Thinking in design teams - an analysis of team communication

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The thinking process of designers is one of the most important issues in design research. This paper intends to enlarge design thinking theory and research by taking a close theoretical and empirical look at the very basic elements of thinking in design. Based on theoretical assumptions, thinking in design is reduced to the four basic cognitive operations of generation, exploration, comparison and selection, which, in various combinations, are applied to the goal space and the solution space of a given problem as well as to the organisation of the collective process of teamwork. These basic cognitive operations can be mapped onto different stages of the design process, thus establishing a generic model of design team activity. The generic model can be used to describe both, activities directed towards the content of a design problem as well as activities towards the organisation of the group process. Three laboratory teams solving a complex design problem extending over six hours have been studied in order to investigate the collective thinking process. Team communication has been recorded and analysed sentence-by-sentence, with each communicative act being classified according to the generic model. Based on previous results in the psychology of human information-processing and decision-making, a two-process-theory of thinking in design teams is proposed capable of explaining the results from the empirical investigation. The implications of the two-process-theory for training and practice of designers are discussed.

Keywords: collaborative design, communication, problem solving, design process, protocol analysis

How do designers think when trying to solve a design problem in their daily work? This question is of great importance for both research and practice in design and related fields. Researching design thinking provides insights into human thinking in general, while at the same time bearing implications for training and practice in design.

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In design research there are several strains of research that have focused on different aspects of design thinking. Three important strains can easily be identified. We will label these strains the *normative strain*, the *empirical strain* and the *design-as-an-art-strain*.

The *normative strain* is dominated by design methodologists. Researchers such as Pahl & Beitz[1], Cross[2], Hubka & Eder[3] have proposed systematic approaches to designing in architecture, engineering and product design in order to obtain optimum results. This body of work derives from a rational analysis of design tasks and their requirements and thus has culminated in widely-known guiding principles for designers within standard educational textbooks (VDI Design Handbook 2221[4]).

Research conducted in the *empirical strain*, however, has revealed that designers, in practice, rarely follow the methodology prescribed by normative theories. In fact, empirical studies raise the question of whether designers follow any methodology at all. Criticism against design methodology has emerged from empirical studies in design, depicting design methodology as a rigid prescription that does work not even under ideal conditions in laboratory situations (see Günther & Ehrlenspiel[5]). Moreover, the prescriptive accounts of design neglect many of the specific factors and constraints designers need to cope with in their daily work, such as economic constraints, time pressure (Ehrlenspiel[6]) and teamwork.

Relief for the design practitioner came in the form of *design-as-an-art-theorists* (Schön[7]), who have turned trouble into a virtue by stating that the design process simply cannot be grasped by any methodology, but that the work of designers much resembles the work of an artist who applies different kinds of methods in a flexible manner in a process of appreciation, action and re-appreciation, constantly reflecting on his own work (for a deeper analysis see e. g. Roozenburg & Dorst[8]).

Despite the large contribution of each of the three strains highlighted above to the field of design research, each strain has its specific shortcomings. Theory-building and research conducted under the normative strain has often neglected to look at what people actually do — simply prescribing a methodology may not meet the needs of the designer "out there". Research conducted under the empirical paradigm is not always theory-based — a clear direction to/of the research is sometimes missing. Although research conducted under the design-as-an-art-paradigm has revolutionised design theorising, much of this research is suffering from "romanticising" design. If designers are artists, not every designer is a good artist — there may be designers who do self-reflect their own business and have a great deal

1 **Pahl G and Beitz W** *Engineering design* Springer, London (1984, 1995)
2 **Cross, N** *Engineering design methods: strategies for product design* (2nd edition) John Wiley & Sons, Chichester, UK (1994)
3 **Hubka, V and Eder, W E** *Engineering Design in Heurista*, Zürich (1992)
4 **VDI Design Handbook 2221** *Systematic approach to the design of technical systems and products* VDI-Verlag, Düsseldorf (1986)
5 **Günther, J and Ehrlenspiel, K** 'Comparing designers from practise and designers with systematic design education' *Design Studies* Vol 20 No 5 (1999) 439–452
6 **Ehrlenspiel K** Practicians — How they are designing? … and Why? *Proceedings of the ICED '99 München* Vol 2 (1999) pp 721-726
7 **Schön, D A** *The reflective practitioner: How professionals think in action* New York, Basic Books (1983)
8 **Roozenborg, N F M and Dorst, K** 'Describing design as a reflective practice: Observations on Schön's theory of practice' in **E Frankenberger, P Badke-Schaub and H Birkhofer** (eds) *Designers — The key to successful product development*, Springer, London (1998) pp 29–41

of awareness about their own thinking and acting — however, there are also designers who get stuck in routines and suffer from a lack of self-reflection. We know that designers are different, and that designers perceive and interpret design problems differently, depending on individual and group prerequisites and characteristics of the current situation (Dorst & Cross[9]).

What is intended in this paper is to offer a theory on the basic elements of thinking in design. This theory is used in order to take a closer empirical look at what design teams really do while designing. This look, however, will be solidly grounded in theory again, taking into account aspects of normative design theories, theories of creativity and problem-solving and cognitive theories of human decision-making. Empirical studies which provide a deeper understanding of design thinking from a cognitive perspective may aid in advancing normative theories of design and adapting these theories for education (see for example Ball, Evans & Dennis[10]).

1 *The basic elements of thinking in design*

Design problems are complex problems. Problem-solving in general, and designing as a specific area of problem-solving, requires that a goal space and a solution space must be brought to overlap in such a way that an optimum fit between the goal space and the solution space is being established — the solution should meet all of the relevant requirements. Both the goal space and the solution space represent problem spaces i.e., they are both characterised, on a very abstract level, by a number of elements and by certain relations between these elements. In contrast to domains such as the arts, in design the goal space is much less flexible than the solution space — requirements and constraints are mostly fixed and can only be negotiated to a certain degree. Discrepancies between different requirements are not an exception, but the rule — for example, a motor should at the same time provide optimum performance, but take up very little space. Therefore, the goal space needs to be carefully analysed. Conflicts between requirements need to be settled by prioritisation.

Similar to domains such as the arts, however, the solution space in design is usually quite large. There is rarely simply one single solution — there are many possible solutions, with every solution representing a trade-off between certain advantages and disadvantages. Thus, design does provide many opportunities for creative thinking — while at the same time placing a considerable number of constraints on the designer that need to be taken into account.

If design means operating on problem spaces, a set of operators is needed that enables the problem-solver to act on the problem spaces.

9 **Dorst, K and Cross, N** 'Creativity in the design process: co-evolution of problem–solution' *Design Studies* Vol 22 No 5 (2001) 425–437

10 **Ball, L J, Evans, J St B C and Dennis, I** 'Cognitive processes in engineering design: a longitudinal study' *Ergonomics* Vol 37 (1994) 1753–1786

In their work on creative thinking, Ward, Smith & Finke[11], in establishing the so-called Geneplore model of creative functioning, distinguish two distinct cognitive operations: *generation* and *exploration*. According to Ward et al. creative action can be described as an interpolation of generative and explorative processes. Solutions are being generated and then being explored in the light of the goal space. In an iterative process, solutions may be modified or new solutions may be developed until a 'satisficing' (Simon[12]) or optimal solution has been found.

Both generative and explorative processes aim at widening the problem space. While we agree with Ward et al. that both generation and exploration are essential ingredients to creative thinking and problem-solving, these two operators are not sufficient in order to solve a problem. In addition to operations that widen the problem space, operations are also needed that narrow the problem space. This holds especially for large problem spaces in which the range of possible solutions may be quite broad. Theories of creativity following an evolutionary paradigm (Campbell[13]) compare creative thinking to natural evolution. The core of Campbell's creativity theory is that creative action as well as natural evolution can be represented through two distinct processes, *blind variation* and *selective retention*. According to Campbell, both operations that create variation, thus widening a problem space, and operations that select from the created variation, thus narrowing the problem space, are required. Building on Campbell's second principle of selective retention, we propose two additional basic cognitive operations that both serve to narrow an already widened problem space, *comparison* and *selection*. In comparison, two or more ideas, objects, etc. are being compared in the light of one or more criteria. For example, three different solution ideas may be compared according to cost and function, or one solution idea may be compared to other relevant criteria of the goal space. Following comparison, one or more ideas can be selected. This selection corresponds to Campbell's selective retention. With comparison and selection, the problem space, after having been extended through generation and exploration, is narrowed again.

Summarising, we propose four basic cognitive operations that are necessary in order to deal with any kind of problem space, the first two serving to widen a problem space and the last two to narrow a problem space:

- generation
- exploration
- comparison
- selection.

11 **Ward, T B, Smith, S M and Finke, R A** 'Creative Cognition' in **R J Sternberg** (ed.) *Handbook of creativity*, Cambridge University Press, Cambridge (1999) pp 190–212

12 **Simon, H A** *The sciences of the artificial* MIT Press, Cambridge MA (1969)

13 **Campbell D** Blind variation and selective retention in creative thought as in other knowledge processes *Psychological Review* Vol 67 (1960) 380-300

We propose these four basic cognitive operations to be the basic ingredients of any kind of thinking and problem-solving, not only in design, but also in other domains. We further propose that on a very basic level any kind of complex thinking process can be reduced to some more or less complex sequence or interpolation of these four basic elements.

2 *Applying the basic elements of thinking to design teams*

Trying to analyse the thinking and reasoning process of designers, difficulties occur because we have no direct measures to inspect the process in the designer's brain. In contrast, designers working in groups have to communicate what is going on during their current thinking and thus provide us with the basic thinking process. Furthermore, design teams are of major importance in any organisational context because, with increasing complexity, groups of individuals work together in order to accomplish problems they cannot solve on their own.

When applying the four basic thinking operations to design teams, we distinguish between two main focuses of action which we call *content* and *process*. With this differentiation we take into account that teams as opposed to individuals in order to successfully solve a design problem must not only deal with the design task itself, but must also direct part of their activity at structuring and organising the group process. Social psychologists Morgan, Glickman, Woodward, Blaiwes and Salas[14] make a similar distinction when separating group activities in *task-work* and *team-work* activity. We propose that content and process-related activity of design teams can be described in similar terms, with the same basic thinking operations underlying both process- and content-related activity (see also Fisch[15]). Under both of the two action focuses (content and process) a set of steps can be proposed, which are related to the content similar in different kind of theories: systems engineering (see for example Haberfellner, Nagel & Becker[16]), problem solving theory (see for example Dörner[17]) as well as design methodology (see for example Ehrlenspiel[18]; Pahl & Beitz[1]). The six steps concerned with the content can be defined as follows:

- *goal clarification:* communicative acts dealing with the goal space
- *solution generation:* proposals and solution ideas concerning the design task
- *analysis:* questions and answers concerning the solution space
- *evaluation:* positive and negative evaluations concerning the solution space
- *decision:* decisions for or against a solution idea

14 **Morgan B B, Glickman A S, Woodward E A, Blaiwes A and Salas E** *Measurement of Team Behavior in a Navy Environment* (NTSC Report No. 86-014), Orlando, FL: Naval Training System Centre (1986)
15 **Fisch, R** 'Eine Methode zur Analyse von Interaktionsprozessen beim Problemlösen in Gruppen' A method for the analysis of interaction processes in problem-solving groups 'A method for the analysis of interaction processes in problem-solving groups' *Gruppendynamik* Vol 25 (1994) 149–168
16 **Haberfellner, R, Nagel, P and Becker, M** *Systems engineering in Verlag Industrielle Organisation* Zürich (1999)
17 **Dörner, D** *The logic of failure in Metropolitan Books*, New York (1996)
18 **Ehrlenspiel, K** *Integrierte Produktentwicklung Integrated product development in Hanser*, München (1995)

- *control:* control of the implementation of a solution idea

Concerning content, the first step of goal clarification relates to the goal space, the following four steps relate to the solution space. The last step of control is simultaneously concerned with the goal space and the solution space.

With regard to the process we define five steps comparable to the content that can be defined as follows:

- *planning:* proposals concerning the group process (how to proceed, how to distribute tasks, etc.)
- *analysis:* questions and answers concerning the group process
- *evaluation:* positive and negative evaluations of the group process
- *decision:* decisions concerning the group process
- *control:* summary or control of group members' work.

Fig. 1 depicts the defined steps in the design process and the underlying thinking operations.

This generic model represents an application of the four basic cognitive operations to the team design process. The model enables us to decompose complex design team activity into small chunks which can be analysed by a variety of methods and tools, thus providing a precise picture of what design teams really do. Furthermore, we assume that there are strategies (consisting of a certain combination of elements) which may lead to successful outcomes, in contrast to strategies which bring about different kinds of problems in design team activity. Nevertheless, compared to normative

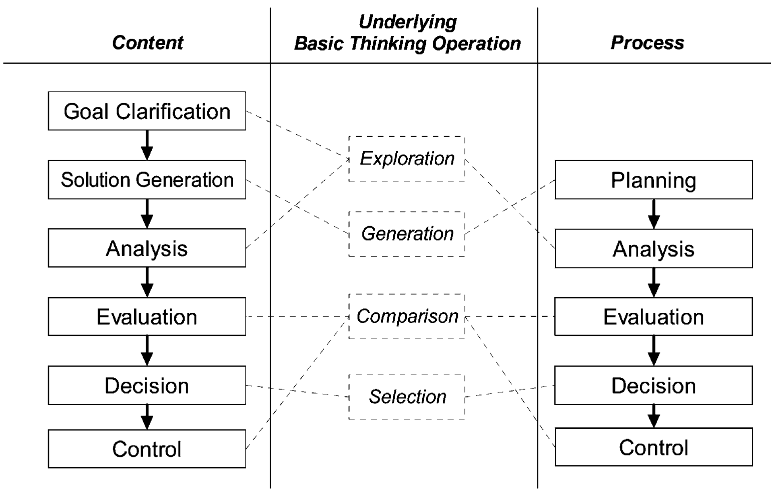

Figure 1 Generic step model of design team activities.

design theories, we do not propose any fixed order in which these single steps should occur. On the contrary, we are interested in the order in which these steps empirically occur. We expect all of the steps to occur repeatedly with possible loops comprised of two or three steps occurring frequently. We assume that the same design steps are being applied in different stages of the design process, such as the conceptual stage, the detail design stage, etc., — even though on a different resolution level.

3 *Method*

The proposed theory has been applied to the analysis of the design process of three laboratory teams. The teams were comprised of 4–6 students majoring in mechanical engineering at the Technical University of Darmstadt, Germany. Although generalisations from student teams to design teams in industry must be drawn with caution, we think that in some cases it is necessary to use laboratory studies for the sake of methodological strictness. In the laboratory it is easily possible to induce the same task with the same embedding context for different groups of similar age, professional background, and group history. This does not hold for research in an industry context. Thus, the comparability of design processes of different teams in practice is not possible in a rigid experimental sense. In the controlled setting of the laboratory we expect to gain some insight into basic thinking processes which are not contaminated by unknown and unpredictable factors which occur in a field setting (for further discussion see Cross, Christiaans & Dorst[19])

The student teams were assigned a complex design task that they were to solve in a one-day period. The task consisted of designing a mechanical concept for a sun planetarium. This sun planetarium should be able to visualise the way of the sun across the sky for different positions on the hemisphere, as well as for different seasons. Many of the requirements (strength of the light source, size, weight, etc.) were specified in a requirement list which was part of the comprehensive assignment. All technical information was given on information sheets; in addition, handbooks about materials and techniques were available. The groups interacted with a simulated customer at three fixed points in time during their one-day working period.

Protocol analysis was used in order to capture the thinking process in the group (see also Goldschmidt[20]). Team communication has been completely recorded and analysed sentence-by-sentence for all three teams. Utterances were broken down into communicative acts, defined as a statement concerning a specific subject. If a speaker changed subjects throughout the course of a longer speech, the speech has been broken down into several

19 **N, H and K** (eds) *Analysing design activity*, John Wiley & Sons, Chichester, UK (1996)
20 **Goldschmidt, G** 'The designer as a team of one' in **N Cross, H Christiaans and K Dorst** (eds) *Analysing design activity*, John Wiley & Sons, Chichester, UK (1996) pp 65–91

communicative acts. In group 1, a total of 810 communicative acts has been recorded, compared to 1056 communicative acts in group 2 and 2877 communicative acts in group 3. The fact that the number of communicative acts greatly differs between groups is remarkable, since all three groups were given exactly the same amount of time (6 h) for solving the problem.

Based on the assumption that communication provides a prime access to the thinking and problem-solving process of design teams, a multi-level coding system has been developed for the analysis of the recorded data. The coding system was designed for use not only in a design context but also for different problem-solving domains (economics, ecology, etc.). The coding system for team problem-solving behaviour is depicted in Table 1.

On the highest level, the coding system reflects the two main focuses of activity, "content" and "process". Under each activity focus the steps elaborated on earlier in this paper are being attached. Each step is then defined by one or several actions. Classifying communicative acts consists of assigning each act to a single, distinct category. A statement like "We should use three arches", for example, would be categorised as a content-related "solution idea". The classification has been conducted by two independent raters. A software tool has been developed in order to automatically analyse the coded data. Although communicative acts are only classified on the lowest level of actions, the software tool automatically calculates results for higher levels of analysis (activity focus and steps). In this paper, only results from the top two levels of analysis, activity focus and steps, are reported.

Communicative acts have then been analysed in three ways:

- *Analysis of frequencies:* Analysing the frequencies in which the different communicative acts occur provides a basic understanding of the role of the different design steps in the design process.
- *Process analysis under a macroperspective:* The occurrence of the design steps over the whole period of the design work provides insights into the order in which the different steps occur during different stages of the collective design process.
- *Process analysis under a microperspective:* Analysing transitions between different design steps sentence-by-sentence provides insight into the basic thinking process of the observed teams.

4 Results

4.1 Analysis of frequencies

Fig. 2 depicts the frequencies of communicative acts under the two main focuses of content and process in the three groups. In all three groups a

Table 1 Coding system for team problem-solving behaviour

Activity focus	Step	Action
Content	Goal Clarification	Goal-related statement or question
		Requirement-related statement or question
	Solution Generation	Solution idea
	Analysis	Question
		Answer, piece of information
		Hypotheses, implication
	Evaluation	Question for opinion or evaluation
		Positive evaluation/agreement
		Negative evaluation/disagreement
		Prioritising
		Expression of uncertainty
	Decision	Decision
	Control	Control of facts and effects
Process	Planning	Planning, discussion of order, in which tasks are to be completed
		Assigning tasks to group members
	Analysis	Question
		Answer, piece of information
		Hypotheses, implication
	Evaluation	Question for opinion or evaluation
		Positive evaluation/agreement
		Negative evaluation/disagreement
		Expression of uncertainty
	Decision	Decision, arrangement
	Control	Control of group members
		Summary, consensus
Residual	Residual	Residual

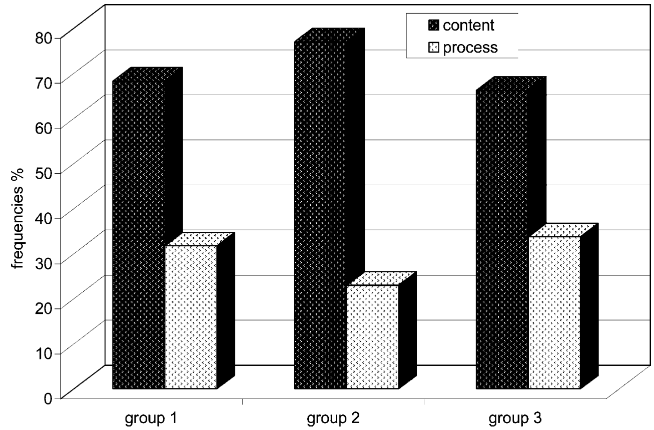

Figure 2 Frequencies of communicative acts by activity focus.

similar distribution of communicative acts among the main categories results. This distribution can roughly be described by the "2/3–rule": In 2/3 of their communication design groups deal with the content whereas 1/3 of the group communication aims at structuring the group process. Similar results are reported from problem-solving groups in non-design contexts (Fisch[15]).

On the level of steps in the design process (see Fig. 3 which displays the frequencies of steps as an average of the three groups) the distribution of communicative acts among the steps is quite similar in the three groups as well, with a medium correlation between the distributions of 0.98 between the three groups. In the three observed teams (groups averaged for these results), most of the team communication is concerned with the *analysis* of both the content (46%) and the process (17%,). The next frequent category is the evaluation of content (13%) followed by goal clarification (7%) and evaluation of process (5%).

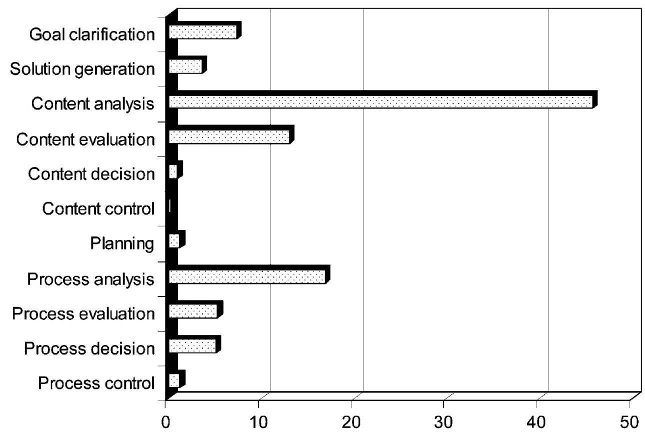

Figure 3 Frequencies of communicative acts by design steps in the three groups in per cent.

Overall, about 7% of team communication is related to the goal space, 63% is related to the solution space and in 30% of their communication the observed teams deal with the group process. The two operators with the highest quantitative importance when dealing with the solution space are analysis and evaluation.

Given the fact that the pure number of recorded communicative acts greatly differs between the three groups, as mentioned in the previous chapter, the consistency between the distribution of communicative acts between the three groups is quite remarkable. Regarding the pure frequencies of the communication categories, the thinking processes of the observed design groups cannot be very much differentiated. On the other hand, differences in the path of action of the groups exist that apparently cannot be explained by the findings reported so far. The question that remains is how do groups go about their design process? What are the similarities and the differences between the processes of the different groups?

4.2 Process analysis: A macroperspective

Fig. 4 depicts the sequence of communicative acts according to the two main focuses of content and process over the whole period of design work. Note that whereas, in all three groups, a distinct period in which the group focuses mainly on the process can be discovered with the remaining time of group work dedicated to the content, the stage in which this period occurs differs between the three groups. In group 1, the process-centered period occurs at the beginning of group work; in group 2 this period occurs at halftime, whereas in group three this period does not occur before the very end of group work. This finding is rather remarkable. The three groups

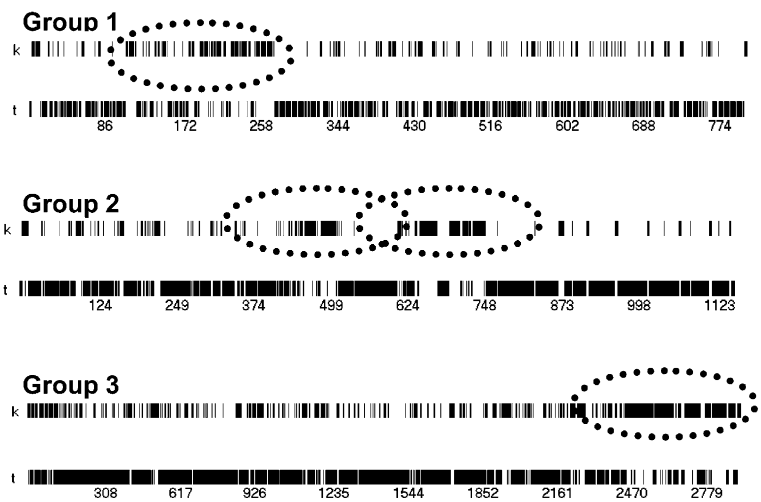

Figure 4 Activity focuses over the course of design work (k=process, t=content).

proceeding in the design task can be labelled from "chaotic" (group 3) to "planned" (group 1).

In empirical investigations Gersick[21] found that project groups usually practise a muddling-through strategy until halftime of the task completion or until critical events occur which make a (re-)structuring process in the group necessary. These findings cannot be replicated by our investigation. Obviously, the three groups, although they spend nearly the same amount of communicative acts on content- and process-related topics, evolve completely different strategies in order to solve the two main aspects of the task.

Fig. 5 depicts the distribution of communicative acts over time on the finer resolution level of design steps in the three groups. Since this paper focuses mainly on design thinking, only design steps related to the content are being displayed. The last step of control has been omitted due to very small base-rates of occurrence ($<1\%$). As can be seen in the figure, there are both commonalities and differences in the three groups regarding the distribution of design steps over time. In all three groups, goal orientation is much more present at the beginning of the collective design process than in later stages. In accordance with prescriptive accounts of design methodology (Pahl & Beitz[1]) and theories of problem-solving (Dörner[17]), all three observed groups focus on the goal space in early stages of their work, whereas in later stages the focus shifts onto the solution space. Concerning goal clarification, however, a significant difference between the groups can be observed: whereas in group 1 and group 2 virtually no goal clarification takes place in the second half of the design process, in group 3 goal clarification decreases towards the middle of the design process but increases again in frequency towards the end. Group 3 is the only group that, in the end, takes a second look at the requirements as stated in the goal requirements. In group 1 a major problem arose from the fact that this group neglected goal analysis in later stages of their work: the group established a solution that was impossible to realise due to the excessive weight of their construction. A quick look at the requirement list would have given sufficient evidence to realise that the weight of their construction exceeded the maximum weight as stated in the requirements.

Concerning the solution space, no systematic accumulation of design steps can be detected at any specific stage of the design process. Thus, whereas it is obvious that the observed teams deal with the goal space in early stages and then shift to the solution space in later stages, no characteristic agglomeration of steps concerning the solution space can be detected at any stage of the design process.

21 **Gersick, C J G** 'Time and transition in work teams: Toward a new model of group development' *Academy of Management Journal* Vol 32 (1988) 9–41

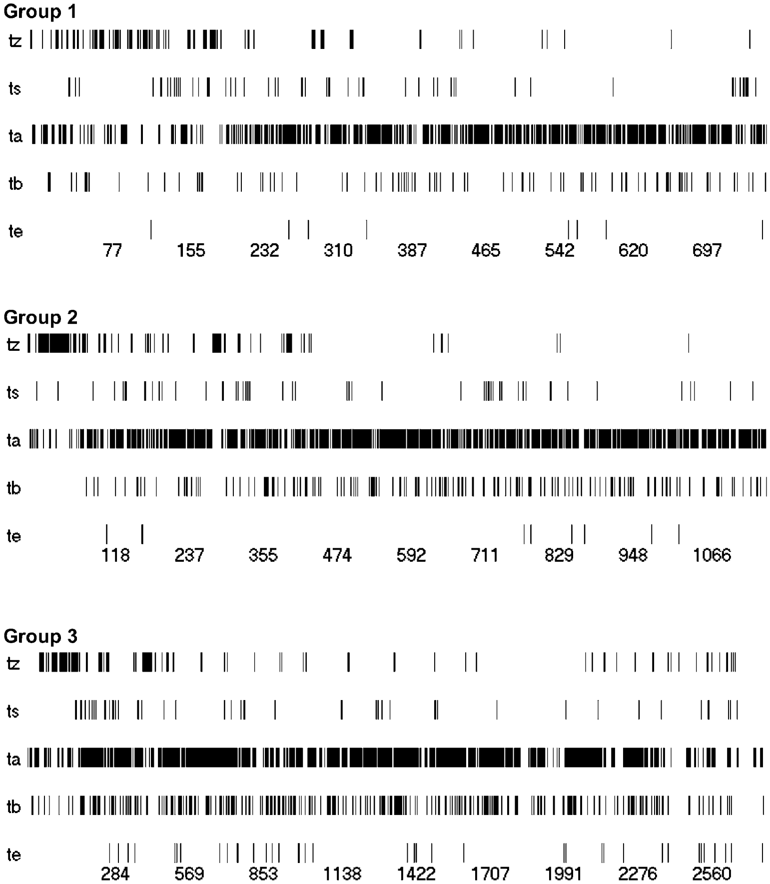

Figure 5 Design steps over the course of design work (tz=goal clarification, *ts*=solution generation, *ta*=analysis, *tb*=evaluation, *te*=decision).

4.3 *Process analysis: A microperspective*

Analysing transitions between design steps under a microperspective, two-step-sequences of design steps have been examined. The question to be answered is: Is team communication "chaotic" in the sense that any sequence of design steps is likely to appear, or are there regularities, with one step systematically following after another specific step? In order to answer this question, the transition probabilities between all of the steps have been calculated and then compared to the baselines of the steps. If, for example, content analysis occurs in 46% of all team communication, but after a content analysis in 55% of all cases another content analysis follows, this means that sequences of content analysis are highly likely to occur in team communication. A Chi^2-test allows for calculating whether the observed transition probability is significantly higher compared to the baseline of the categories.

Fig. 6 displays transition probabilities between the two communication

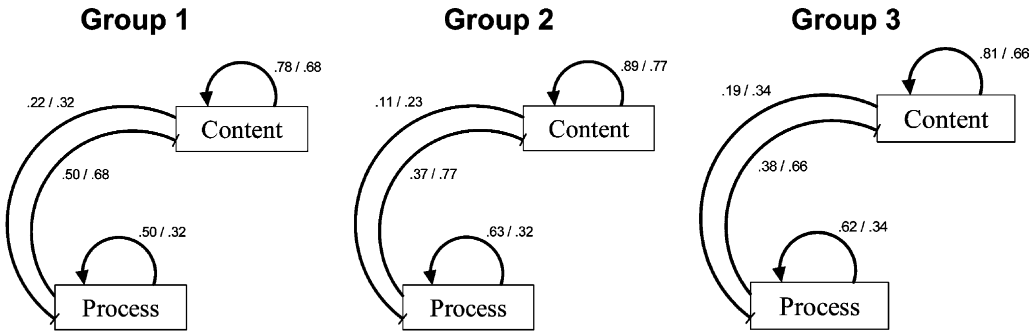

Figure 6 Transitions between activity focuses.

focuses of content and process in the three groups. In the figure, a connection that ends with an arrow displays a transition that is significantly more likely to occur compared to the base rate (as calculated by a Chi^2-test). A connection that ends with a straight line displays a transition that is significantly less likely to occur compared to the base rate. The first number behind the connection represents the transition probability, the second number represents the base rate probability.

As Fig. 6 reveals, in all three groups a transition *within* the same focus of action is highly likely, whereas a transition to the complementary focus of action is highly unlikely. These findings are significant for all three observed teams with $p<0.1$. In other words: Once teams are dealing with either content or process, they tend to stick to the communicative focus for several communicative acts before switching to the complementary focus.

On average, the three teams spend 8.3 communicative acts on content-related communication before switching to process-related communication, whereas sequences of process-related communication have an average duration of 3.7 communicative acts. These findings reveal that the design process in teams is best described by *a constant interweaving of content-directed sequences with process-directed sequences*, both of some duration.

On the level of design steps, transitions between design steps have been analysed in the three teams. Since the focus in this paper is on the thinking process in design, we will focus on content-directed communication only in the following. Fig. 7 displays transitions between design steps.

One interesting result is that for every design step except the step ‘decision’ a transition *within* the same step is highly likely to occur. The proposed design steps thus seem to be steps indeed in the sense that groups tend to

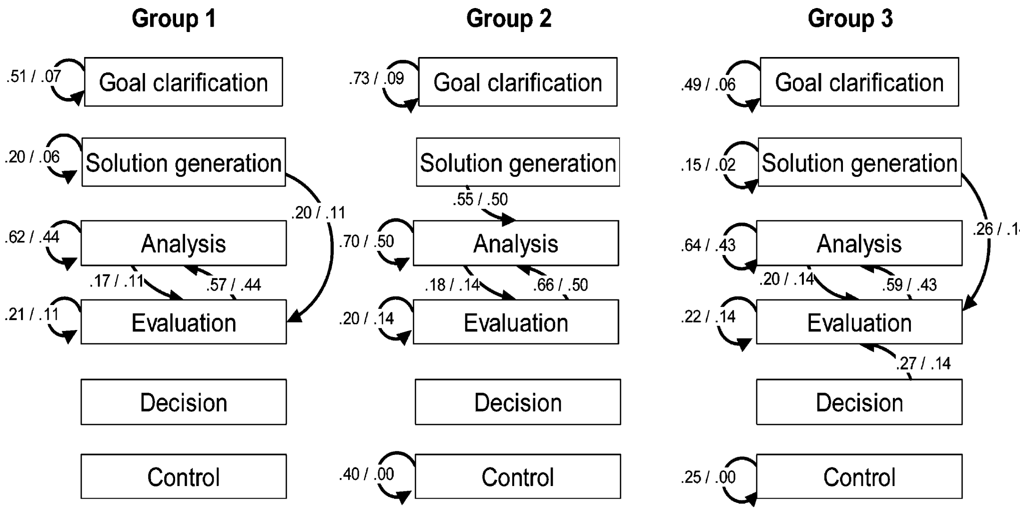

Figure 7 Transitions between design steps.

spend more than one communicative act on the same step before moving on to the next step.

Furthermore, there is an interesting feedback loop consisting of analysis and evaluation. The repeated loop of analysis and evaluation thus seems to represent the core of the collective thinking process in the observed teams. As we have pointed out above, analysis enables the teams to widen the solution space, evaluation serves to narrow it down again. The constant interpolation of analysis and evaluation might enable design teams to keep the size of the solution space at an acceptable level.

Of great interest is the fate of solution ideas. When a new solution idea is being proposed, the team's immediate reaction often decides the fate of the solution idea. From a methodological perspective, one would expect new ideas to be followed by a thorough analysis. What one would not expect is an immediate evaluation. In fact, creativity techniques such as brainstorming (Osborn[22]) explicitly prevent groups from premature evaluation. Our results show, however, that groups frequently do not follow such recommendations, but *do* evaluate solutions immediately without prior analysis. In two out of the three observed groups, a new idea is highly likely to be followed by an immediate evaluation, not by analysis. Only group 2 frequently progresses from solution generation to analysis.

From a theoretical viewpoint, an immediate evaluation of solution ideas without prior analysis must be regarded as a severe problem during the process of solution generation. Two errors are likely to occur. One is

22 **Osborn, A F** *Applied Imagination — Principles and Procedures of Creative Thinking* Scribner, New York (1957) premature rejection of a solution because it does not seem to fit the constraints of the task structure. Oftentimes, however, a solution that does not fit at first sight can be transformed in order to produce a fit with some effort. A second error likely to result from premature evaluation of solution ideas is the premature adoption of a solution that proves problematic later on. A complex design task comprises many different requirements and constraints, often too many for people to keep in mind. Thus, a crucial constraint may be forgotten, with a false positive evaluation of a solution idea resulting. Both errors are grave. In the first case of premature rejection of a solution idea, an ingenious idea may be discarded and lost for the group. In the second case of premature adoption of a problematic solution, groups may spend considerable time working out a solution only to find out later on that the solution does not work.

Given the proposed negative effects of premature evaluation of solution ideas, how can we explain the findings in groups 1 and 3?

5 *A two-process-theory of thinking in design teams*

In interpreting the results described above, one must free oneself from assumptions that underlie "normative" design theories. For example, most evaluation methods (Pahl & Beitz[1]) implicitly assume that what is sought is the "best" solution and that designers are willing to invest a considerable amount of time and cognitive effort into finding this solution. Research in cognitive psychology, however, has long proven that in their natural thinking humans rarely strive for *optimum* solutions, but rather for *satisficing* solutions, that is for solutions that exceed some (consciously or unconsciously held) threshold (Simon[12]). In other words, when trying to explain human thinking, apart from the quality of the result other parameters must be taken into account, such as the time and the cognitive effort spent on the thinking process. In design theory, such notions are taken into account by Ehrlenspiel[6]. The cognitive psychologist Gigerenzer[23] has provided many intriguing examples of heuristics humans apply in their everyday thinking. All these heuristics have a common purpose: reducing complexity, thus enabling us to take action quickly based on fuzzy (not exact) information. Research on natural decision making (Beach[24]) has shown that in contrast to popular models of a "rational" decision-maker, natural decision making does not consist of generating many alternatives, then evaluating all these alternatives and finally taking a decision. On the contrary, what humans mostly do much more resembles a sequence of several consecutive "screening"-processes. When confronted with a decision, humans usually generate only one, at best some few alternatives. As soon as an alternative exceeds a certain threshold and seems acceptable, a decision in favour of the alternative is taken (although there may well be

23 **Gigerenzer, G** *Simple heuristics that make us smart* Oxford University Press, New York (1999)
24 **Beach, L R** 'Four Revolutions in Behavioral Decision Theory' in **M M Chemers and R Ayman** (eds) *Leadership theory and research. Perspectives and directions*, Academic Press, San Diego (1993)

many better alternatives available). When no suitable alternative is found, however, people may reconsider already discarded alternatives, analysing them in some more detail or modifying their internal threshold value.

Summarising these findings, there is much evidence that evolution has optimised us to think and act in a “quick-and-dirty”-way, reducing complex information to manageable chunks and taking decisions rather quickly, even if this might lead to less correct decisions. This enables us to act even in highly complex environments, we are not doomed to freeze in contemplation — although individuals differ in respect to that point, as Shakespeare’s Hamlet shows.

In the light of these deliberations, the findings presented in this paper make much more sense. If we take a look at the basic thinking operations we have proposed, we have distinguished operations that serve to widen a problem space (generation, exploration) from operations that serve to narrow a problem space (comparison, selection). By widening a problem space, complexity is increased; by narrowing the problem space, complexity is decreased. If humans tend to reduce complexity whenever possible, an early evaluation of solution ideas seems the logical consequence. Discarding a poor solution idea early, for example, can save a lot of time and energy. Thus, a sequence of solution ideas being followed by immediate evaluation does make sense under the aspect of reducing complexity, time and cognitive effort. We call the sequence of solution ideas being followed by immediate evaluation *process 1*. We propose process 1 to closely match the “natural” thinking process of design teams. The flow chart in Fig. 8 demonstrates the functioning of process 1 in more detail.

As displayed in Fig. 8, solution ideas will frequently be followed by an immediate evaluation. If there are questions or misunderstandings in the group as to the nature of the solution idea, however, an analysis might take place before evaluation. If the quick evaluation of solution ideas yields a positive result, the solution is accepted. If the solution is discarded, new solution ideas will be sought. If no more solution ideas can be found, however, then already discarded solution ideas may be reconsidered and analysed in more detail. Oftentimes, this analysis consists of thinking up a set of transformations capable of turning an unworkable solution into a workable one (for example, a motor that has been discarded due to its excessive weight may be reconsidered, with possible alternative materials for the motor being discussed).

Process 1 does provide several advantages. If all goes smoothly, a solution can be decided on very quickly. Thus, process 1 represents a time-saving

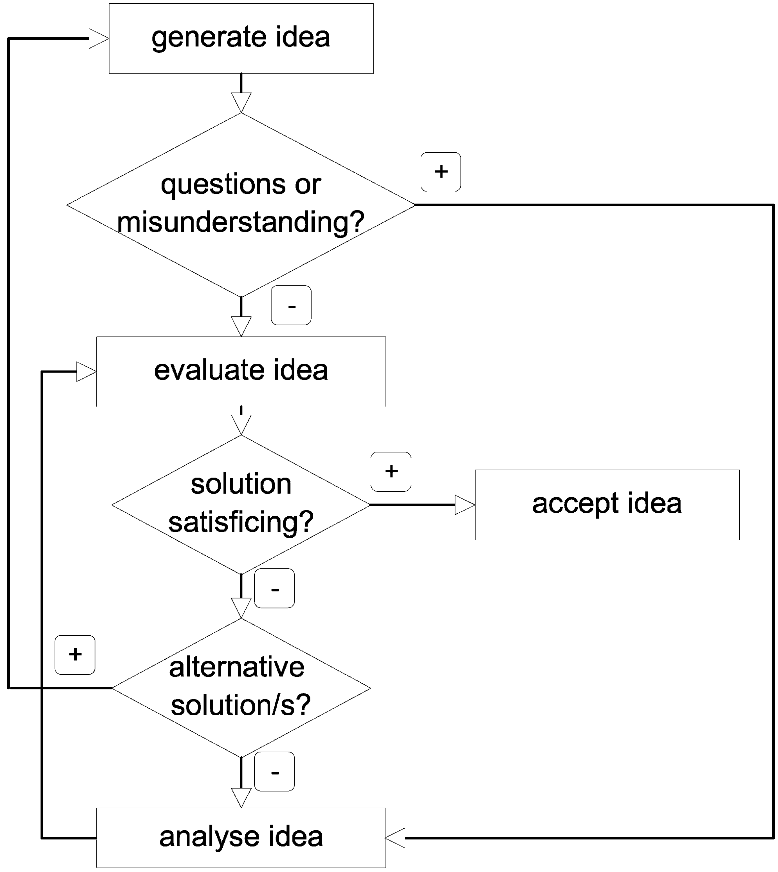

Figure 8 Process 1.

alternative compared to time-intensive evaluation techniques such as those proposed by design methodology (Pahl & Beitz[1]). Furthermore, process 1 will not threaten the collective self-efficacy of the group as only a few questions are being raised and the problem seems to be solved easily. The more analysis takes place the more difficult a task usually appears, as the analysis brings up new points of uncertainty. Perceived difficulty of a task and the non-availability of solutions reduce one's feeling of competence and self-efficacy. For simple problems, process 1 is thus likely to yield positive results quickly. The more complex a problem, however, the more likely errors will result from applying process 1. These errors will occur for several reasons. First of all, complex problems are frequently characterised not only by a large number of elements in the problem space, but also by many interrelations between these elements. Evaluating a solution idea implies taking into account all of the influences of all of the elements of the problem space. The number of these influences can be quite large. Due to limited cognitive capacities of humans, however, it is unlikely that designers will be able to take into account all of these effects in an immediate evaluation of the solution idea. This may lead to premature adoption of a poor solution. Furthermore, solution ideas usually consist of many elements. There are numerous ways to change a solution idea by adding, dropping, modifying or interchanging some of the elements of the solution idea. As a consequence, a seemingly poor solution idea may well be transformed into a workable one by means of one or a set of transformations. Thus, a premature evaluation may lead to a premature rejection of a seemingly poor solution idea that may well be turned into a workable one.

For these reasons, we propose that process 1 is effective for well-defined problems, whereas with increasing complexity of the problem at hand it is more likely to result in failure.

We do propose the possibility, however, that teams employ a different thinking process under certain conditions which we will call *process 2*. Process 2 is depicted as a flow chart in Fig. 9. This process very much resembles a structured design process as stated in design methodology. In process 2, one or more ideas are generated, then analysed and only evaluated after analysis has taken place. If no workable solution is being found,

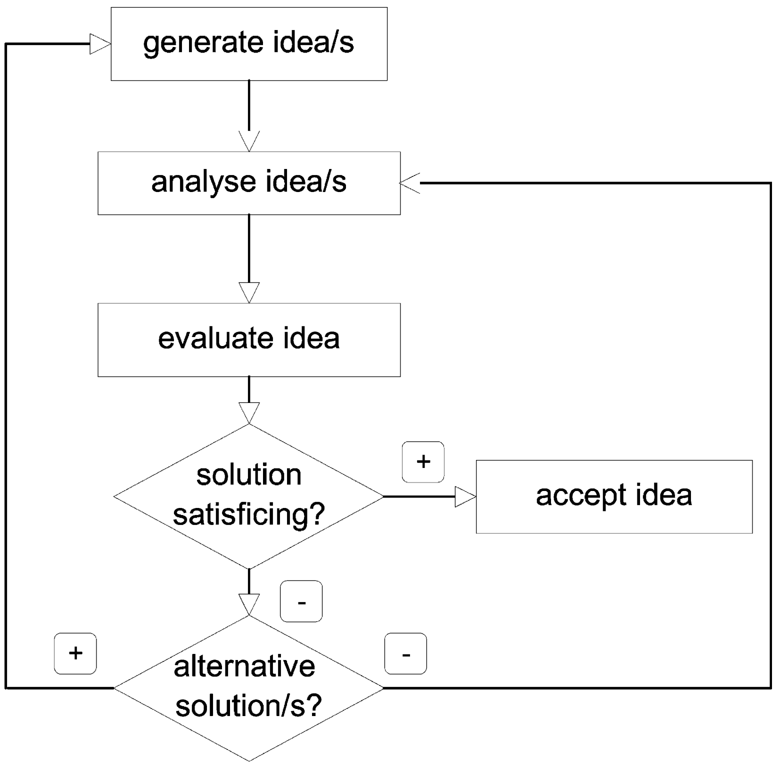

Figure 9 Process 2.

either new solutions are generated or the already discarded solutions are further analysed in order to find possible transformations serving to turn them into workable solutions.

As well as process 1, process 2 also has its specific advantages and shortcomings. One important shortcoming is that this process consumes much more time and cognitive effort than process 1. Analysing solutions takes a lot more time than a quick screening process. However, process 2 will minimise the risk of an erroneous solution. Thus, the more complex the design task, the more successful process 2 will be, compared to process 1.

If there are two distinct processes which teams can use in tackling a design task, what factors are responsible for the group's choice of which process to use? This study does not provide enough data in order to be able to answer this question on an empirical basis. However, based on theoretical deliberations we want to propose five important conditions that will cause a group to shift from process 1 to process 2.

5.1 Lack of common understanding

This condition is already apparent in Fig. 8. In a heterogeneous group in which group members have different levels of understanding, it is highly likely that solution ideas will not be understood by everyone in the team right away. This will provoke questions, thus causing the group to go into analysis prior to evaluation. This mechanism could be one of the reasons why heterogeneous teams have repeatedly been found to outperform homogenous teams in complex problem-solving tasks (e. g. Thomas[25]). If the group lacks a shared mental model, such a mental model must be built (Klimoski & Mohammed[26]; Mohammed & Dumville[27]). This building of a mental model will take place through questioning. Even if the questions are not meant to challenge a solution idea, but simply aim at filling in facts, thinking in detail about the problem may still cause previously unseen things to come up during the discussion.

5.2 Disagreement and challenging of ideas

As has been observed in one of the teams, disagreement and the challenging of ideas can lead to a careful analysis of solutions. In one of the groups one team member frequently challenged solution ideas that others had already accepted. This stance of challenging led to a careful re-analysis of the solution idea, often with new and important insights evolving. In the same manner, the same group member kept uttering one solution idea repeatedly although the team had already decided to drop this idea. After the fifth re-analysis of the solution idea, however, the idea was finally

25 **Thomas, A** 'Group effectiveness. A balance between heterogeneity and homogeneity' *Psychologische Beiträge* Vol 40 (1999) 226–236

26 **Klimoski, R and Mohammed, S** 'Team Mental Model: Construct or Metaphor' *Journal of Management* Vol 20 (1994) 403–437

27 **Mohammed, S and Dumville, B C** 'Team mental models in a team knowledge framework: expanding theory and measurement across disciplinary boundaries' *Journal of Organizational Behavior* Vol 22 (2001) 89–106

accepted by the team. Disagreement thus seems to provoke analysis, as team members try to back their points with arguments.

5.3 Failure of process 1

Once a team has discarded a considerable number of solution ideas without coming up with a workable solution, the team may be forced to re-analyse the solutions that have already been discarded for the lack of alternative solution ideas, thus switching from process 1 to process 2. As has been noted before, Beach[24] has observed a similar process in decision-making tasks, with subjects conducting a second screening process with a relaxation in the constraints if the first screening failed to produce an acceptable alternative. The lack of new solution ideas may thus lead to a re-analysis of already existing ideas, with a more lengthy analysis taking place this time.

5.4 Adoption of a methodology

In the three observed teams only one team (team 2) tried to structure their design process by use of a methodology. This team actively used creativity techniques such as brain-writing, as a consequence consciously separating the processes of solution generation, analysis and evaluation. This approach enabled the team to avoid premature judgement. As can be seen in Fig. 7, team 2 is the only team in which solution ideas are frequently followed by analysis, not by evaluation. Many creativity techniques suggest suspending judgement, thus allowing oneself to explore even “off-the-wall”-ideas. The use of such techniques may help to progress from process 1 to process 2.

5.5 Self-reflection

We agree with Schön[7] in stating that self-reflection is the key to successful designing for both individuals and teams. Self-reflection, in the sense of reflecting not on the content of a problem, but on one’s strategies in tackling the problem, may lead teams to consciously realise that they are stuck in a process-1-approach. From this point, teams can alter their proceeding and their strategies. The beneficial effects of self-reflection in teams have been emphasised by multiple authors (Badke-Schaub[28]; Blickensderfer, Cannon-Bowers & Salas[29]; Edmondson[30]; Mohammed & Dumville[27]; Valkenburg[31]). The power of self-reflection in complex problem-solving has been documented by Tisdale[32]. Tisdale describes self-reflection as the most powerful weapon in dealing with complexity. Thus, Schön’s notion of self-reflection in design seems to converge with a large body of research conducted in other fields. We do not agree with Schön, however, in that individuals and teams do self-reflection *by themselves*. In the teams we have observed so far, we have not yet met a single “reflective practitioner”. Turning to the literature, the work of Tisdale[32], Dörner[17] and others (e. g. Schaub[33]) on typical errors in complex problem-solving has yielded numer-

28 Badke-Schaub, P ‘Group effectiveness in design practice: Analysis and training by a critical-situation-approach’ *Psychologische Beiträge* Vol 41 (1999) 338–355

29 Blickensderfer, E, Cannon-Bowers, J A and Salas, E ‘Theoretical bases for team self-correction: fostering shared mental models’ *Advances in Interdisciplinary Studies of Work Teams* Vol 4 (1997) 249–279

30 Edmondson, A C ‘Psychological safety and learning behavior in work teams’ *Administrative Science Quarterly* Vol 44 (1999) 350–383

31 Valkenburg, R C *The reflective practice in product design teams* Industrial Engineering Design, Delft University of Technology (2000)

32 Tisdale, T *Selbstreflexion, Bewusstsein und Handlungsregulation Self-reflection, consciousness and action regulation* Beltz, Weinheim (1998)

33 Schaub, H ‘Decision making in complex situations Cognitive and motivational limitations’ in **R Flin, E Salas, M E Strub and L Martin** (eds) *Decision making under stress. Emerging themes and applications*, Ashgate, Aldershot (1997) pp 291–300

ous examples of situations where people actively tried to *avoid* self-reflection, mainly because this might harm their feelings of competence and self-efficacy. Realising one's own failure can be quite detrimental to one's self-efficacy and is therefore often avoided. In design teams we have observed both in the industry and in the laboratory in our own research (Badke-Schaub[28]), genuine self-reflection occurred very rarely. In the few instances where we have observed criticism of the team's approach, the reactions of the team have mostly been unfavourable. We therefore conclude that if self-reflection is to occur in teams, it must be actively encouraged.

In addition to the five conditions stated above, we assume that individual experience in terms of high procedural knowledge represents a condition under which 'implicit' methods or heuristics will emerge. These heuristics may cause a highly productive interplay between process 1 and process 2, with experienced designers knowing when to apply process1 and process 2 in their design work. However, the claim that higher experience in design goes along with a more adequate use of problem-solving strategies can not be supported by our empirical data yet.

6 Conclusion

The purpose of this paper was to investigate how design teams deal with design problems, with a focus on the cognitive processes of design teams during the design process. On the basis of the four postulated basic cognitive operations of generation, exploration, comparison and selection, a generic model of design activity in teams has been proposed. This model focuses on describing both activities directed at the content of the design problem and at structuring the group process. The model has been applied to the design process of three laboratory teams in terms of a theory-based coding system. An analysis of team interaction has been conducted on the basis of the generic model. This analysis has yielded a number of interesting results:

- *Content- and process-directed activity:* All three observed teams spent about 2/3 of their interaction on the content, 1/3 on the group process. These results show that beside the design problem itself, structuring the group process is an important issue also in design teams. Based on our results, the collective design process can best be described as a constant interweaving of content-oriented and process-oriented sequences, both of some duration.
- *Steps in the design process:* An analysis of the activities of the teams during the design process has shown that teams spend about 10% of their content-directed activity on the goal space, whereas the remaining 90% of all content-directed activity focuses on the solution space. When dealing with the solution space, the most frequent operators used by the

teams are analysis and evaluation. A loop consisting of analysis and evaluation seems to mark the core of the collective design process. By the constant interpolation of analysis (widening of the solution space) and evaluation (narrowing of the solution space), teams seem to be able to keep the complexity of the solution space at a manageable level.

- *Two-process-theory:* Comparing the three teams, an important difference has occurred between the teams concerning the treatment of solution ideas. Whereas in one team solution ideas were frequently first analysed, then evaluated, in two teams solution ideas were frequently immediately evaluated before an analysis has taken place. In order to explain this finding, a two-process-theory of thinking in design has been proposed. Process 1 is characterised by an immediate evaluation of solution ideas. Process 1 results in considerable savings in time and cognitive effort spent on a problem. On the other hand, with increasing complexity of the design problem process 1 is likely to produce errors. Process 2 on the other hand is characterised by solution ideas being followed by analysis. Whereas process 2 will yield qualitative better results for complex problems, it does take more time and greater effort. It has thus been argued that design teams will naturally tend to employ process 1. However, given certain conditions, a transition to process 2 is possible.

The results given in this paper have implications for education and practice in design. Traditional design methodology has been developed from the viewpoint of a scientific perspective. The end-product, the solution concept, is the main focus in traditional design methodology, aspects of the process that leads to the end-product such as time and cognitive effort spent in order to develop the concept have been neglected. For this reason, design methodology has not been as readily accepted in industry as design methodologists have expected. In our opinion a change of mind is necessary in design methodology and design education. What is necessary is a methodology that does not start from a normative point of view, but starts out from where practitioners are now, taking into account the constraints the practitioner faces in his everyday work, such as time constraints, financial constraints, cognitive overload through multiple projects that must be treated simultaneously, etc. Research conducted in cognitive psychology has provided many results that illustrate how humans deal with complex problems under varying conditions. These findings could provide the basis for a practitioner-centered design methodology. What is necessary in education is to take into account aspects of teamwork as well as the various conditions designers are confronted with in the industry. As a general recommendation, designers should not only be taught specific methods, techniques or tools that can help to structure the design process. What is much more important is to teach designers to reflect on their own strategies and heuristics in dealing with design problems. There are several studies which indicate that the analysis of one's own thinking process is a prerequisite for modifying inadequate thinking processes (see for example Cannon-Bowers, Tannenbaum, Salas & Volpe[34]; Tisdale[32]). Individual designers and design teams need to be able to assess the conditions of the given situation quickly, and to flexibly adjust their own path of action depending on the requirements of the situation. This flexibility can not be taught, but must be learned through experience and self-reflection. However, education can emphasise the importance of continuous self-reflection, thus enabling the future designer to become a true reflective practitioner.

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34 **Cannon-Bowers, J A, Tannenbaum, S, Salas, E and Volpe, C** 'Defining team competencies and establishing team training requirements' in **E Salas and R Guzzo** (eds) *Team effectiveness and decision making in organizations*, Jossey Bass, San Francisco (1995) pp 333–380