INTERNATIONAL DESIGN CONFERENCE - DESIGN 2006
Dubrovnik - Croatia, May 15 - 18, 2006.

DESIGN 2006

NOVELTY METRICS IN ENGINEERING DESIGN EXPERIMENTS

B. Lopez-Mesa and R. Vidal

Keywords: novelty, measures of creativity, KAI inventory

1. Background

Measuring novelty is important since it has been identified as one of the primary measures of creativity and innovation. As widely recognised, assessing creativity and innovation is useful for research, for team recruitment, etc. The key measures of creativity discussed in the literature are novelty, fluency, and how well intended functions satisfy desired specifications [Shah and Hernadez 2003].

In a design experiment [López-Mesa 2004], the problem-solving style of designers was measured using the widely researched psychometric test called the Kirton Adaption-Innovation (KAI) inventory, and the novelty of the outcomes of the design experiment applying some concepts inferred from the KAI theory. Surprisingly, there was no match between the expected results and the actual ones. A complementary new method is developed here with which there is a match. In this paper, the first and the second methods to measure the novelty of the outcomes are presented, and the implications of their match/no match with the psychometric test results are discussed.

2. Research method

The research method has the following steps:

- Review available literature on the psychometric test used, and on novelty measures in design.
- Analyse the research gap, i.e. the differences and similarities between the first method used to measure novelty, the psychometric test used, and the reviewed literature.
- Propose a complementary new method for measuring novelty.
- Test and verify the new method by comparing the expected results (a match between the results from the psychometric test and the results from the design outcomes measures) with the actual results.

3. Literature survey

3.1 Definitions of innovation, creativity, and novelty in design

Novelty has mainly been discussed as a component of innovation, creativity, and patentability:

- In the managemente literature, the innovation process has traditionally been considered to have three main phases named invention, innovation, and diffusion. The literature accepts the term innovation as comprising the development of technical solutions ranging from radical new to plain imitations, as far as they represent a major change for the company implementing them. Within this line of thought, Freeman [1982] defines innovation as 'the actual use of a nontrivial change in a process, product, or system that is novel to the institution developing the change'. Slaughter [1998] defines invention as 'a detailed design or model of a process or product that can clearly be distinguished as novel compared to existing arts'. Hence, invention involves newness (or novelty) and detailed development, but does not require implementation. Innovation involves nontrivial change implementation with its newness being referred only to the company implementing it, and not to the existing arts.

- When patent applications are reviewed, the criteria for being granted an invention are [Thomson Scientific 2005, scientific.thomson.com]:
    - Novelty: an invention must never have been made public in any way, anywhere, before the date on which the application for a patent is filed.
    - Non-obviousness: an invention must not be obvious to others with good knowledge and experience of the subject of the invention.
    - Usefulness: an invention must be capable of being made or used in some kind of industry.
- Creativity is generally regarded as the ability to develop novel and useful ideas. Novelty has been defined as a measure of how unusual or unexpected an idea is as compared to other ideas [Shah and Vargas-Hernandez 2003].

3.2 Measures of innovation, creativity, and novelty in design

Measures of creativity and innovation have mainly been realised in the psychology, management, and engineering fields:

- In the psychology field, the measures have focused on the people and the environment. Psychometric tests have been created, such as the Torrance Tests of Creative Thinking, as well as instruments for measuring how conducive to innovation and creativity organisational structures and work environments are, such as Ekvall's creative climate questionnaire.
- In management, the focus has been on types of innovation of new products or processes. A broadly accepted classification distinguishes between incremental innovation entailing small improvements, and radical innovation involving a paradigm shift [Marquis 1988]. The classification has been extended including three more categories between incremental and radical innovations. The five types of innovation suggested are incremental, modular, architectural, system, and radical innovations [Slaughter 1988]. A specific innovation falls into one of the categories depending on the magnitude of change associated with the innovation from a current state-of-the-art perspective and the effects it has on other components or systems.
- In the engineering field, metrics have been developed to measure the effectiveness of ideation by means of measuring some parameters of the outcomes of design experiments [Shah and Vargas-Hernandez 2003, Mulet and Vidal 2001]. Metrics to measure a product novelty and a product invention gain have also been developed using respectively relative weightages for various criteria [Chakrabarti and Khadilkar 2003] and differential contribution, which is the difference between system achieved and previous state-of-the-art projected value [Redelinghuys 2000].

  Shah and Vargas-Hernandez [2003] have proposed to measure novelty, variety, quality, and quantity to evaluate the effectiveness of idea-generation methods. 'Novelty is a measure of how unusual or unexpected an idea is as compared to other ideas. Not every new idea is novel since it may be considered usual or expected to some degree and this is only known after the idea is obtained and analysed' [Shah and Vargas-Hernandez 2003].

  Shah and Vargas-Hernandez [2003] suggest two approaches to measure novelty:
    - Defining before hand what is not novel (what is usual or expected), and comparing the obtained ideas with the reference
    - Collect all ideas generated by all participants, identify key attributes such as way of opening, way of storing, etc. Then find all the different ways in which each of those attributes is satisfied, and count the number of instances of each solution.

3.3 The KAI inventory

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]. Style of creativity is not equal to level. Kirton did not try to measure the level of creativity of people but rather their style of problem solving. He 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 adaptive and innovative problem solving approaches can have creative outcomes as far as they are unique and they add value. López-Mesa et al. [2002] discuss examples of creative adaptive and innovative designs. Kirton 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.

Kirton has developed a psychometric test, called the KAI inventory [KAI 2005, www.kaicentre.com], that quantifies the preferred problem solving style of people. The test diagnosis is based on a resulting number in the range [32-160]. The lower the number, the more adaptive an individual is; and the higher the number, the more innovative an individual is. 67% of people are approximately in the range [70-115]. Approximately is written here because the original source is graphical, and it is not precise. According to the studies of Kirton, the mean KAI score for teachers in UK, and US is 93-97; for engineers and military officers in US is 95-96; for managers generally and engineers generally in UK, US, Italy, Canada S'pore, and Slovakia is 96-97 [Kirton 2001]. López-Mesa [2004] discusses that adaptor/innovator principles can be mapped over onto problem characteristics and design methods.

4. Research gap

4.1 The design experiment

The objective of the design experiment was to study the effects different idea-finding methods have on the design process and the outcomes of four design teams, and to compare these effects to those produced by the problem-solving characteristic of the team members.

The participants were Engineering Design PhD students or doctors, most of them with experience in designing. The task was to generate ideas for a tubular map case allowing for one-by-one removal and insertion of maps. The KAI inventory was used to identify the problem solving style of each individual from a group of 17 potential participants. The result was used to form two similar innovative teams of three designers and two similar adaptive teams of three designers (table 1).

A hypotetically adaptive idea-finding method (Visual stimuli) and a hypotetically innovative one (SCAMPER) were selected for the study. One adaptive team and one innovative team used the hypotetically innovative method to solve the design problem. The other adaptive team and the other innovative team used the hypotetically adaptive method (table 1).

To measure the influence of the problem-solving characteristic of the team members and of the methods, the experiment analysis consisted of outcome-based measures, and protocol analysis. The latter was done by means of the analytical method of design as reflective practice to study the way the design activity unfolded for the four teams.

To be able to make an outcome-based evaluation, the solutions generated by each team were identified and classified using the concepts of Action Function [Deng 2002], Structure and Detail. Action functions are related to physical principles. For example, for the purpose function 'allow for one-by-one extraction of the maps', action functions are 'devices to secure the diameter of concentrically rolled up maps', and 'divisions inside the case for individual rolls storage'. The structure represents the way the function action is transformed in material form. Two levels of definition of this material form are considered, conceptual structure and detail structure.

Table 1. Teams' arrangement in the experiment

Team name	Group problem solving style	KAI score of group members (Posible scores: 32-160)	Stimulus
2444	Adaptive	79, 79, 96	Images
2422	Innovative	106, 117, 122	Images
2418	Innovative	112, 116, 123	SCAMPER questions
2443	Adaptive	76, 82, 95	SCAMPER questions

The alternative solutions produced by a team with a similar Action function belong to the same global solution, to which a number was assigned. The different alternatives within the same global solution of a team are then distinguished by a letter following the number. Different alternatives within the same global solution of a team can be different at the levels of conceptual structure or detail structure.
The criteria considered for the outcome-based evaluation were:

- **Quantity,** which was measured by considering the number of alternative solutions
- **Variety**, which was measured by considering the number of alternative solutions at action function, conceptual structure, and detail structure levels.
- **Novelty**, discussed in this paper.
- Quality was also considered for measurement. The quality of a solution developed at a conceptual level is to a large extent related to its feasibility. **Feasibility** is, however, an uncertain measure at early stages. In the search for objectivity of this measure, two parameters that may not give an exact measure of feasibility were chosen, though they have a potential to be positively correlated to it: refinement level measured in time dedicated to a solution and number of reflections (using reflection in Schön's terms).

4.2 Novelty metrics I: measuring newness with respect to current paradigm

As novelty started to be analysed, it became clear that it is a relative term: there is for example newness with respect to the current paradigm and newness with respect to what others are able to produce given a problem (or non-obviousness). The relativity of novelty has also been by pointed out by other authors [Chakrabarti and Khadilkar 2003]. Since in Kirton's definition of innovators, doing things differently is a key aspect, it was decided to measure the outcomes newness with respect to the current paradigm, assigning to each design alternative produced a change type of the following four change type patterns:

- Type 1: New parts are added to the tubular case to change its characteristics.
- Type 2: The tubular case is changed so much that it is not a tubular case any more.
- Type 3: The change involves changes even in the characteristics of the paper.
- Type 4: The whole system changes.

Then, the number of alternatives falling in the different change types is counted for each team. The results obtained are presented in table 2. To be able to compare the results between the different teams, the relative number of alternatives for each type of change is calculated with respect to the total number of alternatives produced by each team.
The change types 4 and 3 are more revolutionary than 2 and 1. Therefore, the higher the percentage of change types 4 and 3, the higher the novelty of the team behaviour.

4.3 Differences between the expected results and the actual results

The expected possible patterns were:

- Since innovative individuals, according to the KAI inventory, prefer to solve the problems by doing things differently, it was expected that the two innovative teams would produce more solutions of type 4 and 3 than the adaptive teams.

- Another expected possible pattern was that the influence of the methods was so important that two teams (one innovative and one adaptive) using the same method (presumably SCAMPER) would produce more novel solutions (of type 3 or 4) than the others.

Surprisingly, none of these possibilities was found. In fact, as shown in table 2, no trend could be drawn on the influence of people's problem solving style or type of method on the novelty of solutions. The teams with a higher novelty behaviour (highlighted grey) are one innovative team and one adaptive team using different methods.

Table 2. Types of change of alternative solutions

Team	Team style	Method style	Measure	No. of alternatives	Change type 1	Change type 2	Change type 3	Change type 4
2444	A	Visual stimuli	Absolute	30	23	5	1	1
			Relative	1.00	0.77	0.17	0.03	0.03
2422	I	Visual stimuli	Absolute	16	13	3	0	0
			Relative	1.00	0.81	0.19	0.00	0.00
2418	I	SCAMPER	Absolute	10	4	2	3	1
			Relative	1.00	0.40	0.20	0.30	0.10
2443	A	SCAMPER	Absolute	10	8	2	0	0
			Relative	1.00	0.80	0.20	0.00	0.00
Total			Absolute	66	48	12	4	2
			Relative	1.00	0.73	0.18	0.06	0.03

5. Proposal of novelty metrics II: measuring non-obviousness

A second method to measure the novelty of the team behaviour is proposed here. This one takes into consideration the non-obviousness of solutions. Obvious solutions in this experiment are those that, even if being far from the current paradigm, were produced by all teams. Non-obvious solutions are solutions which few teams thought about. Therefore, the lower the number of teams that produce a solution, the higher the level of non-obviousness of this solution is. Solutions can have four levels of non-obviousness in this experiment: solutions produced by just one team, solutions produced by two teams, solutions produced by three teams, and solutions produced by the four teams. The objective of the new method proposed is to measure the percentage of solutions in a team for the different non-obviousness levels. It was observed in the analysis of non-obviousness of solutions of the four teams that no solution of a team was equal to any of the solutions of the other teams in all respects. Therefore, what was analysed was similarity and not equality. The novelty of solutions was explored, by identifying the similiraties of every alternative solution of a team with every alternative solution of the other teams at the levels of action Function (F), conceptual Structure (S), and Detail strucutre (D). Once all similarities were found, given a solution Xy, where 'X' is given the form of a number representing the global solution, and 'y' is given the form of a letter used to differentiate between different alternatives of that global solution, the total number of teams having this solution or a similar one at F level was calculated with the following expression:

$$N_{F,Xy} = n_{F,Xy} + 1 \qquad (1)$$

Where $n_{F,Xy}$ is the number of teams with a similar solution to Xy at F level, ranging from 1 to 3. Similar calculations were performed for the S and D levels:

$$N_{S,Xy} = n_{S,Xy} + 1\,;\; N_{D,Xy} = n_{S,Xy} + 1 \qquad (2; 3)$$

Given a specific team, for example team 2418, the following definitions are given:

- $f_{2418,1}$ is the number of Xy solutions for which $N_{F,Xy} = 1$.

- $s_{2418,1}$ is the number of Xy solutions for which $N_{S,Xy} = 1$.
- $d_{2418,1}$ is the number of Xy solutions for which $N_{D,Xy} = 1$.
- $f_{2418,2}$ is the number of Xy solutions for which $N_{F,Xy} = 2$.
- $s_{2418,2}$ is the number of Xy solutions for which $N_{S,Xy} = 2$.
- $d_{2418,2}$ is the number of Xy solutions for which $N_{D,Xy} = 2$.
- $f_{2418,3}$ is the number of Xy solutions for which $N_{F,Xy} = 3$.
- $s_{2418,3}$ is the number of Xy solutions for which $N_{S,Xy} = 3$.
- $d_{2418,3}$ is the number of Xy solutions for which $N_{D,Xy} = 3$.
- $f_{2418,4}$ is the number of Xy solutions for which $N_{F,Xy} = 4$.
- $s_{2418,4}$ is the number of Xy solutions for which $N_{S,Xy} = 4$.
- $d_{2418,4}$ is the number of Xy solutions for which $N_{D,Xy} = 4$.

The percentage of solutions of a team, for example team 2418, which have only been produced by this team at F level is:

$$F_{2418,1}(\%) = \frac{f_{2418,1}}{f_{2418,1} + s_{2418,1} + d_{2418,1}} \cdot 100 \tag{4}$$

The percentage of solutions of a team produced by one or two teams at F level is:

$$F_{2418,1+2}(\%) = \left(\frac{f_{2418,2}}{f_{2418,2} + s_{2418,2} + d_{2418,2}} \right) \cdot 100 + F_{2418,1}(\%) \tag{5}$$

The percentage of solutions of a team produced by one, two, or three teams at F level is:

$$F_{2418,1+2+3}(\%) = \left(\frac{f_{2418,3}}{f_{2418,3} + s_{2418,3} + d_{2418,3}} \right) \cdot 100 + F_{2418,1+2}(\%) \tag{6}$$

The percentage of solutions of a team produced by one, two, three, or four teams at F level is:

$$F_{2418,1+2+3+4}(\%) = \left(\frac{f_{2418,4}}{f_{2418,4} + s_{2418,4} + d_{2418,4}} \right) \cdot 100 + F_{2418,1+2+3}(\%) \tag{7}$$

These percentages and the corresponding ones for the S level can be graphically represented as in figures 1 and 2 for the four teams. A mean behaviour line can be used to divide the space in a 'novelty above the mean behaviour' area and a 'novelty below the mean behaviour'area, relative to the participating teams. The upper the deviation is above the mean behaviour line, the higher the novelty is. The lower the deviation is below the mean behaviour line, the lower the novelty is. The expected behaviour is that innovative teams produce more non-obvious solutions.

6. Discussion of results from novelty metrics II

The influence of the problem solving style of the teams can be observed regarding non-obviousness at F level (figure 1). Innovative teams produce a higher percentage of non-obvious solutions than adaptive teams. According to results, the teams behaviour is ordered from the highest level of non-obviousnes (highest novelty) at F level to the lowest level as follows:

1. 2418: innovative team using SCAMPER
2. 2422: innovative team using visual stimuli
3. 2443: adaptive team using SCAMPER
4. 2444: adaptive team using visual stimuli

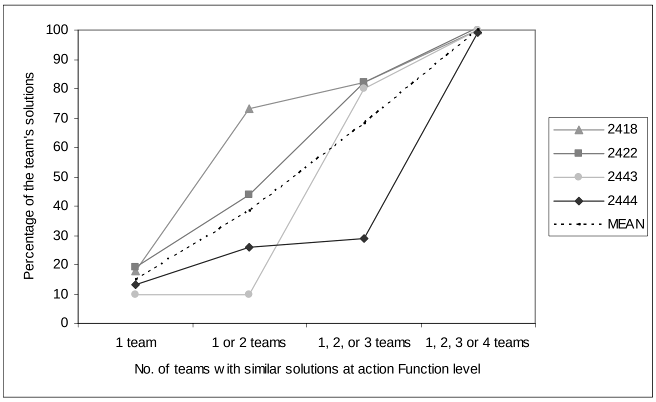

Figure 1. Analysis of solutions at F level

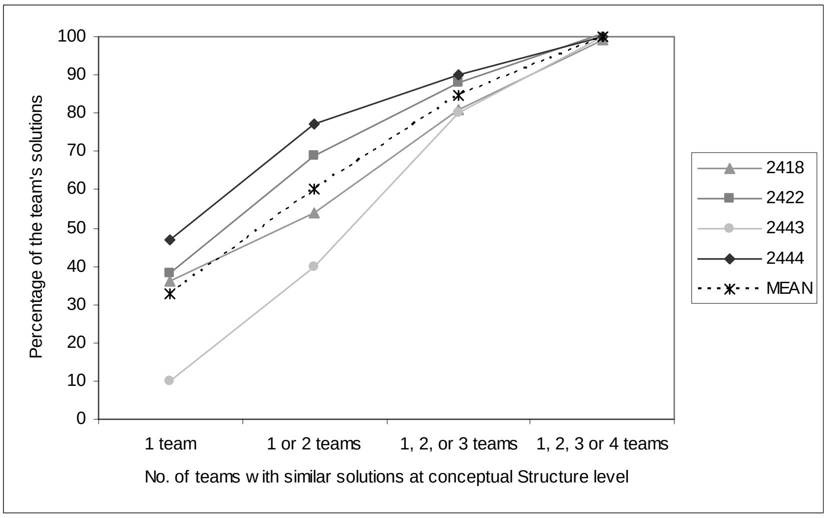

Figure 2. Analysis of solutions at S level

At the conceptual structure level, the influence of the problem solving style is not observed, but the influence of the method is observable (figure 2): the level of non-obviousness is higher for teams using visual stimuli. According to results, the teams behaviour is ordered from the highest level of non-obviousnes (highest novelty) at S level to the lowest level as follows:

1. 2444: adaptive team using visual stimuli
2. 2422: innovative team using visual stimuli
3. 2418: innovative team using SCAMPER
4. 2443: adaptive team using SCAMPER

The novelty metrics proposed here have been tested in just one experiment with four teams. For a more reliable testing, the number of cases should be increased.

7. Conclusions

The KAI inventory is a broadly researched tool to measure the adaptive-innovative problem solving style of individuals. One of the key components that distinguish adaptors from innovators is their tendency to produce a narrower number of novel ideas.

Two complementary novelty measures are defined in this paper: newness with respect to current paradigm and non-obviousness. The experiment shows that for the experiment conditions:

- The difference between innovative and adaptive teams, regarding novelty of the design solutions they produce to solve a problem, is not on the change type of the solutions produced during the ideation process, but on the degree of non-obviousness of the solutions at the action function level. Innovative teams tend to produce a higher percentage of non-obvious solutions at the action function level than adaptive teams.
- At the conceptual structure level, the method used is proven to be more influential than the problem-solving style of the teams regarding non-obviousness of solutions.

The concept of non-obviousness has traditionally been related to innovation measures and patenting. In this paper, it has been proven to be a key measure when evaluating creativity style of individuals.

Acknowledgement

We acknowledge the assistance of Graham Thompson, Elena Mulet, M. José Bellés, Sara Romero, and Raquel Oliver, who contributed to make the experiment possible, and the participation all the designers in the experiment. Gratefully acknowledged financial support has been provided by the Spanish Ministry of Science and Technology, project DPI 2002-04357-C03.

References

Chakrabarti, A., Khadilkar, P., "A measure for assessing product novelty", CD-rom Proceedings of the International Conference on Engineering Design ICED03, Stockholm, August 19-21, 2003.

Deng, Y.-M.; "Function and behaviour representation in conceptual mechanical design", Artificial Intelligence Design, Analysis and Manufacturing 16, 2002, pp. 343-362.

Freeman, C., "The Economics of Industrial Innovation", Harmondsworth: Penguin, 1982.

Kirton, M.J., "Adaptors and innovators. Styles of creativity and problem solving", London: Routledge, 1994.

Kirton, M.J.,"Kirton Adaption-Innovation Inventory. Feedback Booklet", 1985, 1992, 1999.

López-Mesa, B., Thompson, G., Williander, M., "Managing uncertainty in the design and development process by appropriate methods selection. Proceedings of the 7th International Design Conference - DESIGN 2002, Dubrovnik, 2002, pp. 829-836.

López-Mesa, B, "The use and suitability of design methods in practice. Considerations of problem-solving characteristics and the context of design", doctoral thesis, Lulea University of Technology, Sweden, 2004.

Marquis, D. G., "Anatomy of successful innovations", Readings in the Management of Innovation, Tushman M. L., Moore, W. L. (ed.), Ballinger Publishing Co., Boston,, 1998, pp. 79-87.

Mulet, E., Vidal, R., "Classification and effectiveness of different creative methods in design problems", Proceedings of ICED01, Glasgow, 2001, pp. 363-370.

Redelinghuys, C., "Proposed criteria for the detection of invention in engineering design", Journal of Engineering Design, 2000, Vol. 11, No. 3, pp. 265-282.

Slaughter, E.S.,"Models for construction innovation", Journal of Construction Engineering and Management, 124 (3), 1998, pp. 226-231.

Shah, J.J., Vargas-Hernandez, N., "Metrics for measuring ideation effectiveness", Design Studies Vol 24 No.2 March 2003, pp. 111-134.

Dr. Belinda López-Mesa, Assistant Professor
Universitat Jaume I, Department of Mechanical Engineering and Construction
Av. Sos Baynat s/n, ESTCE, 12071, Castellón, Spain
Tel.: +34 964 72 8114 / 9252
Fax.: +34 964 72 81 06,
Email: blopez@emc.uji.es, www.gid.uji.es