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MANAGING UNCERTAINTY IN THE DESIGN AND DEVELOPMENT PROCESS BY APPROPRIATE METHODS SELECTION

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1. The engineering design process and the CPS process

Descriptions of the engineering design processes are extensive in the literature. The models are prescriptive and explain the different design activities and the order in which they must occur. They all represent step-wise processes of an iterative nature. The most basic of these models describes four main stages named Specification, Concept, Schematic Design and Detail [Cross 2000]. Others show further aspects such as the specific steps to undertake within the basic stages [Pahl & Beitz 1996] or the crucial multidisciplinary considerations to make during the product design process [Pugh 1991].
In the field of creativity a problem solving model for application in a wide variety of disciplines has been defined [Vehar et al 1999]. The Creative Problem Solving (CPS) process is a helpful model that provides individuals and teams a flexible set of easy-to-use tools to tackle problems or challenges. The tools have been created to support the understanding of problems, the generation of ideas, their sense-making and their selection. Its flexibility lies in the fact that it does not aim to substitute the existing processes but to provide additional tools to deal with them, such as ladder of abstraction, brainstorming, visual connections, morphological matrix, brain-writing, idea checklists, Pluses – Potentials – Concerns - Overcome concerns (PPCo), highlighting, card sort, paired comparison analysis, etc. Therefore there is no conflict between these two approaches. Quite the reverse, they can be seen as complementary.

2. The use of methods in industry and the need for a classification

The number of methods used in industry is relatively small. Of those that are used, some are used at the wrong stage of design and some methods are not practised correctly. Inappropriate methods implementation leads to poor and dissatisfying results and to distrust of design methods generally.
Many modern products involve a high degree of functionality. For example, automotive design involves complex electro-mechanical systems that must perform numerous tasks with a high degree of reliability and safety, low fuel consumption, minimal noise and vibration, attractive design, safe and pleasant handling, low cost manufacture, and minimum environmental impact etc. Potentially, design methods have much to offer in this complex multi-objective product design activity, if selected and used properly.
In this paper a framework for the classification of the existent engineering and creativity tools will be proposed. The classification is selection oriented, that is, it is intended to help engineers select methods so that they can be used effectively. The basis of the classification is principles from the field of creativity that concern the way people think.

3. Adaptor-Innovator theory

The initial studies of creativity in the individual concentrated on the determination of the level of creativity of people and the characteristics of highly creative people. However in 1976 research began in the field of creative style [Kirton 1994]. Kirton explored the relationship between creativity and cognitive style and he stated that people can be creative in different ways. He found that there are people who *prefer* to make continuous improvements within the paradigm, and he called them adaptors. Whilst others, whom he called innovators, *prefer* to produce novel unexpected solutions. Both kinds of character can be creative.

Since many people tend to confuse the terms creativity and innovation, a definition of creativity is given next. Creativity is here understood as the conjunction of originality and usefulness. Both adaptive and innovative problem solving approaches can have creative outcomes as far as they are unique and they add value. For example, concrete is a construction material, made of gravel and other pieces of hard material contained in a mould of lime, sand and water. It has been used in construction since the Roman times. However it was not extensively used until Portland cement was invented in 1824. Portland cement added great strength, durability and fire resistance to concrete that the old cement lime could not provide. The uniqueness and usefulness of the invention of Portland cement is obvious and still we consider it as an adaptive contribution since the solution remains loyal to tried and understood principles of the material behaviour. A few decades later the reinforced concrete was invented. This novel concept in which steel reinforces the concrete where it needs tensional strength and where the concrete protects the steel from rust and fire allowed the construction of longer and thinner structural elements. The reinforced concrete was therefore unique at that time and useful, and we consider it innovative since the working principle behind the new composite material was extremely different. The Portland concrete meant an adaptive or evolutionary step in the field of the concrete as a construction material, whilst the reinforced concrete was an innovative and revolutionary step that created a completely new composite material with new possibilities. Both solutions were however very creative and they are still in use. Style of creativity is not equal to level.

Creative people are therefore those that are able to create original and useful ideas. However, Kirton did not try to measure the level of creativity of people but rather their style of problem solving. He realised that people are not absolute adaptors nor absolute innovators but may have intermediate locations in a continuum between such extremes. Kirton has identified the main traits of high adaptors and high innovators and have quantified them by studying their problem solving *preferences*. High adaptors *prefer* to produce a low number of sound ideas, they *prefer* to pay meticulous attention to detail and they *prefer* to use approved structures to solve problems. High innovators *prefer* to produce a large number of potential ideas, they prefer to have a wide overview of the problem and they *prefer* to solve the problems by doing things differently.

People *preferences* are those problem solving tactics that they tend to take naturally, that is, without big effort. Everybody can solve a challenge adaptively by developing an idea within the current paradigm in great detail, but for some people that detailed work is easier than for others. Likewise everybody can develop an innovative idea by solving a problem in a radically novel way, but for some people it is easier to think up new ways than for others. Therefore problem solving *preferences* are those approaches to challenges that people can handle easily. For innovators it is easy to deal with less defined problem structures, whilst for adaptors it is easy to work with detail.

While a preferred problem solving style is stable over time according to the studies of Kirton, the actual style used by engineers must vary according to the company and market needs. That capacity to vary of problem solving behaviour has been called capacity to flex between styles [Kirton 1994]. Flexing is something that all of us can do and have practised since we were children because, for instance, different subjects at school required different problem solving skills. It is important to have a wide assortment of problem solving skills and the comprehension and use of tools and methods can provide it, as some authors have pointed out [Puccio 1990] .

Lordan proposed that adaptor-innovator theory could be extrapolated to methods classification, but did not take extensive work in this respect [Lordan 1998]. This paper reports research that builds on this earlier work and is concerned with methods classification according to principles of creative style. The paper considers the significance of methods classification according to style with respect to their use by engineers and the overall influence of methods on engineering design practice in industry.

4. Design methods classification and selection

Methods have been classified as divergent or convergent [Jones 1971]. Divergent methods involve searching for ideas and include those used to search for information, to explore the problem, to redefine it, to generate ideas and to combine concepts. Convergent methods imply the imposition of value judgements and include those used to make sense of information, to prioritise items, to compare solutions, to assess ideas and to reject or select concepts. There is a wide range of divergent and convergent methods in the literature. Table 1 illustrates the range.

Table 1. Divergent and convergent methods classified according to their I-A characteristic

INNOVATIVE METHODS ← → ADAPTIVE METHODS

DIVERGENT METHODS				
← more innovative				
Invitational stems	Brainstorming	Attribute listing	635 (brainwriting)	Fishbone chart
Ladder of abstraction	Forced analogy	Classification schemas	Design catalogues	Pluses-Potentials-Concerns
Reverse brainstorming	Morphological matrix	Objectives tree	Forward steps	Systematic doubting
Concept fan	Visual connections	Function structure	Checklist	Value engineering
Personal analogy	Gallery	Factorisation	Lotus Blossom Technique	Process Decision Program Chart
Word dance	Direct analogy	Particles method algorithm	Manupulative verbs list	Closed-world algorithm
CONVERGENT METHODS				
← more innovative				
Highlighting	Compatibility matrix	Interaction matrix	Failure mode and effect analysis	Rating and weighting method
Affinity diagram	Pugh method	Quality function deployment	Fault tree analysis	Strength diagram
Multi-fact picking up method	Prioritisation matrix	Axiomatic analysis	Failure mode and maintainability analysis	Sensitivity analysis
Interrelationship digraph	Weighted objectives tree	Quality benchmarking deployment	Cost-benefit analysis	Value engineering
Card sort	Product-market matrix	Assumption smashing	Hazard and operability (HAZOP)	Desirability function optimisation
Interaction net	Screening method	Analysis graph of ellipses	Risk assessment	Paramater profile matrix optimisation

The framework for methods classification presented in this paper uses the adaptive-innovative characteristics of methods with respect to their divergent or convergent purpose. Adaptors prefer to work with precise information. In contrast, innovators prefer to handle incomplete, imprecise data that involves uncertainty. Applying these principles to methods classification, it can be seen that:

- Adaptive divergent methods are intended to generate solutions to problems that have been identified in a concept through successive incremental improvements. Value engineering is for instance a very adaptive divergent tool.
- Innovative divergent methods facilitate the search of novel concepts, such as the ladder of abstraction and brainstorming.

Adaptive methods are therefore appropriate for products improvements while innovative ones for products renewal.

- Adaptive convergent methods (such as parameter profile matrix) evaluate precise, numerical data.
- Innovative convergent methods (such as affinity diagram) evaluate approximate, soft data.

Therefore, adaptive methods are appropriate when engineers have precise information to evaluate and innovative ones when the information is merely approximate.

It is simple to determine whether a method is divergent or convergent but the 'boundary' between innovative and adaptive characteristics is not. In practice methods have a certain degree of innovation-adaptation (I-A) characteristic. Table 2 presents the properties of highly innovative methods and highly adaptive methods. This chart can be used by engineers for the identification of the I-A characteristic of methods.

Table 2. Guidelines for the identification of the I-A characteristic of methods

INNOVATIVE METHODS | ADAPTIVE METHODS

DIVERGENT METHODS	
HIGHLY INNOVATIVE:	**HIGHLY ADAPTIVE:**
> Facilitate the detachement of the problem from the way it is customarily perceived	> Useful for further development of already known solutions
> Stimulate the generation of a large amount of ideas	> Develop further a single idea
> Tend to produce imprecise ideas of wide diversity	> Tend to produce concrete solutions within a focused solution space

CONVERGENT METHODS	
HIGHLY INNOVATIVE:	**HIGHLY ADAPTIVE:**
> Require approximate or soft information about concepts	> Require hard and precise information about concepts
> Evaluation of a large amount of diverse ideas	> Evaluation of a single concept
> Gather together information that helps to take a decision	> Give a numerical solution

4.1 The relevance of identifying the I-A characteristic of divergent methods

The identification of the I-A characteristic of divergent methods and the selection of the appropriate tool is necessary for two important reasons:

Firstly, because companies must have a careful management of their I-A strategy. Companies can't afford an adaptive or evolutionary behaviour for a too long time, nor can they continuously create revolutionary products. Importantly, the type of method used should be matched to the required adaptor-innovator characteristics of the product. If a product needs to be renewed the use of innovative methods in the initial stages will be favourable. If it is time for incremental extensions then adaptive methods are appropriate.

Secondly, the type of method used influences the uncertainty in the design process. Engineers must pay attention to this factor also since high uncertainty may entail a disproportionate lead time. Innovative divergent methods tend to produce large amounts of immature concepts that imply high level of uncertainty. They are not implicitly worse nor better than adaptive ideas, but they require more feasibility studies of compatibility within the system, of suppliers availability, of cost, of development cost, of manufacturability, of compatibility with other systems, etc. Adaptive divergent methods produce incremental extensions, what is a guarantee of low uncertainty level but which may mean a failure if clients needed a novel product and competitors took advantage of a company's lack of innovation.

Therefore, divergent methods must be classified (and selected) according to the I-A characteristic of the ideas they tend to generate. When choosing the methods to use it is important to balance its implicit uncertainty and the market needs.

The selection of divergent tools in industry can be quite arbitrary. Brainstorming and some of its variations are the used, although not always correctly. When innovative tools are used to solve problems that are adaptive in character, engineers can feel disappointed with the results obtained because they achieve 'unstructured outcomes' and consider the work spent to be a waste of time. Other times, innovative methods are used incorrectly, that is, with judgmental thinking, which destroys their fundamental principle and effectiveness.

Therefore the use of divergent techniques does not necessarily mean that there will be a high level of uncertainty in design because the most innovative ideas (i.e. those with more uncertainty) can be discarded. However if adaptive solutions (i.e. those with high degree of certainty) are required then an innovative solution generating method should not be used. Innovative methods must be chosen to renew and adaptive ones used to improve and keep a low level of uncertainty. That is what in this paper we call *appropriate* selection of methods.

4.2 The relevance of identifying the I-A characteristic of convergent methods

The identification of the I-A characteristic of convergent methods is also relevant. If an adaptive method is used to evaluate diverse sketchily known concepts, it will require an unnecessarily long time to be completed and the results may lead to inadequate decisions based on a false sense of certainty. This happens in industry very often when engineers try to rate with great degree of precision attributes of products that are subjective, soft or simply known vaguely.

A common example takes place with the use of the rating and weighting method. This tool is very useful when engineers have a certain degree of hard information. It requires the rating of different alternatives with respect diverse criteria and the prioritisation of the mentioned criteria. However in industry it is used even in early stages when the precise performance of all the alternatives is rarely known. Engineers spend long time in discussing the rating of vaguely known attributes. In these cases, the use of the Pugh method is more advisable because the only type of value judgements engineers must impose are of comparative nature: "A is better than B with respect criterion 1. A is equal to C with respect criterion 2, etc."

Likewise, if an adaptive method is required but instead an innovative one used, there will be a loss of accuracy in the results. But fortunately this does not take place frequently.

Therefore, convergent methods can be usefully classified depending on the level of precision in the information required for their use. It is important to match the precision of the available information with the I-A characteristic of convergent methods.

4.3 A classification of methods

The guidelines stated in figure 2 for the identification of the I-A characteristic of divergent methods may seem difficult to identify since they depend on the information produced after the use of methods. For example, the amount and diversity of ideas produced in divergent activities does not only depend on the method used, but also on the people that participate and the atmosphere in which they work [Rhodes 1961]. This means that a precise classification of divergent methods according to their I-A characteristic requires the systematic comparison of the outcomes of methods under similar

atmospheres and with people of similar cognitive styles. Studies are presently being carried out in this field at the Center for Studies in Creativity, Buffalo State College, New York.
However the guidelines allow also rough classifications that can be improved with time and experience in methods. For example, we can state with certain firmness that a morphological chart will produce a higher diversity of ideas than value engineering with the same team of people. The more experience engineers have with divergent methods, the more precisely and appropriately they can classify and select them, and the more effectively they can use their potentials.
In contrast, the guidelines for classifying the convergent methods seem more tangible since they refer to the information available about the solutions to evaluate and fit well engineering ways of thinking. Convergent methods, however, cannot be allocated in an exact position in the classification scale since they can be used with different degrees of detail. For instance hazard and operability is normally used post-design to help personnel understand what can go wrong with systems. But it can also be used in earlier stages in a more approximate way to analyse systems before functional units have been designed [Thompson 1999]. Therefore it is possible that different engineers classify a group of convergent methods with slightly different relative positions. This may happen because they use them with different degrees of precision in different stages of the design process. What is important in fact is to check before the method is used that the available information is enough precise for the minimum level of exactness of the information required by the method to operate meaningfully.
A classification of methods is proposed in table 1. Descriptions of most of the classified methods can be found in [Cross 2000], [Jones 1971], [Pahl&Beitz 1996], [Thompson 1999] and [Vehar et al 1999]. Five I-A characteristic groups have been created from the most innovative to the most adaptive. The proposed chart aims to show that a wide variety of methods can be roughly classified to increase their understanding and proper use. This classification can be refined the more experience in methods is gained. And even the number of I-A characteristic groups can be increased when the knowledge about methods I-A characteristic is more precise.

5. Influence of method usage on a company's design activity and products

In this section four theoretical models of company behaviour are defined according to the type of methods used to develop products. The descriptions of these models are not intended to fit wholly particular companies. They are presented to illustrate the influence of the characteristics of design methods on company design practices. The advantages and disadvantages of adopting the different strategies are discussed according to the next four main attributes:

- the uncertainty in the design process (the level of uncertainty of the solutions studied and the minimum time required to launch them),
- the type and level of risk assumed by the company,
- the implicit capacity to react to changing markets, and
- the resultant reliability and refinement of product performance.

Adaptive behaviour.

Adaptive behaviour is when a company uses predominantly adaptive methods (divergent and convergent) throughout the design process. This will give rise to incremental change by continuous product improvement. The design process is characterised by a low level of uncertainty. Such a design strategy will therefore produce highly reliable products, but cannot renew them and so there is a risk of competitive disadvantage in a rapidly changing market.

Innovative behaviour.

In this case, a company uses mainly innovative style methods throughout the design process. It can respond rapidly to changing market conditions but is unlikely to effect continual product improvement because the design team is in a continual state of flux. Insufficiency of refinement and reliability could lead to product failure in the market.
Therefore, the adaptive and innovative types of design strategy lack essential characteristics. Combined strategies are more appropriate for the development of products in companies since they have the potential to provide the sum of the advantages of both approaches: means to react to changing

markets and to develop reliable optimised products. Two kinds of combined strategies are presented next.

Innovative-adaptive top-down behaviour.

In this model, a company follows what may be considered to be a ‘standard’ behaviour by using innovative methods early in the design process and adaptive methods later in the process. In this way, opportunities for radical change are created by the innovative methods whilst the adaptive methods make for efficient convergent in the latter stages of design. This choice of design methods assumes certain risk, but has the potential to produce beneficial effects in the long term. The main disadvantage is the implicit uncertainty in the design process. The election of new promising solutions can lead to excessively long lead time in case of unexpected iterations in the design. In order to adopt this type of strategy it must be checked that the available time is long enough for the project successful conclusion.

Innovative-adaptive bottom-up behaviour.

The company uses adaptive methods to develop product projects mainly. But apart from these development work, there is a parallel research activity of novel solutions for which innovative methods are used. New solutions are not incorporated in the development phase until their feasibility and advantages with respect the old solutions are consistently proven with adaptive methodology. This bottom-up strategy seems convenient for well established industries, where the sophisticated product, developed and industrialised for many years, cannot be renewed as a whole in the early stages of every project. Instead of that, they are gradually renewed through the incorporation of the emergent new functions and technologies. Lower risk is assumed with this bottom-up strategy in the development phase than with the top-down approach and opportunities for radical change are still created in the research stage. However this strategy requires big effort in the early determination of future customer needs and proper allocation of resources in research projects. This strategy suffers the threats of high competition. Being the first company that investigates the possible implementation of future successful technologies plays for instance a very important role. The selection of the appropriate areas of research is therefore essential.

6. Management of change and uncertainty

A company that wishes to obtain certain product outcomes must look carefully at its choice of design method with respect to the timing of the use of the method and the needs of the market and business. The choice of method cannot be left to the preference of designers, since adaptors will tend to use adaptive methods and innovators will tend towards innovative methods. To create specific outcomes, appropriate methods must be chosen according to the available time and market needs. All kinds of methods from innovative to adaptive can be used by adaptors as well as innovators, but they need training in the effective use of such methods. It is responsibility of management to ensure that the appropriate training is given and the methods used.

The selection and use of methods can be seen as a way to manage the uncertainty in the design and the risks assumed by companies. The uncertainty level of upcoming products not only depends on the definition of the aimed product itself but also on how uncertainty is dealt with along the design process through the appropriate selection of methods and of the people who influence the design through the choice and use of methods. Results vary depending on the development team and the process followed. This paper provides some insight on how the uncertainty can be managed through the appropriate selection of methods. The uncertainty is here understood as the level of precision and maturity with what solutions are known by the company personnel in the different stages of design, and the minimum required time to reduce the degree of precision to an acceptable level. Handling the uncertainty in the design is important because of its straight relation with the type of risk assumed by the company as discussed in the previous section. We suggest that engineers must be prepared to deal with different levels of uncertainty in design through the comprehension and use of design methods appropriateness. Innovative methods are more suitable for dealing with uncertainty than are adaptive methods which rely on precise, defined data.

7. Conclusion

The contribution of the I-A characteristic theory resides in the recognition of the relevance that methods selection plays in their efficient management of uncertainty. Adaptive methods must be used to improve products and maintain a low level of uncertainty. Innovative methods must be used to generate radical change. A company whose engineers are trained in a wide assortment of methods is a company with high reaction capability to a broad variety of market needs. Any company should benefit from the understanding and use of innovative, adaptive and intermediate methods appropriately. With that aim a framework for the proper selection of methods has been proposed in this paper.

The work presented in this paper has also managerial implications that should be noted. The selection of methods must not only be seen as a bottom-up issue but also as a top-down. Traditionally engineers have decided what methods to use and what methods not to use on their own. Conversely, we suggest that management must adopt a pro-active attitude in this matter. It is important that the company encourages and provides means for the understanding of the potential of appropriate methods selection. Likewise, the product and its functions required I-A characteristic must be carefully studied as well as the moment at which the product must be launched. This information must importantly be supplied for discussion with development engineers who can supply the necessary knowledge to make this decision meaningful. Management must also study and define a long-term company methods strategy to deal with product development since success will not only depend on knowing the potential of methods, but also on how this knowledge is managed.

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