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Best Practice in Product Design: Concept Outlines and Experiences in Project-Oriented Product Design Education*

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For six years, the ETH Zurich in Switzerland has carried out a project-oriented training exercise on a course entitled 'Product Design'. An international evaluation nominated this course as being both successful and one of the best-practice courses. This paper describes the course in terms of concept, structure and content, and also describes experiences with project-oriented training exercises on this theme.

INTRODUCTION

WHAT DO THE following have in common?

- Carnegie Mellon University, Pittsburgh, USA
- Ecole Centrale, Paris, France
- Ecole polytechnique fédérale de Lausanne, Switzerland
- Georgia Institute of Technology, Atlanta, USA
- Imperial College London, UK
- Kungl Tekniska Högskolan Stockholm, Sweden
- Massachusetts Institute of Technology, Cambridge/Boston, USA
- Rheinisch-Westfälische Technische Hochschule Aachen, Germany
- Swiss Federal Institute of Technology, Zurich, Switzerland
- Technische Universiteit Delft, Netherlands

One of the things they have in common is the fact that they are all technical universities with excellent reputations for their engineering programs. A second characteristic they all share is that they all regularly evaluate their own programs in order to locate strengths and weaknesses and thus implement continuous improvements.

The joint decision to undertake mutual benchmarking was taken at the end of 1999. It was not ranking that was the target of this benchmarking, but rather the mutual location of the three most successful practices at each of the ten universities. The result of this project was called SPINE: 'Successful Practices in International Engineering Education', and was published in the spring of 2002.

One of the three 'best practices' of the Swiss Federal Institute of Technology is a mechanical engineering course—more precisely, the project-oriented part of a 'product design' course. This paper seeks to give an overview of this project, to summarize the experience of the past six years, and to present the reader with the project's conclusions.

CURRICULUM OF THE MECHANICAL ENGINEERING COURSE SEQUENCE IN 1997

In 1997, a new curriculum for mechanical engineering was implemented. Apart from various changes which cannot be described in detail in this paper, we also integrated two earlier subjects, construction and engineering, into the new subject, product design. The content of the earlier curriculum was rather limited and was largely composed of mechanical design methodology, machine elements, and applied mechanics. Although these were retained in the new curriculum, the focus has mainly been placed on the innovation process as a whole; that is, the progression from market to market. Additionally, many new subsidiary objectives that had not previously been well anchored have since been included. The specific aims of this subject, from the first to the fourth semesters, have now been relocated into the following topic areas:

- innovation management 'From market to market';
- processes and methods of product development;
- technical drawing;
- mastery of modern tools such as CAD, PDM and digital communication;
- mechanics of materials, dimensioning of simple components, engineering;
- structuring problems, finding answers in a diffuse solution-space;

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- team organization, teamwork, social competence;
- independence, initiatives for new themes and independent learning;
- oral and written presentation techniques;
- building syntheses with related subjects;
- ability to bring ideas to prototype, capability of implementation; and
- decision-making abilities and the will to complete goals.

The realization of these aims poses some problems, however, because conventional teaching methods, such as lectures, scripts and individual exercises, are largely inappropriate. When these topics are taught in lectures, their relationship to actual problems is not made apparent to students. Furthermore, many important facets of these themes cannot be learned by the individual when they are separated from their surroundings, but can only be acquired in a social context and then integrated into a learning environment, which should be as lifelike as possible.

DIDACTIC CONCEPT OF THE PRODUCT DEVELOPMENT LECTURE

These objectives, when taken together, demand a new and well-balanced program of lectures, which is drawn up as follows:

In one part of the program, the elements of engineering knowledge are offered within conventional lectures. Additionally, the contents of these lectures are integrated into an extensive online teaching platform.

A second part, shown as 'Exercises' in Table 1, concerns technical drawing; this is acquired and practised in groups with the help of assistants. In a third, independent block, modern engineering tools (CAD, CAE, PDM) are mastered in guided independent study.

The remaining goals, mainly metacompetences, are attained in a fourth, project-oriented, course block called the Innovation Project, which covers two semesters. Within this project, the students synthesize what they have acquired in the first and second semesters and integrate the regular lessons of the third and fourth semesters while accumulating real-life experiences and attaining the remaining goals in a practical context.

OUTLINE OF THE INNOVATION PROJECT

The Innovation Project was examined by the other nine universities mentioned above in order to better understand the concept and was eventually nominated as one of the three best practices. The process of the Innovation Project and its different phases are outlined below.

Starting the project

At the end of the second semester, when the students have achieved an initial level of knowledge of innovation management and have acquired some expertise, there is an internal competition in which students recommend possible products suitable for development within the project. The students (approximately 180) have already been grouped into teams of 12–18. Tutors, either postgraduates or students in higher semesters, coach the teams. With the help of the acquired creative methods, each of the 12 teams generates ideas for products. Altogether, there should be around 40 product ideas. A steering committee then selects suitable product ideas and prepares them to fit a formulated market requirement, which includes roughly sketched demands. This product positioning is distributed to all teams at the beginning of the third semester. The students then go through the various project phases arising from this positioning paper until they finally arrive at an actual prototype.

Team organization

One of the central learning aims is to cultivate an extensive ability to operate in teams. It is essential

Table 1. Didactic concept of product development

	Semester 1	Semester 2	Semester 3	Semester 4	
2 h/w	Lecture	Lecture	Lecture	Lecture	} Methods Knowledge Engineering
2 h/w	Exercises	Exercises			
2 h/w	CAD	CAD/ROM			

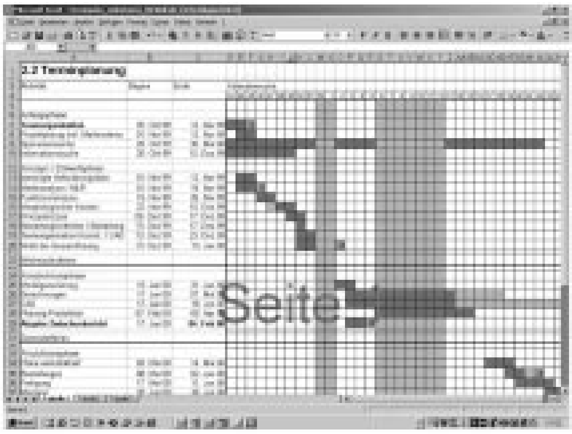
Specialization: drawing norms, teamwork (for all projects), presentation training, creativity, tools

Synthesis: increased competence of application, capability of realization, communication, the will to achieve completion, initiative

Note. h/w: number of hours per week (the terms are in the columns)
Semester 3: winter term; Semester 4: summer term
CAD: Computer Aided Design
PDM: Product Data Management

to integrate the various levels of student ability in order to arrive at the required team ability. The individual student has to be able to integrate into the group, and the group has to be able to structure the initially unclear problem formulation as a team. This process has thus far only been introduced to the students in lectures, and possibly through private activities, but has not yet been put to the test on the scale of the Innovation Project. Interestingly, most teams use a matrix team organization where members, on the one hand, take on long-term organizational tasks (financial responsibility, leadership, search for sponsors, etc.) and, on the other hand, receive special tasks (construction of a product module, engineering). After the first uncertainties in this new working style, appropriate structures are formed in each team and, after the first week, the teams are operating effectively.

The size of the teams sometimes poses problems, however, which are usually solved through substructuring. As always, in such heterogeneously composed teams, the differences in team members are quickly realized. Some members are more motivated and have stronger personalities coupled with greater effectiveness, whereas others are weaker, accomplish less and have to be pulled along. This always gives rise to discussions in the beginning, but this usually subsides after the initial phase. It could be argued that teams compensate for this discrepancy, since tasks must be accomplished by the weaker members too, and this process may reveal previously unknown strengths. Alternatively, also as a part of this learning process, the team may simply resign itself to carrying these less motivated members.


3.2 Terminplanung

Seite 1

Fig. 2. Excerpt of a diary.

Fig. 3. Discussion in front of the sketched solutions.

During the last six years, no problems have arisen that were sufficiently important to be brought to the notice of the steering committee. Teams have always managed to overcome their work and organizational problems without external intervention.

Process of market performance

Teams examine the targeted market and divide it into appropriate segments. In order to understand the client's needs more clearly, they conduct interviews with potential clients. In addition, they conduct current, state-of-the-art patent and competition analyses. This phase results in a clearly formulated and polished paper of the defined requirements prepared by the teams. The teams typically differ strongly in the definitive positioning of the products.

Fig. 4. Mutual explanation and understanding of solution ideas.

Fig. 5. Design study in collaboration with industrial design students (HGKZ, Zurich).

Conceptual process

In this phase, partial and overall solutions are used to tackle problem formation by means of various creative techniques. This is also the stage where students are fully able to express their inventiveness, and where they quickly realize that each team member has a unique solution. A lot of cooperation skills are needed in order to incorporate others' ideas and combine them with one's own or, especially painful, let one's own ideas go. Many discussions are needed, supported by rough visualizations (gallery method) and methodological evaluation in order to help choose a joint solution out of this jumble of ideas; in other words, to find what is presumably the best solution.

In later steps, students first prepare rough drafts and design studies and then build functional models with the help of wood, Lego, or other simple materials.

At this point, the steering committee expects to receive a logical and coherent report. When writing this report, students acquire the ability to construct a thorough report that includes all the necessary information regarding organization, procedures and current progress.

Interim report

All teams must hand in a report, in accordance with regulations, by the end of the winter semester. In this report, they must write about their project organization, their proposed schedule of work, and the methodological process of the concept phase, as well as including rough drafts of the new product. The second part of the project, the final drafting process, begins in the following summer semester.

Fig. 6. A simple functioning model.

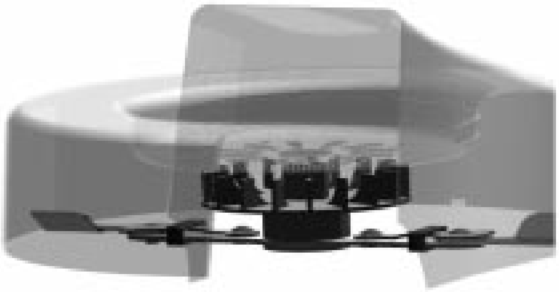


Fig. 7. CAD model of an assembly.

Drafting process

First, the products are constructed digitally with the help of CAD and are dimensioned and managed with PDM. The engineering tools that are learned and mastered in the first and second semesters, such as CAD and calculation tools CAE (finite element method), are used intensively.

In this implementation phase, students require much expertise. Questions they must answer include: which material should be used, which manufacturing process is most suitable, where to find already finished solutions and how to ensure an aesthetically pleasing design.

Considerable amounts of information and knowledge have been gained through the lectures, but teams have much to work out themselves as well, including having discussions with external specialists and finding and preparing their own solutions.

Prototyping process

In this phase, all of the components must be manufactured, which results in further, substantial,

Fig. 8. Intensive discussions at the drafting table.

Fig. 9. Team members during assembly of a real prototype.

learning. Students have to communicate with specialists from different workshops and the door to a new world is opened: talking about a real product serves as motivation to learning. Emotional highs and lows alternate: disappointment at setbacks because a part solution does not function, or, at the other end of the spectrum, the joy of success when all the parts fit perfectly. It is interesting to note that every team that has passed through this critical phase has thus far been able to produce a functioning prototype.

The teams contact different firms, mostly on their own initiative, and evaluate those that manufacture components for them. In part, this is made possible through sponsorship, with the remainder of the cost of materials paid for by the students themselves at a reduced price. Most of the time this is the first contact the students have with industries in regard to real business relations. They must make agreements, discuss alterations and materials questions, and, finally, they have to check the manufactured parts and pay the bills. The steering committee creates a learning environment which is designed to be as realistic as possible.

Final stage of the project

At the end of the fourth semester, after 200 days of intensive teamwork (in addition to all the other lectures, of course), the final presentation is held,

Fig. 11. Student during a presentation.

which requires students to consider marketing and sales aspects as well.

In the last week of the semester, teams present their final solutions to the steering committee in a professional, 15-minute presentation. It is quite amazing to see the extent to which students have progressed over the course of four semesters. There is enormous development in the way they use the presentation tools as well as the way they structure the content of their presentations; they are able to accomplish the formulated task very well.

Students must present their product to a wide, specially invited audience during a fair. Twelve different booths are planned and built by the teams. The stalls show their work by means of

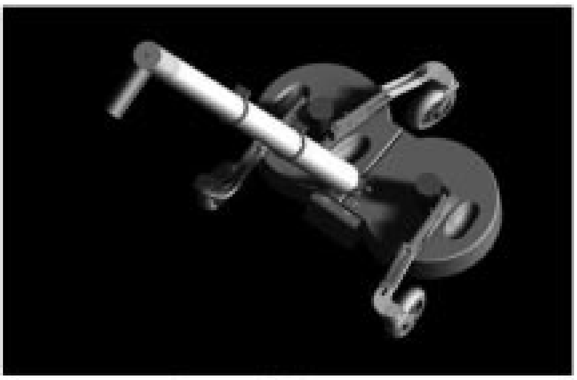


Fig. 10. Digital prototype.

Fig. 12. Booths of the different teams at the fair.

Fig. 13. View of a booth.

posters, videos, computer animation, etc. More than a thousand visitors are usually present and these help celebrate the students' well-earned success.

Final report

A final report and the handing over of the product mark the end of the project. Usually the approach, the structure, and the content of the final reports are of a very high standard. Additionally, it can be seen that the standard rises year after year, which is probably due to the learning transfers from previous years. Students from previous years are usually invited by the teams for talks.

Communication

In order to create an environment for the necessary communication, we provide the most modern communication tools available to the students and introduce these in a short training course. At the online 'first class' discussion platform (BSCW Server), there are discussion forum and general information areas open to the public, but each team also has a closed-off area where they are able to organize themselves individually. Usually the teams use this area as a central management resource for documents and as a discussion place. Regardless of where the team members are, they are still able to communicate and exchange documents.

The software tools are never taught and students receive only a brief introduction to them; nevertheless, they are immediately adapted by the students and put to effective use, which is an excellent source of feedback for the instructors. Additionally, the students use a PDM system (IMAN), with which they are able to manage the CAD data (Unigraphics).

Web presentation

In order to publish their work, students are given a server area for online team presentation at the beginning of the Innovation Project. All teams have used this and now very individual and creative publications continually appear (see http://www.zpeportal.ethz.ch).

Grading the project

The Innovation Project is graded and constitutes 40% of the marks for the entire course. The team receives a single mark, which includes grades for the interim report, the presentation, the final report, and the quality of the product. For the individual student's grades, the differences between the individual achievement of the team members is considered and then the common score is adjusted. The team coach is responsible for the grades and he informs the students.

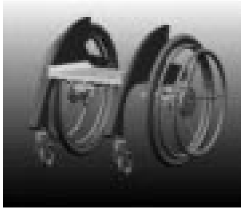
- Team grade = 0.3* report + 0.3* final report + 0.3* product's result + 0.1* presentation
- Individual grade = team grade +/− individual adjustment along with a personal assessment of the student's work over the past four semesters

The individual adjustment is mainly performed by referring to the qualification papers, which the group coach fills in for each team member after each semester. Recently some groups have wanted to categorize the individual achievements within the team themselves and have done so successfully.

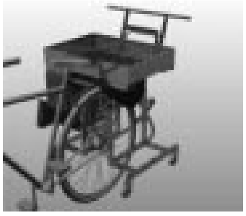
Realization of different projects

The Innovation Project has now been successfully completed six times (up to 2002), each year with a different theme. The project themes and pictures of individual teams' final product are shown below.

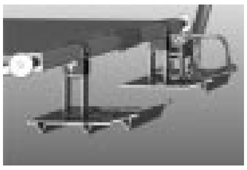
1996/97 Drive enabling hand-driven wheelchairs to overcome steep inclines



1997/98 Vehicle for individual short distance transport



1998/99 Transport for casualties on snow



1999/00 Millennium child-carrier

2000/01 Garden care

2001/02 Physics and games

Financing

Well-known financial sponsors and many other firms finance the projects. They sponsor whole projects at reduced costs or for free, mainly in the form of donations of manufactured goods. Each team receives a budget of €2000 from this financing.

INDEPENDENT LEARNING, NEW THEMES

Interestingly, students become motivated by the themes on their own initiative: themes which have meaning for the formulated topic, or themes that simply interest the students in general. In this way, some students have made extensive studies of the manufacturing and depositing of patents, have made complex multi-body simulation, or deepened their knowledge of mechatronic problem formulations. Often the result is a product in which electrical drives, sensors and control devices have been integrated in a way that has not been taught through lectures at that stage.

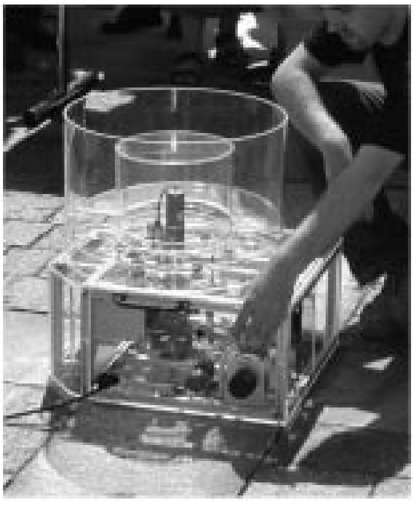


Fig. 14. Mechatronic product to shoot and train with uni-hockey balls.

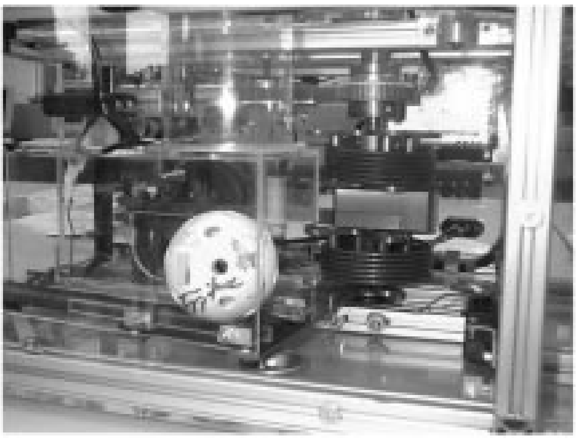


Fig. 15. Detail of the shoot mechanism showing the motor and the spring.

NETWORKING OF THE INNOVATION PROJECT

The Innovation Project has won a lot of attention over the past few years. There is a lot of interest, not only in carrying out the project with students in one's own field, but also in linking the project loosely, or even closely, with other disciplines. In recent years, this has led to the following instances of cooperation:

- Intensive cooperation exists with the department of Industrial Design Study at the University of Art and Design in Zurich for the past three years. Especially valuable here is the opportunity to discuss questions of design and functionality with designers and engineers at an early stage. Thus, we can provide the experience of a communication axis, which is often important in students' future professional careers.
- Educational cooperation between the University of St. Gallen and the Swiss Federal Institute of Technology in Zurich also exist. Students at the University of St. Gallen prepare business plans and marketing concepts around the Innovation Project. In this way, an early communication culture with business management and engineers is fostered.
- We would like to make a stronger attempt to push the mechanical apprenticeship. It is of great value for the students to discuss some of the problems in the manufacturing area with apprentices at an early stage of the project and exchange different experiences and expertise. The discussion of problems between future scientists and engineers and future professionals could produce a positive result at the level of social competence.

A further attempt to push cooperation on an international level would be most interesting. Networking of the Innovation Project with similar projects that cross country and language borders would represent the current situation of globally linked development projects very well and would be a very helpful experience.

EXPERIENCES WITH THE PROJECT-ORIENTED LECTURE MODEL

As with every other lecture model, this configuration has its advantages and disadvantages. The advantages include:

- strong motivation of students for a successful project;
- high learning success according to the formulated goals;
- experience in complex decision-making;
- encouragement of social competence through experience;
- strong learning outcomes, with influence overlapping among students in various years of study;
- self-motivation to learn more about new themes;
- pragmatic use of the most modern development, communication and visualization technology;
- capability for presentation and technical documentation; and
- beneficial cooperation with other disciplines.

The disadvantages include:

- team specialization leads to differing learning outcomes;
- sometimes an excessive focus on securing sponsorship;
- too much perfectionism in reporting;
- negative competition among teams; and
- too much time invested in the project, which may adversely affect other courses.

These drawbacks are the basis for a permanent optimization of the Innovation Project. Every year the goal, results and points of criticism are carefully examined and then improved upon in later projects.

FUTURE

In autumn 2002, the Swiss Federal Institute of Technology in Zurich will begin the new Bachelor's and Master's diplomas. For this reason, the structures and contents of the various lectures are being significantly revised. The Innovation Project will be moved to the fifth and sixth semesters, where the theoretical foundations of the previous semesters will form a more solid foundation for the project. At the same time, the number of hours allocated to the students per week will be increased to 15 hours over these two semesters.

The mechanics of a university seem to be the same as those of product innovation. Demands change permanently and in shorter and shorter cycles. We, as lecturers, are asked not only to take up these changes and implement them, but also to search for new ways and then experiment in order to proactively establish new standards. We would like to thank the SPINE university study for showing that we are on the right track and for further motivating us to build upon our achievements.

Markus Meier has been a full professor of product design at the Zurich ETH, Switzerland, since 1995 (http://www.zpeportal.ethz.ch). He and his group conduct research which focuses on innovation management, data structuring and data management in the product development process, as well as the visualization and simulation of complex mechatronic products in a virtual environment. A central theme of his research is concepts for product platforms. Within his teaching, new concepts of project-oriented training and e-learning are planned, introduced, evaluated and continuously optimized.