Abstract

The competencies to manage an engineering project, work in and lead a team are demanded from a graduate of a higher engineering education. A design education model, consisting of of two linked courses, is presented that allows students to learn key engineering and social competencies by experiencing real situations. During the course “Innovation Project” (IP) approx. 450 freshman solve a development task in a team (creating a mechatronic system). The course “Leading Engineering Projects and Coaching Design Teams” educates IP student coaches in team dynamics and how to coach an innovation team. The aim of this paper is to present the recent development of the educational model. In this paper we focus on the IP course. The team climate curves are analysed and the qualitative data describing the turning points in the team climate curves is used to derive critical competencies for the IP teams. Four different competency clusters were found. The results show that not only technical skills are learned in this course but even more so multidisciplinary skills. The influence of the coaches for competency development is ongoing research and will be evaluated in further research. The results underline the need for educational approaches that focus on technical skills as well as multidisciplinary skills. The education model prepares the students well for their future design challenges.

1. Introduction

In the last years the discussion about the future of professional education for engineers as proposed in various initiatives and guidelines reflects the need for a broader and more competency-based schooling. Crawley et al. [1] formulate the purpose of engineering as follows: “The purpose of engineering education is to provide the learning required by students to become successful engineers – technical expertise, social awareness, and a bias toward innovation. This combined set of knowledge, skills, and attitudes is essential to strengthening productivity, entrepreneurship, and excellence in an environment that is increasingly based on technologically complex and sustainable products, processes, and systems. It is imperative that we improve the quality and nature of undergraduate engineering education”. One of the most influential associations of professional engineers, the german VDI, has issued a new guideline focusing on leadership [2] as one of the expected competencies of professional engineers for nowadays challenges in industry. The ETH Zurich, among other leading universities, has started an initiative on critical thinking, thus focusing on generic competencies and not just technical excellence [3].

These needs of industry and society are mirrored as well by recent findings of competency-research. It seems that social competencies classically defined as important for team-development and good working climate are also crucial for the use of technical skills in working environments. Results of various studies show that technical skills are only usable for groups and therefore organisations if they are enabled by social skills [4–7].

Higher education has therefore two challenges: being able to impart technical knowledge that students and future engineers are able to apply in their future occupations and teach social and individual competencies needed to use the acquired technical knowledge and know-how. In this article we describe a higher education teaching set-up that fulfils both needs. The set-up consists of two connected courses. In a first course students learn in a problem-based learning (PBL) approach [8] to work in teams while gaining knowledge and know-how in basic engineering subjects. The students of this course are coached by senior students. These senior students are taking a course in coaching and leading engineering and innovation teams. In this multilevel educational design students train and practise social and multidisciplinary skills: on a basic level in the Innovation Project (IP) and on a more advanced level in the Leading Engineering Projects and Coaching Design Teams (CDT).

In this paper we will focus on the IP course. The learned competencies in the CDT course are already described in another paper [9]. We will therefore show the contribution a problem-based learning course can do to competency development.
2. Setting

The learning environment as it is implemented in the Mechanical Engineering bachelor’s program at ETH Zurich is presented in the following section. The learning concept consists of two linked courses: Innovation Project (IP) and Leading Engineering Projects and Coaching Design Teams (CDT) \[10,11\]. The multilevel education model impacts the students in different stages of their curriculum. The linkage of the two courses allows all involved protagonists to bidirectionally benefit (Fig. 1). The specific learning goals of the education concept are presented and evaluated in an other contribution which is currently in press \[9\].

2.1. Innovation Project

The IP is a large, project based class with approximately 450 freshmen students. The practice-oriented course concept is an implementation of the CDIO initiative (Conceive-Design-Implement-Operate) \[1\]. The students are divided in teams of five. The teams develop during 14 weeks a fully functioning machine (mechatronic system) which can solve an operational task. All teams have to show and operate a fully functioning system at the end of semester. Know-how and techniques from the fields of engineering design, production and mechatronics are thereby brought together and implemented in the student’s solutions. The students learn and apply techniques to manage innovation processes by undergoing such a process. Meboldt et al.\[12\] describe the essential elements of the course and compare it to trends in engineering education. Several practice oriented course concepts exist in curricula of other universities, e.g. \[13–16\]. The application of high-fidelity prototyping and PBL in a large class setup for first-year students makes the IP unique. The course is constantly developing.

The IP recently developed by the introduction of additive manufacturing, the expansion of the assembly shop floor, a new and more professional mechatronics kit and the variation of the development task. Access to additive manufacturing technology extend the team’s possibilities to produce accurate high-fidelity prototypes directly from a digital model (CAD). In addition to the four already available laser cutters to produce 2D parts \[17\], nine FDM Printers by Stratasys\[18\] can be used to manufacture 3D plastic parts. In order to handle the large class and to improve the quality of prototypes, the capacity of the assembly shop floor and the quality of tools and machines are increased. The students have access to drilling and grinding machines, belt saws, soldering devices and 15 workbenches equipped with a variety of hand tools. A mechatronics kit based on myRIO \[19\] and developed by pdz enable the students to operate their systems without having expertise in programming and mechatronics (Fig. 2). Even though the entry barrier to gain first experience with mechatronic product development is low, the kit has a professional standard. The mechatronics kit consists of several actuators (servo motors, stepper motors, DC motors and solenoids), some contact sensors, a base unit containing power electronics and docking ports, an embedded hardware (myRIO) and a software cockpit to operate and program the system (based on labVIEW). The software cockpit allows to run the system on three user levels: newbie, expert or ultimate. The lowest, “plug & play” level allows manual and sequential driving of motors. The highest level allows fully programming flexibility and automation. In order to keep their intrinsic motivation high the students are challenged by a new development task every year. The most current task “robot fire fighter” demands to develop a robot which can climb up the model of a “burning” multi-story building, extinguish fires and evacuate people and chemical barrels (Fig. 3). The task promotes a high solution variety because its formulation is open and shows the characteristics of an optimisation problem. The performance of the robots is assessed in a competition. Within a specified time frame (five minutes) the robots evacuate respectively extinguish as many units as possible. The specific location defines the varying score of the items. Further, a jury assesses the quality and economy of the design and the degree of technical innovation.

Beside participating in the final competition, the students compile four deliverables: an individual milestone presentation, a report per team, a short video on their project per team and the prototype itself. They receive a grade for each deliverable and one additional grade for participation and approach. The five grades are then integrated into one final grade, all having equal weight. The IP students get 2 ECTS credits for their participation. The course is compulsory.

During the project, the teams are coached and supported by student coaches, more advanced students, in workshop sessions. Each team profits from an hour of individual consultation per week. Each student coach is responsible for three teams. Therefore 30 coaches are involved in the project. Delivery of intermediate results takes also place during the workshops in form of milestone presentations. In a newly developed
Boundaries to build relationships, scout necessary information, and empower their teams to achieve success” [21]. In the IP the CDT participants apply the theory and actively experience being a coach. Additionally, CDT participants are coached by two expert coaches. They act both as role models and teachers. As a third component of the course always two CDT students join together for work shadowing on a regular basis. Mutual observation and feedback accelerate the learning progress and improve the quality of teaching in the IP. CDT students get 4 ECTS credits for their participation in this elective course.

2.2. Leading Engineering Projects and Coaching Design Teams

The course CDT runs parallel with the IP and focuses on team dynamics and social effects in product development teams. It is similar to the IP, a practice-oriented lecture concept. In addition to coaching theory, the participants of CDT acquire competencies by experiencing real-life situations as a student coach in the IP. This basic idea is also practised at the Technical University of Munich (TUM) [20]. The TUM tutors coach student teams with respect to study related topics (e.g. curriculum planning) but they do not learn coaching of development teams. Each CDT participant is responsible for three IP teams, which are indeed real development teams. The aim of the course CDT is to prepare the students for a role as team leader in an engineering project. The course is offered for 15 advanced students only, who all work as coach in the IP.

The team leader of an engineering team is ideally not the decision maker nor the one with the deepest technical understanding. This role should rather empower the team to outperform: "effective external leaders move back and forth across boundaries to build relationships, scout necessary information, persuade their teams and outside constituents to support one another, and empower their teams to achieve success” [21]. In the IP, the coaches support the teams without imparting knowledge. They facilitate and guide the team members in achieving their project and learning goals. "Coaching is unlocking people’s potential to maximise their own performance. It is helping them to learn rather than teaching them” [22]. The CDT participants learn to support the IP students by asking critical questions, by helping them to make their own decisions, by working as a mediator to overcome conflicts, by functioning as an external observer and by enabling a feedback culture. Coaching has also an impact on individual and team creativity and improves the performance of innovating teams [23].

The concept of CDT consists of three central learning elements: theory about coaching, practice in coaching and formation of a coaching mindset. In a traditional lecture set-up coaching theory is conveyed and illustrated with cases. As coach in the IP the CDT participants apply the theory and actively experience being a coach. Additionally, CDT participants are coached by two expert coaches. They act both as role models and teachers. As a third component of the course always two CDT students join together for work shadowing on a regular basis. Mutual observation and feedback accelerate the learning progress and improve the quality of teaching in the IP. CDT students get 4 ECTS credits for their participation in this elective course.

3. Methods

In this article we focus on the IP course and the insights into the team-development and the necessary competencies for collegiate innovation teams. Our first research question is about the team-development. We are especially interested in the course of the team curve. How does the team curve develop over time? Will there be ups and downs similar for all teams or will there be individual team processes not comparable to one another? As a second research question we are looking into the competencies described by the IP teams. What are necessary competencies developed and needed by collegiate innovation teams? Additionally, we are interested in what way the found competencies are similar to the already existing competency catalogue by Goller[23] or if different competencies are important in the self-description of the IP teams.

Jensen and Harmsen[24] describe quite clearly that our knowledge of success factors by now is quite sufficient but we do lack knowledge about competencies. Therefore we lack knowledge about how to improve innovation in organizations and how to train it. Goller[23] deviates a list of competencies for R&D teams and shows that these competencies are trainable. Our question was (among others) if students in a R&D...
“simulation” do need the same competencies in order to be successful. We therefore used a qualitative approach to gather further insights into possible competencies and the team development of simulated R&D teams that are still learning and are not yet experts in the field.

At the end of semester the teams had to fill out a team climate curve and they had to define critical incidents (so called turning points) in their team efficiency or team climate during the semester (Fig. 4). The team climate curve plots the self-evaluated team climate over time on a scale of 0% to 100% (0% = very bad climate, 100% = very good climate). This approach is based on the Critical Incident Technique by Flanagan [25] because we wanted to elicit concrete behavioural descriptions in order to derive at competencies and not just at general statements as well as success factors. An “incident” is best thought of as “any observable human activity that is sufficiently complete in itself to permit inferences and predictions to be made about the person performing the act” [25, p. 327]. In order for the incident to be considered critical, “it must occur in a situation where the purpose or intent of the act seems fairly clear to the observer and where its consequences are sufficiently definite to leave little doubt concerning its effects” [25, p. 327].

The retrospective approach was important because we wanted to know the most important events during the complete semester regarding their success as a team and for their invented device and not just the most important event of the week.

Out of the 90 IP teams and therefore 270 turning points, 90 teams filled out the team climate curve and 78 teams indicated and described the corresponding turning points. In total 224 turning points were captured. All teams were asked to fill in not just a statement about the turning point but describe the reason for the turning point and the concrete change as well as the influence of the coach at the turning point. If there were any additional remarks the team would have liked to make, this was possible. For this analysis we were not interested in the gradient of the turning point (meaning towards good or worse) but just in the qualitative contents.

We conducted a qualitative content analysis [26,27] to cluster (if possible) the described reasons, behaviours and competencies. The data shows that the differentiation between the different questions (behaviour, reason, change) was hard to distinguish for the student teams. Sometimes the behavioural element was given in the change-question, sometimes (as intended) in the turning point description. The reason for the change was also described in various ways. Therefore we used all three categories for the extraction of the competencies.

4. Results & Discussion

The highest average team climate occurs in the second project week ($M = 79.23\%$, $SD = 18.05\%$) and the lowest in week nine ($M = 50.88\%$, $SD = 23.79\%$). The results show that for most of the teams the team climate was high in the beginning of the project, slumps after the first phase of the project and increases again towards the end of the project. This statement does not apply for all teams but represents a majority and is congruent with the team development stage model described by Tuckman, Bruce W. Jensen [28]. Most turning points where reported in project week eleven. The amount of reported turning point increases with the progress of the project (Fig. 5).

The first category “engineering expertise and mastery of tools” consists of statements about the importance of the mastery of tools needed to construct the needed device for the innovation task. Mostly digital design and production tools such as CAD is mentioned in these statements. But also the operation of the laser cutters for example belong to this cluster (Fig. 6). Students realize that mastery of a tool in order to implement innovative ideas is of essence. They describe the successful finish as a milestone that was harder than most students anticipated due to the professional expertise needed. They also realise at that point that innovation is not just a nice brainstorming but time-consuming, hard work. The second category deals with “team dynamics and work organisation”. Students describe all aspects of positive and negative team dynamics in this category. “The team is finally getting together” is seen as something relevant and getting to know each other is described as important behaviour in order to reach this turning point. Other statements in this category described the critical point if a team member is leaving this team (whether or not it was a critical phase or an important team member). It seems to us that teams are disturbed by changes in the team composition and do not deal well with it without intervention. Also described are delays and missed deadlines. Other turning points are characterised by unequal distribution of work load and imbalance of effort and benefit. And of course all sorts of squabbles and crises are described.

The third and biggest category is about “reality shock, test-
“menting and prototyping”. We probably named that category a little dramatic but the effect of testing and prototyping had a truly shocking effect on most teams. One team mentioned: “First test is conducted. The system failed. Further tests aren’t successful either. Frustration.” Most of the teams described the testing of certain functions or the prototype as a painful but healthy experience. Some teams found great happiness in the testing because they were better than expected. It seems that the interpretation and the effect on team climate is connected to the self-assessment of the team. We will elaborate on this further in the discussion section.

The fourth category is “decision taking”. Some teams described the act of (finally) taking a team decision respectively not being able to take a team decision as one of the three most important points in the innovation project, for example: “We agreed on a solution concept. Now, we have only one specific goal in mind. The mood increases.” Decision taking seems to be one of the major components for being successful in this course.

5. Conclusion & Further Research

What did we learn from this qualitative approach? One of the most obvious results is the category “reality shock”. It seems that with all the preparations, all the help reality in innovation projects comes as something unexpected. This is of course common knowledge but leads to different thoughts:

- all preparation and training cannot prepare for reality and testing
- testing and prototyping is a crucial element in the innovation process, as it is also stated by the design thinking theory [29].

Therefore much more time and energy should be invested for coaches and leaders of innovation teams not into preparation but into testing and pushing teams towards testing as early as possible. This insight has already changed our curriculum. We will change our innovation process towards agile development (e.g. scrum) and push teams so faster to testing and “their own reality shock”. It is also connected to competencies found by Goller[23] for R&D teams: Perseverance in the implementation process of ideas and building self-awareness (both personal competencies). Seemingly, industrial and collegiate teams face similar challenges if it comes to preparing for the unknown in innovation processes. We can only hope that the extent of surprise by reality gets smaller with more experience.

Another interesting element of the results are the indications towards social & methodological competencies. Using the competency model by Goller[23] we can infer certain competencies:

- methodological competencies for team settings:
  - Being able to use decision techniques for shared decisions in a team
- social competencies for innovative teams:
  - Cooperation with other team-members
  - Being able to build and to maintain team-cohesion
- personal competencies for shared learning:
  - Awareness of team dynamics in order to be able to deal with team processes and steer them

These competencies should be more looked after in the education of engineering students and in the facilitation of the teams.

Further research and development of the learning concept should address the question how testing and learning in product development projects can be speeded up. The introduction of agile process structures in the IP is an experiment towards this direction. The success and effectivity of this measure must be investigated. Further one must have a closer look on decision techniques for self-managing teams such as the IP teams which also have positive effects on team dynamics. How can a coach optimally support decision taking for example? One hour of coaching per team and week is not that much. How the amount of touching points between IP and CDT students can be increased is another interesting question.

Investigation and constant evolution of design education will guarantee well trained workforce (graduates) with the necessary set of competencies entering the labour market. The competencies of today’s graduates are the driver of tomorrow’s innovations.

In the described educational approach one can learn how teaching applicable engineering knowledge as well as critical thinking and social skills can be achieved not only for small classes but for a broad number of bachelor students. The described team curves and the derived competency clusters show what multidisciplinary competencies are most important for successful mastership of innovation projects. Therefore, this paper does not only contribute to competency research but also to the improvement of education for engineers for their future occupation in industry and academia.
References


