A metric to qualify data maturity in preliminary collaborative design of mechanical systems.

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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 for the designed system to be robust and in accordance with defined specifications. Numerous research works exist considering the link between digital mock-up and analysis models. However design/analysis integration must take into consideration the evolution throughout time numerous mock-up and simulation models, as well as considering system engineering. To effectively manage engineering changes on the system, the dependencies between the different models must be known and the nature of the modification must be characterized to estimate the impact of the modification throughout the dependent models. We propose a metric to take into account the impact of the lack of knowledge in decision making during preliminary collaborative design. To achieve this, a presentation of the complexity of design/analysis link and the need of data qualification are realized.**

***Index Terms*— Decision making, Maturity, Preliminary Collaborative Design**

I. Introduction

Today, collaboration, integration and simultaneous engineering are keywords in product design. The design process is complex and dynamic due in part to the volume of manipulated data and models, the number of exchanges between the different teams of design and businesses interacting during the process and, the product development requirements within Concurrent Engineering (CE). The design teams 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 their experiences and “savoir faire”. Robust design of systems, distributed design and an integration necessity constitute major challenges that necessitates the use of quality approaches for the control of product performance, and collaborative engineering tools to support CE and collective decision making.

Quality Function Deployment (QFD) is a method to translate the customer needs in technical requirements, and is used to ensure a correct formulation of the specifications of the basic needs [1]. Product Data Management (PDM) systems assist in the management of product data, the process of product development, and product realization and documentation [2]. PDM systems and QFD are valuable in supporting the design of multi-disciplinary systems that involve a number of collaborative distributed organizations through the integration of data, models and generated knowledge.

Product development cycles, and more generally product life cycles are becoming increasingly complex. By complexity, we mean the different levels of representation and modeling due to the organizational and technical decomposition of the technical system. These businesses operate simultaneously and must integrate different viewpoints, creating problems relating to the management of modification and consideration of the impact of change. It is therefore necessary to be able to qualify the data or information in the upstream phases of product design and throughout the design process.

This paper proposes a metric to take into account the impact of lack of knowledge in decision making during preliminary collaborative design. A presentation of the complexity of design/ analysis link is realized in order to show the importance of data qualification to evaluate the lack of knowledge.

II. Difficulties with the Design/Analysis Link During the Upstream Design Phases

A. The upstream design phases

The product definition process can be structured in several phases or steps [3]. They are: problem definition, conceptual design, detailed design and production which are illustrated within Figure 1.

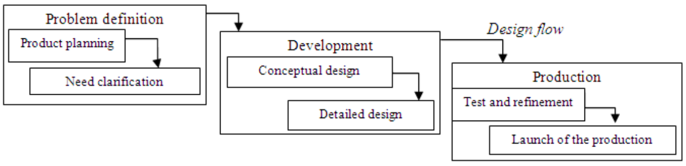


Fig. 1. Product definition process [3]

The upstream phases of design are represented by problem definition, conceptual design and detailed design [4]. The problem definition phase includes the planning phases that identify the goals and strategies of the enterprise, and the problem formulation for the identification and the definition of customer needs. This planning phase is the starting phase of all the models of the product development process [4].

Conceptual design supports the analysis and clarification of potential product ideas that are not explicitly defined in the vision oriented problem [5]. This phase is often regarded as one of the most difficult to realize during the design work [6]. The phase aims to generate several potential concepts, select the most viable concept from those generated, create associated specifications, as well as analyze competitive products and perform an economical evaluation of the product.

The detailed design phase takes these potential concepts and develops them into final engineering drawings to support the production of the artifact. Production is a process which is decomposed into two phases: testing and refinement (a prototype is generally the result of this phase); and production launch.

B. Model diversity

The upstream phase of design is characterized by the steps that define and provide the initial shape of a product. Conceptual and detailed design phases use various different models to represent the product, the diversity of which arises from several factors:

- The diversity of activities associated to the design phases (geometrical model from the design office, simulation models for each domain of expertise),
- The complexity of the product being designed requiring different levels of representation and modeling due to the organizational and technical decomposition of the technical system,
- The dynamic nature of the design process which is a learning process leading to the evolution of the models over time.

During the conceptual design phase, the main activity is related to the study of concepts which offer different technological solutions to the requirements and will compose the system. The architecture of the product and a preliminary sizing (shape and material) result from this activity. During the detailed design [3], the physical representation model has a finer level of granularity, as detailed by Scaravetti [7].

The design can generate many models (geometric and simulation), with respect to the concept to study, the component and configuration of the product, as illustrated by Scheidl and Winlker [8] 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. The aeronautic, automotive and naval industries are generating increasingly complex systems. These systems are characterized by independent functionalities that, together, compose the product (systems of systems). Complex systems are association of several functionalities using diverse technologies to achieve the required operation of the product.

During these 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 requires a multi-view approach. Different engineering domains require different viewpoints on the product. For instance, within an electro-mechanical product, the structural decomposition depends on the engineering domain of the expert analyzing the product: an electrician model considers the gaps between parts while mechanical analyst does not mind about these, and typically they will not use the same product decomposition [9]

C. Modular approach for a system design

Modular design is a strategy that may be used to support the design of complex products [10]. The modules, as defined by Wang and Nnaji [11], are elements of the product that have their own independent functionalities. This provides the opportunity to reduce the design development time by sharing the work between several actors. Modular design is a tool that is closely associated with system engineering which uses top-down and bottom-up approaches in its definition. The top-down phase describes the decomposition of the system and the product definition, whereas the bottom-up phase consists of the integration of modules and in the validation of the integration steps. In the top-down phase, design and simulation at higher levels provide specifications for lower levels. In the bottom-up phase, the definition is integrated by successive sub-assemblies: components are integrated into the product modules. At each phases of integration, a validation step is undertaken to control the process.

D. Synthesis

The co-ordination of design activities within a design environment that includes multiple disciplines and representation models with multiple levels of product decomposition can be complex, and the decision making also. Product definition is commonly validated through simulation which also contributes to specifying the definition. An important number of decisions must be taken during the upstream phases of design. These decisions make interact, often, several views of the product and, by consequences with an important number of models. This interaction and the lack of knowledge due to the preliminary and innovative context of design make decision making difficult. To manage effectively this difficulty, model and data must be qualify in order to help to the next decision making.

III. MODEL AND DATA QUALIFICATION

A. Definition of maturity

Maturity level is a characteristic often used to qualify information in design. It can be defined as the improvement degree through a predefined set of process domains in which all objectives of the set are completed [12].

We define the maturity 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. This is definition is based on Boucher [13]. If any specification is respected 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 to interpret a set of information in order to follow a reasoning in a particular situation (or context of use) and for a stated purpose [14] [15] [16]. 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 parameters 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. [17]
- Aleatory: uncertainty related to the variation inherent in a physical system or environment in question [17].

Aleatory uncertainties need an important knowledge, an important population and are got by probability in opposite to epistemic where the population is poor and the lack of knowledge very important, that is why we focus our research works on epistemic uncertainties. The link between both in a context of preliminary collaborative design (where the lack of knowledge is very high) is particular interesting because this allows to use the past knowledge through probabilities and knowledge of the information transmitter/receiver (they represent the collaborative dimension).

B. Problem definition

We have seen that there exist an important number of representation models with multiple levels of product decomposition. The qualification (evaluation of the information validity) of design parameters (data) during the pre-design phases of a product plays a major role in the decision making, particularly in innovative design where the lack of knowledge is important. We make the hypothesis that the qualification of information of product definition allows to manage more easily the system modification and to help to the decision making. In innovative design, the lack of knowledge is offset, in industrial sector, by experience and feeling of 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 [17] and maturity [14] [15] [16]) in decision making during preliminary design in a collaborative environment?” In order to answer to this problem, we have identified two first questions:

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

This problematic is not only a scientific problematic but it is also an industrial problem that is accentuated today by the need of competitivity and to decrease more and more the time to design product.

Consequently, in order to improve the Computer Aided Design Software (CAD and PDM essentially), the following question is then: “How to model product information and uncertainties in collaborative preliminary design?”.

C. Litterature survey

The table I is a synthesis of different qualitative and quantitative approaches allowing to qualify and quantify data uncertainty and answer to the identified questions (section III.B). The keys points such as sustainability, sensitivity or collaborative dimension are presented more in details during the follow of this section. The product and knowledge models allow to decompose, structure and take into account the different design activities of mechanical systems but do not consider uncertainties.

TABLE I. STATE OF ART OF THE APPROACHES

Uncertainties modeling								Product and knowledge models
Qualitative approaches					Quantitative approaches			
Sustainability [18]	Variation [19]	Sensitivity [20]	Completeness [21]	PEPS: Precision, Accurancy, Parsimony, Specialisation [22]	Fuzzy sets [23]	Possibility theory [24] [25]	Evidence theory [26] [27] [28] [29]	PPO: Product Process Organisation [30] KCM: Knowledge Configuration Management [31] CPM: Core Product Model [32] MOKA: Methods and tools Oriented to Knowledge Acquisition [33] PPR: Product Process Ressource

Qualitative approaches are based on the preliminary information concept introduced by Clark and Fujimoto [34] to allow the parallel execution of activities in the product development processes. Eppinger et al. [35] 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 [36].

The qualification and characterisation 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 [18] 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 below (Table II) represents the sustainability level and corresponding qualification.

TABLE II. SUSTAINABILITY LEVELS [18]

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 programmes.
5	Valid information for the currently used technologies.

Sensitivity levels define the impact of change on information, according to Yassine and al. [20] are classified along a scale from "0" corresponding to not sensitive, to "3" corresponding to sensitive. The ranking (Table III) is detailed below.

TABLE III. SENSITIVITY LEVELS OF INFORMATION (ADAPTED FROM [20])

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 2) from [3] shows the process of characterisation and qualification of data/information from the transmitter to the receiver or user.

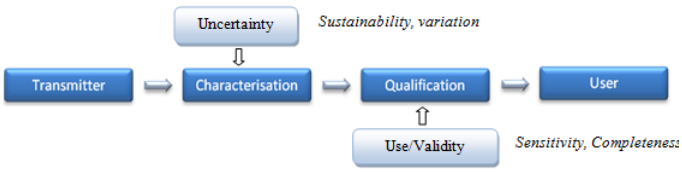


Fig. 2. Uncertainty of information from transmitter to receiver [3]

The first stage within Figure 2 is the characterisation of information uncertainty by its transmitter. The uncertainty characterisation 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 [37, 21, and 37]. 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 [38].

The second stage within Figure 2 is information qualification which is an evaluation of the information use/validity by its transmitter and is characterised 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 been identified for the representation and treatment of uncertainties: fuzzy set theory; possibility theory; and, evidence theory.

Zadeh introduced the theory of fuzzy sets, as an extension of classical set theory [23]. 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]. For example, if we suppose that a truth value of 0.3 is attributed to the proposition "the element B is a member of the set F", then we determine that element B is partially a member of set F, which makes the set F fuzzy.

Possibility theory was proposed by Zadeh [24] as a tool for representing information expressed in terms of fuzzy measures. Possibility theory defines a transformation Π: $2\Omega \rightarrow [0,1]$ called the possible measure, defined on a space Ω with Π (A) for $A \subseteq \Omega$ 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 [25]). They are concise and fast, and there is no joint distribution or other complex relationships. Some research also argues that there is a clear relationship between a probabilistic approach and the theory of possibility. Possibility theory is typically used when there is little available information, whereas probability theory is preferable when there is a lot of available information [25].

Evidence theory, also called Dempster-Shafer theory was presented by Shafer [27] when he expanded the work of Dempster [26]. However, its origins date back to Hooper, Bernoulli and Lambert [28, 29]. 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. For example, consider the case with n = 3. Then Θ = {a1, a2, a3}, the complete list of subsets within the set is {a1}, {a2}, {a3}, {a1, a2}, {a1, a3}, {a2, a3}, {a1, a2, a3}. According to available data, each of these subsets will be supported in some degree. For example, there may be evidence that supports {a1} and {a2} but not {a3} and also does not distinguish between {a1} and {a2}. Thus, the evidence is for the subset {a1, a2} and is assigned using the function of basic belief mass.

IV. Architecture and Methodology

A. Proposed Approach

With the objective of supporting decision making in a collaborative context for preliminary design under uncertainty, the metric defined will qualify and characterize the information to support product designers in making a decision. Collaboration, which is the joint development of a negotiated and consensual solution, requires many decisions, especially in preliminary design.

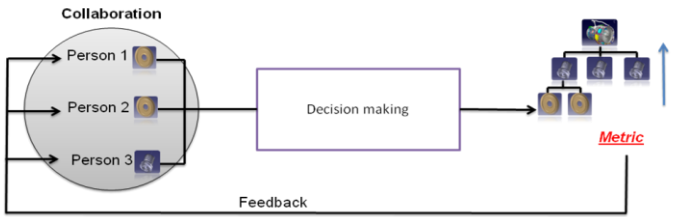


Fig. 3. Place of the proposed metric

Figure 3 illustrates the context for the development of the metric which shows different people working together on a project (to fix the value of the piston diameter, for example) whilst taking into account for example the views of design, manufacturing and thermodynamics. The proposed metric is intended to support decision making by describing and characterizing information. Once the decision is made, the item can be updated (iteration +1).

Different people work together in order to design a product, but each person has knowledge about the data of the product, design process... These people must make decision in order to find a solution to the design problem what are met during design process, particularly in upstream phases where there is an important number of iteration. Decision making integrates the data of these people and allow to get a new definition of the global system. To facilitate the next decision, system maturity and uncertainty must be known.

This metric may be seen like a definition and measure of maturity. This approach addresses different scientific locks such as:

- What is the maturity of a mechanical system and how to evaluate it?
- How to take into account experience and knowledge of the user?
- How to propagate the maturity on the different levels of a mechanical system?

B. Methodology and establishment

Several steps can be respected in order to get the level of maturity of the global system.

Today, a designer designs part and assembly in a Computer Aided Engineering Design (CAED) such as Creo/Element or Catia. This first designer defines the different sketches thanks to a quote, more precisely by defining the value of each parameters (or quote) of the part. The proposed approach allows to the designer to define more exactly these parameters by defining also an uncertainty interval.

For example, if the diameter of a shaft is 40mm then, with this approach, the designer must define an interval such 40mm +/- 25mm. The designer who has created this parameter characterize it thanks to a sustainability level based on qualitative scale like described by Gaudin [18]. This level of sustainability is the time during which information (40mm+/-25mm) is valid.

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

The second point of the methodology allowing to get the maturity level of the system is the definition of the level of performance for the different parts composing system. This 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%.

The simulation of the assembly behavior of different parts composing the system introduces the third step of the proposed methodology. The simulation of the assembly behavior allows to validate it. This study is done thanks to simulation software such as ANSYS, NASTRAN, SIMULIA… The designer does not only simulate the behavior of the assembly but does three points:

- Adjust the uncertainty intervals thanks to the results of the simulation.
- Check if the requirements are met.
- Define 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. The designer qualifies this result thanks to a sensitivity level based on qualitative scale like described by Krishnan [20].

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 translate as a percent of the association of these three factors taking in consideration the goals to achieve, the user experience and knowledge, and the precision of the uncertainty interval.

V. Illustration on a Case Study

A. Presentation

As described in this paper, the creation of a product module has its own design process. The design process uses two types of models:

- Geometric models (from CAD software),
- Simulation models (from CAE software).

During the design process, different models represent the product [7] with different levels of granularity. The simulation model uses information from the CAD models and validates the design. Therefore, when the geometric definition evolves or changes, it could affect the simulation model, depending on the type of modification. The fig 4 represents an assembly of two parts of a plane engine, a shaft and a vane wheel.

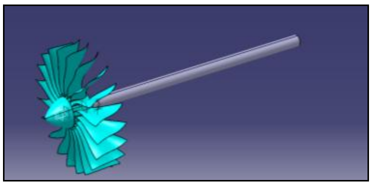


Fig. 4. A shaft with a vane wheel of a plane engine (CAD model)

These models (CAD and simulation models) evolve during the design process due to modification. In the global design process, one level of design interacts with another by a top-down and bottom-up approach. Within a top-down approach, the design activities are to define the geometry and to validate them against the specifications. In a bottom-up approach, each element of the aero engine is validated and integrated from component level to engine level.

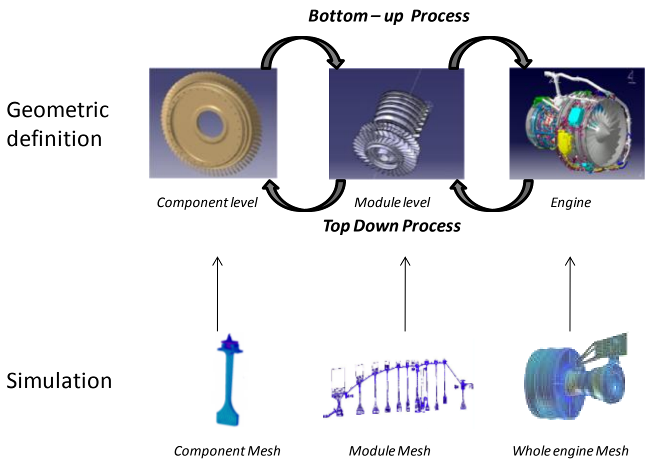


Fig. 5. Decomposition of an aero engine and associates models

In the global process, a modification made on one level could affect the models (CAD and simulation models) on a different level which may in turn necessitate updating the affected models and associated data (results, simulation hypothesis).

B. 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.

The table IV synthesizes the different factors and data of the assembly, at the end of the first iteration. Performance is null because no requirements has been met at this step of design. Association represents the association between sensitivity and sustainability. This value represents the user point of view, experience and confidence about information and is expressed in percent.

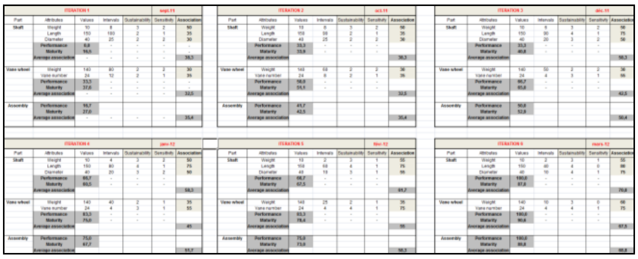
TABLE IV. Representation of the data at the end of the first iteration

ITERATION 1					sept-11	
Part	Attributes	Values	Intervals	Sustainability	Sensitivity	Association
Shaft	Weight	10	8	3	2	**50**
	Length	150	100	2	1	**35**
	Diameter	40	25	2	2	**30**
	Performance	**0,0**	-	-	-	-
	Maturity	**16,5**	-	-	-	-
	Average association	-	-	-	-	38,3
Vane wheel	Weight	140	80	2	2	**30**
	Vane number	24	12	2	1	**35**
	Performance	**33,3**	-	-	-	-
	Maturity	**37,6**	-	-	-	-
	Average association	-	-	-	-	32,5
Assembly	**Performance**	**16,7**				
	Maturity	**27,0**				
	Average association	-	-	-	-	35,4

Sensitivity and sustainability are not defined from the same models. Sustainability is defined by a first user when this one creates and defines data (CAD model). Sensitivity is the impact of the data on the assembly during the simulation. This value is defines by a second designer 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 iteration of design of the system until the level of performance is equal to cent percent. This means that requirements are all achieved.

TABLE V. Representation of different iteration of design



The table V represents the different iterations of design in the design of the set vane wheel and shaft.

C. Results

The proposed metric and methodology allow to get different results represented in graphs. The three factors of the metric are represented for each parts of the assembly and for the assembly itself (the system). Each one of these three graphs allows to represent different special meaning.

Figure 5 shows the evolution of the maturity for the system and its components. It allows to analyze how the evolution is. The points on the graphs in Figure 5 and 6 to represent each design iteration. It is possible to know if the evolution is constant, how the maturity of each part evolves in comparison with this of the system. This graph allows also to identify the problematic parts during the design iteration. For example if the maturity of a part decrease during the design process but not other, then there is probably a problem or a point that must be carefully considered.

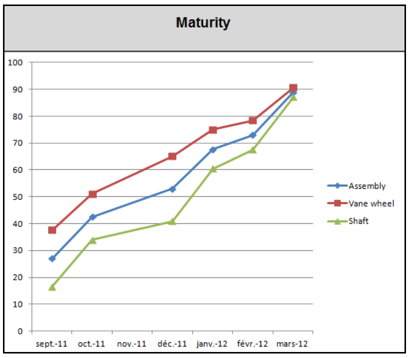


Fig. 6. Evolution of the maturity

The evolution of performance (figure 6) represents the achieved requirements for each iteration of design. Requirements are defined before the starts of design and the part or system may be considerate like final when all requirements are completed.

By this way, it is possible to know how the evolution is, (constant, stepwise, etc) and to compare it with the evolution of the maturity for the other parts or the global system. This graph allows also to know if a design iteration has enabled to meet one or more, or any requirements.

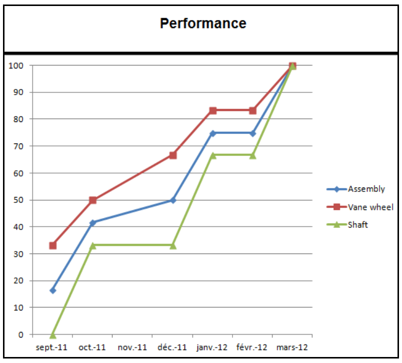


Fig. 7. Evolution of the performance

The third factor of the proposed metric is the association sensitivity and sustainability that represent the point of view of the user, his experience and knowledge. It is interesting to note that the data range is included between 30 and 70% of maturity.

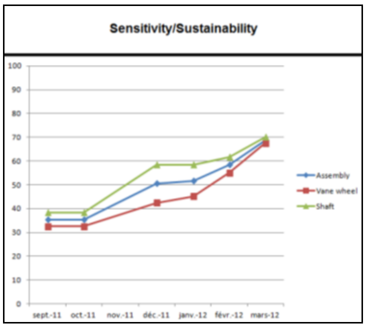


Fig. 8. Evolution of the sustainability/sensitivity

The obtained results show the evolution of the user point of view, and also the level of achievement with respect to the requirements. It enables to analyze how the design evolves during the design upstream phases and in a context collaborative. This allows also to take decision more precisely and under new criteria in order to plan the following design steps.

Thanks to the analysis of these results, designer can see where the difficulties to face with are.

VI. CONCLUSION

Collaboration, integration, uncertainties, decision making, lack of knowledge, time and simultaneous engineering are keywords in product design. There is an increasing tendency for design teams not to wait to get to the later phases of the design life cycle; they anticipate them by making assumptions, and by taking into consideration their experiences

The proposed metric is a first answer to how to take into account 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 user knowledge is capitalized thanks to the methodology used by the metric and PDM systems. The establishment of this proposition allows also to know how the evolution of maturity in preliminary collaborative design of the system is and, on what part the design has a critical aspect and a major impact of the global system.

The future researches linked to this metric will be axed on the algorithm allowing to define the level of maturity and the importance of each one of the factors that are sustainability, sensitivity, uncertainties intervals and level of performance. The use of fuzzy sets or evidence theory are points that will be included in the future works in order to be the most in accord with the reality.

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