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A METRIC TO REPRESENT THE EVOLUTION OF CAD/ANALYSIS MODELS IN COLLABORATIVE 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 for the designed system to be robust and in accordance with initially defined specifications. Research published to date has for example considered the link between digital mock-up and analysis models. However design/analysis integration must take into consideration the important number of models (digital mock-up and simulation) due to model evolution in time, as well as considering system engineering. To effectively manage modifications made to the system, the dependencies between the different models must be known and the nature of the modification must be characterised to estimate the impact of the modification throughout the dependent models. We propose a technique to describe the nature of a modification which may be used to determine the consequence within other models as well as a way to qualify the modified information. To achieve this, a metric is proposed that allows the qualification and evaluation of data or information, based on the maturity and validity of information and models.

Keywords: design process, maturity, validity, digital mock-up, model of analysis

1. 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). 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 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 realisation and documentation [2]. PDM systems and QFD are valuable in supporting the design of multi-disciplinary systems that involve a number of collaborative distributed organisations 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 that they involve a large number of different businesses using specific vocabulary and work methods. 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. A literature review was conducted to define the problem boundaries before proposing a metric to qualify the data or information.
The manufacture design domain proposes a product definition structure that is represented by a sequence of phases or steps [3]. The definition of a product can be represented by four main sub-processes [4] which are: problem definition, conceptual design, detailed design and production which is illustrated within Figure 1.

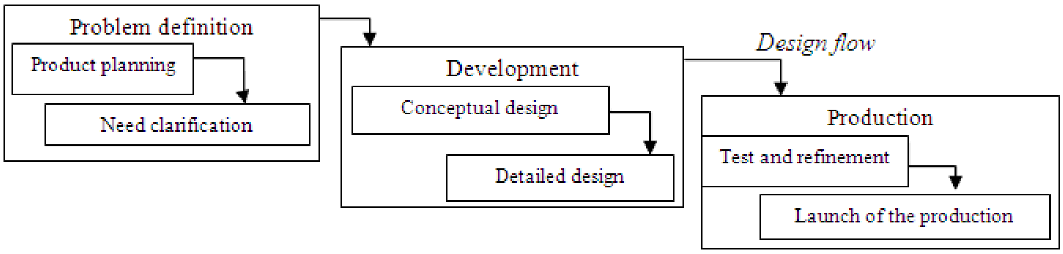

Figure 1. Product definition structure [4]

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. Models using an extended scope of the product development process [5] typically start with the planning phase.

Conceptual design supports the analysis and clarification of potential product ideas that are not explicitly defined in the vision oriented problem [6]. This phase is often regarded as one of the most difficult to realise during the design work [6, 7]. The phase aims to generate several potential concepts, select the most viable concept from those generated, create associated specifications, as well as analyse 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 artefact. 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.

In this paper, we propose to study and analyse in more detail the upstream phases of design (product planning to detailed design) and more particularly the different links between CAD/analysis models of the system. The study will focus on data qualification relating to the concepts of data maturity, to manage modifications during the upstream phases of design and to facilitate engineering change management.

2. DIFFICULTIES WITH THE DESIGN/ANALYSIS LINK DURING THE UPSTREAM DESIGN PHASES

2.1. Model diversity

The upstream phase of design is characterised by the steps that define and provide the final 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 a wide range of different types of expertise,
- 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, the physical representation model has a finer level of granularity, as detailed by Scaravetti [8].

The design environment 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 [9] on the study of a beam, where the different models are clearly identifiable 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 characterised by independent functionalities that, put together, compose the product (systems of systems). Complex systems are association of diverse functionalities using diverse technologies to achieve the required operation of the product.

During these design phases, the models that are used aim to provide a representation of the product in terms of its physical description (geometric) as well as simulating its behaviour. The design of complex systems can necessitate a significant number of models, specific for each discipline and requiring a multi-view approach. Different engineering domains require different viewpoints about the product. Within an electro-mechanical product the structural decomposition depends on the engineering domain of the expert analysing the product: an electrician models the gaps between parts while mechanical analyst does not mind about these, and typically they will not use the same product decomposition [10].

2.2. System dimension

Modular design is a strategy that may be used to support the design of complex products [11]. The modules, as defined by Wang and Nnaji [12], 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.

2.3. 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. Product definition is commonly validated through simulation which also contributes to specifying the definition. Each model associates a definition of the system and sub-systems to a given stage within the design process, and to a given expertise. When one of these models is modified, we must wait for the information feedback and model update of each system level in order to evaluate the impact of the modification on other models. To effectively manage modification within this diverse range of models, the nature of modification must be qualified in order to estimate the impact on other linked models.

3. MODEL AND DATA QUALIFICATION

3.1. Problem definition

We have seen that there exist an important number of representation models with multiple levels of product decomposition. The qualification (degree of maturity) of a model, data or information during the pre-design phases of a product plays a major role in the decision makin. This information qualification is envisaged as a means to contribute to the management of modifications. In other words, the questions that may be asked are:

- How should modifications be managed and where are they?
- What modifications/information/data are important?
- What modifications/information/data are stable over time?
- What is the priority for the treatment of modifications/information/data?

The upstream phases of design, including conceptual design (in reference to the abstraction hierarchy proposed by Ramussen [13]) typically accounts for 5% of the design process, but associates more than 75% of the global costs of the product, as cited by Sharpe [14]. Assisting these phases is both an ergonomic and economic issue [15]. Information qualification is envisaged as a means of modification management, by filtering the modification priority to propagate between the different models. 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 [16]. Modelling of uncertainties, confidence and maturity of reused data and/or knowledge represents a major difficulty and could be the focus for exploitation in distributed preliminary design, in view of integration in a PLM approach.

Two types of approach for modelling uncertainties in product pre-design phases exist which relate to qualitative and quantitative considerations. They are presented in the following section and form the basis for the proposed analysis.

3.2. Literature survey

3.2.1. Qualitative approaches

Qualitative approaches are based on the preliminary information concept introduced by Clark and Fujimoto [17] to allow the parallel execution of activities in the product development processes. Eppinger et al. [18] 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 [19].

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 [20] 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 1) represents the sustainability level and corresponding qualification.

Table 1. Sustainability levels [20]

Sustainability 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.

The ranking below (Table 2) represents the different levels of qualification of the variation which defines the probability that information reaches its final value as proposed by Krishnan et al. [21]. These levels go from "0" for a variation that is very unstable, to "3" for a stable one, meaning that probability that the object approaches its final value is high.

Table 2. Variation levels of an activity (adapted from [21])

Variation levels	Level description of the attribute
0	Very unstable: The probability that an object approaches its final value is zero.
1	Unstable: The probability that an object approaches its final value is low.
2	Moderately unstable: The probability that an object approaches its final value is moderately high.
3	Stable: The probability that the object approaches its final value is high.

Sensitivity levels define the impact of change on information, according to Yassine et al. [22] are classified along a scale from "0" corresponding to not sensitive, to "3" corresponding to sensitive. The ranking (Table 3) is detailed below.

Table 3. Sensitivity levels of information (adapted from [22])

Sensitivity 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 last presented ranking is the completeness level (Table 4) which represents the association of the combination of depth (nature of change) with the magnitude of information. The depth is the nature of the change incident on the object (vagueness, abstraction, level of detail). The magnitude is the importance of information relative to its state of development expected by the user. Completeness represents the amalgamation of these two dimensions. The table below presents this scale going from "0" to "3". The levels of completeness in the table 4 have been proposed in the works of Gebrici et al. [23].

Table 4. Levels of completeness of information [23]

Completeness levels	Level description of the completeness
0	Incomplete: The object has no depth or zero magnitude.
1	Very partial: The object has small magnitude and depth. (The object does not meet most expectations and the majority of its parts have not been finalised).
2	Partial: The object has moderate depth and magnitude. (The object meets most expectations and most of its parts are finalised).
3	Complete: The object has a high magnitude and depth. (The object meets all expectations and all its parts are finalised).

The schema below (Figure 2) from [4] shows the process of characterisation and qualification of data/information from the transmitter to the receiver or user.

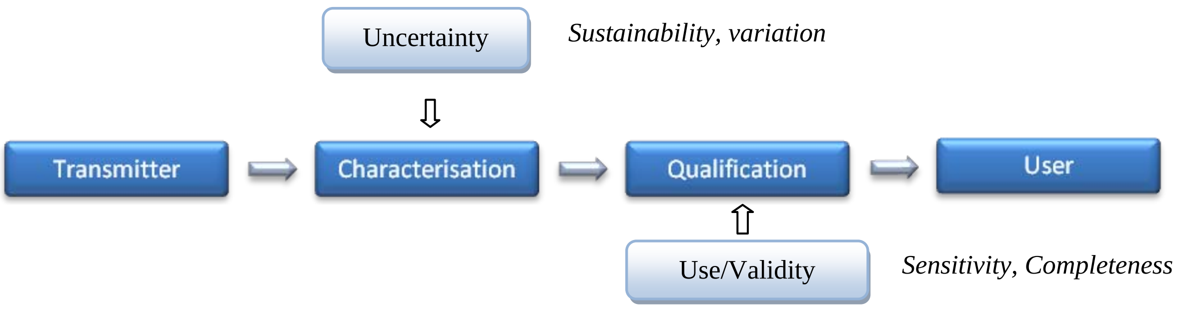

Figure 2: Uncertainty of information from transmitter to receiver [4]

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 [21, 22, and 24]. 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 [25].

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?

The approaches presented here are qualitative; however the following section illustrates how to quantify the information maturity.

3.2.2. Quantitative approaches

We have identified three quantitative approaches for the representation and treatment of uncertainties: fuzzy set theory; possibility theory; and, evidence theory.

Fuzzy sets:

Zadeh introduced the theory of fuzzy sets, as an extension of classical set theory [26]. 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.

Fuzzy logic has been used extensively within the context of fuzzy controllers which aim to generalise the operation of expert controllers [27]. Another notable application of the theory of fuzzy sets is in linguistics due to the inherently vague nature of language [28]. Language can also be regarded as ambiguous, meaning that a phrase or word can be understood in different senses / meanings [28]. For example, if a man is described as tall, what is its height? What is the minimum height that he may have to be qualified as tall? There is no universal answer that can be accepted since it depends on the interpretation of the person.

Possibility theory:

Possibility theory was proposed by Zadeh [29] 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 [30]). 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 [30].

Evidence theory:

Evidence theory, also called Dempster-Shafer theory was presented by Shafer [31] when he expanded the work of Dempster [32]. However, its origins date back to Hooper, Bernoulli and Lambert [33, 34]. 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.

4. PROPOSED METRIC

A system can be decomposed into subsystems that can interact with each other, and a sub-system is composed of different interacting elements. With the objective of supporting decision making in a collaborative context for preliminary design under uncertainty, the metric defined will describe and characterise 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. 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 characterising information. Once the decision is made, the item can be updated (iteration +1).

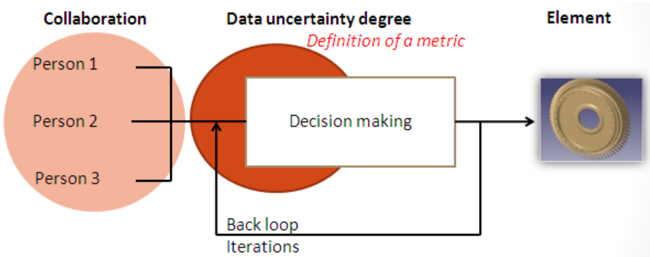

Figure 3: Decision making in preliminary design and under uncertainties

We have presented different qualitative and quantitative approaches that may be used to qualify the information maturity, and to manage modification during the product pre-design phases. We have focused on qualitative approaches by considering the information transmitter as well as the receiver, which can be two people addressing the same information but with two different viewpoints. One generates the information and the second uses this information.

A number of scales are used to allow characterising and qualifying information in function of very specific points (Tables 1 - 4). The proposed metric resides in the construction a value scale divided into three parts. The first is the information characterisation that takes into consideration the information sustainability and variation which is defined in response to the information transmitter. The second part of the metric is information qualification including sensitivity and completeness. The information receiver will determine the value of this scale. Finally, the third part of the proposed metric will be a synthesis of the first and second part in order to determine a global information maturity level. The first two scales are determined in response to questions answered by the users during information evaluation. Additional criteria such as the value of iteration number and the experience of the information transmitter and receiver will be considered.

The validation of the proposed metric will be undertaken using an industrial case study that will allow the development of the metric within a preliminary design, concurrent engineering context where there is a need to reduce product development cycles.

Figure 4: Process allowing obtaining maturity level

A demonstrator will be developed in order to determine the three parts of the proposed metric. The process of creating the information maturity level (Figure 4) is articulated in the following way:

- Information transmitter qualification via the developed application in response to different questions. A first degree of maturity (information characterisation) will be calculated.
- Information receiver qualification in response to different questions in order to calculate the second maturity degree (information qualification).
- Using the first two calculated maturity levels, the global maturity level will be provided to the transmitter and the receiver of the information. This maturity level will benefit integration into a PDM system as a product parameter.

Using this process based on the maturity and validity of information and models, the maturity and validity of modifications and theirs impacts could be evaluated and qualified.

5. ILLUSTRATION ON AN AERO ENGINE CASE

5.1. Diversity of models used in aero engine

As described in the previous paragraph, 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 [8] with different levels of granularity. For example, Figure 5 shows the evolution of a CAD model of an aero engine used in preliminary design and a model in detailed design.

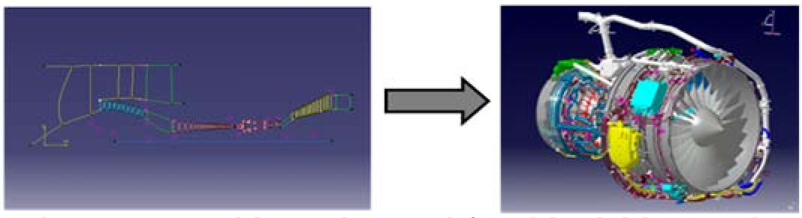

Figure 5: Differences between CAD models in preliminary (left) and detailed design (right) adapted from [35].

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 (Figure 5).

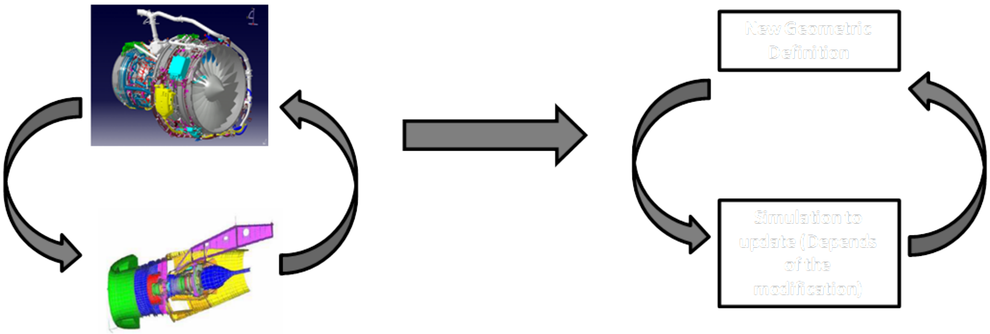

Figure 6: Iteration in design process

In addition to the diversity model due to the iteration, the simulation model is specific to a particular physics domain (thermal, mechanical, fluid mechanics). In taking this factor into account, the number of simulation models and the results associated with a CAD model can increase significantly.

5.2. Illustration on interaction on decomposition level of an aero engine

The design of an aero engine can be decomposed into several parts as shown on Figure 7.

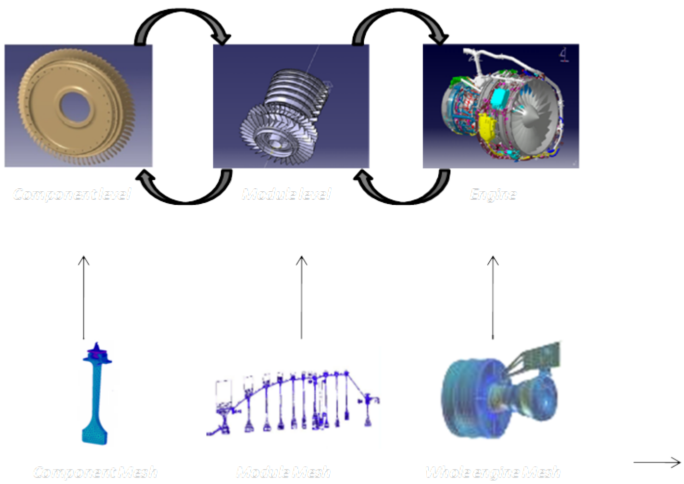

Figure 7: Decomposition of an aero engine and associates models

This final section shows that 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.
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).
Models and data are typically reused for the development of new products, with the aim of reducing product lifecycle development times. This lifecycle and its reuse are presented in this article and more particularly in this part with bottom-up and top-down processes and iteration during the process design. The interest of the data/information/model qualification supports the validation of the data or the model in a specific case in order to reuse it. Research to date provides only an indication of whether the model is valid, or can be reused whereas this research provides a metric for the degree of validity of the model and its iterations. This enhances model reuse, and with a validity degree for future development may subsequently decrease product lifecycle development durations, especially in reducing the number of iterations in the design process. This reduction is not directly on the model developed, but it is necessary to take into account the context of reuse so that the effectiveness of the proposed metric presented in this paper can be fully leveraged.

6. CONCLUSION

Product development cycles, and more generally product life cycles, are becoming increasingly complex. By complexity, we mean that they involve a significant number of different businesses using specific vocabulary and work methods. They work simultaneously and must integrate different viewpoints, which create problems for modification and impact management. It is therefore necessary, to qualify the data or information in the upstream phases of product design. This paper is a literature survey about the existing approaches allowing to determine the maturity of data or information, but any of this one include the system dimension and collaborative dimension. The presented approaches are classed in two categories: qualitative and quantitative. The modelling of maturity and validity of information/data will be based on a qualitative approach associated with the provision of an information maturity scale to the user. Two directions are taken in order to define data maturity: modification and information. The first is a characterisation and the second is a qualification between the information transmitter and receiver. Future works will present the integration of this approach and the resulting scale, in the context of decision making support.

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