INTERNATIONAL DESIGN CONFERENCE - DESIGN 2004
Dubrovnik, May 18 - 21, 2004.

DESIGN 2004

THE DECOMPOSITION AND LINKAGE OF DESIGN METHODS AND PROBLEMS

B. López-Mesa, S. Eriksson and G. Thompson

Keywords: design methods, decomposition of methods, linkage of methods and problems, design practice

1. Introduction

Companies generally feel insecure about the efficiency of their intuitive design procedures, especially in the early design stages where the level of uncertainty and consequences of decisions are high. The numerous design methods generated by academia in recent decades (Pahl & Beitz, Jones, Pugh, etc.) have the potential to ensure efficiency in design; however, they have not had the expected impact on industry [Eder 1998, López-Mesa 2003].

Design methods are systematic techniques composed of several steps. Each step is carried out using a sub-method (or elementary method [Pulm and Lindemann 2002]). Different design methods can be used for the same type of problem. For example, when engineers need to select between alternative solutions a number of different methods can be used, such as the Pugh method, Rating & Weighting method, Advantages-Limitations-Uniqueness-Overcome limitations (ALUO), and others. The selection of the most appropriate method depends on the problem conditions [López-Mesa 2003]. Correspondingly, the different steps of a design method can be carried out using different sub-methods. For example, to calculate the weight of criteria in the Rating & Weighting method, different sub-methods, such as Paired Comparison Analysis, Analytical Hierarchy Process (AHP), and others may be used.

Previous studies concerning why design methods have not had the expected impact on industry point out that systematic design methods do not appear to apply to real design activities and are liable to be misused [López-Mesa 2003]. The research presented in this paper is based on two premises:

- Methods are not generally valid; they are useful for specific situations [Bouyssou et al. 2000, López-Mesa 2003, Pulm and Lindemann 2002].
- For engineers to use methods properly they need to know when the methods are valid and useful [Bouyssou et al. 2000, López-Mesa 2003].

If a number of methods or sub-methods can be used for the same type of problem, then knowing when each method is useful is necessary. The concept of design rule must be introduced. A design rule connects a design method or sub-method (HOW and WHAT FOR) with usability or validity conditions (WHEN). An example of a design rule is:

- WHAT FOR: to select a solution from a number of alternatives.
- WHEN: when detailed information about the solutions is not available.
- HOW: the solutions can be compared with each other in terms of better, worse, and equal (Pugh method)

One objective of this paper is to show the need to define methods comprising of sub-methods and to link them to problem/sub-problem conditions. Additionally, the paper aims to identify the fundamental characteristics of problem conditions that can be linked to design methods or sub-methods in the formulating of design rules. The conditions that make a specific method useful represent its validity or usability space. The fundamental characteristics of problem conditions can be used as guidelines to define the validity conditions of methods and, thus, increase the chance of successful selection and use of methods [Isaksen et al. 1994, Fox & Fox 2000, López-Mesa 2003].

2. Contribution of the paper

The literature maintains that academic methods have not had the expected impact in industry [Eder 1998, López-Mesa 2003], though intuitive structured procedures may still be used to solve problems. The completeness and reliability of methods originating from industry is questionable, however they are naturally adapted to the problem to be solved. This research aims to understand the procedures of design practitioners to develop technical solutions and the way they are linked to the problems. This understanding can be helpful in the development, improvement, and adaptation [Lindemann 2002] of academic methods. The specific questions to answer are:

- How are solutions developed? What procedures (labelled or not as methods) are used in industry?
- Do they differ from academic design methods? Are they similar? How do they differ?
- What are the fundamental conditions of problems that influence the adoption of different methods/sub-methods to solve industrial problems?

2.1 State-of-the-art in validity conditions of methods

Here, existing models or studies that contribute to the identification of validity conditions are named, even if it was not the primary purpose of those models or studies:

- The notion of Innovative-Adaptive characteristic of methods [López-Mesa 2003] links method selection to the innovative-adaptive characteristic of the problem.
- The method selection tree [López-Mesa 2003] suggests a graphical way to represent validity conditions of methods and handles the selection between different sub-methods.
- The Process-oriented Method Model (PoMM) [Birkhofer et al. 2001] deploys all the elements of a method ensuring its complete description, which can be used as criteria for the selection of methods.
- Most classification of methods, e.g. [Mulet & Vidal 2001], provide hints on when the methods within each group can be used.
- The theories of an individual's problem solving style, e.g. [Kirton 1994], explain the influence that participants have on the selection of methods.

The study presented in this paper complements these models or studies by looking at the subject of method selection from the industrial problem perspective.

3. Method

The study was conducted through interviews with 10 experienced engineers of Volvo Car Corporation (VCC) in December 2003. The questions were semi-structured and aimed to indentify procedures (labelled or not as methods) used in the development of nine successful technical solutions. The circumstances in which those procedures proved useful were also explored.

Each interviewee talked about one solution he had participated in, except for one interviewee who talked about two solutions. The interviews had a mean duration of 1,5 hours. Every solution was discussed by one engineer, except for two solutions that were discussed by two engineers.

The interviewees worked as project managers or development designers of the projects where the solutions were developed. Their problem-solving style was measured with the KAI instrument to find any possible relation between their style and how the challenge and development procedure were perceived; here, no relationship was found.

The use of theories was avoided to the possible extent to facilitate the finding of potential new problem conditions. The interviews focused on the challenge they had to solve, degree of novelty, motivation, participants, and the means and procedure to develop the solution. To understand the whole procedure, the questions went from general to very specific until the level of precision was so high that specialised technical knowledge would be required to understand the answers. Documentation was provided in certain cases.

3.1 Selection of projects

Most solutions were developed in the framework of so called Advanced Engineering (AE) projects within VCC, i.e. new solutions for car systems. The projects explored in this study were developed at the Power Train or Chassis departments and were initiated during 1993-2003.
Two engineers from VCC provided a list of potential solutions that could be explored. One of the two engineers is co-author of this paper. The criteria for selecting solutions were that they were already in production or close to it and that they were novel solutions. Solutions close to production were requested because its feasibility must have already been proven and it must have been "sold" to a car project as the best solution available for that car programme [see López-Mesa 2003]. Before the interviews, the interviewees were contacted through e-mail and a short introduction was organised to prepare them for the reflection activity that the interviews were going to require of them. Two solutions were discarded after the interviews for not fulfilling one of the initial criteria.

3.2 Analysis of interviews

The interviews were typewritten. The unit of analysis is the technical solutions. The procedures/methods used to develop each solution were mapped and linked to the problem conditions of that solution. Some of those links were explicitly indicated by the interviewees, while others were found by their logical connection. For each described method/sub-method that originated from industry, the analogous academic method/sub-method was searched.
Two lists of fundamental conditions of problems were separately created, one by the industrial author of the paper, the other after the analysis of the mapped links between problem conditions and methods used. The two lists were compared, discussed, and merged into one.

4. Results: procedures to develop industrial system solutions

Table 1 reflects the interview results. Each row of the table captures one technical solution. The information of each solution has been organised under three headings:

- Challenge description: the type of technical challenge and degree of novelty of the solution are described.
- Influencing factors: aspects of the development process, mainly related to the existing resources, as indicated by the interviewees are described.
- Process overview: the main steps for the development of the solution are described, as well as the methods or procedures for realising the different steps and some details about the sub-methods.

In the left column of the table, where the specific problem conditions for the projects are stated, each item has been assigned a code. In the right column of the table, listing the procedures to solve the problems, the relationship between the procedural approach and the problem condition is represented in parenthesis by the code of the problem condition that has influenced the adoption of that specific procedural approach. For example, in project 1, the project was started by exploring what in the market was ready to be implemented because of problem condition 1C1, which explains that the legal demands were going to become more stringent.
In the right column some methods and sub-methods used in the projects are presented. When no analogous academic method was found the method appears in *italics*. Since the number of methods developed in research centres is high, it cannot be claimed that analogous methods have never been

developed by academics, but that they are not included in broadly known methods reference books like Pahl & Beitz, Pugh, Jones, etc.

Table 1. 7 projects of technical solution development in industry

PROBLEM CONDITIONS	PROCEDURAL APPROACHES
Challenge description - Project 1 **[1C1]** Development of a new solution for a function so that an undesired product characteristic is reduced. The legal demands for that characteristic will become more stringent. **[1C2]** The project was an improvement of an existing solution, but also an enabler for a future technology. **[1C3]** A car manufacturer had already done this. Management wanted a similar technology. **Influencing factors - Project 1** **[1F1]**. The team began the project before another group could do it. The rush meant that the solution was not questioned. **[1F2]** From very early on in the project, management thought that this solution should be implemented even if they really did not know so much about it. **[1F3]** The car project started at the same time. **[1F4]** Involvement & enthusiasm from designers	**Steps - Project 1** - What is readily available in the market to be included? (1C1) A similar solution to an existing technology was taken (1C3) - Can this fit in the engine? What are the consequences? (1F2) - Division of the project into different items. The focus was on how to make the best out of the solution (1C1, 1F3). - All was merged into a concept. Different alternatives were tested and evaluated. Method: A structured matrix-based method was used for the final evaluation of the best alternative incorporating the results from the tests. Sub-method***:*** *For the final selection in the matrix-based evaluation the leading factor was the property that had to be reduced . If the solution reached a certain performance with respect to the criterion, the rest of the performance criteria were compared* (1C1).
Challenge description - Project 2 **[2C1]** Development of a solution that performs well over time. **[2C2]** It is built on a previous VCC solution. **[2C3]** The motivation for this project is the need to fulfil increasingly tough legal requirements. **Influencing factors - Project 2** **[2F1]** Involved 2 task leaders and 10 development engineers. **[2F2]** The time available was sufficient to select the best concept with certain confidence at the end of the project.	**Steps - Project 2** - Tasks, deliverables, and budget were defined (2C2). The work was divided into two main parts managed by the two task leaders (2C3). - Most ideas originated from discussions with suppliers (2C3). Others came from within the organisation (2C2). - Milestone for the main technology selection. Method: 60 technical criteria used as guidelines organised in 6 groups. Submethod: *The discarding process in the main technology selection was not always systematic. Even if you see a potentially good solution, a lack of resources occasionally means having to leave it out* (2C3). - Combination of the main technology with other technologies or features, testing and final selection. Method: Matrix-based Pugh-type, six solutions were compared regarding a reference concept. Submethod: *the concepts did not have to exceed a certain performance concerning the leading parameter. What they did is to check how that level affected the other parameters* (2C3). Submethod:. They had up to 28 criteria. *There were up to three levels of worse and three of better. They also had a column with comments, references, and the person responsible for the different criteria*.

PROBLEM CONDITIONS	PROCEDURAL APPROACHES
Challenge description - Project 3 **[3C1]** Development of a highly accurate technical system that adapts to ANY driving conditions. **[3C2]** How to use the kind of technology developed is new in this field and the ideas behind it are unique. **[3C3]** At the hardware level, VCC is no longer unique, though they are still in the way of handling performance parameters and the integration of the software part into the car. **Influencing factors - Project 3** **[3F1]** The human resources were slightly lacking, with only two people working part-time. The time was sufficient. **[3F2]** This was the first work of the interviewee at VCC. The idea had been suggested 10 years earlier and numerous studies had been done during this time.	**Steps - Project 3** - Much involved looking at previous work done in this area and evaluating the different philosophies (3F2). - "What can be reused? (3F2) What has to be added? What has to be done to get the driving conditions of the car accurately?" was the approach to generate many alternatives (3F1) - The different philosophies were evaluated (3C1-2). Method: How the property levels could be estimated or calculated was studied to evaluate the different philosophies. Property level engineers, suppliers, and tests were used to calculate or estimate the performances. Submethod: The evaluation was made on estimated or calculated property levels vs. cost level. *The final evaluation did not result in one solution selection, but in a spectrum of solutions with recommendations/guidelines*.
Challenge description - Project 4 **[4C1]** Development of a very compact, technical solution with a new feature that has to be combined with another system, greatly limiting the available space. **[4C2]** VCC incorporated the new feature relatively late, but is leading the market in compact design and the combination of the two systems. **[4C3]** It was an enabler for the future **Influencing factors - Project 4** **[4F1]** No steering from upper management in the concept phase. **[4F2]** Two very creative designers and a project leader. One of them with long experience in the innovative side of solution development and high synthesis capacity. **[4F3]** Many people from other departments giving feedback. **[4F4]** Very long AE project because it was not sold to an industrialisation project until after a few years. The technical solution was good, but expensive and they had to wait several years until they could do a business case out of it.	**Steps - Project 4** - Early concept layout design. The two creative designers produced around 15 different solutions drawn in 2D (4F2). The ideas came from following the technology very closely when visiting seminars, exhibitions, suppliers, reading magazines, etc. Daily discussions on the drawing board (4C3, 4F1, 4F4). - Initial evaluation to select the most promising solutions (4F3). At the end of this evaluation, four alternative solutions were left. Method: *The main criteria were defined. Every concept was discussed concerning each criterion. If it did not fulfil one of the important criteria, it was inmediately discarded. Cost was estimated for each concept. The same was done with for new ideas.* - The four remaining solutions were deeply analysed (4F4). Structured evaluation of the four alternatives. Method: Matrix-based evaluation Submethod: A requirement specification was done. The criteria were scored and weighted. *For scoring the criteria, all eight or nine members of a team of were given a score that they had to split up among the different criteria.*

PROBLEM CONDITIONS	PROCEDURAL APPROACHES
Challenge description - Project 5 **[5C1]** Development of a technical solution with high demands on crash safety because it should provide small cars with as much safety as the larger models have. **[5C2]** It is a big step in performance, implying a change of material. **[6C3]** It required big effort to make it cost-effective. **Influencing factors - Project 5** **[5F1]** Before the project was initiated, a project with Luleå University of Technology (LTU) had been conducted, proving that the target requirement was reachable. One of the 30 students from LTU would become leader of the project 2 years later. Afterwards, six or seven different master theses were also used to improve the results of the students' project. **[5F2]** The AE project had a design engineer and a project leader. **[5F3]** When Volvo was purchased, cost became more important, and the numbers of targeted cars and participants increased.	**Steps - Project 5** - For the project involving the university, VCC specified the requirements. The students brainstormed many of the ideas and VCC selected the best ones. In the master thesis phase, the project was divided into six or seven parts for the further improvement of different solution parameters. - When the AE project started, the students' solution was presented to the suppliers. They were unable to produce it at a low price. Therefore a design competition between suppliers was organised. Method: *A standard procedure was used to select the supplier and his suggested technical solution design, combining solution-related and company-related criteria. If the supplier satisfies the company-related criteria, the technical solutions are compared.* For the technical criteria, a weighting and rating technique was used. Submethod: A *scoring system is used to check the company-related criteria. The company is validated from a certain total score*. - When VCC was bought the supplier selection was delayed 1 year.
Challenge description - Project 6 **[6C1]** Development of a software integrating several systems to avoid conflicts and create new features that can be found by synergies between integrated systems. **[6C2]** More like a major advancement than a natural continuation of the old philosophy. **[6C3]** When the project began, it was something new in the market. Today, there are several solutions. VCC's solution continues to be unique in the way the systems are integrated. **Influencing factors - Project 6** **[6F1]** Strategy managers from different departments analysed the future situation of the systems that were later integrated in the solution and understood that something had to be done. They created a group of three people to investigate the future. **[6F2]** Group of three participants with different knowledge domains and long experience in general positions. **[6F3]** No time pressure. **[6F3]** The "future group", as it was called, found the task very stimulating.	**Steps - Project 6** - A study from the strategy group about the future was used as an initial input for this project (6C2, 6C3, 6F1). This study was improved and made more complete (6F3). The idea of the integration system came fairly quickly. It should sort out the problem of the systems' increasing complexity. - Structures for the integrating system were brainstormed (6C2). - The problems of standardisation and flexibility were explored. The integrating system was becoming more and more refined. Method: *different standardisation possibilities were discussed relating to standardisation and flexibility parameters*. - Simulations in pen & paper were continuously done. Also, an experiment was designed and commissioned to technical development. The design of the experiment required much mathematics. - The outputs of this project were the definition of the levels of integration, the study of how to mirror the integration in the organisation, a new AE project for standardisation, the possibility of new features from synergies between the integrated systems, and the need for a new group in the company to deal with this integrating issues (6C3).

PROBLEM CONDITIONS	PROCEDURAL APPROACHES
Challenge description - Project 7 **[7C1]** Development of a complex method to monitor a performance parameter with higher precision than the existing solution without increasing the number of sensors. **[7C2]** A simpler system already existed in the market; this was new for VCC. They wanted something better. **Influencing factors - Project 7** **[7F1]** Team of two or three people with general knowledge of system demands and legislation. **[7F2]** Two innovative experts on detail design. **[7F3]** Enough manpower and time. **[7F4]** Available information about the existing system in the market.	**Steps - Project 7** - The general knowledge team created the demands for the system (7F1). - The general knowledge team and one expert listed 13 different methods (7C2, 7F3), one of them adapted from a solution in the market (7F4). Method: Weak points of the existing solution were explored. - The experts developed a new method and explored the feasibility of the whole system (7F2). - All methods were evaluated by the general knowledge team with help from consultants (7F1, 7C2). Method: The evaluation was carried out in a matrix-based method. - They further developed the methods in parallel (7C1).

Engineers tend to describe their development processes as disorganised. However, after mapping these seven cases, we observe a certain level of structure, possibly because in this study successful solutions were chosen or that the chaotic sensation engineers experience is due to the difficulty to plan from the beginning of a project process and fulfil it. What is certain is that since in each case the number of factors that can affect the development of a project is so high, surprises arise and plans have to be redone. The following characteristics have been observed in all these projects:

- Every project is unique in the way it is solved
- Every problem is unique in the way the challenge is manifested
- But there are features in the solving approaches and the problems that are similar

The same can be observed at a more detailed level, e.g. a task level like evaluating alternatives. Every task represents a different challenge, every method is deployed in a unique manner, but there are common characteristics between the various tasks and methods.

5. Differences and similarities between academic methods and methods originating in industry

If the methods originated in industry are compared to academic methods, we can observe that at a high level, they are very similar. For example, all the project teams that participated in these seven projects had a natural tendency for multi-objective evaluations as academic methods propose. However, the more closely a method used in industry is observed, the more differences between those methods and those from academia can be appreciated. Note that most of the methods in italics in Table 1 (methods with no analogue in academia) are at the sub-method level.

Academic methods are researched and therefore, tend to be more reliable than methods originating in industry, but they do not appear to adapt to all design situations [López-Mesa 2003], thereby diminishing their potential extended use. To provide flexibility to academic methods the number of sub-methods with which they can be realised can be increased to augment the validity space of that method (Figure 1). Some methods share sub-methods and the whole range of existing methods could therefore be described as a network of sub-methods (Figure 1).

To increase the validity space of a method it is useful to explore what are the fundamental characteristics of problem conditions affecting the usability conditions of methods and sub-methods. Those fundamental characteristics are explored in this paper and presented in the next section.

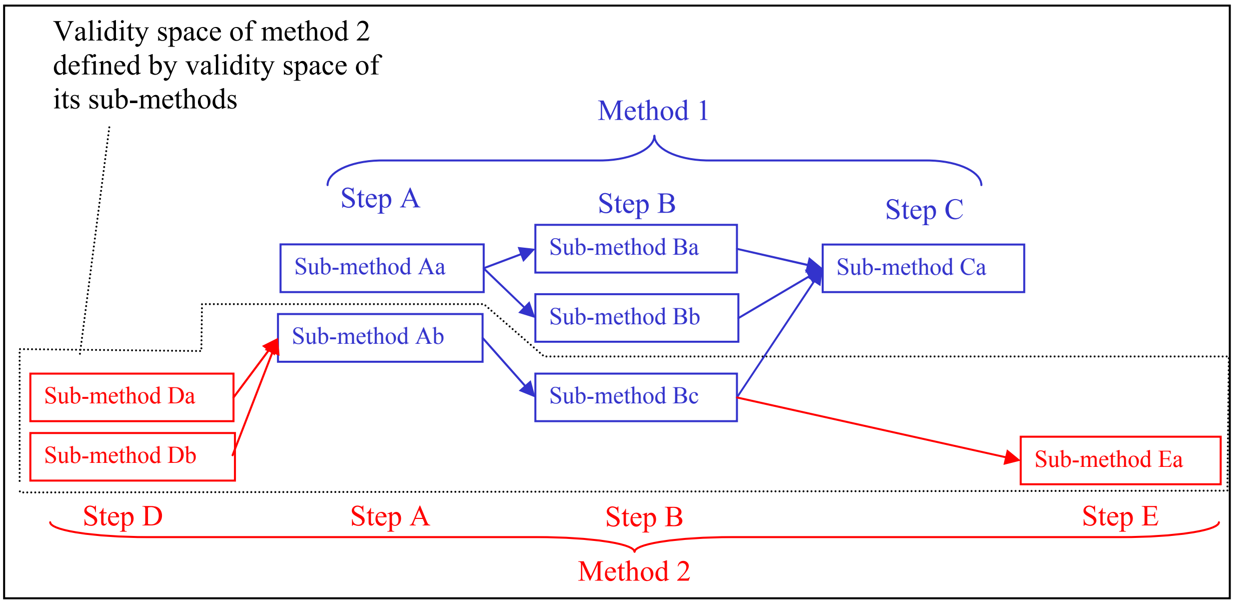

Figure 1. Network of sub-methods

6. Fundamental characteristics of problem conditions

The following list of fundamental problem conditions can be used as a check list for numerous tasks: to identify the validity space of existing methods; to develop new methods; to increase the validity space of a method by increasing the available number of sub-methods; etc. As mentioned before this list of fundamental problem conditions has been generated by merging two lists into one. The first list was done by analysing the links found in Table 1 between procedural approaches and problem conditions. The second list was created by the industrial co-author of this paper after reading the interview transcripts, since there could be fundamental conditions that could go unnoticed by an academic. The final list of fundamental problem conditions has been organised in three groups: technical challenge, resources, and character of requirements.

6.1 Group 1 of fundamental characteristics of problems: TECHNICAL CHALLENGE

1. Technical challenge description.
   The description of the task affects the method choice. For example, a bottom-up approach like project 1, where the aim is to make the most of a technical solution, is very different from the top-down driven development of project 4, where they try to find solutions for a certain problem. Methods should exist for different challenge descriptions.
2. Degree of novelty.
   When the concept developed is based on known existing technology within the company the design process has less surprises and can be planned from the beginning. Adaptive methods are recommended in that case [López-Mesa 2003]. Methods should exist for different degrees of novelty.
3. Difficulty to achieve.
   The difficulty to achieve a certain goal may require innovative methods that help the engineer break with the paradigm solution. Methods should exist for different degrees of difficulty.
4. Complexity.
   Certain methods are used because they reduce the whole complexity by taking the user's attention to different items at a time. Methods should exist for different degrees of complexity.

5. Clarity of goals.
   Certain methods are used because the goals are unclear at the beginning of the project. Methods should exist for different levels of clarity.

6.2 Group 2 of fundamental characteristics of problems: RESOURCES

1. Budget, manpower, material.
   Available resources limit the possible use of certain methods. Alternative methods should exist in case of high restrictions.
2. Available knowledge, experience, and invention capacity.
   The knowledge and available experience determine the type of approach. A lack of experience necessitates spending more time analysing the problem.
3. Possibility of testing.
   The possibility of testing allows for accurate estimations and therefore accurate methods. Methods for varying degrees of accuracy should be available.
4. Possibility of simulation.
   The possibility of simulation allows for iterative processes. Methods taking advantage of the iteration opportunity should be available.
5. Involvement of supplier
   The involvement of suppliers allows for higher certainty in many aspects of design; therefore, alternative methods should exist for different levels of certainty.

6.3 Group 3 of fundamental characteristics of problems: CHARACTER OF REQUIREMENTS

1. Rush/urgency of project.
   The time allocated to a project and deadlines imposed by market competition or legislation affect the choice of method. When time is lacking, the problem approach should produce feasible solutions with low lead-time.
2. One leading design criterion or several leading design criteria.
   All the methods used in the seven examples have a multi-criteria character. However, it has been observed than in some instances, one of the criteria is leading the evaluation process. In these cases, the types of methods used are different than when there is not a single leading criterion.
3. Design objectives are a must or a wish.
   The compulsory/optional character of the criteria influences the accurate/exploratory character of the methods selected.
4. Required certainty of output information.
   Certain design decisions require high certainty. Accordingly, the methods are chosen so that the required information is obtained and used to evaluate.
5. "Free hands" to think without restriction.
   Lack of restrictions allows for more daring approaches, where the appropriate method should also be available.

7. Conclusions

Engineers need to know a variety of methods for the same type of activity and a range of sub-methods for the different steps of a method; one that can adapt to the specific problem condition. A number of design methods use the same design sub-methods. A number of industrial design problems share the same characteristics. By identifying the fundamental characteristics of design problems and linking them to a wide range of suitable sub-methods, the flexibility of the academic method could resemble the natural adaption of methods originating in industry.

Acknowledgement

We acknowledge the assistance of the Power Train and Chassis departments of Volvo Car Corporation, especially of Ove Backlund and Johan Wedlin who have facilitated the realisation of the interviews. Gratefully acknowledged financial support has been provided by the Polhem laboratory at Luleå University of Technology.

References

Birkhofer H., Lindemann U., Albers A. and Meier M., "Product development as a structured and interactive network of knowledge – a revolutionary approach", Proceedings of ICED'01, The Design Society, Glasgow, 2001, pp. 457-464.

Bouyssou, D., Marchant, T., Pirlot, M., Perny, P., Tsoukiàs, A., and Vincke, P., "Evaluation and decision models. A critical perspective, Kluwer's International Series, Boston, London, Dordrecht, 2000.

*Eder, W.E. "*Design modelling – A design science approach (and why does industry not use it?)", *Journal of Engineering Design, Vol. 9, 1998, pp. 355-371.*

Fox, J.M., and Fox, R.L., "Exploring the nature of creativity". Kendal Hunt Publishing Co, Dubuque, Iowa, USA, 2000.

Isaksen S.G., Dorval, K.J., and Treffinger, D.J., "Toolbox for creative problem solving", Creative Problem Solving Group – Buffalo, Williansville, NY, 1994.

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

Lindemann, U. (2002), "Flexible adaptation of methods within the design process", Proceedings of Design 2002, The Design Society, Dubrovnik, 2002, pp. 81-86.

López-Mesa B., "Selection and Use of Engineering Design Methods using Creative Problem Solving Principles", Licentiate thesis, Luleå University of Technology, Sweden, 2003.

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

Pulm, U., and Lindemann U., "Towards a flexible and adequate use of methods in product development", Proceedings of Design 2002, The Design Society, Dubrovnik, 2002, pp. 229-234.

Belinda López-Mesa, MSC., Tech. Lic.
Luleå University of Technology, Division of CAD
SE-97187, Luleå, Sweden
Telephone +46920493050, Telefax +46920
E-mail: belinda@cad.luth.se