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EARLY VALIDATION OF A DESIGN METHOD BASED ON STRUCTURED REFLECTION

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1. Introduction

The idea of structured reflection has recently been discussed in the thesis of I. Reymen [Reymen 2001]. In [Ivashkov 2001] this idea was carried one step further and extended with an operational model for design processes. The next step is to devise a formally defined semantics in order to develop software tool support. However, we first need a better understanding of the merits of Design Method based on Structured Reflection (DMSR). Obviously, DMSR should provide practical help to designers in educational settings or/and in professional design projects. Therefore, our goal is to validate and evaluate (further for convenience just validate) the basic ideas of DMSR as early as possibly and parallel to the development of the formal underpinning and subsequent development of software requirements.

2. DMSR

DMSR is a design method based on a state-transition model of the design process where the phases of the design (D) and reflection (R) are alternating: DRDRD. Our developed operational model aims to provide a framework to administrate, during the R-phases, the knowledge that resulted from the D-phases. This knowledge is administrated in an incremental way by systematic updates of the DMSR's knowledge representation structure. The updates that we support are: the addition or deletion of a concept (C); the addition or deletion of an attribute (A); and the modification of a value (-expression), where a functional relationship between concepts, attributes and values is maintained: V=A(C).
In our operational model we use attributes in a more formal way than design methods such as morphological analysis [Zwicky 1969] and attributes listing [VanGundy 1988]. An attribute A is a function that returns a value V in dependence of its argument, where this argument is a concept C. This function can express a condition, an observation, a guess, an assumption etc. The attribute has an associated range from which the attribute-function can take its value. A range could be a discrete set of alternatives, but also data such as numbers.
A concept in our approach is a generic issue that has to be defined or distinguished. For a concept C, we agree that all relevant information that is contained in C is only accessible via the set of attributes that are meaningful for C. Then the goal of the design process is to define the concept that corresponds to the artefact-to-be-designed and to select optimal values from the ranges of all its attributes. If optimality can be expressed in a numerical format, the method seamlessly interfaces to numerical (combinatorial) optimisation algorithms such as genetic algorithms [Zitzler 1998].
For example: in designing a vehicle, a concept could be the vehicle (VEH) that we are designing; one of its attributes could be its type of motor (MOT) and values could be 'electromotor (ELM)', or 'diesel

engine (DEN)'. Both ELM and DEN are concepts in their own right; an attribute that applies to both of them is the type of energy source (ENS) with values 'electricity (ELE)' and 'diesel oil (OIL)'. The knowledge thus far built up gives rise to expressions such as

MOT(VEH)=IF(*condition*) ELM ELSE DEN
ENS(ELM)=ELE
ENS(DEN)=OIL

The *condition* is an expression that depends on other aspects of the vehicle; it has to evaluate to *true* or *false*. Depending on its value, we can get that ENS(MOT(VEH)) evaluates either to ELE or to OIL. The various value-expressions, such as 'IF(*condition*) ELM ELSE DEN' are administrated in the cells of a spreadsheet-type data structure where every row corresponds to a concept and every column to an attribute. The above format for knowledge representation can be exercised with pen and pencil; however, it is obvious that software support drastically enhances the usefulness, since then the propagation and evaluation of decisions can be automated and optimization can take place in the way mentioned above.

As a result of the functional view of attributes, our approach differs from the object orientation approach in software, where an attribute is meaningful only in the context of a class. The functional view of attributes allows us to apply the same attributes to new concepts, which may produce new ideas and thus stimulate creativity. We call such inspiring attributes 'productive attributes' because they may potentially produce new ideas. Additional features of this approach include the ability to postpone decisions, to work with conditional decisions, and to follow up several alternative lines of decisions simultaneously for an extended period during the design process (in paragraph 4.2 three alternatives of a bicycle light are considered).

Currently, we have a simple prototype of DMSR, but important functions are still lacking. Various forms of consistency checking and user operations such as (re-) grouping concepts and attributes are still to be developed. This needs a more rigorous formal underpinning of the mechanism, but prior to extending the mechanism, we first need to evaluate the basic. Both the correctness and the usefulness of the model need to be assessed.

3. Validation of DMSR: the approach

One technique for early validation is to use *rapid prototyping* as proposed in [Bracewell 2001]. However, even for a prototype, we should have a fully developed formal model. Therefore, we will use a different approach, which is described as follows. The full formal model, among other things, supports postponing decisions, conditional decisions, multi-valued decisions, and partial evaluation of expressions. In *ab-initio* design settings, these are necessary ingredients. Many design processes, however, are forms of *re-engineering*, where a first stage consists of making an inventory of properties of an *existing* artefact. Then, postponing of conditional decisions and multiple valued decisions is not yet required, and a simplified form of the formalism can already be implemented with standard database and/or spreadsheet tools. Therefore, our validation will be based on re-engineering cases.

Further, re-engineering is a meaningful context for testing our approach since

- Many designs really start from existing products
- Re-engineering allows benchmarking of the results obtained using DMSR with the results obtained in a different way, for instance with design methods conventionally used in re-engineering, such as QFD [Prasad 1998], LCA [Berg 1995].
- It should be possible to compare an initial artefact and a re-designed version thereof using quantitative criteria (cost, performance etc).
- It should be possible to compare new ideas in a re-designed version with already invented or patented ideas related to the artefact.

In order to validate our method, we need to identify opportunities to practice DMSR. In our situation we had to find or organize courses with suitable re-engineering assignments. It turned out that already running courses were also suitable. We asked students to reflect on their progress made by re-engineering an artefact and to propose alternative solutions using DMSR. Additionally, we organized a workshop in order to observe students while they were using DMSR.

The next step was the choice of assessment methods (AM). While the consistency of DMSR (validation) can be assessed from students' results, the students' opinions about DMSR, its usefulness and usability (evaluation) were important as well and these also had to be assessed. Similar to [Atman 2000] we use several well-known assessment methods in order to get more credibility of our results. Moreover, each of the methods 1,2 and 3 support the appearance of new ideas in a different way. The used methods are described in Table 1.

Table 1. Assessment Methods (AM) suitable for early validation experiments

Method	Advantages	Disadvantages	Outcome
1. Closed-ended surveys	Easy to administrate and analyse. Allows statistical analysis within the known space of options.	Narrows down the number of possible responses. Not efficient with a small number of participants.	Structured and concrete opinions about the proposed issues.
2. Open-ended questionnaire	Stimulates the appearance of new ideas. Can work with any number of participants. Gives more evidence of the experience	Difficult to draw conclusions, useful information can be hidden	Some new ideas but in unstructured fashion.
3. Observations and interviews	Direct access to attitudes and interactions	Requires an extra model in order to interpret the observations. Time consuming.	Implicit information on how students experienced the method.

4. Validation of DMSR: the procedure

A set of three practical experiments with the model was performed in the period September 2000 – November 2001. The experiments took place at the Stan Ackermans Institute (SAI) in Eindhoven with involvement of 25 students. SAI, which is a subsidiary of Eindhoven University of Technology, organizes postgraduate design programs in different technical disciplines. These programs lead to the degree of Master of Technological Design [MTD]. The students became acquainted with DMSR during a course in design methodology taught as SAI. We have chosen two ongoing courses in order to validate DMSR. As the result of periodical contact with the students we had limited observational data and the main experimental data came from the students' reports and surveys using AM 1 and AM 2. The third experiment was a workshop organized by us. During the 3 hours of the workshop we could observe students using AM 3, which gave us more evidence of actual usage of DMSR. For this reason and in order to demonstrate a practical use of the methodology we will describe the workshop in more detail.

4.1 On-going courses

In the first experiment two groups of two students from the IPPS program (Intelligent Product and Production Systems, one of the SAI programs mentioned above) had to re-engineer a coffee maker and a desk-lamp. The goal of the course was to concentrate on one of the issues: environmental aspects, lifecycle, energy, or material consumption. The students used the Quality Function Deployment (QFD) techniques to work with the requirements and the Life Cycle Assessment (LCA) method to deal with the complex interaction between a product and the environment.

In the second experiment five groups of 2-3 students from the USI program (User System Interaction) had to design various communication systems, for example: a communication system for grandparents and grandchildren, Electronic Interactive System for Supporting Brainstorm Sessions and others.

In both experiments the students were asked to describe an existing artefact (in the second experiment it was a system that they designed themselves) using the terms of the model, thereby representing the knowledge in the DMSR format (concepts, attributes and value-expressions). Both the descriptions in a provided spreadsheet format and students' opinions about the model were attached to their final reports.

4.2 The workshop

In the third experiment ten students from different programs (USI, IPPS, Mathematics for Industry, Process and Product design, Software Technology) volunteered to participate in an interdisciplinary workshop organized at SAI. The system to be re-engineered was chosen such that it was well known, interesting and challenging enough for the students. We have chosen a light system of the bicycle, based on a mechanical dynamo.

A conventional dynamo for a bicycle has a rotor driven by the outer surface of a rotating tire of the bicycle to generate an electric current when a rider pedals the bicycle. As a consequence, the headlight is not lit if the bicycle is stopped – which compromises the rider's safety. Of course, present day bicycle lights (in particular rear lights) typically have electronic provisions that keep them burning for a couple of minutes even when the bicycle has stopped. The purpose of our experiment, however, was not to design a realistic and competitive substitute for the existing solution, but rather to monitor the process of idea generation and reasoning in terms of concepts, attributes and values.

The workshop started with the description of an existing system in DSMR terms. The information was kept on the white board in spreadsheet format. After the main attributes of the system were identified, namely the energy transport, the energy storage, the energy generator, and the light source, the students were divided in groups. Each group proceeded with more detailed insights into one of the found attributes. Each time this gave rise to a new concept in its own right. Comparison of the found attributes for different concepts has shown that:

- Many attributes were the same or had similar meanings. For example: cost, size, power, weight, principle, location, material, etc. were present in almost every group. This mean that these *shared* attributes apply to several concepts: they allow direct comparison of these concepts.
- Other attributes such as shape, dynamics, and reliability were present in only one of the groups; therefore they applied to only few of the concepts. Such attributes could be considered as potentially productive and tested on their applicability to other concepts.

After that, each group came up with several alternative values, for most of the found attributes. The spreadsheet with some of the final results is shown on Figure 1.

In the spreadsheet each attribute is associated with a column. The first row in each column contains an attribute name e.g. principal, material, generator, light source. The next six cells in a column contain an attribute range with possible outcomes of an attribute e.g. for the attribute material the outcomes are: plastic, rubber, dielectric, Ni-CD. The left most column contains concept names e.g. dynamo, bulb. Each cell may contain an expression, which can be a name of a concept, a numeric value, a logical expression, or a more complex expression (e.g. EXP1, EXP2,…). Evaluation of such expressions, for instance plus(light system3.light source.cost,… etc) requires a dedicated software tool support.

5. Validation of DMSR: the results

The correctness of DMSR was assessed from the outcome of experiment 1,2 and 3. The review of the descriptions as given by the students has shown that the students were capable to convey the architectural description of their designs in terms of DMSR. We gathered more evidence that the functional view of attributes invited students to think about alternative values, which produced meaningful results they might otherwise have overlooked. Moreover, the descriptions were useful for reviewers in understanding the architecture of the designed systems. The usage of DMSR for representing the design decisions invited students to include alternative designs, which might be skipped in conventional, less structured reports. We stress that we do not recommend DMSR as an alternative to report formats; we rather consider it to be an addition.

In the workshop it happened several times that the mechanism of "productive attributes" gave rise to quite unorthodox solutions that nevertheless should be taken seriously. For instance the students did not know that the value "discrete" for the attribute "dynamics" earlier led to US patent 5,804,927 , September 1998. "Light emitting apparatus for a bicycle". The authors propose to emit light using impulses instead of conventional continuous emission, which allows saving energy. A value “piezoelectric” for attribute “Energy Generator” (EG) is the main idea of US patent 5,624,175, April 1997, “Bicycle safety light”. The power source includes piezo-electric elements, which generate electricity when struck by a moving weight.

Microsoft Excel - SAI workshop data-copy

File Edit View Insert Format Tools Data Window Help

T24 =

	B	F	P	S	T	AD	AF	AG	AI	AL	AM
1	ATTRIBUTES	principle	material	dynamics	cost	power	safety	usability	storage	generator	light source
2	RANGE	electrical	plastic	continuous	integer	integer	0:10	0:10	elastic string	dynamo	fluorescent
3		thermal	rubber	discrete					AA	fuel cell	halogen
4		mechanical	metal	explosive					accus	piezoelectric	bulb
5		chemical	glass	slow					falling weight	sound	gas
6		potential	dielectric						flywheel	bio-reaction	
7			Ni-CD							biker	
8	CONCEPTS										
10	light system 0				plus(dynamo.costs; bulb.cost;...)	EXP 9	EXP0	EXP3		dynamo	bulb
11	dynamo	mechanical	metal	continuous	10	3		EXP6			
12	bulb	electrical	glass	continuous	3	2.4					
13	wires	electrical	metal		3			EXP7			
14	light system 1				plus(dynamo.costs; bulb.cost;...)	EXP 10	EXP1	EXP4	accus	piezoelectric	bulb
15	accus	chemical	Ni-CD	continuous	5						
16	piezoelectric	potential	dielectric		8	0.2					
17	light system 2				plus(dynamo.costs; bulb1.cost;...)	EXP 11	EXP2	EXP5	elastic string	dynamo	alt(bulb;bulb1)
18	elastic string	mechanical	rubber	continuous	2						
19	bulb1	electrical	glass	discrete	6	EXP 8					

Figure 1. Spreadsheet resulting from the workshop with some of the data

The usability and the usefulness of DMSR were assessed using the assessments methods 1-3. From the collected data we realized that the students did not have problems in understanding and using DMSR. In the first experiment we used more closed questions which allowed us to assess students’ opinions about DMSR from specific viewpoints. Besides questions directly related to DMSR, the opinions of students about DMSR as tool for decision-making, knowledge management, idea generation, and communication, were assessed. The broadness of the initial survey helped to spot the most useful points of the method which appeared to be (1) stimulation of creativity and (2) facilitation of communication with the group. In the second and the third experiments we used the AM2 more extensively in order to assess the extent of (1) and (2). Furthermore, it gave us more ideas about the students’ opinions. Again it turned out that (1) and (2) are recognized by the majority of the students, while some students commented on difficulties to manage the knowledge due to the somewhat formal appearance of the information format.

Questioning and open feedback of the students also gave us better understanding of the merits of DMSR and new ideas arose from the students’ responses. For instance, we realised new ways to simplify the model by preserving its consistency using other ways of representing “has-a” and “is-a” relations. After the experiments we had a better understanding of the importance of supporting ranges in expressions. New ideas related to the user interface appeared from actual observations of how students used Microsoft Excel to work with DMSR. Summarizing, our experience indicates that:

- Students’ creativity is stimulated by formulating design decisions in terms of attributes and values
- Administrating the concept, attribute and value according to DMSR is appreciated by most of the students, provided that students have had the opportunity to get used to the slightly more formal way of formulating their thought.
- Above all, DMSR seems to be appreciated as a tool to improve (clarity of) communication among the members of a design team.

Of course, the above experiment should be repeated with larger group of participants in order to gain statistical significance. However, that was not the purpose of this endeavour: we only wanted to have an early indication of the adequateness of our approach in order to decide whether further development has a chance of being fruitful. With a more elaborate version of our system we will perform broader experiment.

6. Conclusions

The early assessing of a design method based on DMSR allows validation of underlying ideas even without the formal underpinning of the model and the dedicated software support being completely available. The use of various assessment methods supports the generation of novel ideas and provides more credibility to assessing the usefulness of the method. The use of design assignments based on re-engineering provides practical help in the choice of assignments and the validation of results. Furthermore, it allows us to assess the consistency and usefulness of DMSR independent from each other. The described experiments show how the methodology was applied to validate a particular DMSR.

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