IMPART 'DESIGN FOR PRODUCTION' KNOWLEDGE BY APPLICATION OF FUNCTIONAL PROTOTYPING

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ABSTRACT
In engineering design the early consideration of 'Design for Production' aspects is of particular importance to avoid high costs and time efforts caused by late redesign iterations. In design education this knowledge needs to be imparted theoretically as well as practically. Students have to experience the consequences of incorrect estimations or incomplete design definition when producing. This paper presents an educational project work that was recently carried out as a part of the 'Innovation Process' course at ETH Zurich with 550 participating undergraduate students of mechanical engineering. The project work especially includes the production of physical prototypes, which provides the advantage of making design knowledge more tangible. The paper presents the differences of simple funky prototypes and more complex functional prototypes and reflects their application in the context of educational objectives with a special focus on imparting 'Design for Production' knowledge.

Keywords: Design for production, iterations, prototyping, tangibility

1 INTRODUCTION

Engineering design is essentially characterized by a multitude of different requirements that strongly influence the detailed design of product's components. A key competence to consider these relevant requirements is the ability to think ahead in the product lifecycle. Therefore it is important to early include production aspects into theoretical and practical design education. Although the relevance of 'Design for Production' is well known in engineering design, educational project work usually ends with a detailed design in the virtual form of 3D-CAD models. Thus, the producibility of components designed by students can only be discussed theoretically and cannot be experienced in a personal way. In order to enable students to directly evaluate their design's suitability for production its components have to be realized physically. Due to this the whole process is considered from ideas to concepts, from concepts to virtual models and from virtual models to the product.

This paper presents an educational concept of project-based learning, in which students are theoretically and practically trained in the early application of 'Design for Production' knowledge. One central aspects of 'Design for Production' is to consider production constraints in the design. Due to the fact that the design definition is temporally separated from the final design realization it often comes to mistakes caused by insufficiently taken into account requirements originate from production. The consequences are usually time-consuming and expensive iteration that should be avoided. In order to allow students experience the consequence of their design in production, their design has to be produced. One promising way to implement real production aspects in educational projects is supplement the design work by physical prototyping.

The idea of evaluating a design by physical prototyping is well established in the context of design thinking. Here, the ideation process is supported by the development of simple models usually made of paperboard or modelling clay. In order to support the education of 'Design for Production' these so called 'funky prototypes' are not enough – instead 'functional prototypes' are required, which fulfill the set functional requirements qualitatively as well as quantitatively.

This paper gives a closer insight into the project work that was recently carried out as a part of the 'Innovation Process' course at ETH Zurich. In order to realize project-based learning the 550 participating undergraduate students of mechanical engineering were grouped in design team of five persons. The educational concept, which especially includes the production of physical prototypes (funky and functional prototypes) is finally discussed in the context of educational objectives with a special focus on imparting 'Design for Production' knowledge.

2 EDUCATIONAL CONCEPT

The purpose of engineering education is to provide the learning required by students become successful engineers [1]. In this context a central challenge is to be seen in the handling of the overall complexity of the product life cycle. A successful engineer has to be permanently aware of several interacting life cycle aspects decisively affect the product's design. In design research these different aspects are subsumed within the term 'Design for X' (DfX) [2].

2.1 Design for Production

In industrial practice the most applied DfX-approaches are 'Design for Manufacturing' or 'Design for Assembly'. These approaches primary consider production aspects focusing on the evaluation of manufacturing feasibility and costs and the reliability and ease of assembly. Against this background Hermann et al. [3] describe that in order to successfully developing new products engineering designers must be able to early predict downstream production issues in order to assure the product's quality and to avoid high cost and time efforts caused by late redesign activities.

Although 'Design for Production' knowledge is obviously of particular importance for engineering designers in practice, higher education often seems to neglect these contents. Indeed, most design engineering courses try to impart 'Design for Production' knowledge theoretically, but only a few allow their students to directly experience the consequences of incorrect estimations or incomplete design definitions when producing. Here, project-based learning (PBL) offer the opportunity for a tangible education of engineering design students (1) in selecting adequate productions techniques, (2) in adapting the design in alignment with resulting production constraints and (3) in estimating of the design's cost and quality.

In fact, the realization of this educational concept meets a basic challenge that is also well known in design practice: series production just for testing and learning is too expensive. Thus, in practice design engineers usually work with single physical prototypes. According to Hesse and Weber [4] physical prototypes are an important source for both information about the product's functionality and information about its producibility. They further describe that physical prototyping still comes along with appreciable time and cost efforts. Consequently, physical prototyping seems to be completely sufficient to impart 'Design for Production' knowledge within educational project work.

2.2 Physical prototyping

In engineering design physical prototyping plays an essential role. Lande and Leifer [5] emphasize that physical prototypes are not solely the culmination and resulting artifacts: the production of a physical or tangible artifact rather has be understood as evidence of learning and iterations of prototypes to be commonplace both in the early part of the design process to disambiguate among possible solution concepts and in the latter part of the design process to reduce uncertainties about the engineered implementations of a solution. Based on this understanding physical prototyping is most suitable to improve engineering design education in two different ways.

Firstly simple prototypes help to explicitly express and communicate individual thoughts and ideas (funky prototypes). Here, they are physical representations of mental models supporting the iterative synthesis and analysis of solutions in individual and cooperative work [6]. This kind of prototypes have to be built up quickly and easy, e.g. by paper and glue or by modelling clay. The resulting iterations are short learning cycles allowing the student to better understand both the design problem and the corresponding solutions. Meboldt et al. [7] define this kind of iteration as 'in-stage iteration'. They describe them not only to be unavoidable in engineering design process, but also to be consciously provoked in order to reduce uncertainty early in the process.

Secondly more extensive prototypes support imparting 'Design for Production' knowledge (functional prototypes). As described above the high class realization of a product design requires a detailed definition of the embodiment, which is based on calculations and estimations primary depending on the product's functional requirements. This kind of prototypes needs to be produced by machine tools, e.g. laser cutting or rapid prototyping machines [8]. Thus, the students also have to consider specific production constraints resulting from the used production techniques and raw material. At this point mistakes can cause a 'cross-gate iteration', which means that already made decisions become obsolete and a redesign as well as a reproduction becomes necessary. In this case the students are able to directly recognize the consequences of their design and the importance of its producibility.

3 PROTOTYPIC PRODUCTION IN EDUCATION

This section gives a closer insight into the purpose and the production of the two different kinds of prototypes presented above: Funky prototypes and functional prototypes.

3.1 Funky prototypes

Funky prototypes are simple prototypes made of materials that are easy to handle (e.g. paper, cardboard, wire and tape). The basic purpose of funky prototypes is to quickly illustrate key functions or interfaces to the user or the product environment. They are usually used to improve communication and understanding within design teams by making ideas tangible (cf. figure 1). Funky prototypes allow quick and easy adaptions. Consequently spontaneous ideas can be directly implemented and evaluated. The application of funky prototypes in education allows students to early identify strengths and weaknesses of their design. Due to this additional case-specific knowledge can be gained very quickly so that the students can directly improve their solutions even during the production of the prototypes. Here, the close interrelation of form definition and form realization allows a high number of iterations in a short period of time. In the early stage of development these iterations are of a high value for the development and thus should by provoked and supported.

The materials and tools for the production of funky prototypes are usually already available for students. But it seems to be very important to early train them in methods leading to creative and well supporting prototypes. Here, an educational workshop at the beginning of a student project is most recommended. First experiments showed that undergraduate students are able to apply basic methods by solving two different production tasks.

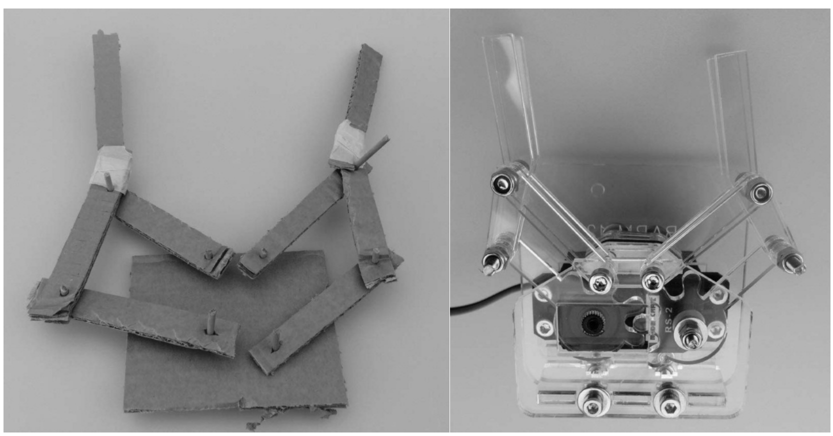

Figure 1. Funky and functional prototype of an parallel gripper

3.2 Functional prototypes

The purpose of functional prototypes is not just to illustrate an idea, but to qualitatively and even quantitatively validate the fulfilment of required functions. Due to this functional prototyping requires more valuable materials (e.g. wood, plexiglass or metal) and in consequence also more complex production tools (e.g. power tools or machine tools). At this point prototyping take one fine step forward from handicraft work to a series production with the quantity one.

In engineering design education functional prototyping allows students to directly experience the relevance of design for production. In contrast to funky prototypes the design definition and the design realization of functional prototypes are temporally separated (cf. figure 2). This separation, which is also well-known in industrial practice, complicates the design work. Mistakes or false estimation can cause time-consuming and expensive iterations that need to be avoided by consideration of design to production aspects. Thus the application of functional prototypes in engineering design education makes ‘design for production’ knowledge tangible and animates the students to early deal with the production process and its impact on the product design.

When transferring the separation of design definition and design realization to an educational project work additional aspects have to be considered. The application of machine tools requires the qualified preparation of CAD models or mechanical drawing that are suitable for production. Consequently the present interfaces need to be clearly defined. Furthermore the access to the machine tools is limited by their capacity utilization and thus needs to be fairly managed by an operation schedule.

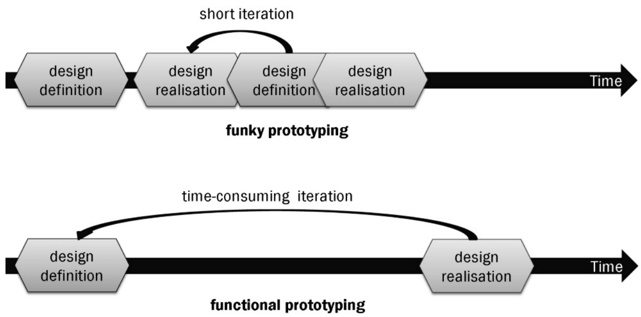

Figure 2. Design definition and design realization in funky and in functional prototyping

4 PROJECT WORK WITH PROTOTYPES

The project work presented in this section integrates the production of funky and functional prototypes in the 'Innovation Process' course at ETH Zurich. The 550 participating undergraduate students of mechanical engineering are grouped in design teams of five persons. The project work is oriented to the lecture and additional supplemented by weekly workshops supporting the transfer of theoretical content to application in the practical project work.

Within the first half of the project the students are encouraged to implement their ideas in simple funky prototypes made of paper or cardboard. Due to this they should improve their design ideas by many small and short iterations and experience the advantages of funky prototypes. At the beginning of the second half the students get access to additional material in order to also realize functional prototypes. Each team is equipped by a complete Lego Mindstorm sets consisting of one programmable NXT Brig, three motors and a selection of different sensors. A linear motor and additional servo motors are available on request. Furthermore one student of each team is briefed in save operation of 2D laser cutters, which allow the production of solution specific parts cut out of acrylic and wood panels (300 x 600 x 3 or 5 mm). 2D laser cutters have several advantages in comparison to simple 3D printers. Firstly they are easy to use, secondly they work very robustly and thirdly they are most suitable for a high production rate. In the project each team gets only 30 minutes production time per week on the laser cutters. Thus the team have carefully to decide, at which point the design of an part is finished and released for production.

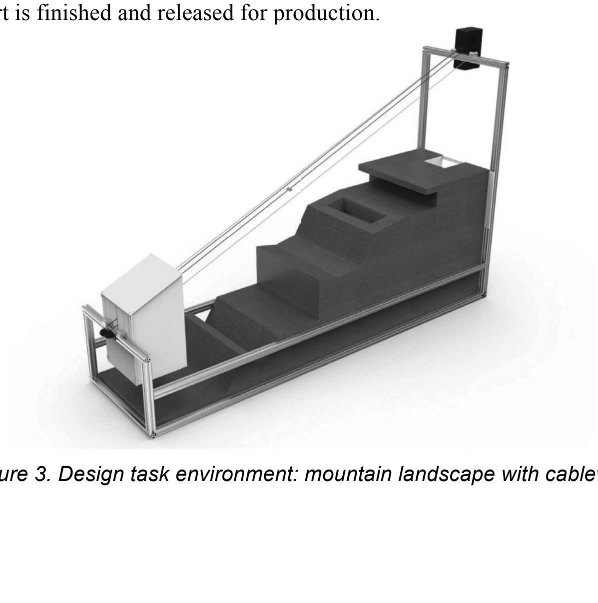

Figure 3. Design task environment: mountain landscape with cableway

The task each team has to solve involves the design and the prototyping of a small cablecar that is able to ride a cableway in order to pick up building material from the mountain landscape and transport it to the upper station. The mountain landscape (cf. figure 3) has a size of 2500 x 600 mm and a maximum height difference of 1200 mm and on the landscape different building materials (steel bars, wooden cubes and wooden beads) are unequally distributed. The given cableway consists of a supporting structure carrying the lower and upper station as well as the bearer cables and the hauling cable. The hauling rope is driven by an electric motor can be control by the students.

At the end of the project the solutions developed by the students are compared within a competition. The goal is to design a cablecar that is able to collect as much building material as possible within three minutes and to deliver it safely to the upper station. The evaluation of the different designs primary depends on the performance, but also secondary criteria like amongst other the successful realization of 'design for production' knowledge.

5 CONCLUSION

'Design for production' knowledge is of particular importance for engineering designer in order to avoid high cost and time efforts caused by late redesign activities. Thus, this knowledge needs to be imparted theoretically as well as practically. Students have to experience the consequences of incorrect estimations or incomplete design definition when producing. Due to this they are able to gain sufficient knowledge regarding design for production aspects. In engineering design education this can be successfully realized by project-based learning, which includes the production of physical prototypes.

The application of physical prototypes can improve design education in two different ways. Firstly simple funky prototypes allows students to explicitly express a new design idea, to make them tangible and to early identify its strengths and weaknesses. Due to the fact that funky prototypes can easily and quickly adapted – i.e. design definition and design realization are directly gear into each other – short but intensive learning cycles can be achieved. These iterations always leads to the gain of additional case-specific knowledge.

Secondly functional prototypes can be applied to support imparting design for production knowledge. Functional prototypes are made out of more valuable materials than funky prototypes. Consequently they are produced by using power or machine tools. Design definition and design realization of functional prototypes are temporally separated. Thus, iterations in producing these prototypes should be avoided. By transferring this separation to educational project work students can learn to deal with this situation by early consideration of 'design for production' knowledge.

This paper presents an educational concept implementing both types of physical prototypes in student project work. In this project work students learn to consciously use the advantages of each prototype to successfully solve their design task and to train the application of 'design for production' knowledge. So far it could be shown that the educational concept is most suitable to make design for production aspects tangible. In a next step it is planned to implement a documentation system during producing prototypes in order to be able to get examples of short iterations supported by funky prototyping. In addition significant examples of functional prototypes and typical errors in design will be collected and made available to students in the form of an exposition.

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