Implementing Constructive Alignment in a CDIO-oriented Master's Program in Integrated Electronic System Design

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Abstract *- This presentation reports on the design and implementation of a Master's program in Integrated Electronic System Design at Chalmers University of Technology from the perspectives of CDIO and constructive alignment. CDIO is an innovative educational concept originating from Massachusetts Institute of Technology (MIT) in which engineering fundamentals are stressed in terms of a* Conceive, Design, Implement*, and* Operate *process. Constructive alignment is a concept for creating an integrated learning environment where the teaching and learning activities are aligned with the assessment tasks to ensure that the achieved learning outcomes will correspond to the intended learning outcomes. In a process based on these two concepts, we have built a Master´s program that not only offers the basic theoretical background but also gives the student an opportunity to become competent in the skills that industry needs. Program focus is on the engineering process, on the technology platforms, and on the design tools and methodologies needed by the engineer to be able to contribute to the development of complex electronic systems and products while working in an engineering team.*

1. INTRODUCTION

Today, renewal of technical education of engineers at Chalmers University of Technology, and in Sweden at large, is most often discussed in terms of a Conceive-Design-Implement-Operate[1] (CDIO) process and in terms of constructive alignment. However, even though these concepts have been around for some time we believe that they are still new to many microelectronics education communities at universities around Europe. Therefore, we would like to describe our efforts to design and implement a new Master´s program in integrated electronic system design in terms of these two concepts.

In 2007, Chalmers University of Technology implemented a 3+2 two-tier Bachelor/Master's educational model, thereby abandoning its traditional one-tier integrated engineering education. The first three years of the new engineering programs are still taught in Swedish, and after having successfully completed these three years of study the student obtains a "Teknologie kandidat" degree, equivalent to the Bachelor's degree. From 2007 the two senior years are offered as advanced Master's programs and taught in English to stimulate EU student mobility and to provide opportunities for international students. The Electrical Engineering program offers six Master's specializations, one of these being the one in Integrated Electronic System Design (IESD) to be discussed here.

Already before 2007 Chalmers had some experience of international Master's programs from some one-year programs offered in English for international students. Two such examples are the Communication Engineering and the Power Engineering programs. However, these programs were given in parallel to the engineering specializations offered in Swedish for domestic students. Electronics design was one of the specializations offered in Swedish only. After 2007 all advanced specializations are offered in English only, in the form of integrated Master's programs.

While the predecessor specialization of electronics design was more or less an *ad hoc* collection of courses, the new IESD program has been carefully planned in detail. The program content and its learning outcomes have been presented before [1], but here we would like to focus on the planning and implementation processes in terms of CDIO [2, 3] and in terms of constructive alignment [4].

2. THE PLANNING PROCESS

Planning of the new Master's programs started already in 2006. In this process, we spontaneously formed an academic team that with enthusiasm and dedication set out to plan and implement the new program in Integrated Electronic System Design (IESD). During the planning process, the academic team was not fully aware of the CDIO concept. Nor were we then aware of the fact that Chalmers and two other Swedish universities actually were among the first universities in the world to become MIT partners in promoting the CDIO concept. Today the CDIO concept is widely accepted at Chalmers and future reforms of the Bachelor's programs are discussed in terms of CDIO. Also, the Ministry of Education plans to evaluate the education offered by Swedish universities in terms of CDIO and constructive alignment.

Nevertheless, when we now observe in retrospect the pedagogical ideas behind the IESD program and the program development process, we find many similarities with the processes for initiating CDIO that we can now read about on the web pages of the MIT Aeronautics and Astronautics Department [5]. Of course, these similarities are not there by sheer coincidence. Even though the CDIO concept was never explicitly spelled out, as far as we can remember, the instructions from Chalmers' university administration were quite clear that the new Master's programs were to be based on learning outcomes rather than on taught content.

In the planning process, the members of the academic team worked tightly together to formulate relevant learning outcomes based on the academic and industrial skills that we believed were needed by the graduating students to become productive and innovative engineers. A list of abilities was compiled and, for reference, these abilities were discussed with an informal group of industry representatives. Also, a matrix was formed in which the intended learning outcomes were mapped to the outcomes of the individual courses to ensure that these would reflect the overall learning outcomes of the program.

[1] CDIO is an innovative educational concept originating from MIT (Massachusetts Institute of Technology) stressing engineering fundamentals in terms of process steps that engineers use when creating complex systems and products, see http://www.cdio.org/.

The next step was to modify, remove and add courses in the existing electronics specialization to meet the new learning outcomes. Just as described on the MIT web page, we changed the sequence and manner in which the courses were taught as well as their content. However, what took precedence over all other issues was the need to include a comprehensive design project. For CDIO-based learning, design projects and laboratories are key elements.

The final, and still ongoing, process is the process of aligning the teaching and learning activities with the assessment tasks of the individual courses in such a way that the *achieved* learning outcomes correspond to the *intended* learning outcomes.

In the next section the program planning and implementation process is discussed in more detail from the perspectives of CDIO and constructive alignment.

3. Engineering Skills and Learning Outcomes

The process of formulating intended learning outcomes has served as a major stepping stone in a university-wide process of replacing the traditional lecture-based teaching focus with a student-oriented learning perspective. This is a necessary step to take at any university if CDIO is to be successfully implemented. As far as the intended learning outcomes of the IESD program are concerned, we believe that they reflect the broad engineering skills required from an electronic system designer. The key goals of this program are to educate IESD graduates that are able to work as productive engineers in an industrial team designing and building electronics products, and qualified enough to undertake graduate studies leading to a doctorate in the field of electronic system design. In particular this means that our graduates should be

- proficient in the basic trade of *conceiving, designing, implementing, and verifying complex electronic systems*; a trade ranging from software for embedded electronic systems to analog transistor circuits
- proficient in the use of various computer-aided design tools used in industry
- aware of *the fundamental limitations of both the design tools and methodologies, and the technology platforms* that represent current best practice
- able to analyze new technical challenges and to generate technical advancements at either the electronic system level or at the device and circuit level
- able to carry out qualified industrial tasks within given constraints by applying *suitable methods*, also when in an industrial context technical aspects might be secondary to constraints associated with economy and environment
- able to critically, independently and creatively identify, formulate and solve complex problems in the field of integrated electronic system design
- able to critically and systematically integrate knowledge, to model, simulate, predict and evaluate behavior and events, also with limited or incomplete information.
- able to clearly and unambiguously communicate their conclusions, and the knowledge and rationale underpinning these conclusions

4. Program Structure and Curriculum

The next step in the process was to outline the overall structure of the Master's program. Once the overall program structure was determined, existing courses were modified or removed, and new courses were added to meet the new intended learning goals, see Table 1. In accordance with the CDIO concept it was decided already at an early stage of the planning process to include a first-year spring design project with the obvious goal to enhance student learning by doing and to develop their engineering skills by working in teams on realistic design project specifications. This decision came to have an important impact on most of the curriculum, since the fall courses in year 1 were planned to prepare the students with the skills and knowledge needed in the spring project.

The first year has a set of mandatory courses with a fall semester of introductory courses and a spring semester dominated by the design project. The second year has a fall semester with elective courses and a spring semester with a final individual Master's thesis project. This mandatory/elective structure keeps the class together during the first year, while the second year is dominated by individual specializations.

Fall semester, year 1		**Spring semester, year 1**	
1st quarter	**2nd quarter**	**3rd quarter**	**4th quarter**
Introduction to Electronic System Design	Computer Architecture *OR* Analog Integrated Circuit Design	Electronic System Design Project	
Digital Integrated Circuit Design	Methods for Electronic System Design and Verification	*Elective course, e.g. Data Conversion Techniques*	*Elective course, e.g. Hardware Description and Verification*
Fall semester, year 2		**Spring semester, year 2**	
Topics in Electronic System Design		Master thesis project	
Elective courses	*Elective courses*		

Table 1. Outline of IESD program curriculum.

The program learning outcomes helped us identify courses that were vital to the program. For example, the first-year spring project was immediately assigned a dominating role in the curriculum: Skills like "*conceiving, designing, implementing, and verifying complex integrated electronic systems*" using "*suitable methods*" based on the awareness of "*the fundamental limitations of both the design tools and methodologies, and the technology platforms*" can only be acquired in a project, working as a member of a team. Obviously, this concept is at the very heart of the *Conceive, Design, Implement*, and *Operate* (CDIO) concept.

We were convinced that the project should not be just *any* course, but that it should be *the unifying course* of the program; a program with a wide technical scope[2] promoting engineering and project-management skills on top of a thorough theoretical training. A design and implementation project like ours supports active modes of hands-on learning including experimentation, social interaction, team building, and team activity. Already in place at Chalmers

[2] Embedded software, computer architecture, principles of EDA tools, digital circuit design, and analog circuit design.

were facilities for computer-aided design of integrated electronic systems, license agreements with Cadence, Mentor Graphics, and Synopsys for access to industrial software tools, access to silicon through multi-project chip fabrication via Europractice and CMP, and a laboratory with test equipment to operate the implemented systems.

Existing courses were modified so that their learning outcomes reflected the learning outcomes of the program, and two new courses were developed to fill up gaps in the curriculum: *Introduction to electronic system design* takes a top-down view to practical system design and trains the student in hardware description and verification in an FPGA context. *Methods for electronic system design and verification* focuses on principles behind EDA tools and trains students in ASIC synthesis and verification tools from register-transfer to layout level.

5. Constructive Alignment

Constructive alignment represents a marriage between a constructivist understanding of the nature of learning, and an aligned design for outcome-based teaching education [6]. There are two parts to constructive alignment:

- Students construct meaning from what they do to learn.
- The teacher aligns the planned learning activities with the intended learning outcomes.

The Swedish translation of constructive alignment is *lärcentrerad undervisningsplanering*[3]. Real learning can only be managed by the students [7], and what we can do as teachers is to provide a learning environment that the student finds stimulating enough to spend the time and effort to meet the intended learning outcomes. Then we must also align the assessment methods and criteria for giving feedback on outcome fulfillment, to the suggested learning activities, see Fig. 1.

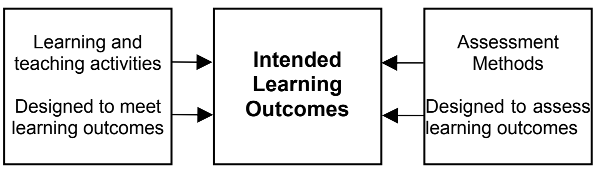

Figure 1. Aligning learning outcomes, learning and teaching activities and the assessment. From [7].

We have implemented constructive alignment at two different levels: First, courses have been aligned at the program level to provide for student progression. As already mentioned, first-year fall courses are aligned to prepare students for the spring project. Secondly, learning activities like lectures, home assignments, and laboratory exercises are aligned at the course level to support student progression towards achieving the intended learning outcomes at the end of the course. In the following, we will discuss in more detail constructive alignment at the course level by providing a summary of how it has been implemented in some of the courses in the program.

Introduction to Electronic System Design – The main intended learning outcome of this course is that the students should obtain a strong proficiency in design at the gate and register-transfer levels, using VHDL as hardware description language. VHDL proficiency is assessed by lab exercise reports submitted throughout the course; these are enough to earn a passing grade.

The IESD program has a wide technical scope and, thus, our students have very different backgrounds, ranging from analog circuits to computer systems. Making sure that all students have a certain core competence is important for succeeding courses, and this course ensures that all students are proficient in VHDL. The course also introduces a number of system design issues, offers a chance to work with FPGAs, and, via the VHDL exercises, revisits a selected number of signal processing applications. In addition, a lecture series gives a top-level overview of electronic system design. A written exam on the topics of this series is offered for students who desire higher grades.

Digital Integrated Circuit Design – The intended learning outcome of this course is twofold: After the course the student should be able to

- design basic combinatorial logic gates, clock trees, and adders and to optimize these for speed using paper and pen and some basic design and optimization principles
- validate these implementations by using advanced computer-assisted design (CAD) tools for schematic capture, circuit simulation, layout, design rule checking, layout vs. schematic etc.

A CAD design environment is set up using wide-spread industrial design tools. Lectures, home assignments and the hands-on lab series are aligned to take the students from simple concepts to more advanced implementations as the performance specifications are gradually tightened to meet stricter timing constraints.

Analog Integrated Circuit Design – The major intended learning outcome is to make students able to design a known circuit topology to a given specification using hand calculations for prediction and circuit simulations for verification as their tools.

The learning process is centered on five labs that use pre-lab hand calculations for prediction, the Cadence design suite in lab (for verification of the hand calculations), and post-lab reports for documentation and reflection. The class-room teaching is mainly viewed as a support for what is done in the lab and the topics covered are centered on those that are useful in this context. Two of the labs are "real" designs where the students design op amps to a given specification. Feedback from the teachers is given on the student designs before coming to the in-lab session so as to make the most of the time spent in the lab and increase the learning. The examination for passing the course requires that all prelabs and lab reports are satisfactorily carried through. An optional written exam is used only for assigning higher grades.

Methods for Electronic System Design and Verification – Here the emphasis of learning outcomes is on the *methodology* skills that are required for complex digital system design. For five (out of seven) course weeks, the students are active in a lab series that makes use of the Cadence Encounter system. The series is cohesive in the sense that the *same* digital block is considered throughout all labs; starting from block specification, via logic verification and timing- and power-driven implementation, ending with place and route. During the lab series there are number of hand ins, which forces the students to plan the

[3] *Learning-centered education planning*

work so that several critical deadlines are met, see Results and Discussion for more details.

The other important learning outcome relates to "softer" skills, in this case to critically and systematically assimilate new knowledge and to communicate this new understanding in a clear and unambiguous manner. To this end, the course includes a term paper assignment that allows the students to focus on a design and verification related topic.

Electronic System Design Project – The learning outcomes of the design project focus on the project approach and on the design process. Design, tool, and method skills taught in the fall semester are applied to solve a system design problem of modest complexity, going from a terse specification to a complete implementation. The system is chosen to offer design tasks spanning the range of sub-disciplines covered in the program (analog and digital circuit design; FPGA and monolithic implementation; processor-based and HDL-based behavior; etc). Thus, the course approximates a real-world design project, with extra emphasis on reflection on the process.

Students work in small teams which plan their work independently. Plans and results are documented in written reports and through oral presentations according to a prescribed project model. Project plans are continuously revised to handle inaccurate estimates of effort needed for certain tasks. Importantly, students are called upon to initially assess the collective team skills and to set aside resources to acquire additional skills by independent study. Progression in more general skills is provided by a "team roles" exercise carried out prior to a reshuffle of the team member responsibilities halfway through the project.

Examination is based mainly on the documents produced as part of the project work, and also on mandatory individual web log books kept by the students. The design task is the same for all teams and thus friendly competition is encouraged. The best design is a candidate for chip fabrication following a final design review.

In 2008 and 2009, the students designed the vital parts of a speed and distance measurement system; from refinement of the system specification to tape-out of a digital 130-nm ASIC. In 2010, the design task is a complete digital hearing aid in a 130-nm process.

6. RESULTS AND DISCUSSION

In this section we would like to share and discuss some of the experiences that we have gained in the process of planning, starting up, and running a new master´s program for three years. An attempt will also be made to quantify the results of our efforts.

In the Chalmers' IMPACT report [8] the Dean of education wrote: "In January 2006 the largest re-organisation of the education system in Chalmers' history was initiated. The goal was to start forty-four new Master's programmes in the autumn of 2007, and Chalmers would be one of the first universities in Europe to fully adopt the so-called Bologna structure. Existing final year programmes, international Master's programmes and about twenty new programmes would be integrated into the Chalmers' programme structure. This endeavour was monumental; however with fantastic support from Chalmers Foundation, the departments and many dedicated teachers; we can look back today, and realise that we have achieved a fantastic result with forty-nine well operating Master's programmes and many satisfied students. The latter was clearly confirmed in an evaluation which was conducted by the Quality Committee and IMPACT during spring 2009."

First of all, we are proud and happy to have developed a Master's program taught in English that we can offer to domestic and international students; a program that we consider up-to-date and well organized. This is in itself a major achievement starting from the *ad hoc* specialization offered in Swedish for domestic students only. The program has been running for three years now with 41, 46 and 28 participants, respectively. The fraction of international students has been 17%, 76%, and 61%. So far the program has been offered to all students free of charge, but from 2011 a tuition fee will be charged to all non-EU students.

A clear group identity: One good feeling that we have about our program, even though it is difficult to quantify, is that we now appear to have a group of students with a well-defined identity as a group. Before the start of the Master's program our impression was that of individual students taking one or many of our courses on an *ad hoc* basis.

One of the reasons for this improvement is that the provided learning activities have stimulated students to cooperate. For the mandatory lab courses we enforce an assignment of students into groups to provide for a well-balanced mixture of domestic and international students. Also, for the spring project, which is a major unifying undertaking in the program, we have tried to form as multi-national groups as possible. The effect of these efforts can also be seen in that working groups spontaneously formed by students for solving some assignment problems often are multinational.

The positive effect of a clear identity, associated to the profession of electronic system design, lingers throughout the program. In contrast to the time period before the Master's programs, many of our students today are integrated in the research work of the groups. To reinforce this trend, a new elective course *Topics in Electronic System Design* was introduced in the fall of 2009. Here a limited number of students (15 at most) can participate in smaller research-oriented projects, as a precursor to research-oriented Master thesis work and, later, PhD studies. In the first installment of the Topics course, twelve students participated. The projects carried out were mainly in one of three different categories; seven students made evaluations of new EDA tools and/or new technology platforms, three students made in-depth studies of their favorite topics, and two students contributed to on-going research projects. The latter cases both led to conference paper submissions.

What about improved examination results? One important question that has been raised is whether the course examination rates have improved. Has student performance improved in the new learning environment, and if so, by how much? For many reasons this question is a bit difficult to answer. One reason for this is that many courses were so heavily revised that examination results are not comparable; another reason is that some of the courses are totally new. One of the courses where comparisons are most easy to make is the Digital integrated circuit design course, a course that essentially follows the same main outline as before the Master's program was started. The examination results from this course are shown in Fig. 2.

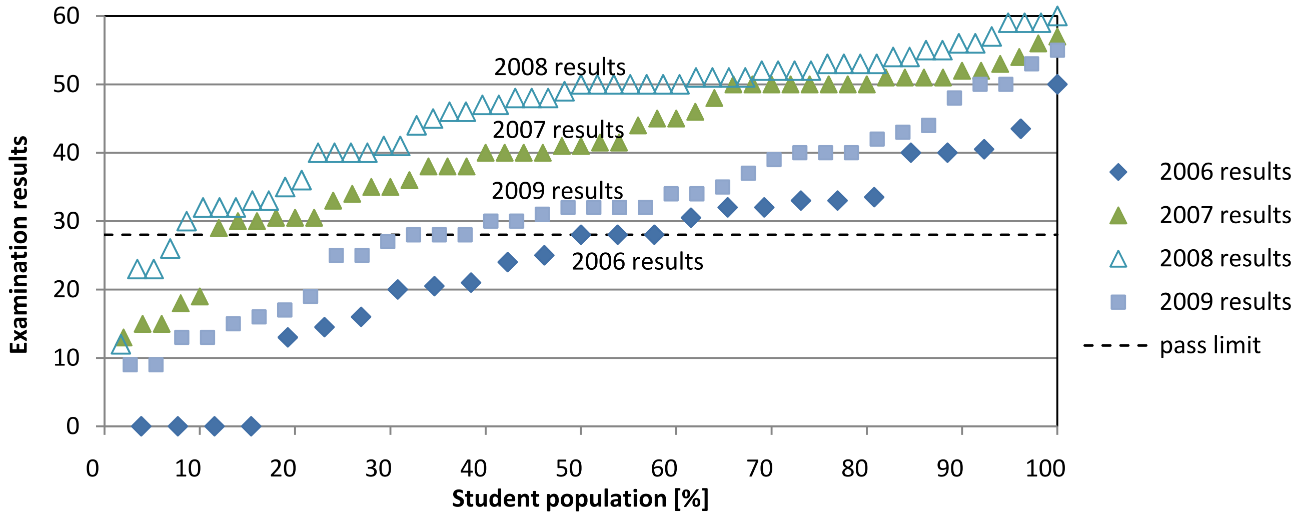

Figure 2. Examination results for the Digital integrated circuit design course 2006-2009.

In this diagram each marker represents the result of one student in the final written examination. The 2006 results are from the academic year before the course revision in connection to the start of the international Master's program. The cumulative diagram shows that 46% of the students (12 out of 26 students) failed in reaching the written examination pass limit.

The results from 2007 and 2008 indicate a considerable improvement as a result of introducing the new learning environment influenced by CDIO and by constructive alignment. During these two years only five and four Master's students, respectively, failed in the written examinations corresponding to as low as seven to ten per cent failure rates. We believe this is a result of the introduction of a set of home assignments that were well aligned to the lecture schedule and to the laboratory assignments. Hence, the students could constructively take advantage of the provided learning activities to ensure a good result in the written examination as they were already well aware of the intended learning outcomes.

Unfortunately, the 2009 results indicate a considerable set-back as the failure rate suddenly increased to almost 30% (11 out of 37 students). We do not know for sure whether this is a result of a more difficult written test or a result of a parallel course consuming too much student effort. Also, there are some indications that students paid less attention to the home assignments in 2009 since they might have heard from second-year students that these were not graded. Also, they were essentially the same assignments as in 2007 and 2008. Renewal and constant change appears to be one key to improved student performance.

Other courses are either new or so heavily revised that direct comparisons in examination rates cannot be made between the situations before and after the start of the Master's program. The discussion should rather focus on the improvement in the learning outcomes that we believe that we achieve. The main point is not the increase in examination rates per se, but rather that we have a much better control of the learning outcomes that we achieve. Also, due to the much better defined intended learning outcomes and the improved assessment, we as teachers have a much better picture of the differences between the achieved and the intended learning outcomes. Therefore, today we have a rather good idea of how we could work for continuous improvements.

As an example of new approaches to assessment, *Methods for electronic system design and verification* exposes the students to an applied design methodology. The student's progress in learning methodology is hard to assess by, for example, using traditional written examination, so we have been trying a different approach, which impacts both grading and feedback. The core lab series contain three deadlines pertaining to specification, implementation and verification, and for each deadline the students are required to hand in documents and(or register-transfer level (RTL) code. To make it possible for the students themselves to do an assessment of whether they fulfill the learning objectives or not, the lab memo details the intended learning outcomes for each of the four labs. The teachers assess several parts of the laboratory work, including the initial specification of the digital block and the verification testbench, the actual RTL code and the final report.

Training students in methodology by using practical projects and labs makes much of the teaching student-team oriented. This is both good and bad. Practicing team work is important as the skills acquired while working in a team are applicable to the engineering role. However, it is hard for the teachers to assess individual efforts. In the first installments of the course, the ambition was to assess actual work in the lab halls to gather information on the work of the each student. For several reasons, this proved to be a challenge.

Beside the problem of finding a uniform way to assess students when several teaching assistants are involved, such a continuous and informal assessment makes the student feel they have limited time for their own exploration. For example, a student may think that asking a question, and thus acknowledging missing knowledge, may reflect badly on the grade. The collected experience from dealing with methodology training is that there must be several assessments during the course, however, the rules and timing of assessment must be clear, and the exploration time in between assessment must be generous enough to allow students to reflect and explore "what if" questions.

The spring design project replaced a set of incoherent small design projects. New intended learning outcomes were formulated, focusing not only on technical aspects but also on aspects of working as a member in a project team. We have opted to use a common project model with a small number of mandatory deliverables and presentations. The first deliverable is the initial time plan for the complete project. In most cases, this first time plan will be unrealistic; teachers will however point out only mistakes deemed potentially fatal. Students are encouraged to regularly adjust the time plan and to redistribute the work within the group as necessary.

What about student workload? In the design project course, students are required to keep individual log books of their efforts, detailing the number of hours spent on different tasks. Stopping short of time sheets, the log books still facilitate periodic follow-up of the time plan devised by the students at project start; additionally, it lets teaching staff assess student workload. As the log books were not used previously, they provide no definite data of how workload has changed; still, we believe the average level of effort spent has increased somewhat and that the minimum level has increased significantly.

What about staff work load? Staff work load has definitely increased. Other shortcomings notwithstanding, the traditional course organization with lectures and a written exam is quite efficient in terms of teacher workload. Thus, our improved achieved learning outcomes and examination results have come at a cost. It is difficult to quantify the load increase; but quality individual feedback for home works and for pre- and post-lab reports would be difficult to provide with a class larger than the present ones, whereas "traditional" courses are routinely taught to classes of 100 students and more.

What about e-learning? Practical computer-based work forms a large part of most of our courses. Our use of industry-standard tools means that many tasks can be carried out at a distance thanks to the network transparency of the X Window System [9]. Still, most laboratory moments require presence in the lab hall for examination: we find that especially the weaker students benefit enormously from the presence of a tutor who will not let them pass a certain checkpoint until they are ready for it. In addition, Chalmers uses the Ping Pong Learning Management System [10], which provides tools for web-based collaboration, group submissions, polls, etc. Our use of these tools can undoubtedly still be improved.

7. Conclusion

By using constructive alignment in a CDIO environment, a Master's program has been designed where the suggested learning activities are aligned with the intended learning outcomes and where assessment is aligned for checking whether the achieved learning outcomes coincide with the intended. An integrated learning environment has been created where students are stimulated to progress to take on more and more challenging design tasks, while in this process acquiring the skills necessary to become productive engineers. A variety of examination methods are used to assess different skills. In conclusion, building a Master's program and creating its learning environment is an ongoing process constantly subject to improvement.

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