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Creative design: Analysis, ontology and stimulation

Galina Medyna, Eric Coatanéa, Lauri Lahti, Thomas Howard, François Christophe and William Brace

Abstract. This paper establishes an ontology of creativity and innovation processes. A comprehensive review was undertaken describing the four key perspectives of creativity research, namely the creative-output, -process, -person and -environment. The focus of this review is based around the metrics for measuring creativity from each of the above perspectives. These metrics are drawn together in a common model which highlights key considerations when attempting to measure creativity. It was observed that many of the measurements were trying to identify patterns associated with creativity which correlated to a higher potential for creative output. It is argued that metrics linked directly to the creative output provide direct measure for creativity when other metrics related to the environment, person and process are correlated positively or negatively with the potential for creativity. In addition, the FBS framework established from design literature is linked to the principle of continuity argued as a necessary element of creativity in design. It is also argued that innovation requires creativity as an enabler.

Keywords. Creativity, Engineering Design, Models, Cognitive Science, Collaborative process, Creative metrics, Analogy, Knowledge bases.

Introduction

The aim of this article is to analyze the concept of creativity in the design process and propose ways of stimulating it. We do not intend to analyze here the innovation process. In order to avoid confusion, a clear distinction between the two concepts is established by the authors at the end of this introduction. The perspective about creativity selected in this article is described below. Creativity is the generation of ideas that are both novel and appropriate to the problem (the plurality represents the importance of frequency of ideas generated). Innovation is an artefact that has one or more creative ideas and requires creativity as its starting point (Amabile et al., 1996). Even though creativity has been historically considered somewhat mystical, the definition and formalization of creativity have been the interest of scientists, especially in the community of cognitive science.

During our research work discussion, different perceptions of applied creativity emerged: creativity applied to art versus technical creativity. Some researchers considered that there is a difference between technical creativity, as constrained by schedules, performance and market, and artistic creativity, considered free from all constraints. We advocate for creativity in a holistic point of view, hence creativity as a process of the mind is not different for art or engineering. For example, in blues and jazz music, improvisation, which is a form of creativity, only appears on the basis of a well framed melody. This is, in our viewpoint, an example of a necessary basis for creativity in art too.

The article is organized in the following manner:

- Section 2 describes the state of the art of existing research both in engineering design and creativity. The creativity chapter is extended and considers several perspectives of creativity summarized in Figure 1.
- Section 3 develops a conjoint analysis of creative and engineering design models presented in section 2 in order to present an integrated model first introduced by Howard (2008). This chapter pushes the analysis further by proposing a new type of metric to assess the creative design process.
- Section 4 analyses the creative design environment, the individuals and the group. This section proposes several hypotheses for metrics that are integrated in section 5.
- Section 5 is the discussion-conclusion section. The section develops an ontology of creativity from the perspective of engineering design. Conjointly, the section summarizes the metrics gathered and proposed in the article.

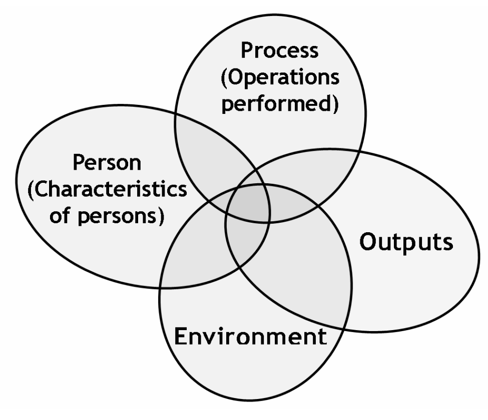

Figure 1: Four viewpoints on creativity

2 - State of the art in creative design

2.1 – Design considerations

During this study, we will consider creativity through the viewpoint of engineering design, as opposed to artistic design, because we aim to explain more systematically the structure of the creative engineering design activity. This chapter proposes an overview of design and, more precisely, its early stage: conceptual design. In this section we will present a perspective on knowledge representation in engineering design and present the state of conceptual design representations. We will also describe the collaborative aspects of the engineering design activity.

2.1.1 – Knowledge representation

As Davis (1993) pointed out, even though knowledge representation is one of the most familiar concepts in Artificial Intelligence (AI), the question of what is knowledge representation is rarely answered directly. In this article we use the Davis representation of knowledge to present five important and distinctly different roles played by knowledge representation (KR).

The first and most fundamental role of KR is a surrogate, a substitute for the thing itself, which is used to enable an entity to determine consequences by thinking rather than acting. This enables reasoning about the world rather than taking action in it.

Second, KR is also a set of ontological commitments. This aspect answers the question, *In what terms should I think about the world?* Selecting a representation means making a set of ontological commitments. The commitments are, in effect, a strong pair of glasses that determine what we can see, bringing some part of the world into sharp focus at the expense of blurring other parts.

Third, KR is a fragmentary theory of intelligent reasoning expressed in terms of three components:

- the representation's fundamental conception of intelligent reasoning
- the set of inferences that the representation sanctions
- the set of inferences that it recommends

Fourth, KR is a medium for pragmatically efficient computation, that is, the computational environment in which thinking is accomplished.

Fifth, KR is a medium of human expression, that is, a language in which we say things about the world.

2. 1. 2. – Situated FBS: A representation of the conceptual design process

Since Pahl and Beitz's systematic description of engineering design (Pahl, G. and Beitz, W., 1984), there have been a multitude of descriptions of the design process. Nevertheless, an interesting attempt to describe conceptual design in terms of necessary knowledge for designing artefacts has been proposed by Gero and his Function-Behaviour-Structure model (FBS) (Gero, J.S. et al., 1992). Recently, Gero has submitted a new vision of his model (Gero, J.S. and Kannengiesser, U., 2004), called "situated FBS model" which includes a contextual viewpoint. The conceptual design process is presented in a dynamic environment because, as things get created, the world gets modified and so does the knowledge available in order to create new things. Figure 2 shows the situated FBS model of conceptual design.

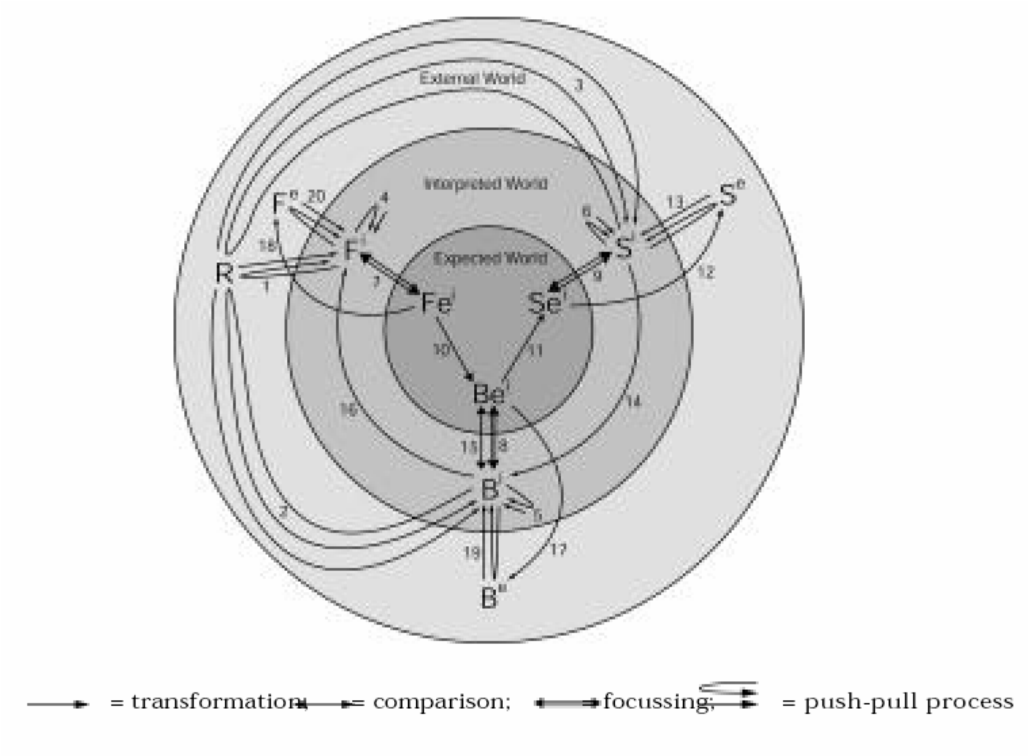

Figure 2: The situated FBS framework

2.2 – Creativity considerations

Creativity is a complex concept presenting several facets. Creativity is undeniably influenced by the personal characteristics of individuals such as knowledge, the ability to create analogies, age, psychology, culture, environment and many other factors. Another interesting aspect is that creativity can also emerge from collective activities. In this case creativity is not attached to an individual but to a group which manages to create the appropriate alchemy between individuals allowing a fruitful creative process. Another element is the process itself. Undeniably, creativity can be influenced positively or negatively by the succession of operations and activities performed, their order and type are influencing factors. An additional factor influencing creativity is the environment. This means geographical, climatic, culture, historical, sociological and ethnological considerations. The outcomes of the creative activity influenced by these interacting considerations need to be evaluated, this is the role of the measurements.

2.2.1 – Creativity and cognition models

The definition and formalization of creativity have been the interest of scientists, especially in the community of cognitive science. Cognitive science is the study of mental representations and processing, those of creative thoughts have first been modeled by Wallas and Smith and their five stages (Wallas, G. and Smith, R., 1926) and an updated perspective of this model is proposed by Simonton (1999). In this study we particularly consider Guilford's work (1957) and the relations between convergent and divergent thinking. Whereas convergent thinking deals with evaluating a relevant solution to a problem, divergent thinking involves the creation of multiple solutions to a problem. Therefore, one aspect of creativity is the duality between the convergent and divergent thinking. Amabile et al. proposed to distinguish creativity from innovation as the first being the starting point of the latter. As they suggest, "... creativity by individuals and teams is a starting point for innovation; the first is a necessary but not sufficient condition for the second" (Amabile, T.M. et al., 1996). Innovation can refer either to incremental, radical or revolutionary changes in products or services, processes, or in organization. This perspective is adopted in this article.

Many creativity processes modelled throughout the literature and one of the most famous and still relevant is Wallas' five-stage process (Wallas, G. and Smith, R., 1926). It is decomposed as follows:

1. Preparation to a problem that focuses the mind of individuals and explores the problem's dimensions,
2. Incubation: the problem is internalized into the unconscious mind; nothing appears to be happening externally,
3. Intimation: the creative person has a "feeling" that a solution is coming,
4. Illumination: eureka! The creative idea bursts forth from pre-conscious processing into conscious awareness, and
5. Verification: the idea is verified, elaborated and starts towards application.

This process brings up an interesting question: *Is creativity due to some magic or can a method be applied for it?* (Harnad, S., 2001). In fact, through Wallas' description of the process (Wallas, G. and Smith, R., 1926), we can perceive that creativity contains some unknown factors as we do not know the mechanisms of the unconscious. Nevertheless, the first and the last two stages can be methodically applied and therefore enhance the core creative process itself. In his recent publication, Howard has compared several different descriptions of the creative process (Howard, T.J., 2008). Several described processes involve the re-definition of the problem and even the use of requirement (Kryssanov, V.V., 2001). This shows the importance of the preliminary stages of the creative process and the importance of setting a frame enabling creativity. Nevertheless, every process contained more or less the same stages as described by Wallas.

Models of creativity need experimental evidence which however can be hard to obtain. Experimental research about creativity began rather late, possibly in 1950 with J.P. Guilford presenting his structural model concerning divergent and convergent thinking (Guilford, J.P., 1957). Advances in neurological research may allow joining more hypothetical theoretic models with objectively measurable brain activity patterns.

2.2.2 – Measures of creativity of a person

As briefly shown above, there are numerous possible definitions of creativity and there is no standard way of measuring the creativity of a person. Attempts have been made to produce a Creativity Quotient (CQ) similar to the Intelligence Quotient (IQ) which have failed, mainly due to a lack of objectivity in assessing creativity (Plucker, J. and Renzulli, J.S., 1999). Nevertheless, there are multiple assessment methods and metrics of creativity. They are divided into two categories: those that are person-centred, which tend to assess attributes such as knowledge and personality, and those that are process and output-centred, which concentrate on the result of a creative process. Overall, creativity is a complex process with many nuances and thus multiple tests on different criteria are necessary to capture all its aspects (Furnham, A. et al., 2008).

Sets of measures and metrics of individual creativity can be found in the literature, as an example in this article we provide on three of them. For brevity's sake, we chose not to go into detail of each technique. Santosa et al. (Santosa, C.M. et al., 2007) present three evaluation techniques: the Barron-Welsh Art Scale (BWAS), the Adjective Check List Creative Personality Scale (ACL-CPS) and the Torrance Tests of Creative Thinking (TTCF).

Batey and Furnham (2008) propose to measure self-assessed creativity, creative personality and creative achievement. The final assessment of the creativity was done by taking into account the three scores. The self-rating creativity was done using a 10-point Linker-type scale.

A third set of tests is made up of Divergent Thinking (DT), Biographical Inventory of Creative Behaviours (BICB), Self-Rating of Creativity (SR) and Barron-Welsh Art Scale (BWAS) and was studied by Furnham and Bachtiar (2008).

Hocevar (1981) presents numerous assessment methods that necessitate people (supervisors, peers, teachers, etc.) to make judgements about products, ideas or other people. Assessments which can be described as "peer reviews" tend to be influenced by a "halo" effect in which such notions as intelligence come to interfere with an unbiased evaluation of only creativity. Therefore creativity assessments should be done by a party which is in no way connected with the person being evaluated.

There is a great need for a metric measuring creativity to simplify the assessment of creativity tools but such an abstract notion as creativity requires the definition of strict boundaries as well as the presence of absolute objectiveness. Every single being is creative if the definition of creativity is broad. Indeed, the simple fact of putting an object under the leg of a wobbly table can be considered as creative as it leads to a novel outcome on at least one level, it's new to the person and happens at the appropriate time.

2.2.3 – Knowledge aspects in the creative process

- The CK viewpoint

C-K theory has been developed by Hatchuel and al. (2002) to offer a theory where creative thinking and innovation are not anymore external to the design theory. C-K is an interesting perspective to explain the refinement and synthesis process taking place during the design process. The validation of solutions (i.e. comparison, evaluation and ranking of design solutions), even if mostly grasped by the model, is not really explained in detail. In this respect, C-K theory is not really a unified design theory in a comprehensive and complete manner. Nevertheless, C-K theory exhibits an interesting perspective of creative design. The main aspects of C-K theory are summarized below:

- Creative design is defined as a form of reasoning where *creativity* is integrated in its definition,
- Design is defined as a process where *knowledge expansion* is integrated in its definition,
- Design can lead to processes whose output could be new design issues.

The design process itself is described as: 'assuming a space of concepts C and a space of knowledge K, Design is defined as a process by which a concept generates other concepts C or is transformed into knowledge K (i.e. propositions in K).

One interesting aspect with C-K theory is that the theory is built on mathematical foundations. The foundations rely on the *set theory* developed by Georg Cantor in the later part of the 19th century. The key aspect in our context is that the theory is based on four operators. These operators are used later in this article to support our analysis of the measurement of creativity.

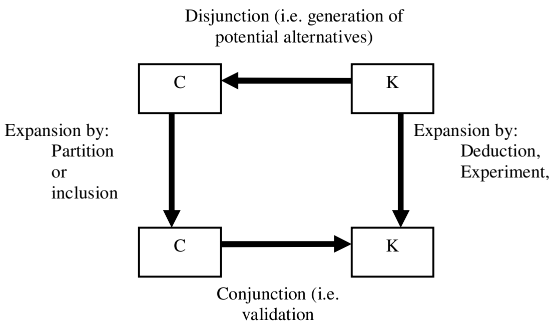

Figure 3: The four operators of CK theory

Disjunction is an operation which transforms propositions of K into concepts (going from K→C). Conjunction is the reverse operation (going from C→K). These two operations are adding and subtracting properties to and from concepts or propositions. Disjunction (K→C) and conjunction (C→K) are external operators; the two others are internal operators (C→C and K→K). They are the expansion operators, expansion by partition or inclusion and expansion by deduction or experiment. Figure 3 summarizes the four operators of the C-K theory and the viewpoint of the process of designing in C-K theory.

- Cultural knowledge and social aspects and collective building of knowledge bases

The term "culture" has many definitions, from being commonly attributed to tribes or ethnic groups in anthropology to being used to describe the full range of learned human behaviour patterns. The English anthropologist Tylor (1924) defined culture as; " that complex whole which includes knowledge, belief, art, law, morals, custom, and any other capabilities and habits acquired by man as a member of society". Thus from this definition it can be abstracted that there is the existence of cultural knowledge (K_c)which, according to Hoerr (2007), are those ideas gained from experience and stored in the brain. Studies by researchers on the nature of creativity have found evidence that creativity is very much grounded in the individual's knowledge and how they combine their knowledge of dissimilar concepts to create new perspectives (Breneman, 1999.

Inkeles and Levinson (1954) classify the dimensions of culture by limiting themselves to the level of nations to come up with three standard analytical issues which met the following criteria: 1) Relation to authority; 2) Conception of self, including the individual's concepts of masculinity and femininity; and 3) Primary dilemmas or conflicts, and ways of dealing with them, including the control of aggression and the expression versus inhibition of affect.

A fifth dimension was later added on the basis of further research works (Hofstede, 2001; Hofstede & Bond, 1988). Five dimensions of cultural variations are identified by Hofstede (1991; 2001) and these dimensions are labelled:

(1) Power Distance, related to the different solutions to the basic problem of human inequality;

(2) Uncertainty Avoidance, related to the level of stress in a society in the face of an unknown future;

(3) Liberalism versus Collectivism, related to the integration of individuals into primary groups;

(4) Masculinity versus Femininity, related to the division of emotional roles between women and men;

(5) Long Term versus Short Term Orientation, related to the choice of focus for people's efforts: the future or the present and past.

Although people vary considerably, there has been reliable support that Hofstede's dimensions are stable over time (Kirkman & Shapiro, 1999; Hoppe, 1990; Merritt, 2000). Our interest in these dimensions concerning creativity lies with power distance, uncertainty avoidance, and liberalism versus collectivism, conceptually, variations in an individual's creativity can be explicated by variations in the characteristics of a nation's culture. These aspects are developed in section 4.

- Knowledge shared by a community: an analogy with Internet

Evolution of online knowledge bases, such as Wikipedia, can give inspiration for understanding collaborative processes in creative work. According to a study 97 % of the first definitions for a new article are written by another person than the one who first proposed it (Spinellis, D. and Louridas, P., 2008a; 2008b). This indicates that initial suggestions stimulate collaborative expansion of online knowledge bases. This aspect is exploited in section 4.2. as well as the notion of "power law". Power law indicates a hierarchical clustering of information for example in article sizes, the number of connecting links, editing times and collaboration distribution.

It is appealing to imagine that similar principles also exist in the creative design process. In practice, creative design typically aims to reach new levels of thinking in the form of creative output. However, even the most novel ideas have some constraints that link them to previous knowledge. It is often challenging to find a balance between far-reaching and pragmatic aspects in the generation of new ideas.

3 - Creative design process: model and Proposal for an evaluation metric

As shown in Figure 1, creativity has several facets. One of them concerns the operations that are performed, they constitute the creative process. In the context of this article we are specifically interested by the engineering design process. When trying to understand where and how creativity is taking place in the engineering design process, we are faced with the challenge of describing a model of the creative design process. This model is used later in this article in order to explicit some parts of the ontology that constitutes a key outcome of this article.

The state of the art has presented two separated models; the creative model of Wallas (Wallas & Smith, 1926) and the design model of Gero et al. (1992). A synthesis of those models has been proposed by Howard et al. (2008). According to Howard, a creative process can be simplified and encompasses mainly three major stages named the analysis, the generation and the evaluation.

It is possible to analyse an engineering design process by integrating these stages in the FBS model previously presented. Figure 4 presents a modified FBS model integrating the design problem reformulation.

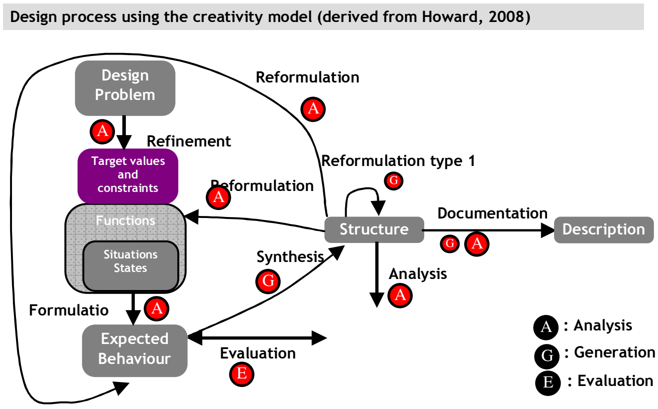

Figure 4: Modified FBS model (derived from Howard) (Howard et al., 2008)

The interest of Figure 4, in addition to presenting an integrated model of the creative design process, is to highlight that a creative design process is the result of several mapping between well established design stages. Each of these mappings corresponds to an arrow in Figure 4. This is the moment where the concept of continuity/discontinuity takes place. The creation of a creative outcome can be achieved if at least the phases of refinement, formulation, synthesis, analysis and evaluation of the FBS model can be successfully performed. In other terms, this can be done if continuity exists in these phases of the design process.

The meaning of the concept of continuity is very profound and is used to evaluate two aspects of a creative design process model: its coherency and its decidability

(Nonaka et al., 2000). Coherency means in our context conservation of meaning between the initial needs provided at the beginning of the design process and the final result of the creative design process. Decidability means that our creative design process model should allow us to determine if an outcome is really novel and appropriate. Novelty and appropriateness are the two fundamental properties of creativity defined in the introduction. Consequently, measuring the creativity process can be done directly through the analysis of the continuity of the mapping between one design stage and another. This can be achieved in practice via the development of meaningful filters and ontology but also by transforming the design space into a specific space called metric space (i.e. a design space with a single metric) best suited for evaluation (Bourbaki, N., 1989).

Figure 5 summarizes in red the concepts that allow the evaluation of the creative design process from the viewpoint of coherency and decidability.

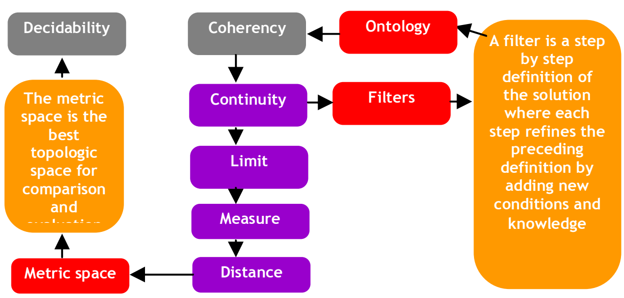

Figure 5: Evaluation of the coherency and decidability of creative ideas

The main goal of section 3 and 4 is to propose hypotheses which will lead to promoting creativity. The hypotheses are made based on the research conducted so far and will be tested in the future. The analysis made in this section allows us to pose an initial hypothesis.

> Hypothesis 1: A necessary but not sufficient condition for a creative design process to take place is the verification of the continuity of the process described by the FBS model.

4 - Creative design environment and persons: Proposal for measurement metrics

4.1 – Cultural influence on creativity

In paragraph 2.2.3, we have introduced the concept of cultural knowledge K_{c_n}. As recognized in Taylor's definition of culture (Taylor, 1959), an individual in a particular society or nation possesses a unique cultural knowledge. We have tried to show through the analysis of the CK theory that creativity is also strongly influenced by knowledge.

The present chapter tends to link five other properties of culture that can influence creativity: (1) Power Distance, (2) Uncertainty Avoidance, (3) Type of integration of individuals into primary groups, (4) Division of emotional roles between women and men, (5) Long Term versus Short Term Orientation.

> Hypothesis 2: Cultural knowledge may positively or negatively affect creativity depending of the context,
>
> Hypothesis 3: The lower the power distance the more positive the effect on creativity,
>
> Hypothesis 4: Lowering uncertainty avoidance positively affects creativity
>
> Hypothesis 5: Integration into primary groups providing individual freedom positively affects creativity.
>
> Hypothesis 6: Long term orientations positively affect creativity.

These properties can be used to assess the manner cultural aspects influence creativity aspects. They do not constitute direct measures of creativity but instead they as inhibitors or facilitators of creative thinking.

4.2 – Influence of collaboration aspects on creativity

Learning and teaching creativity is challenging. Many tasks required in life can be adequately performed with routines and creativity lacks encouragement. In collaboration, all contributors need to make efforts to reach a consensus and to maintain continuity in the collective creative working process. However this requires making compromises in continuity of individual creative work. To minimize this burden of collaboration there must be cost-effective communication to guarantee mutual understanding of the shared aims. Originating from research about informational requirements for various communities an abstract concept of boundary objects has been widely adopted to represent things that can help people from different communities build a shared understanding (Star & Griesemer, 1989).

Despite having different practices, people can use these objects as a common point of reference for conversations and thus agree on what they are talking about. Boundary objects should be general and formal enough to be capable of traversing through various collective contexts but also specific and flexible enough to convey individual meanings.

Hypothesis 7: Use of boundary objects affects positively the potential for creativity of a group.

4.3 – Analogy between the Wikipedia online encyclopaedia and measurement of creativity output in engineering design

It has been shown that without any specific human coordination many features of Wikipedia automatically evolve to structures that follow a "power law" which is a hierarchical clustering of information for example in article sizes, the number of connecting links, editing times and collaboration distribution. It has been suggested to be a product of a natural optimization process that guarantees the most efficient average connectivity between all nodes. It seems possible by analogy that ideas in the human mind can form a scale-free network which obeys power-law distribution. This would imply that the network of ideas contains clusters that can be assimilated to gateways allowing the most effective connectivity among the ideas. Based on this fact, an initial analogy can be proposed in the field of engineering design.

> Hypothesis 8: Hierarchical clustering of information for example in article sizes, the number of connecting links, editing times and collaboration distribution affects positively creativity.

Time restriction is another important part of the Wikipedia principle. When a new page is created, significant content must be added within a certain amount of time to show the validity of adding the page. In the context of engineering and design creativity, time limits are important and strict. The ideal output of a creativity tool is the generation of the idea which will lead to the ideal solution for a given problem in the least amount of time.

> Hypothesis 9: A measure of the interest of creative ideas in the field of engineering design is the amount of other ideas associated to the creative idea in a limited amount of time.

5 – Discussion and Conclusion

The analysis provided in the previous sections develops multiple viewpoints and perspective. The key goal of this article is to develop an overall vision of creativity in the field of engineering design by focusing simultaneously on several aspects such as the environment, the creative design process, the person, the group, and the outcomes.

The authors have obviously been obliged to limit their analysis in this article because of the limited format allowed. Nevertheless we have tried to give an overall vision of creativity in the field of engineering design. Figure 6 presents the ontology and the metrics gathered and proposed at every stage. The chapters where the metrics and aspects of creativity are discussed are indicated on the right column of the figure. Building this vision is necessary because other progress in the understanding of creativity requires at first the development of a clear and consistent supporting framework. The present article tries to add its contribution by developing an ontology of creativity associated with a list of metrics that can be used to assess creativity directly or indirectly. The indirect metrics are enablers of certain factors influencing positively or negatively creativity. Other elements in our ontology provide a mapping between the different facets of creativity such as the CK operators but also the induction process. The present ontology does not pretend to be complete. This is a first attempt to capture the essence of creativity in a compact format. The list of metrics is an attempt to evaluate different aspects of creativity; this is a phase which is very important and seldom considered as a study topic in most of the studies on the subject.

In this article we have voluntarily decided not to focus explicitly on innovation, even if innovation is clearly mentioned in the design output part of the ontology of Figure 7. Many people discuss extensively about innovation without sometimes making a clear difference between the two terms creativity and innovation. The authors have considered innovation as the stage appearing sometimes after the development of creative concepts. The transformation of a creative concept into a real innovation is by itself an entire research field and we considered in this article that it will make sense to start by understanding creativity and its evaluation more broadly.

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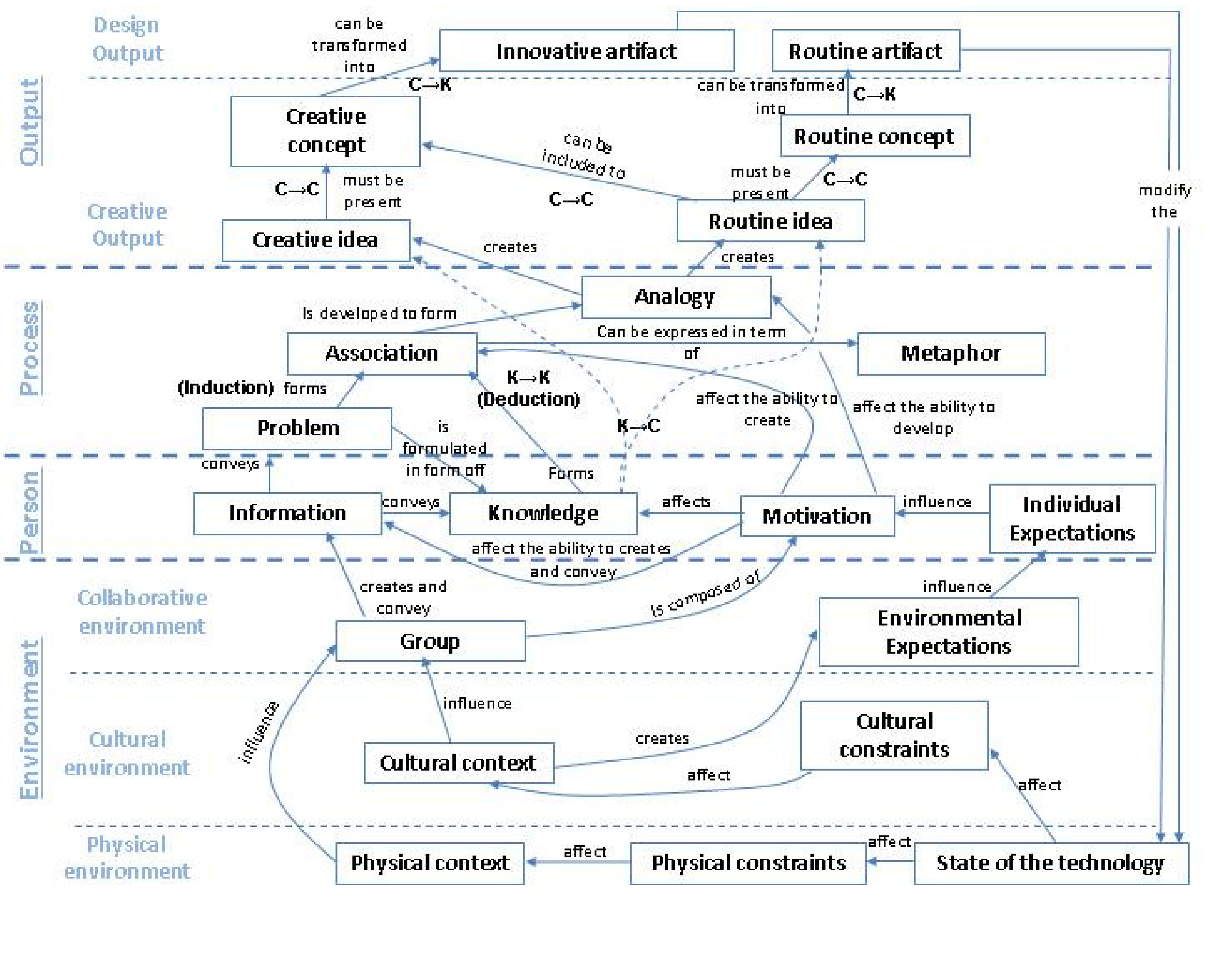

Section		Direct measures of creativity	Indirect measures of creativity
3		• Novelty • Radical Improvement • Edit history • Word count	
3		• Novelty • Appropriateness • Number of ideas associated or added to a creative idea in a limited amount of time	
3		• Continuity vs. discontinuity (filters, ontology) • Metric space	• Number of representations • Abstraction level • Number of generic solutions
4		• Barron-Welsh Art Scale (BWAS) • Adjective Check List Creative Personality Scale (ACL) • Torrance Tests of Creative Thinking (TTCF)	• Divergent Thinking (DT) • Biographical Inventory of Creative Behaviours (BICB) • Peer review (word count, number of reviewers, edit history, connecting links)
4			• Boundary objects (Repositories, ideal type of objects, coincident boundaries, standardized forms) • *SECI* and *Ba* models, power law
4			• K (Cultural knowledge) • P (power distance) • U (uncertainty avoidance) • I (individual freedom) • L (Long term orientation)

Figure 6: Ontology of Creativity and evaluation metrics

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