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Where have all the inventors gone?

Is there a lack of spirit of research in engineering education curricula?

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***Abstract*—In political discussions and the research and innovation policy of the European Union, the topic "creativity" seems to become increasingly important. Innovation depends on good ideas, so the need of innovative solutions in a globalized world puts creativity in focus. Engineers, who embody the creative inventors and tinkerers more than any other occupation group, carry an important contribution (or even the societal responsibility) to solving current problems. However, engineering education has not been known to be particularly creative or to foster creativity. Based on the results of several interwoven research projects, this paper presents an approach to the nature of creativity in the context of higher education and a small pre-study about the actual activities to foster creativity in two engineering courses. The results indicate a lack of fostering creative learning to establish a spirit of research among students. For this reason, two examples of well elaborated didactical concepts are given, able to foster creativity in engineering education in adaptable dimensions.**

Keywords. fostering creativity in higher engineering education, higher engineering education research, remote labs, creativity supporting learning scenarios, curriculum development

I. INTRODUCTION

The European Union has declared the year 2009 as the European Year of Creativity and Innovation. Facing tremendous problems, creativity and innovation were seen at the heart of the strategy to transform Europe into a knowledge-based society that is able to cope with ongoing and future problems. For example, new techniques to tackle climate change are urgently needed, new ideas on how to retain mobility of people, new concepts for energy production without fossil fuels. Engineers play an important role in addressing these challenges. Their ideas, their inventions, their creativity have brought Europe's prosperity, and it will depend on their inventions and creativity to ensure that progress in the future.

According to Feisel & Rosa [1] an engineer should be able to "demonstrate appropriate levels of independent thought, creativity, and capability in real-world problem solving" (p. 127). But where, how, and when may s/he generate these competencies? The core of the questions raised here can also be found in a parable told by Hans-Jörg Bullinger, president of the Fraunhofer Gesellschaft, on the opening of the ball of the Association of German Engineers (VDI) 2005: "Our students found the lectures on the meaning and purpose of DIN standards only limited fun. In a nice irony they told the story that a mathematics student and a physics student had just met an engineering student. They could not agree on the volume of a golf ball. So everyone picked up the methodology which corresponded to his field. The mathematician measured the diameter and the indentations on the surface and began to count. The physicist put the ball in a full glass of water and determined the displacement of water. And what did the engineer? He looked in the DIN standard for golf balls."[2]

In summary, the question is raised, in what way universities contribute to educate creative engineers nowadays.

To find an answer to this question, two projects have been conducted. First, the German research project "Da Vinci – fostering creativity in higher education" started in 2008 (supported by the German Federal Ministry of Education and Research BMBF, 2008-2011). This project followed an interdisciplinary approach and was with the object of designing generic creativity supporting learning scenarios. A second project, the ELLI project ("excellent learning and teaching in engineering education", 2011-2016 funded by the German Federal Ministry of Education and Research "BMBF") still runs today and has the task to bring engineering students into focus and foster their creativity, based on the results of the Da Vinci project.

II. FOSTERING CREATIVITY IN HIGHER EDUCATION

Research on creativity in formal education hasn't led to an own discipline yet, but a lot of work on this topic from different disciplines has been done so far (e.g. psychology, philosophy, economics, pedagogy). The parallel activities from various disciplines are one reason for the immense heterogeneity of approaches that try to explain the nature of creativity, but even within the subjects contradictory attempts coexist [3],[4]. Choosing one of those approaches as a basis for fostering creativity at universities would always mean to exclude those students, teachers, and researchers who favor an opposite concept of creativity. Against this background, the existing research work on creativity can be used for inspiration, but it doesn't provide an expedient working basis.

Regarding higher education, only few researchers have already tried to contextualize creativity. The effort of some British researchers has to be highlighted [5],[6]. They created the Imaginative Curriculum network, which carried out some sensible and helpful concepts of promoting creativity at universities. With quite an open understanding of creativity, they tried to include all individual perspectives on this issue. However, even their respectable attempt to explain creativity wasn't a proper science base for the DaVinci project. Due to the concept's openness, no concrete and practically manageable anchor points for fostering creativity in higher education were provided.

For this reason, the DaVinci project was faced with the task of operationalizing the concept of creativity in higher education. In a qualitative study, 20 expert interviews were conducted. 10 interviewees were supposed to be experts in creativity, because they have won teaching awards, got a good review at 'my prof' ("meinprof.de"[1]) or offered a course about creativity. These experts came from different disciplines (for instance, computer science, science of economy, sociology, engineers). In contrast, the other 10 interviewees were teachers of pedagogy in order to find out how creativity is characterized in everyday teaching and whether there are disciplinary focuses.

All interviews were transcribed, labeled, and ordered. The analysis results show a model of creativity in higher education (across all disciplines), which consists of 6 different facets (see Fig. 1) [7],[8],[9],[10]:

1. **Self-reflective learning** – teachers help learners to break out of their receptive habitus and start to question any information given by the teacher. An internal dialogue takes place and knowledge becomes constructed rather than adopted.
2. **Independent learning** – teachers stop to determine the way students learn (different learning pathes, personalized learning). Instead, they support students to start for example to search for relevant literature on their own, they make their own decisions about structuring a text or they even find their own research questions and chose the adequate methods to answer it.
3. **Curiosity and motivation** – teachers support learners to be curious and to question the topics; this aspect relates to all measures that contribute to increased motivation, for instance the linking of a theoretical question to a practical example.
4. **Learning by creating something** – Teachers foster students to learn by creating a sort of product. Depending on the discipline, this might be a presentation, an interview, a questionnaire, a machine, a website, a computer program or similar. Students act like researchers.
5. **Multi-perspective thinking** – teachers create a learning environment where learners overcome the thinking within the limits of their disciplines or prejudiced thinking. They learn to look automatically from different points of view on an issue and they use thinking methods that prevent their brain from being "structurally lazy"[2].
6. **Reach for original ideas** – teachers help learners to aim to get original, new ideas and prepare themselves to be as ready-to-receive as possible. Getting original ideas cannot be forced, but by the use of appropriate creative techniques and by creating a suitable environment (that allows making mistakes and expressing unconventional ideas without being laughed out or rejected), the reception of original ideas can be fostered.

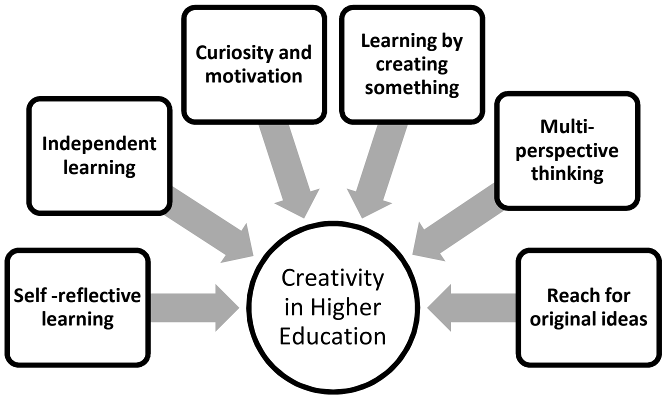

Figure 1. 6 facets of creativity in higher education

To validate this model, an interdisciplinary online survey of teachers at three German universities[3] was conducted. Almost 300 teachers participated in the (non-representative) survey (n=296) and gave 600 answers to the question "What is a creative achievement of your students?" (multiple answers possible). In the next step, they were asked to map their responses to one or more of the 6 facets. In addition, they had the opportunity to choose the option "does not fit" in case they thought that none of the 6 facets was suitable. Again, multiple answers were possible, and altogether 1.844 assignments were made (see Fig. 2, Fig.3).

It is quite remarkable that the option "does not fit" was selected for nine answers only, which makes about 0,5% out of all answers. This result indicates that the 6 facets are actually able to comprise almost all of teachers' concepts of creativity in higher education. What is more, all six facets are about equally represented, which suggests that (across all disciplines) all 6 facets are equally important. There is no facet that really dominates the concept of creativity or that doesn't matter.

1 A German Internet portal where students can rate their teachers.

2 According to [11] brains are used to work with mental patterns. The more successful such a pattern is, the stronger it becomes and the more often it is remembered and used again. Considering Spitzer's theory, for example most adults' brains have saved a very strong mental pattern for brushing their teeth. Regarding the brain, this is very helpful and effective, because those adults don't need to figure out each morning anew how to brush their teeth. Regarding creativity, this is obstructive, because those adults won't ever invent a new, maybe more effective way of brushing teeth.

3 The University Alliance Metropolis Ruhr: University of Duisburg-Essen, Ruhr-Universität Bochum and TU Dortmund University.

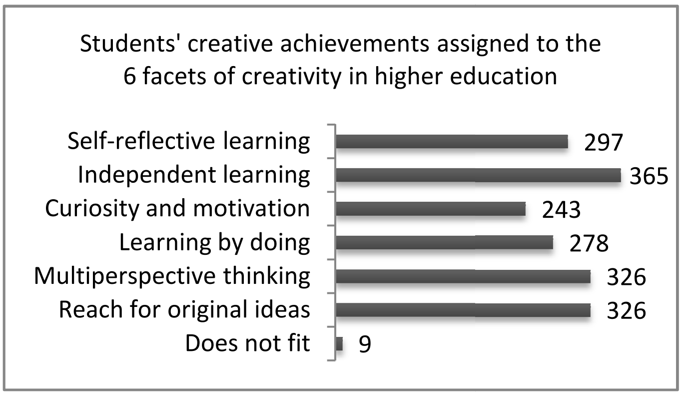

Figure 2. Validation of the 6 facets of creativity in higher education

As a result of the DaVinci project, this model of creativity in higher education has been used as a reflection tool for fostering creativity by many university teachers in several higher education workshops and has proven its usefulness.

III. Is there a lack of creativity in higher engineering education curicula?

Regarding creativity in the field of engineering education, some work has already been done: Thompson & Lordan [12] review essential findings and techniques in the scientific literature about creativity and try to transfer them to engineering education. Though, they don't substantiate the benefit of simply using creativity techniques in teaching courses, nor do they present appropriate learning scenarios. Cropley & Cropley [13] remarkably work on different theories about creativity from various disciplines, but even they are faced to the problem to define creativity and somehow remain stuck in the discussion about assessing creative efforts. Nevertheless, they describe an interesting learning scenario that guides students to reflect their own creativity. Byrge & Hansen [14] present the creative platform, a concept that focuses on confidence, concentration, motivation and diversified knowledge. Though, a concrete didactic scenario for engineering education is missing. Finally, such a scenario is delivered by Zhou, Holgaard, Kolmos & Nielsen [15], and Zhou [16]. They combine principles of enhancing creativity with problem based learning and project based learning in engineering education. They justify their actions very well, prove the creative benefits, and show concrete actionable educational measures. Unfortunately, such fine concepts are still very rare.

To sum up, there a several good approaches, but still far too few or they are limited to single aspects of creativity. To foster creativity in engineering education, a lot work still has to be done. More knowledge about creative education is necessary.

Based on the interdisciplinary results of the DaVinci project, the ELLI project has the task of promoting subject-specifically the creativity of engineering students at universities.

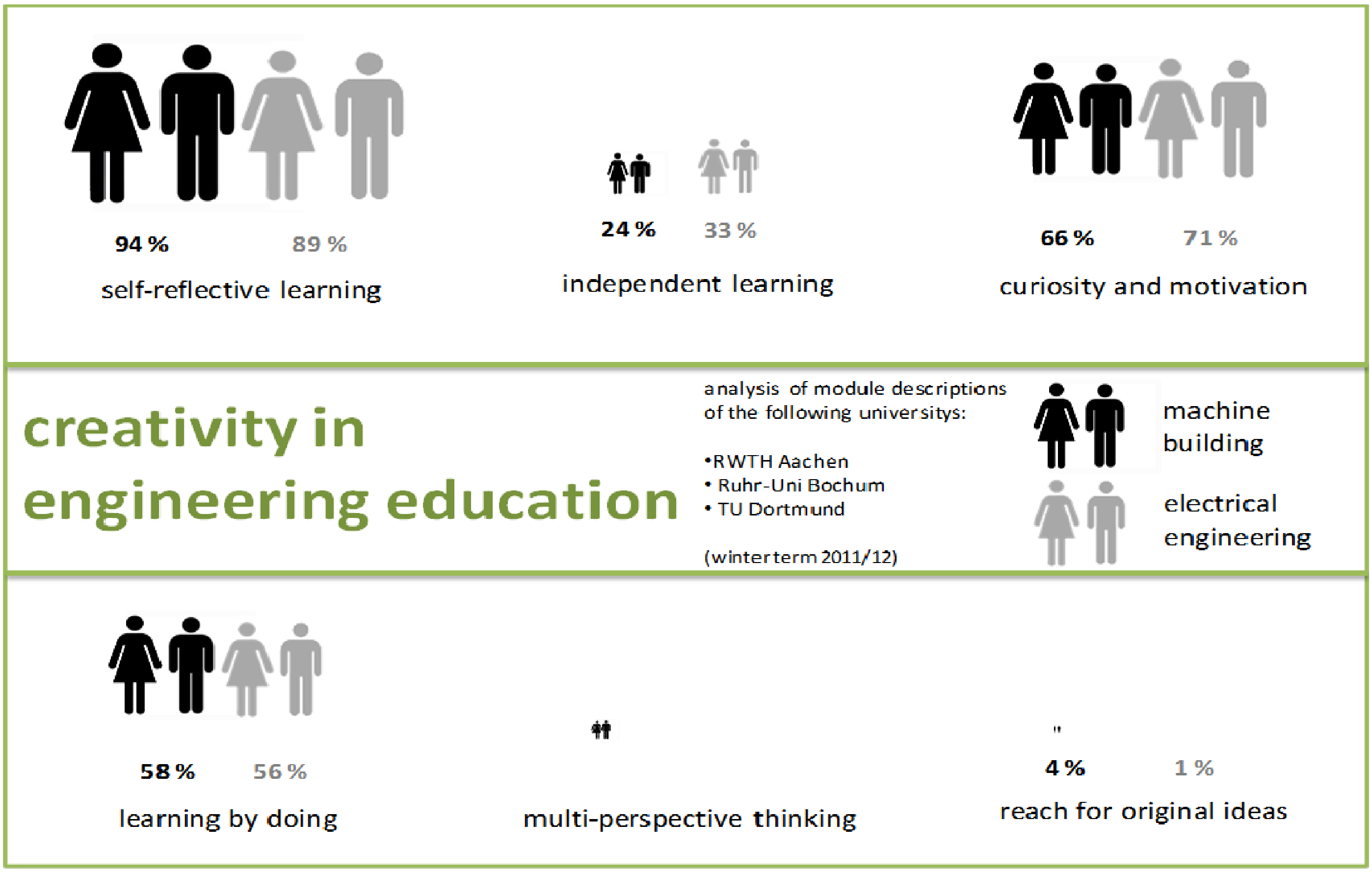

Figure 3 creativity in engineering education

As a first step, a preliminary study was carried out, which should identify the actual need. For this purpose, we analyzed the module descriptions of six engineering education curricula (Manufacturing Engineering and Electrical and Electronic Engineering IT) of three German universities (Aachen, Bochum, Dortmund) in order to get to know which aspects of creativity are fostered in today's engineering education (see Fig. 3). The module description is only one small piece of the picture and we know this. But it is a start to analyze creativity.

As a result, fostering the creativity-aspects 1 (self-reflective thinking), 3 (curiosity and motivation), and 4 (learning by doing) is highly developed in both courses of all three universities. With one exception these aspects have shares of over 50%. On the other hand, the aspects 2 (independent learning), 5 (multi-perspective thinking) and 6 (reach for original ideas) can be found only in small proportions with percentages below 50%, in aspects 5 and 6 with one exception even below 10% .

To sum up, these pre-analysis of the module descriptions shows that in the considered courses students were encouraged to think critically and self-reflective. They had to demonstrate motivation and commitment in their courses and they were trained to create something, to work practically. Independence, collaborative development of ideas and the exchange with other disciplines and for open-minded discussions, scenarios and experiments, however, were almost not required and promoted.

Together with empirical experiences in engineering education a picture of diligent students is emerging, who rather work conscientiously on given tasks than finding new problems, questions and solutions on their own and in discussion with others. Also, the fact that in some of the courses the students were not free to choose the topic of their thesis reinforces this picture. Instead, they have to choose it out of a pool of given topics developed by the teachers.

In this way, many learning processes that require creativity weren‘t done by the students, but by the teachers: the detection of relevant research questions, the deliberation whether an issue is workable, the creation of a structure and the assessment of eligible methods. Due to this, students aren't able to see the "big pictures" of their discipline, which is only seen by the teachers. They don't get in touch with the spirit of research: the (collaborative) reasoning about current issues in the community, setting up and discussing new (and sometimes as well risky) theories, the making of own decisions and seeking collegial advice. When students are able to see the big picture, they get a feeling about the value and importance of their work.

Through these findings, the question rises whether this understanding of fostering creativity in engineering education is appropriate. However, students seem to have a different understanding of creativity. An interdisciplinary survey (n=320) at TU Dortmund University (Germany) shows that students regard "openness", "freedom", "stimulation", "inspiration" and "empowerment" as factors that promote their creativity (see Fig. 4). Pressure, constraints, boredom and monotony, on the other hand, hinder their creativity (see Fig. 5).

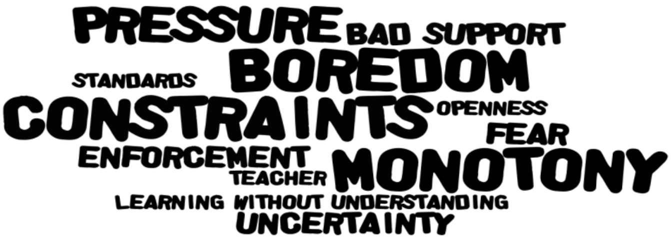

Figure 4. Students' perspective on factors that *hinder* creativity

Figure 5. Students' perspective of factors that *foster* creativity

At this stage of the investigation these results need to be treated very cautiously; they depend on a very small, arbitrary sample of only six courses from three different universities. Further studies must and will be done. Nevertheless, the study's results provide first hints about where to start when coming to fostering creativity in engineering education. In the following two approaches are described, which also take the spirit of research into account.

IV. Two Examples of Best Practices

A. Fostering Creative Learning by iPad-Didactics

In a municipality in Denmark, seven K9 schools implemented iPads for all 200 teachers and 2,000 students from grade 0 to grade 9. In a first study, we conducted 15 classroom observations and 13 interviews with teachers. Here, we make one creative example visible that illustrated a typical iPad-Didactics case that can be easily transferred into engineering education [29].

1) A Creative Task for Science Learning

The case was a 9th grade physics classroom with a male teacher and 15 students (8 F; 7 M) from 8:00-9:30 a.m. in the morning. The main learning activity for the students was to design new experiments based on the prior knowledge the students gained from previous classes. The objective was to apply the recently learned knowledge and to show the teacher the learning outcome in the field of Sound, Light, Magnetism, Electricity and Chemistry. The teacher's instruction to the students was, "Please, show me something essential about sound or light, and create a new experiment". He also asked them to document their process of planning and conducting the experiment.

2) iPad-based Group Learning

While some students gathered and built groups and started to work on the assignment, one group of two students were not sure how to start. The teacher thus created a new assignment for their personal needs but asking them to create a joint mindmap using the app Popplet. They brainstormed to collect their knowledge into one mindmap to identify their personal gap in knowledge. That gap then served as the starting point to plan the experiment.

The other groups had some ideas already and started with the experiment without making a mindmap. In one group there were up to 7 students who worked together, in other groups there were 3 students. As part of their experiment, the students used the Camera and Video recording features in the iPad, and took photos and made podcasts. They also podcast the preparation of the experiment in case the experiment would fail, to show the teacher what they had done till that point and to analyze why the experiment failed. iPads were thus used by the students to document the process of creating the experiment, in addition to the following ways in which they used them:

- Searching for information (in Google/Bing, Youtube etc.),
- the 'Textbook' app (an app that has a lot of textbooks),
- Pro Tuner (a tuning app),
- to upload their documentation (Dropbox app).

In this case, the students got the opportunity to reflect on their existing knowledge and to create new knowledge. The assessment was process-based and part of the learning process because the teacher could gauge how much the students had understood from previous lessons. The teacher said in the interview that followed, "How do I know when the students have learnt something? When they can apply it to the real world". He stressed that the students are able to check their theoretical knowledge by transferring this into concrete physical experiments. The teacher also immediately checked the results of the experiment in the class and gave feedback. Students then shared the results in Dropbox and got feedback from their peers.

3) Classroom Oberservations

One classroom observer described the feeling in the classroom "somewhat chaotic, but in a good way". He stated that, "some teachers would not have liked the informal way of doing teaching". However, the observers noted that all students were engaged in the task and looked genuine interested in their experiments. The main communication in this classroom was among the students. This corresponded to the teacher's statement during the interview that he strongly focused on "informal teaching", where he would rather be in the background and let the students experiment. He liked to foster a role change, where students become the person who teaches other students, and he acts like a process mentor who supports the personal learning needs of the students instead of telling them the facts.

One example of this – during classroom observations – the teacher asked the students to first present their idea for a new experiment on a blank sheet of paper and so, the students themselves got a "aha" effect; they suddenly saw that the idea was not clear enough and why the experiment went wrong. The teacher stated that this assignment was based on his philosophy of students "learning by mistakes." He said his designs for learning are based on the idea that students "test their theories through experiments within a given field (e.g., sound, light) and translate it, to learn how it works in reality".

4) Creative Process-Product-oriented Learning Outcomes

This case presented here represents active learning where there was a focus on action and a focus on students "to produce something." Read the digital didactical designs in detail in Jahnke & Kumar 2012 [29]. The teachers' design for teaching and their design for learning included active student participation, student engagement and student motivation by "doing" something. The students produced something and while doing so, they reflected and learned; the reflection research points to a positive relationship between being active and a deeper learning outcome [30].

5) Enabling the Spirit of Research

The didactical designs by the teachers were both process-oriented and product-oriented (see creativity facet 4, 'learning by creating something'). The teachers did not only focus on outcomes or exams/test only and did not expect students to reproduce the facts. Both the teachers had a learner-centered approach – they allowed their students to learn by making mistakes, they wanted to challenge their students, and yet, they scaffolded the learning process by providing feedback and personalizing the learning experience for students who struggled.

This example illustrates how the iPad served as a "booster" to support the spirit of research in a way where learning is didactically designed as a *process* where the students *produce* something to stimulate communication and social exchange. The students acted like researchers; they planned an experiment and made it come true. In those stages, some students made mistakes and the experiment failed. But this is part of good research and the teacher supported his students to learn from their mistakes. Together, they analyzed what went wrong. Then, the students revised the plan and made a revised successful experiment.

In all of our classroom observation cases, the iPad was integrated into a digital didactical design, in addition to active learning and a process-orientation, the didactical design included both teacher-student and student-student interaction and feedback. These elements together form the digital didactical approach that can foster a creative learning approach to establish a spirit of research among students.

B. Fostering Creativity with Remote Labs: PeTEX – Platform for E-Learning and Telemetric Experimentation

The didactical concept of the "Platform for E-Learning and Telemetric Experimentation" (PeTEX) is another example [17],[18],[19],[20],[21],[22],[23],[24],[25]: The PeTEX system is designed for the usage in higher education and for workplace learning.

PeTEX combines a tele-operated experimentation platform (material testing, particularly forming, cutting, and joining) with a collaborative learning environment based on Moodle. It provides three different learning levels deploying three different didactic approaches, addressing three different problem types. The three levels correspond to three of the six facets of fostering creativity (see table 1).

1) Three Consecutive Problem Levels to Foster Different Facets of Creativity

a) Beginner Level Learning with Interpolation Problems

Students in the beginner-level are guided through the learning platform and are asked to create predefined and expected order in a given complexity of elements and actions by identifying, assembling and executing all given elements and actions in the right order to solve the task, in the PeTEX case to correctly carry out predefined experiments. These predefined experiments consist of interpolation problems. According to [26],[27],[28] interpolation problems consist of three elements:

- a predefined starting point (1),
- a concrete terminal point (2), and
- a concrete and predefined solution process how to bridge the gap between starting point and terminal point (3).

The challenge of this kind of problem is to correctly fulfill a sufficient complex task according to the given and scripted path. It deals with recognizing of and acting in complexity: e.g. understanding the manual, identifying the relevant units of the real equipment introduced in the manual. The next step is to combine, assemble, and connect these elements in the right scripted technical and logical order in order to fulfill the pregiven task, and to produce the expected results.

TABLE I. THREE CONSECUTIVE LEARNING LEVELS, CORRESPONDING TO THE PROBLEM TYPES AND THREE FACETS OF CREATIVITY

Learning Levels	Didactic approach	Problem type	Creativity facet
1. level: Beginner	scripted learning paths	interpolation problems	1. self-reflective learning
2. level: Intermediate	real world scenarios	synthesis problems	4. learning by creating something
3. level: Advanced	research based learning	dialectic problems	6. reach for original ideas

The main creativity facet addressed by that kind of task is to break out of the receptive habitus and to start questioning the given information by transforming them into correct action.

b) Internediate Level Learning with Synthesis Problems

In the intermediate-level, learners have to transfer their knowledge to given real-world scenarios and are encouraged to perform their experiments in a self-directed way. According to [26],[27],[28] real world scenarios relate to synthesis problems which consist of three elements:

- a predefined starting point (1),
- a concrete terminal state (2), and
- no defined solution process to bridge the gap (3).

The challenge of this problem type is to find, to develop and to deploy a sufficient solution path to a given problem consisting of a presented starting point and an expected terminal point by applying divergent and convergent thinking to find and implement an appropriate solution for the given problem. The creative final product is the developed solution which is gained mostly "by doing" and the competencies the learner has gained with this kind of tasks are generated with "learning by doing" according to II.4 presented in this paper.

c) Advanced Level Learning with Dialectical Problems

Learners at the advanced level have to design own research questions and to develop the appropriate experiments. According to [26],[27],[28] those dialectical problems consist of

- no predefined starting point
- no predefined terminal point
- no predefined solution process

The challenge is to apply the developed knowledge, skills, and competencies of the learners to find and define novel and origin problems as research questions, defining a starting point, a final state, and the means for gaining it, like a concrete new product, prototype, theory, process, and so on.

2) Dealing with Increasing Complexity in PeTEX for Fostering "The Spirit of Research"

The more the students have worked with PeTEX, the more freedom they get to define their own research problems and to find the answers on their own. Furthermore, PeTEX provides collaboration, not only with other students (from other universities and even other countries), but also with lifelong learners. In summary, PeTEX offers an important contribution to foster the "spirit of research".

V. RADICAL CONSEQUENCES AND CHALLENGING OPEN QUESTIONS

It remains unclear whether these points also play an important role from the perspective of the teachers and, furthermore, parts of the society:

- How to foster creativity in science and engineering education courses and curricula?
- How to train teachers efficiently and successfully in creativity fostering techniques?
- Are open experimentation and trying out new ideas, the search for the unknown new really important for a society in a globalized world economy?

- Does our economic society indeed need diligent professionals who execute given tasks instead of developing their own initiatives?
- Does our industry require graduates that are used to think multi-perspectively?
- What is the role of a new thinking culture?
- What wishes and visions do teachers, researchers, industry representatives, professional association representatives have with regard to the education of tomorrow's engineers and to their creativity and their "spirit of research"?
- What kind of education will be needed, if a society wants to bring up future inventors who are able to cope with the problem mentioned by the European Union?

These questions should soon be discussed in a broad social debate. Further studies on the impact of teaching creativity need to be done urgently.

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