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HUMAN-CENTERED SUPPORT OF EDUCATION IN DESIGN PROBLEM SOLVING

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1. Introduction

Engineers' work and the corresponding education are characterized by an increasing complexity of tasks [Pahl et al. 2007] and an ascending share of temporary employment. This development is associated with increasing division of labour which involves an increasing number of interfaces. Thus the demands on communication and – usually temporary and interdisciplinary – cooperation grow as well. Successful cooperation in interdisciplinary teams requires integrating knowledge, i.e. building shared mental models of the task. Therefore non-technical psychologically founded support techniques and tools are important for the engineers´ initial and further education [Lindemann and Baumberger 2004]. An important approach which integrates teaching technical as well as non-technical ("soft") skills is the "Conceive-Design-Implement-Operate" (CDIO) approach proposed by Crawley, Malmqvist, Östlund, Brodeur (2007).
Techniques and tools concerning non-technical ways of proceeding in engineering design have especially been developed for support of the decisive early creative phases of design problem solving as well as for superordinate aspects of proceeding in engineering design, in particular for planning and scheduling and for the effective organization of teamwork.
For task analysis as well as for the evaluation of design solutions question-answering-techniques following the system of semantic relations have been developed; their effectiveness for solution quality has been demonstrated successfully in predominantly experimental studies [e.g. Winkelmann and Hacker 2009]. These question-answering-techniques motivate critical reflexion about the design solution and led to significant improvements of solution quality of medium effect size in a series of experimental studies [Wetzstein and Hacker 2003]. For a more effective generation of design solutions the utility of external representations such as manuals sketching and modelling could be demonstrated [e.g. Sachse et al. 2004]. Decision-making in the design process requires the consideration of a magnitude of features which usually exceeds the designers mental capacity [Weißhahn and Rönsch 2002]. Decision support systems provide sufficient capacity for simultaneous processing of information and thus improve the decision quality. Planning and documenting the design process may be supported by the "Design Map" - a low-effort tool which also serves reflexion about the design process and thus enables learning for further design projects [Jahn 2002]. The challenges of cooperating in a design team can be encountered by a specific hybrid organization of teamwork combining episodes of individual work and group work.
The goal of this study is to investigate the utility of integrating these non-technical psychologically founded support techniques in engineers´ initial education. For this purpose a balanced set of support tools and techniques was developd. It refers to the early creative phases of the design process (i.e. task analysis, generation of design solutions, evaluating design solutions and selecting on design solution for further elaboration) as well as to superordinate aspects of the design process, namely planning and

scheduling, and the effective organization of teamwork. The set of tools and techniques leans on well-established models of engineering design: The model of the design process proposed by the German Association of Engineers (VDI 2221) and the Task-Episode-Accumulation-Model [Ullmann et al. 1988] emphasizing the iterative alternation between predominantly intuitive concept generation based on implicit declarative and procedural knowledge, and the subsequent systematic and rational evaluation of design concepts [see also Petrovic et al. 2006, Visser 1994]. It considers the fact that the decisive "early" phases of the design process may hardly be assisted by software systems [see e.g. Sachse et al. 2001] by focusing on low-effort methods for the support of design problem solving.
Within the framework of a research project kindly supported by the Volkswagen Foundation (II/ 82 497) the mentioned support techniques and tools (shortly: support modules) were integrated in engineering students´ initial education by handing the written support modules to the students and giving them an introduction to each of the modules; the actual use of the modules was left up to the students. Since the modules are intended to transport information concerning generic non-technical skills, we investigated the benefit of this unforced teaching method for the students´ knowledge concerning non-technical skills for design problem solving, the quality of their design solutions and for their ways of proceeding.

2. Questions and Hypotheses

The main question of our study is whether the teaching method chosen here is sufficient for improving the students´ non-technical skills concerning design problem solving. In particular, the following questions were asked:

1. Does the system of support modules lead to additional action-guiding knowledge for the early phases of design problem solving, and
2. is this additional knowlege related to better solution quality of engineering design tasks?

We are talking about additional action-guiding knowledge since the support modules are applied additionally to the lecture and concomittant tutorials in engineering science.
The following hypotheses refer to the questions (2) and (3).
We expect:

Hypothesis 1: Intervention group A (receiving the support modules and an introduction to their utilization) as well as intervention group B (not receiving the support modules) significantly improve their knowledge concerning non-technical skills (provided by the support modules); the effect is small.

A significant increase in knowledge about non-technical skills is expected for both intervention groups (A and B) since the participants of both groups take part in the lecture concerning design methodology which stresses topics covered by the intervention (support modules + introduction to their utilization) as well. The participants of intervention group A additionally receive the modules in written form. An exchange between the two intervention groups concerning the contents of the support modules is to be expected. Above, the lecture and concomitant tutorials impart substantial knowledge which are also aspects of knowledge related to non-technical skills. The support modules handed to the students may thus – even if they are studied extensively – only cause a further improvement of the general learning process that is taking place.

Hypothesis 2: The increase of knowledge concerning the contents of the modules is only marginally – but not significantly - major in the teams of intervention group A (modules + introduction) compared to intervention group B (no modules).

This expectation is motivated by the only small differences between the effective interventions and by a methodological effect analogous to the concept of "marginal benefit". It concerns the fact that non-technical ways of proceeding are more or less explicitely referred to in the lecture and in the concomitant tutorial in engineering design as well.
The hypothesized small effect sizes concerning the improvements of the intervention groups are due to specific conditions of the current application of the support modules in the given field of study which regard to content and method. Firstly, the differences between former experimental studies concerning the *intraindividual* effectivity of singular support modules and the field study approach investigating

interinterindividual differences realized here are to be remembered. The most important difference is that the complete and thorough application of the support modules was *forced* in the experimental studies whereas it was left up to the students in the actual study approach. In addition, former field studies [Beitz et al. 1997] could demonstrate that an especially detailed education in engineering design not only does *not* give rise to better solution quality, but also involve worse solution quality compared to proceeding without this education. This finding was accounted for firstly by a goal conflict and secondly by the dual burden on mental capacity (i.e. learning to deal with design tasks on the one hand and explicitely learning a sophisticated methodology on the other hand; see Beitz et al., 1997, p. 18).
In the research procedure applied here, the utilization of the suggested methods and tools is not forced; accordingly we do not expect a significantly higher solution quality in the intervention groups A (using the provided support modules) compared to the intervention groups B (without the modules). A benefit of the modules is - even in the case of their thorough utilization - expected to arise not until a stage of sufficient familiarity with construction methodology and the non-technical skill domains in relevant professional experience has been reached.

Hypothesis 3: The non-technical ways of proceeding reported by the participants of both intervention groups (A and B) differ at most marginally. The ways of proceeding reported by participants of both groups are expected to show deficits regarding to non-technical skills.
This expectation is – analogously to the gain of knowledge in general - constituted by a small share of practising the non-technical skills and by the non-commital demonstration of the additional non-technical educational objectives in the tutorials.

Hypothesis 4: Since we do not expect any differences of large effect size concerning non-technical procedural knowledge, we also do not expect a significant difference between intervention group A (support modules + introduction) and B (no support modules) with regard to solution quality.

3. Method

Sample. 238 subjects studying Mechanical Engineering (major) at Technische Universität Dresden voluntarily participated in the study. This sample comprises all participants of the lecture in design methodology and the concomitant tutorial. The students were randomly assigned to an intervention group A (getting the support modules plus an introduction to their utilization) and an intervention group B (not getting the support modules).
Data analysis included 92 complete datasets. 74 percent of the students included in data analysis studied in the 5th semester, 20 percent in the 7th semester; 6 percent of the students studied in higher semesters. The medium age is 22 years (SD = 1.22). The majority of the students was mal (86%) and did not have any kind of vocational training yet (86%).
Design Tasks. The participants of the study were to work on a smaller design project (conceptualizing either a machine for baking rolls or a machine for cleaning up waste containers) during one semester. They had to work in groups of four to five students and present one design concept per group plus the associated report (comprising the documemtation of all the finished steps in developing the design concept) at the end of the semester. The design tasks were randomly assigned to the groups.
The analysis of task complexity (according to Schroda, 2000, with regard to contradictory goals, complexity, transparency, degrees of freedom, dynamic and required knowledge) showed that both design tasks were low in complexity.
Independent Variables. The independent variable of this study was the opportunity of using a balanced system of support modules handed to the participants of intervention group A in written form. This system consisted of six modules supporting the crucial early phases of concept design (namely analysis of the design task, generating design solutions, evaluating design solutions and selecting one design concept for further elaboration) as well as superordinate aspects of designing, namely planning and documenting of the design process and organizing work in a design team. In the following the modules will be outlined in short.

Modul 1 ("Design Map") is a low-effort support tool for planning and documenting the design process. It is based on the design methodology suggested by Pahl et al. (2007) and on the Munich model of proceeding in concept design [Lindemann 2007]. The design map facilitates estimating the time needed for finishing the design concept and documenting the actual expenditure of time, documenting developed design alternatives, sketches, models and data files, and reflecting the design process critically.

Modul 2 („Organizing team work effectively") contains recommendations for a hybrid organization of team work in product development concisting in an optimal application of individual work and group work. It shows stategies and rules for avoiding losses of teamwork [e.g. Stempfle and Badke-Schaub 2002] and for decision-making as a team.

Modul 3 ("Task analysis") supports the iterative clarification of goals by individual group members and design teams. It takes up recent findings affecting (opportunistic) proceeding in design processes [Winkelmann and Hacker 2009] and suggests the use of an question-answering-technique following the system of semantic relations (instead of pure mental consideration; Krause, 2000). The modul supports complete task analysis, clarifying the importance of singular demands, building up a function structure and documenting task analysis.

Modul 4 ("Generating design solutions") was developed in order to stimulate the use of "external thinking" [see Sachse 2002] in generating principal design solutions [Ehrlenspiel 2007]. It demonstrates simple low-cost ways of external thinking (e.g. discussing with colleagues, customers or potential users, manual sketching, impromptu-modeling with material which is at hand) and gives recommendations for combining low-cost early prototyping [Ehrlenspiel 2007] with IT-solutions (rapid prototyping).

Modul 5 ("Evaluating design solutions") supports the generation of design concepts by explicitly and rationally evaluating design solutions. Analogously to modul 3 the use of generic interrogative questions is recommended. These questions have proved to trigger reflexion in terms of reminding the designer of demands (written down in the list of requirements) and in terms of intitiating thinking about the design solutions [Winkelmann and Hacker 2009].

Modul 6 („Selecting one design concept for further elaboration") is a tool that supports deciding between several design solutions. It hints to prevalent deficits in decision-making (due to the limited capacity of working memory) and motivates the use of tools for decision-making, if necessary [Weißhahn and Rönsch 2002]. The modul refers to hierarchical goal analysis and the technique of the stepwise completion of decision matrices which include evaluating and weighting demands and desires.

Protocols. Both intervention groups (A and B) were asked to fill out structured procotols in each of the team meetings and deliver them to the research personnel four times throughout their work on the design task. These protocols were analysed with regard to the ways of proceeding throughout the design process, in detail documentation and planning the design process (short-term and mid-term), reflexion of the design process (with regard to achieved goals), iterative task analysis (indirectly by intermediate monitoring) and role allocation in the design team.

Dependent Variable. As a first dependent variable the students´ *knowledge* concerning the contents of the support modules (i.e. knowledge concerning non-technical skills relevant for planning and documenting the design process, team organization and the early phases of design problem solving) was measured at the before working on the design task (pretest) and after having finished it (posttest).

Secondly, the *solution quality* of each groups final design concept each team was investigated by two experts in engineering design using an self-developed evaluation scheme. The experts were trained in using the scheme and asked for a critical reflexion of the evaluation criteria. The interrater reliability with respect to all evaluations was high ($\kappa = 0.9$).

The third dependent variable were the *ways of proceeding* throughout the design process reported by the students. These ways of proceeding were investigated by an semi-standardized interview subsequent to the completion of the design concept. It was conducted in order to investigate the perceived usefulness of the modules and to deduce further need for support perceived by the students. The interview data were analyzed using a system of categories which had been discussed beforehand.

Covariates. Besides demographic variables (age, gender, professional experience) the students´ styles of acting in everyday life, in particular their affinity to planning and scheduling, their persistency in tracking goals and their flexibility in adapting goals were surveyed by a questionnaire proposed by

Heisig (1996). These variables have proven to be especially relevant for mid-term planning and scheduling [see Winkelmann 2005].

Reasearch design. The study follows a two-factor-within-subject-design with a stepped intervention and random samples. The within-subject factor is the students´ knowledge concerning non-technical skills. The groups´ ways of proceeding as well as the quality of the design solutions were investigated after the intervention had finished.

Procedure. In the course of a lecture in design methodology the students were asked to state their demographic data and to fill out the questionnaires concerning their knowledge about non-technical skills and their styles of acting.

The students were randomly assigned to the intervention groups A and B (see "Independent variable"). In the tutorial accompanying the lecture the two intervention groups were separated territorially. The 16 teams of intervention group A received a detailed introduction in the purpose and potential utility of the support modules as well as detailed instructions for using the modules and protocols during their design process in three consecutive tutorials. They were offered the opportunity to ask questions during all the tutorials. Each team received the support modules in written form and digitally.

The 31 teams of intervention group B did not receive the support modules. However, they were asked to fill out the structured protocols in the course of their team meetings as well.

After having finished the design concept the singular students were asked to fill out again the questionnaire concerning their knowledge about non-technical skills. Above the students of intervention group A were to take part in a semi-standardized interview investigating the ways of proceeding during the design process. The interview lasted about 30 to 45 minutes.

Data analysis. The first step of data analysis consisted in categorizing the information provided by the students (concerning knowledge about non-technical skills and proceeding during the design process). The categories were established concept-driven (by suggestions of the relevant literature) as well as data-driven (by the empirical data and their codification).

The process of codification was conducted by two independently working raters. Their interrater reliability was very good ($\kappa = 0.72$). Accordingly the relative frequencies of the singular categories were identified.

The proprocessed data were analyzed using SPSS 16.0. At first, the requirements for data analysis were checked. The analyses were carried out using analyses of variance (within-subject procedure) as well as U-Tests by Mann and Whitney and T-tests.

4. Results

4.1 Requirements for data analysis

The intervention groups A (support modules + introduction) and B (no support module) do not differ significantly with regard to age, gender, previous duration of university education and former occupation ($T_{age} = -0.66$; $T_{semester} = 0.22$; $T_{experience} = 1.42$; jeweils $p > .05$). Furthermore the groups do not differ significantly with respect to personal traits relevant for work, in particular their affinity to planning and scheduling as well as their flexibility in adapting goals ($T_{affinity\ to\ planning/\ scheduling} = -0.38$; $T_{adapting\ goals} = 0.35$; jeweils $p > .05$). However, the participants of intervention group A score significantly higher in the scale "persistency in tracking goals" compared to the participants of intervention group B ($T_{tracking\ goals} = -2.16$, $p \leq .05$). Thus the measured covariates – except of the persistency in tracking goals – are not to be considered in further comparisons of both intervention groups regarding knowledge about non-technical skills, solution quality and reported proceeding in the design process.

4.2 Utilization of the support modules 1 to 6 (Treatment Check)

The protocols of the students´ team meetings as well as the interview after having finished the design concept showed that the support modules 1 („Design Map", used by 87% of the groups), 2 ("Organization of team work"; used by 75% of the groups) and 3 („Task analysis"; used by 81.25% of the groups) had been used in the course of working on the design concept by the majority of the groups. 50 percent of all intervention groups A had used the modules 4 ("Generating design

solutions") and 5 ("Evaluating design solutions"). Modul 6 supporting the selection of one design concept for further elaboration was used by only 18.75% of all intervention groups A.
Relating the modul use to the four preset deadlines for delivering the procotols of the team meetings shows that all modules have predominantly been used in the design phases they had been earmarked for.

4.3 Knowledge concerning non-technical skills

Table 1 shows the results for the individual students´ knowledge concerning non-technical skills which was measured prior to and after working on the design task.

Table 1. Knowledge about non-technical skills in the intervention groups A and B (overall score composed of 10 items)

	Intervention groups	N	Mean	Standard error	Significance
Pretest	IG A	28	17.18	.94	n.s.
	IG B	54	16.76	.70	
Posttest	IG A	28	17.92	.97	n.s.
	IG B	54	16.39	.74	
Pre-post-comparison	IG A	54	16.76	.94	n.s.
	IG B	54	16.39	.97	
Pre-post-comparison	IG A	28	17.18	.70	n.s.
	IG B	28	17.92	.74	

IG = intervention group

None of the comparisons displayed in the table yields a significant difference between the intervention groups A and B with regard to knowledge concerning non-technical skills. The groups do not differ significantly in the pretest, nor in the posttest either. Furthermore the alteration of knowledge during the design process does not differ significantly between the two intervention groups; there is no increase of knowledge concerning non-technical skills in both groups.
However, an extended risk analysis shows that the number of students improving their knowledge concerning non-technical skills is major in intervention group A compared to intervention group B; the effect is not significant yet: Whereas the students of intervention group A improve or keep their knowledge in six of the questions asked (mean number of scores), the students of intervention group B improve or keep their knowledge in only four of the questions.
Hypothesis 1 expecting a significant improvement of knowledge concerning non-technical skills in both groups is to be rejected. Hypothesis 2 covering the assumption of an only marginally (rather than a significantly) major improvement of knowledge concerning non-technical skills in the intervention group A (working with the support modules) needs to be rejected as well.

4.4 Differences in proceeding – Comparison of intervention groups A and B

The ways of proceeding during the design process in the intervention groups A and B were extracted from the procotols of their team meetings. The comparison of both groups with regard to their ways of proceeding during the design process by U-Test demonstrates that there are several significant differences in proceeding. The number of protocols containing statements about (favourable)

proceedings intended by the modules is significantly major in the intervention groups A compared to the intervention groups B. In particular, the intervention groups A significantly more frequent investigated relations between demands/ desires ($Z_{A,B} = -2.88$; $p < 0.01$), distinguished between demands and desires ($Z_{A,B} = -2.27$; $p < 0.05$), distributed subtasks to the singular team members ($Z_{A,B} = -2.73$, $p < 0.01$), developed several solution alternatives ($Z_{A,B} = -2.35$, $p < 0.05$) and used tables and matrices for evaluating design solutions and for selecting one design solution for further elaboration ($Z_{A,B} = -3.30$; $p < 0.01$). Thus, the intervention groups A (having used the support modules) use more efficient ways of proceeding as regards to organization of team work, task analysis, generating design solutions and evaluation as well as selection of design solutions than the intervention groups B.
Hypothesis 3 assuming at most marginal differences in non-technical ways of proceeding reported by the students, is to be rejected. There are several significant differences in the reported ways of proceeding reported by the students which are all in favour of intervention group A having used the support modules throughout the design process.

4.5 Solution quality

The solution quality results from summing up the values of ten evaluation criteria concerning the quality of task analysis, solution and documentation. Table 2 displays the results of comparing intervention group A and B with regard to solution quality using the U-test by Mann and Whitney.

Table 2. Solution quality

Criterion	Intervention groups	Number of teams	Median	Mean rank	Z	Significance
Solution quality (overall score)	IG A	16	31	21.44	-.92	n.s.
	IG B	31	32	25.32		

There are no significant differences between both intervention groups with regard to solution quality, i.e. using the support modules (as done by intervention group A) is not associate with higher quality of the design solution compared to the teams not having used the design modules (intervention group B). Hypothesis 4 expecting no significant differences between both intervention groups A and B with regard to overall solution quality may be accepted.

5. Discussion

Generic non-technical skills concerning for example planning and scheduling, the organization of teamwork, or decision-making are increasingly important for engineers´ work since engineers´ working tasks become increasingly complex. Since engineers´ initial education includes teaching non-technical skills at most in a minor degree the purpose of this study was integrating the transfer of such skills in engineers´ initial education.
The main question was, whether suggesting the utilization of a balanced system of psychologically founded support tools and techniques referring to these non-technical skills will verifyably improve the students´ knowledge concerning these non-technical skills, their proceeding during the design process, and the quality of the students´ design solutions. The applied support tools and techniques have proven to be effective (e.g. in terms of higher solution quality) in preliminary experimental studies; here it was tested whether are supportive as well if they are offered for utilization in engineering students´ education.
The results show that merely suggesting the use of the support modules without enforcement to actually use them is not sufficient: The students having been offered the support modules do not show a major improvement of knowledge concerning the non-technical skills stressed in the modules nor a significantly major quality of their design solution either. However, the students´ reported ways of proceeding during the design process differ significantly in some aspects concerning the non-technical

skills tought by the support modules. All these differences are in favour of the intervention groups having been provided the modules.
The lacking differences between the two intervention groups with regard to the alternation of knowledge during the research period and to solution quality may partly be explained by the results of the treatment check: The support modules were not used by all the groups who the modules had been offered to. A further explanation is that learning to deal with design tasks and explicitely learning a sophisticated methodology at the same time is a dual burden on mental capacity [Beitz et al. 1997, p. 18; see also literature on the two ways of mental processing) which impairs the achievement in problem solving.
This has consequences for further interventions aiming at an integration of teaching non-technical skills in engineers´ initial education. A first consequence is keeping the students´ time and effort for the acquisition of the non-technical skills preferably low. Thus an overload of mental capacity may be avoided and the acceptance of the teaching materials may be increased. A possible approach would consist in integrating the information concerning non-technical skills in the protocols filled out by the students anyway. This approach is recently traced to by our research group.

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