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CDIO design education collaboration using 3D-desktop printers

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Abstract

Desktop 3D-printers are now a low-cost commodity product, and have been increasingly used in engineering education. The ability for students to print a prototype of their design is naturally a step forward in the education of engineering design. This paper describes a new approach for using 3D-printers where the students shall collaborate on a design of a compounded product, consisting of different parts. Functional requirements, distribution of tolerances, design envelopes etc. must be handled. QA measures, 3D-printed material properties, variation management etc. need to be addressed. The paper describes the pedagogical methods used and the results from interviews among the students in the class. The education is based on the CDIO educational framework.

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Keywords: Additive manufacturing; design education; CDIO; didactical framework

1. Introduction

Thompson et al. [1] describes the evolution of additive manufacturing. Additive manufacturing is a method where parts can be produced layer by layer directly from a CAD model. While some machines and processes have the potential to manufacture high-end products in advanced materials such as Inconel 718, another branch is low-cost desktop 3D-printers mostly based on polymers jetting or extrusion. These 3D-printers are now a low-cost commodity product, and has a potential to be utilised in practical design and engineering education.

Junk et al., Greenhalg et al., Mo et al. and Stickel et al. [2-5] are all reporting about application of 3D-printing for design education. However, as Junk et al. [2] reports, there are only a few examples of systematic approaches on the use of 3D-printers for design education. "*Design education focuses on teaching students how to do the design*" [6]. Tomiyama et al. describes the state-of-the art on design methodologies. The paper reports that fresh candidates from the universities sometimes lack the design competence needed by the industry, and that design education has been more real life project oriented. "*The best way to learn engineering design is doing design*"[6]. Heinis et al.[24] describes the challenge of design education as the challenge of being "*...able to impart technical knowledge [...] and teach social and individual competencies needed to use the acquired technical knowledge".*

The background of this work is a hypothesis that practical group work will have a positive effect on the education of design and engineering students. This may be effects such as:

- Enhanced learning outcome.
- Better ability to see the relationship between theoretical technical disciplinary knowledge and practical work.
- Better personal and interpersonal skills, and product, process and system building skills.
- Better motivation, which improves the performance and increases the probability of completing the study program.
- Better preparation for professional work life.

1.1. Didactical framework

Because the frames of any given educational situation vary; factors like teachers, classrooms, politics and curriculum is never similar, generating a common theoretical framework is very difficult. All didactic choices are supposed to be taken always having the learners need in mind according to the *"Model of Relations between Didactical Categories*" [7]. CDIO is an innovative educational framework for

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engineering education developed to aid teachers in planning the content of a course or any learning process in general [8-10]. CDIO emphasizes didactical relations and say that the learning content must be closely linked to students' knowledge level as well as the need of the practice field, and must be relevant for the subject area and as such has a common understanding with the model of relations between didactical categories [7]. Didactical processes must be a part of a learning process, but review show that there is still a lack of research conducted on learning and teaching methods in practise-oriented teaching and learning in manufacturing education. There is a focus on practice-oriented learning processes in manufacturing education [11-13], but the effects on learning outcome and best didactical approaches need more exploration. This case-study was a collaborative project work, and collaborative learning is efficient if the participants engage at a more advanced taxonomic level [14, 15]. The CDIO framework supports the notion of collaborative learning, leading to a deeper form of learning; ability of critical thinking; understanding, decision making and even longer memory spans. (e.g., [16]; Johnson & Johnson, 1999 in [17] Research has then seemingly started to focus on how to control the learning processes in order to achieve wanted results/effects. (ibid.)

1.2. CDIO

A CDIO program is based on the principle that product, process, and system lifecycle development and deployment are the appropriate context for engineering education [8] CDIO (Conceive – Design – Implement – Operate) is a model of the entire product, process, and system lifecycle [8]:

- The Conceive stage includes 1) defining customer needs considering technology, enterprise strategy and regulations, and 2) developing conceptual-, technical-, and business plans.
- The Design stage focuses on creating the design, i.e. the plans, drawings and algorithms that describe what will be implemented.
- The Implement stage refers to the transformation of the design into the product, process or system, including manufacturing, coding, testing and validation.
- The Operate stage uses the implemented product or process to deliver the intended value, including maintaining, evolving and retiring the system.

In addition to learning outcomes for technical disciplinary knowledge, the CDIO syllabus specifies learning outcomes as personal and interpersonal skills and product, process, and system building skills [8]:

- Personal learning outcomes focus on individual students' cognitive and affective development, for example engineering reasoning and problem solving, experimentation and knowledge discovery, system thinking, creative thinking, critical thinking and professional ethics.
- Interpersonal learning outcomes focus on individual and group interactions, such as teamwork, leadership, communication and communication in foreign languages.
- Product, process, and system building skills focus on conceiving, designing, implementing, and operating systems in enterprise, business, and societal contexts.

The whole CDIO-approach is too extensive to implement in this work [10]. In this early stage, practical group work using 3D-desktop printers was implemented in two courses.

First a pre-study was made in the course "Introduction to engineering", where only students from mechanical engineering participated. The students studied the relationship between the print-parameters: 1) temperature, 2) acceleration and 3) speed and the 3D-print quality of a test boat. The aim was to maximise the print speed without a significant reduction of the print quality.

The response from the students was positive regarding the 3D-printing itself. However, since changing the input parameters had little effect on the print quality in most of the cases, printing many almost equal boats was considered a bit boring in the long run. Some of the groups also had some bad experiences with lack of participation from some of the group members. In this pre-study the students were not allowed to choose the groups themselves. The feedback from the students were taken into consideration when 3D-printing was implemented in the next course.

The next time, practical group work using 3D-desktop printers was implemented in the course "Computer aided design". This course has both mechanical engineering students and design students. The mechanical engineering students participated in the pre-study, but the design students had no previous experience with 3D-printing. This work is presented in the next chapters.

2. Methods

2.1. Presentation of case study

In the course «Computer aided design», the students learn to draw 3D-parts, assemble the parts into a model with natural movements, animate movements of the parts and create photorealistic pictures. They also learn to create 2D-production drawings with measurements, tolerances etc.

During the course, the students have a compulsory assignment which is divided in two subtasks: In task 1 they 3D-model the parts of a vise based on 2D-drawings which are not optimally made. The parts are assembled to a vise with natural movements, and the students create some photorealistic pictures (Fig. 1). The vise is also parameterized, so that the length and the width can easily be changed.

In subtask 2, the students also create 2D-production drawings with dimensions, tolerances etc. The drawings are supposed to be more optimally made than the original drawings. An example of one of the original drawings is shown in Fig. 2. The red text on the drawing are comments on aspects the students need to pay attention to and/or improve. This could be missing or not optimally placed dimensions, comments on tolerances and recommendations on how to place dimensions when the parts are parameterized.

Some of the learning outcomes of the course related to this assignment, are:

- Know the commonly used methods for 3D-modeling and variant design.
- Be able to carry out "feature-based", parametric modeling.
- Be able to realize a product as a 3D-model with drawings and documentation.
- Be able to prepare documentation and 2D-machine drawings according to ISO standard.

These learning outcomes are part of the description of the course, which is given to the students at the beginning of the semester, but not specifically given as part of the assignment.

The first two learning outcomes and the 3D-modelling part of the third are related to subtask 1 of the assignment. Most of the students manage subtask 1 very well.

The learning outcomes regarding 2D-drawings and ISO standards are related to subtask 2. When the students are creating their own 2D-drawings according to standards, they do more errors than with the rest of their work. The work related to standards is the most theoretical part of the course, and probably the part that is least motivating to work with. It is thought that a more practical approach will improve the motivation and the understanding of why it is important to create accurate drawings with tolerances according to standards.

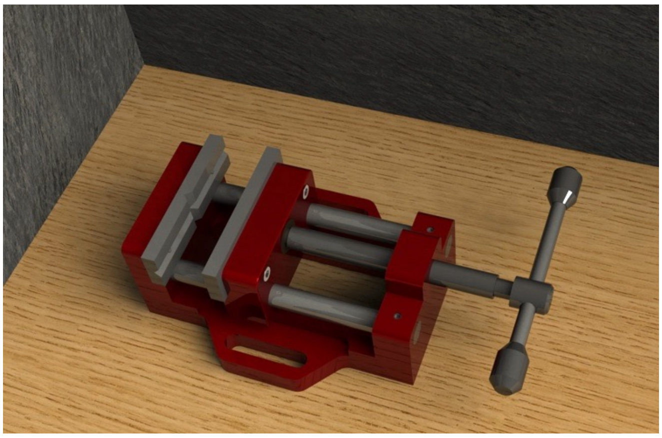

Fig. 1 Example of photorealistic picture of assembled vise.

As part of this work, a new optional assignment was added to subtask 2. The students were going to 3D-print the parts of the vise in plastic (PLA), using desktop printers of the label Original Prusa i3 MK2S. They then had to measure the parts that were going to fit together. If necessary, they had to change the dimensions in the digital 3D-model to make the parts fit. The idea was that the students would gain practical experience showing them that the printed parts had deviations from the dimensions in the digital 3D-model. Next they had to figure out which changes that had to be made, to make the parts fit together. It could also be other adaptions that had to be carried out, i.e. due to threads that may not fit together.

For practical reasons some of the parts were planned to be printed in a more advanced nylon printer of the label EOS P395. This was to avoid problems with some of the threads which could be challenging to print in the desktop printers the students were using. Some parts were therefore printed in nylon (PA2200) and some steel screws and nuts were also handed out to the students.

Subtask 1 was delivered before the start of subtask 2. The duration of subtask 2, which included the volunteer work with 3D-printing, lasted approximately three weeks (23 days).

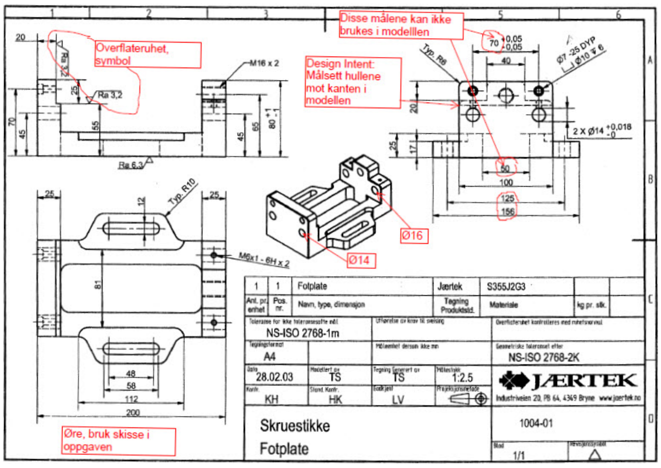

Fig. 2 Example of a 2D-drawing which is not optimally made.

2.2. Qualitative research and semi-structured interviews

The aim of this study was to investigate the effect practice oriented teaching has on manufacturing students' learning outcome. A qualitative approach generates empirical evidence that give insight in the experience of those going through, in this case, a learning process. Here, semi-structured interviews helped generate this data. Where the informants' daily experience of a phenomenon is in focus, a preferred methodical approach is "semi-structured lifeworld interviews" [18, 19] where an interview guide act as a guide and basis. By having some structure the important topics are covered, but there is no rigor control of the information flow. New ideas and restructuring of the focus is dependent on the informants and the interview [20]. The use of semi-structured interview allows for a more two-way communication and give greater opportunity for extra information, learning, confirmation and the reasons and background of the answers compared to a questionnaire. [21, 22].

Three groups participated in the study, with 4-6 participants in each. Two groups are students from a bachelor program in mechanical engineering and the third is from a more design oriented study program, with less focus on strict engineering requirements. An interview guide was introduced to the groups up front of the interview sessions. Not all informants had read the guide in advance, but a paper version was handed out to look at during the interview. Three group interviews were conducted, lasting from 35-45 minutes. There was no correlation between time and the size of the groups. Interviews were recorded, and this data is stored according to NTNU regulations. The empirical data collected are descriptive and qualitative, thus describing the participant's current state of mind and practice [20, 22].

The interview guide was developed based on the CDIO framework [8] and had this structure:

- Project as a whole
- Process
- Process evaluation
- Self-evaluation of own learning
- Suggestions for changes

3. Findings

There were three groups that chose the optional assignment with 3D-printing. One of the groups were design students, and two of the groups were mechanical engineer students. The students chose the group members themselves.

3.1. Practical results of the process

The assignment was not carried out exactly as planned. The students were supposed to get the nylon parts before they started, but because the nylon printer had a failure and needed to be repaired, the students got the parts at the end of the project period. These are the white parts in Fig. 4 and Fig. 5.

Nevertheless, all the groups managed to complete the assignment within the deadline, and ended up with a fully functional vise. The vices made by the mechanical engineer students are shown in Fig. 3 and Fig. 5. The vise made by the design students is shown in Fig. 4.

The design students used this unforeseen opportunity to experiment and then print the missing parts in plastic with the cheap desktop printers, as shown in Fig. 6. They also managed to print the small screws in plastic, although steel screws were handed out (see the two screws at the bottom in Fig. 6). Beforehand it was considered unlikely that the threaded parts could be printed in plastic, but the design students did it anyway. They did however experience that the smallest plastic screws broke during assembly because they were not strong enough, and the threads on the spindle (see third part from the top in Fig. 6) needed a brush up to run smoothly.

In addition to the 3D-printed vises that the students made in groups, each member also delivered a set of individually made 2D-drawings. They made drawings of ten parts plus a drawing of the assembly. An example of one of the drawings is shown in Fig. 7. It is not possible to know how the quality of the drawings would have been if the students had not taken the optional additional work with 3D-printing. However, it should be noted that the 14 students participating had from none (0!) up to max three comments on their set of 2D-drawings, which is an indication of an increased level of understanding when comparing with those students not taking on this task.

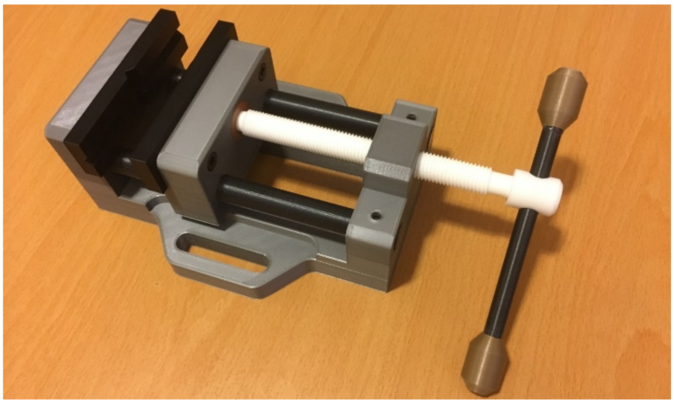

Fig. 3 Photograph of vise no. 1. Made by mechanical engineer students.

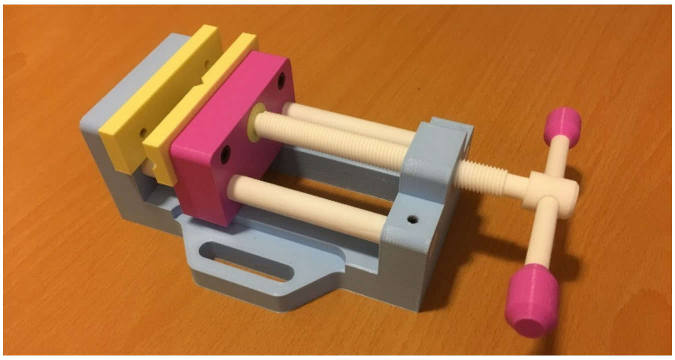

Fig. 4 Photograph of vise no. 2. Made by design students.

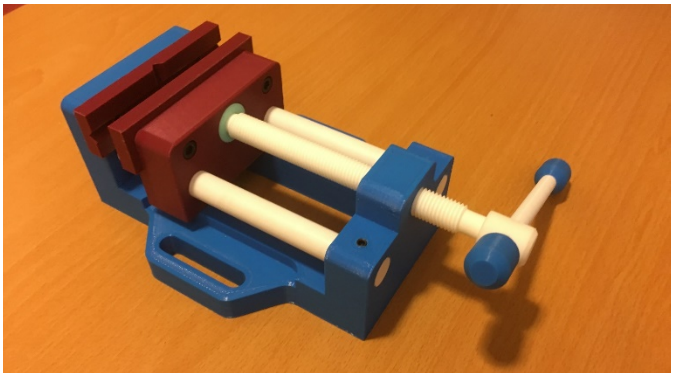

Fig. 5 Photograph of vise no. 3. Made by mechanical engineer students.

Fig. 6 The additional parts printed by the design students.

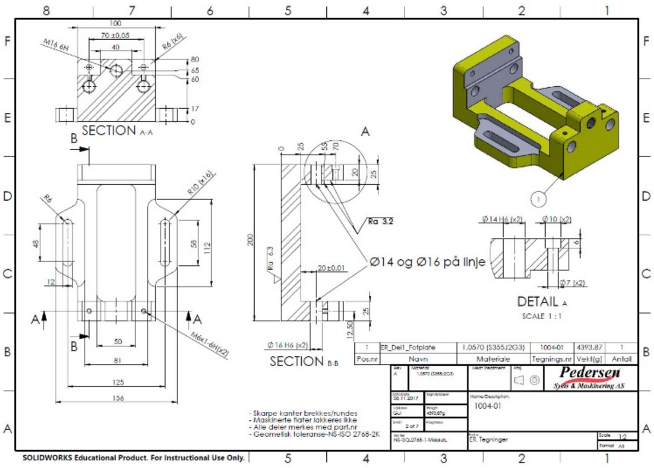

Fig. 7 Example of a drawing made by one of the students.

3.2. Cognitive result; students' learning outcome

Results are presented in accordance with the structure of the interview guide presented in 2.2.

The project as a whole: The two engineering groups both said that the time allocation was more than sufficient, and had it not been for printing time, this part of the assignment could have been completed in one day. The design students who were new to 3D-printing said the project was relatively extensive due to many unfamiliar processes. The concept that this supposedly was an engineering project was not entirely met, as parts of the engineering process were prepared up front by the teacher. However, overall, all the students reported a meaningful experience and saw a transfer value for their coming work practice.

Regarding the process, all three groups thought they had collaborated well throughout the project with no special issues, but this was probably due to the fact that they knew each other well already. They had democratic work processes, and no decisions were made without group consensus, unless someone felt strongly about something. Then the groups were willing to let that group member have his/her way.

Process evaluation: The 2D-drawings they were going to work with were of relatively low quality, but this came out as an enhancement of their learning processes as it challenged them more when making the 3D-models. They learned how to interpret 2D-drawings, and how to generate correct work drawings themselves later on. In general, the students gave feedback on that errors, ambiguities and deficiencies in the learning material just provided further challenges, and enhanced their learning. The design group had a mini conflict regarding printing, which they thought could have been solved through better time management and scheduling. This was the group with less initial knowledge. The group who had no problems with their product in the printing-process, felt they did not really learn that much. However, all said that time allocated was ok. If the work had taken too long, results would not have come that quickly, and it would have been less fun. Waiting and queuing would have destroyed their motivation.

Self-evaluation: The project was motivating and working on a topic in practice instead of e.g. writing theoretical texts were inspiring and they meant they would learn more this way. All groups suggested projects like this should be mandatory for all students because they clearly saw that this gave more learning than just working theoretically. Some students expressed increased awareness of double-checking dimensions and being accurate. Some learned to read drawings. All reported that this gave them an understanding of prototyping as a useful tool; an important part of a development process. The design students exploited opportunities to experiment and test more, like on colors/design, thickness of layers and angles of the threads, even though they felt the assignment did not open much for such processes. They did also experience that being able to make a physical prototype is useful when communicating with customers.

Suggestions for changes: Both engineering groups strongly thought that all parts that were promised should have been ready at the beginning of the project period. The design students solved this by printing the missing parts themselves; to test whether it was even possible to do that. They also did some adaptations to the parts and just saw this as an additional opportunity to learn. One group suggested to find or design a product themselves as a possible change to the project content. Two groups suggested having more theory on 3D-printing.

4. Discussion

Overall, we see that the engineering students to a large degree followed the project descriptions. They did not see any reason to experiment, since the assignment was clearly described. The design students had a different approach. In addition to the fact that they chose to test print the parts that were missing/delayed, they also discussed color/design and how different combinations would affect the final product.

When we discussed if this way of working had any transfer value for later working life, all the groups commented independent of each other, that this gave them understanding that prototyping to customers would be useful and a smarter way of presenting a product than drawings.

The design students were more conscious regarding their learning outcome, the opportunities the project gave them along the way and that participating in the project gave them additional value compared to those who did not participate in this practical project.

All three groups thought that such practical projects gave useful learning and that perhaps they should have practical projects in other courses as well.

Some of the experiences the students had in a CDIO context are illustrated with green text in Fig. 8.

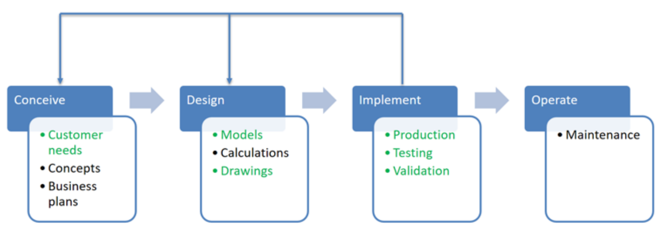

Fig. 8 The students experiences in a CDIO context.

Regarding the learning outcomes from the course description, like being able to create 2D-drawings according to ISO standards, some students expressed increased awareness of double-checking dimensions and being accurate. It is also noted that the students that participated in the work with 3D-printing, also had few or no errors in their individual work with 2D-drawings. It is not possible to know how the quality of the drawings would have been if the students had not taken the optional additional work with 3D-printing, but generally good results are at least a good indication that there has been a positive effect.

5. Conclusion and further work

Although this study is on just one part of a course, there are several indications that practical group work had a positive effect on the education of the design and engineering students. In this study this may be the case first and foremost regarding: (i) Enhanced learning outcome, (ii) Better ability to see the relationship between theoretical technical disciplinary knowledge and practical work and (iii) Better motivation. It is necessary with more studies to determine if there is a positive effect on other factors, such as: (i) Better personal and interpersonal skills, and product, process and system building skills, (ii) Better motivation, which improves the performance and increases the probability of completing the study program and (iii) Better preparation for professional work life.

The next phases of this work will be to create revised and more extensive projects in the courses "Introduction to engineering" and "Computer aided design", based on the experiences so far. NTNU is currently investing in an Industry 4.0 learning factory – a high fidelity industry simulator where students can experiment and learn in "close to reality"- laboratories. We will make a new course based on the cyber physical learning factory. In this course, we will utilise the 3D-printers to simulate Business to Business (B2B) design challenges. One group of the students will act as the Original Equipment Manufacturer (OEM) and other groups simulate different Tier 1 suppliers who has won the contract for delivering a specific sub-system or component. The suppliers are given the design envelopes by the OEM, tolerances and demands to the design, but still with a freedom to choose the geometry within the envelope. The groups will learn how to manage the project and the supply chain in the design phase, including QA-process, how to administrate tolerances and variation management, measurement system analysis, Failure Mode and Effect Analysis (FMEA) and production and part approval process etc. This will be followed up by questionnaires and interviews with the students and teachers.

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