the possible reasons for the change; and, what is the degree of confidence that the information transmitter has on this information? The answers to these two questions determine the degree of knowledge that the transmitter has on information that is produced (Go et al., 2005).

The second stage within Figure 1 is information qualification which is an evaluation of the information use/validity by its transmitter and is characterized by the levels of pertinence, completeness and confidence previously presented. The following questions require consideration: is the information produced/transmitted by an expert; does it support the user-defined objectives; and what are the risks associated with the use of this information?

Three quantitative approaches have also been identified for the representation and treatment of uncertainties: fuzzy set theory, possibility theory, and evidence theory.

Zadeh (1965) introduced the theory of fuzzy sets, as an extension of classical set theory. In the theory of classic sets, the membership of an element within a set has a binary value; it is either in the set, or it is not. The theory of the fuzzy sets allows partial adhesion, which means that the membership of an element may be any real number of closed set [0, 1]. Fuzzy set theory is therefore closely associated to fuzzy logic. In traditional Boolean logic, a statement is either true or false. In classical set theory, the proposition “the element B is a member of the set F” could have a truth value of 0 or 1; whereas in fuzzy logic it can take a truth value of any real number in the interval [0, 1].

Possibility theory was proposed by Zadeh (1978) as a tool for representing information expressed in terms of fuzzy measures. Possibility theory defines a transformation Π: 2Ω → [0,1] called the possible measure, defined on a space Ω with Π (A) for A ⊆ Ω being the degree of possibility that A occurs (or is true if A is a logical proposition). One argument in favour of its use in design is the simplicity of its operations (see for example Du and Choi (2006)). They are concise and fast, and there is no joint distribution or other complex relationships.
Evidence theory, also called Dempster-Shafer theory was presented by Shafer (1976) when he expanded the work of Dempster (1967). However, its origins date back to Hooper, Bernoulli and Lambert (Shafer, 1978) (Shafer, 1986). The theory of evidence takes n possible outcomes (or states) and forms an exclusive and exhaustive set {a1, ..., an} of n results. This set is called the frame of discernment Θ, and the set members are called focal elements. This is not different from the formulation of the probability of n exclusive and exhaustive events {E1, ..., En} constituting the sample space S. The difference is the way in which evidence or probability is assigned through these results. Rather than assigning probabilities to events or individual exclusive beliefs, the theory of evidence assigns belief to any element in the result set.
Different aspects are taken in consideration, quantitative and qualitative approaches exist. The quantitative aspect supports the definition of maturity with a quantifiable value, whereas the qualitative aspect allows the consideration of the subjectivity of the designers. The proposed metric will use a mixed approach in order to define the maturity level of the product. As the different product and knowledge models support the representation of different viewpoints of each design activity but without uncertainties, we propose to model the uncertainty in the product model to support the calculation of maturity, the collaborative information transmission and synchronization, andcollaborative decision making.

4 A METRIC TO EVALUATE THE MATURITY OF A MECHANICAL SYSTEM

4.1 The key factors and the metric

The proposed metric allows the maturity of a mechanical system to be evaluated by calculating the maturity of each component for each iteration of design. Equation 1 presents how the maturity of a component (Ci) is defined, where 'i' is the number associated to the component. The metric evolves to each design iteration, by consequence, each parameter is constantly updated until the full technical specification is met. Values are stored in the PDM (Product Data Management) system and updated for each design iteration.

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

The factors are:

- "n", "value", "tolerance", SusSen", "Perf" and "Coi".
- "n" is the number of design parameters that contains a part such as diameter, length, etc.
- "value" is the nominal value of the design parameter, for example diameter=25mm.
- "tolerance" is the the domain of variation of the value, for example diameter=25 +/-5mm.
- "SusSen" represents the user point of view who is placed to the center of the metric because in the upstream phases of design, the main problem is the lack of knowledge retained by designers. This parameter represents the association of Sensitivity and Sensibility of the information. A first designer who has created this information (design parameter and tolerance) characterises it using a sustainability level based on qualitative scale like described by Gaudin (2001). This 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 this result using a sensitivity level based on qualitative scale like described by Krishnan (1996).
- "Perf" is the level of performance is defined by the percent of requirement number achieved to the end of the design iteration in comparison with the number of total requirements of the concerned part. For example, if a part has three requirements and only two are achieved to the end of the design iteration, then the level of performance for this part is 66%. When 100% is

achieved, this 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 allow adjust the level of maturity.

4.2 Methodology to use the metric

The result of the metric (level of maturity) is actualized at each end of design iteration in order to help the decision making for the next design iteration.
The first step to build and use this metric is done by the first designer when they define the design parameters in a CAD software such as CREO ®[1] or CATIA ®[2]. More than the nominal value of the parameter, the designer defines the tolerance of possible values ("tolerance") and the level of sustainability based on qualitative scale such as that described by Gaudin (2001).
The part (parameters, values, tolerance and level of sustainability) is integrated in a PDM system, as metadata, in order to capitalize knowledge. This will also allow information sharing and tracing 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 different parts composing the system. This study is done using simulation software such as EXCEL, ANSYS, NASTRAN, SIMULIA, etc. The designer does not only simulate the behavior of the assembly but also:

- Adjusts the uncertainty intervals (tolerance) 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 uncertainty intervals).

The level of sensitivity is the impact importance of the data on the assembly. A sensitivity level based on qualitative scale described by Krishnan (1996) allows to the designer to qualify this result.
At this step, all needed factors are defined to calculate the level of system maturity. These factors are levels of sensitivity and sustainability of information, importance of uncertainty interval in function of the value and the level of performance. The maturity is translated as a percentage of the association of these three factors taking into consideration the goals; the user experience and knowledge; and the precision of the uncertainty interval.
This metric supports decision-making for the next design iteration by highlighting the parameters where the unknown is greatest. For example, the designer could devote more effort on a design parameter with a low level of sustainability and a high sensitivity in comparison with a parameter having a high level of sustainability and less level of sensitivity. By this way, it may be easier to make decisions between different points of view and design activities.

5 CASE STUDY

5.1 An aero engine

The case study is a sub-part of an aero engine including a shaft and a vane wheel. Two designers interact on this design during the preliminary collaborative design. Designer 1, is designing the 3D geometric model of the different parts. Designer 2, is testing and evaluating the behavior of the assembly with FEA models.

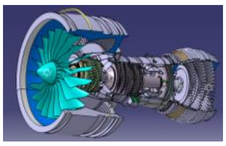

Figure 2. Case study: full assembly

[1] http://www.ptc.com/product/creo/
[2] http://www.3ds.com/products/catia/welcome/

5.2 Use of the metric on the case study

This illustration shows only the establishment of the metric in this context with the definition of the three factors previously presented, and constituting the metric. It is applied to an assembly of two parts of an aero engine, a shaft and a vane wheel.

ITERATION 1					oct-11	
Part	Attributes	Values	Intervals	Sustainability	Sensitivity	**Association**
Shaft	Weight (kg)	10	8	3	2	**50**
	Length (mm)	150	100	2	1	**35**
	Diameter (mm)	40	25	2	2	**30**
	Performance (%)	**0,0**	-	-	-	**-**
	Maturity (%)	**17,2**	-	-	-	**-**
	Average association	-	-	-	-	**38,3**
Vane wheel	Weight (kg)	140	80	2	2	**30**
	Vane number	24	12	2	1	**35**
	Performance (%)	**33,3**	-	-	-	**-**
	Maturity (%)	**36,4**	-	-	-	**-**
	Average association	-	-	-	-	**32,5**
Assembly	**Performance (%)**	**16,7**				
	Maturity (%)	**26,8**				
	Average association	-	-	-	-	**35,4**

Figure 3. Representation of the data at the end of the first iteration

Figure 3 synthesizes the different factors and data of the assembly, at the end of the first iteration. Designer 1 provides the level of sustainability and the second, the level of sensitivity. Performance is 0% because no requirements have been met at this stage. Association represents the user point of view, experience and confidence about information and is expressed as a percentage, based .

Sensitivity and sustainability are not defined from the same models. Sustainability is defined initially when a user first creates and defines the data (CAD model). Sensitivity is the impact of the data on the assembly during the simulation. This value is defined by Designer 2 from the Simulation model (CAE software). This process is realized for each main parameter of each part constituting the assembly.

This methodology is applied to each design iteration of the system until the level of performance is equal to 100%, meaning that all requirements are achieved.

5.3 Results

The three factors of the metric are represented for each parts of the assembly and for the assembly itself (the system) – Figure 4, which illustrates the evolution of the maturity for the system and its components. It illustrates if the evolution is constant, as well as how the maturity of each part evolves in comparison to the system. This graph also enables the identification of the problematic parts during the design iteration. For example if the maturity of a part decreases during the design process but not the other, then there is perhaps a problem or a point that must be carefully considered.

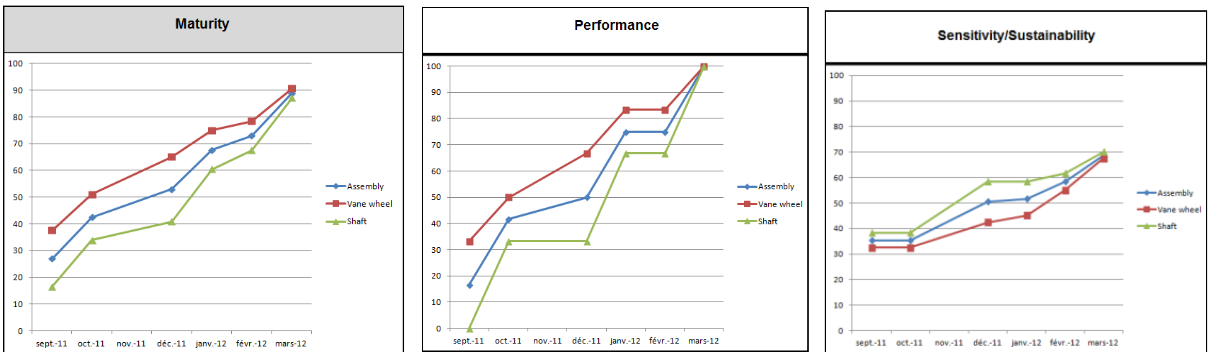

Figure 4. Obtained results: Maturity, Performance and Sensitivity/sustainability

The evolution of performance (Figure 4) represents the achieved requirements for each iteration of design. Requirements are defined before the design is started and the part or system may be considered complete when all requirements have been satisfied.

The third factor of the proposed metric is the association between sensitivity and sustainability that represents the viewpoint of the user, in terms of experience and knowledge.

The obtained results show the evolution of the designers' viewpoint, and also the level of achievement with respect to the requirements. It enables the analysis of how the design evolves during the design upstream phases and in a collaborative context. This supports more precise decision-making and under new criteria in order to plan the following design steps.

Figure 4 helps decision makers and designers to have a global vision on the evolution of the work and 'qualification and characterization' helps them to know which design parameters are central and have a high impact on product design, due to the lack of knowledge or experience.

6 CONCLUSION

The proposed metric accounts for the lack of knowledge (uncertainties and maturity) in decision making during preliminary design in a collaborative environment. This metric defines maturity and uncertainty, and identified what data are needed to take decision in collaborative design. The designers' knowledge is capitalized due to the methodology used by the metric and PDM systems. The establishment of this proposition supports an understanding of the evolution of maturity in preliminary collaborative design of the system and, on which part the design has a critical aspect and a major impact on the global system.

Further work consists to validate the use of this metric on several product development in order to consolidate the algorithm and get feedback from designers and decision makers regarding its usefulness in preliminary collaborative design.

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