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Implementing Design-Based Learning in Teaching of Combustion and Gasification Technology*

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Design-based learning (DBL) is a pedagogical model that promotes deep learning of technical fundamentals and of practical skills in the context of real-world design experiences. Solving design problems in project-based setting provides a natural and meaningful venue for integrated learning of both science and design thinking skills. In this study, we explore the practical implications of the design-based learning model within two Master's level courses on energy technology. We describe the implementation of DBL model at Aalto University Design Factory platform, present the resulting course grades and drop out rates of 244 students registered in the courses between 2010–2012. Anonymous feedback was received from 106 students and we analyze it utilizing thematic analysis. We conclude that design-based learning results in a good balance between theoretical knowledge and design thinking skills. DBL motivates the students by providing them with a real-life engineering problem. The project of building a physical deliverable provides a natural setting for intensive teamwork and communication. The study presents theoretical framework and practical example for implementing DBL model in engineering education.

Keywords: design-based learning; pedagogical development; energy technology

1. Introduction

In the 1960s, young engineering scientists began challenging the traditionally practice-oriented engineering education. Consequently the engineering programs began to move from a practice-based curriculum to a science-based model. The aim was to offer the students a theoretical, disciplinary foundation to address future technical challenges. The shift diminished the perceived value of the key skills and attitudes related to the engineering profession. From the late 1970s onwards, industrial representatives began to get concerned about the change in the knowledge, skills, and attitudes of graduating engineers. They found that graduating students, while technically adept, lack many professional skills required in real-world engineering situations [1–3].

In the 1990s the discussion around the desired attributes of graduating engineers spread among the leaders in academia, industry, and government. To encourage universities to meet real world needs and rethink their educational strategies, major companies as well as the Accreditation Board of Engineering and Technology listed their expectations for graduating engineers. Common among these listings was an implicit criticism of current engineering education for prioritizing theory over practice. Teaching the theories of technical disciplines was not seen to put enough emphasis on professional skills and attitudes [1, 3, 4]. There was a need to implement approaches to instruction that further connect knowledge to the context of its application [5] and develop the necessary skills to successfully handle ill-defined, complex design problems [6].

The criticism towards the science-based engineering education model reveals a tension between two key objectives within the contemporary engineering education: educating engineers who are both specialists and generalists. Professional engineers need to master high levels of specific technical knowledge. At the same time, they need a range of skills for applying the technical knowledge in varying situations. These abilities include design, teamwork, and communication skills alongside interdisciplinary and multicultural awareness [1, 2, 7]. Some academics are concerned that the increasing interest on providing the students with professional skills, also referred to as design thinking skills [see e.g. 8], might compromise the teaching of disciplinary theoretical basics. Consequently, the predominant model of engineering education has still remained similar to that practiced in the 1960s with lecture-based, teacher-centered delivery of theoretical knowledge [2, 3, 9, 10].

In this paper, we argue that practical experience can enhance the learning of theoretical disciplinary content. Our study explores the possibilities of design-based learning model in enhancing the learning of disciplinary knowledge and the development of design thinking skills. In order to evaluate the practical implications of the model in teaching and

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Table 1. Design thinking skills [adapted from 12]

Practices	Cognitive approaches	Mindset
Human-centered approach	Abductive reasoning	Experimental & explorative
Thinking by doing	Reflective reframing	Ambiguity tolerant
Visualizing	Holistic view	Optimistic
Combination of divergent and convergent approaches	Integrative thinking	Future-oriented
Collaborative working style		

learning, we describe the implementation of design-based learning elements within two Master's level courses on energy technology. Finally we present the outcomes of the implementation and discuss the benefits and challenges of design-based learning within the presented context.

2. Design-based learning in engineering education

The term design thinking has been used to refer to the ways of working which are inherent to producing creative outcomes. Whilst being professionalized within the design disciplines, design thinking is representative of a set of skills and approaches that are useful for any professionals dealing with creative work [8, 11]. A holistic literature review conducted by Hassi and Laakso [12] depicts design thinking as a combination of elements related to practices, cognitive approaches, and a mindset (see Table 1).

Providing the students with design experiences is essential for the development of design thinking skills [2]. While there is an increasing emphasis on design in engineering education curricula, the attempts to improve the predominant lecture-based, teacher-centered education have typically been based on problem-based and project-based learning (PBL) [3, 4, 13]. Previous research suggests that PBL courses improve retention, student satisfaction, and learning. However, some of the reported shortcomings of PBL have included inability to connect interdisciplinary subjects to the narrowly defined disciplinary knowledge, failure in identifying and valuing the contributions of multiple fields to complex problems [8, 14], and failure in understanding the disciplinary fundamentals [2, 15, 16]. PBL should be supplemented by addressing the development of design thinking skills more directly [17].

In order to promote deep learning of technical fundamentals and of practical skills in the context of real-world design experiences, design-based learning (DBL) was introduced in 1997 at the Eindhoven University of Technology [13]. As DBL consists of solving design problems in a project-based setting, it provides a natural and meaningful venue for integrated learning of both science and design thinking skills. The model situates the student at the center of a learning process. Consequently the role of the teacher changes from a lecturer to a facilitator of the learning process. Typical stages of DBL include defining the problem and identifying the need, collecting information, introducing alternative solutions, choosing the optimal solution, designing and constructing a prototype, and evaluation. These stages are usually repeated several times before reaching the final conclusion. The design process is parallel to problem solving [17]. The stages of DBL are illustrated in Fig. 1.

When examined on middle-school level, design approach for teaching science concepts has proven to increase knowledge gaining, engagement, and retention of the students [15]. Design-based learning has the potential to increase study motivation, interest, and in-depth understanding of design and science related topics [17]. However, some academics fear that replacing lectures with more activating methods will reduce the amount of material that can be covered which may result in gaps in specific knowledge areas. The methods may also contradict the expectations of students and lead to dissatisfaction, resistance, and negative feedback [16, 19]. Even though many engineering educators

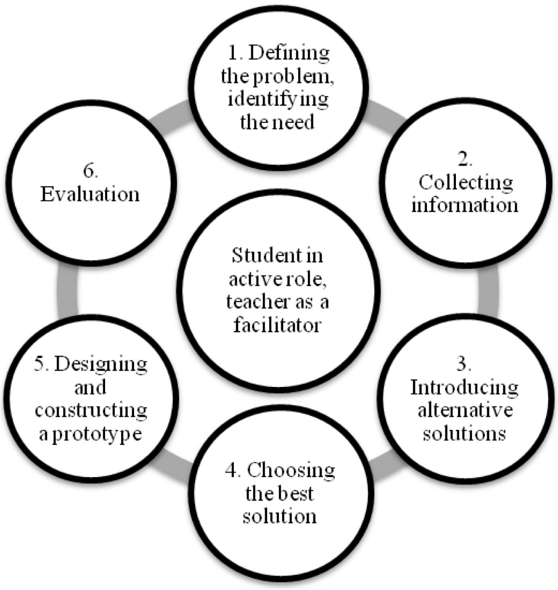

Fig. 1. Typical stages of design-based learning [based on 17].

are aware of the design-based methods, their adoption rate remains low [20].

While design projects are becoming an increasingly used method in engineering education [19], empirical research on implementing DBL in higher education has been largely absent. To discover in what respect DBL can be considered as preparatory for the engineering practice requires empirical research in collaboration with engineering educators conducting courses that adopt a DBL approach [13]. In this paper we explore implementation of DBL approach in the field of Energy Technology.

3. Context of the study

For the past decade, universities have experienced considerable pressure to develop as a teaching and learning environment. Mass participation in higher education, and changing national economic requirements has forced universities to reform their pedagogical practices. Also the growing number of university mergers has affected the work of all academic staff [21, 22]. In Finland, one of the recent mergers was established in the beginning of 2010 when a new university was formed. The merger brought together the nation's three leading universities in the fields of technology, art and design, and economics. The aim of the merger was to open up new possibilities for strong multi-disciplinary education and research. The new university was initially coined as the "Innovation University" and was eventually named Aalto University. It has been seen as a flagship project in the larger scale development of the higher education and innovation systems in Finland [23].

3.1 Aalto University Design Factory platform

Acknowledging the needs of the twenty-first century education, Aalto University aims at preparing the students for entering professional life as a key goal of the student-centered teaching. One of the spearhead projects of Aalto is Aalto University Design Factory (ADF), which strives to realize this goal by providing a platform for experimenting with student-centered learning approaches. Established in 2008, Design Factory provides a flexible, low-hierarchy, constantly developing physical collaboration environment for students, teachers, researchers and business practitioners across hierarchical, professional, and disciplinary boundaries. The facilities include various group working spaces, machinery and spaces for model making and prototyping as well as flexible teaching and learning spaces.

In addition to hosting interdisciplinary courses, ADF offers faculty a Teaching Partner mentoring program that aims at supporting the implementation of new pedagogical approaches into practice. After discussing the development ideas and needs of the participating teacher, a design-based teaching experimentation is planned, executed, and facilitated at the ADF premises. After the experimentation conducted by the teacher and the mentor, student feedback is analyzed and the possibility of continuing with the development efforts is discussed. The collaboration enables an effective use of the ADF platform as a supportive environment for DBL activities. Mentoring provides ideas for implementation of the learning model, support for the practical experimentation as well as insights for reflection.

3.2 Degree program of energy and HVAC technology

Energy and Heating Ventilating and Air Conditioning (HVAC) Technology is one of the Master's Degree programs of Aalto University with an annual intake of approximately 50 students. In addition to the regular Master's Degree students, there are international students who are participating in either some student exchange program or an international degree program, where some part of studies is being conducted at Aalto University. There are also some 40 post-graduate students who already possess a Master's Degree and are pursuing doctoral degrees.

After graduation, majority of the Energy Technology students have traditionally moved to work for Finnish industry. Several branches in the industry have needed engineers with knowledge and skills related to combustion and gasification: manufacturing of power plant and kraft recovery boilers, diesel engines, gasifiers, burners for gaseous, liquid and solid fuels, metallurgical equipment, etc. Many graduates begin their careers as designers, and may later either work as senior designers or move into other activities such as marketing, sales and management. Many are also employed in technical research in companies, technical research centers and universities. It is anticipated that in the future, an increasing number of engineering graduates will continue their studies to get a doctoral degree.

4. Design-based learning reform in Combustion and Gasification Technology

Combustion and Gasification Technology I (CGT1) and II (CGT2) are courses offered by the Department of Energy Technology of Aalto University School of Engineering. Both are 3 credit courses in the European Credit Transfer System (ECTS). CGT1 is intended to initiate the students to the field of combustion and gasification. CGT2 is intended to be a continuation of CGT1 for those students who wish to go deeper into the field.

Language of instruction is English. The majority of the students are Bachelor's or Master's level students of Aalto University, but many foreign exchange students and doctoral students also take the courses.

4.1 *Background of the courses*

The CGT courses have been offered since the beginning of 1990s. Prior to 2010, the teaching had been arranged in a rather teacher-centered manner with lectures and demonstration exercises. CGT1 was intended to give the students the basic knowledge of combustion and gasification technology, while CGT2 concentrated on current research topics. Assessment of student performance was based on a final exam in CGT1 and on six sets of homework in CGT2. As was the practice at that time, the contents of the courses were described in the course catalog but no learning outcomes had been defined.

In 2010, the number of students from the International Master's Degree Programs ISEE and SELECT increased on both courses. This change also affected the schedule so that both courses had to be fitted to the Fall semester. Thus, from 2010 onwards both of them were compressed into one period of seven weeks. In 2010, the position of the courses in the curriculum also changed and CGT 1 was no more obligatory to the energy engineering students. As the students had normally taken the course during the third year of their studies, this change became fully effective in 2012.

4.2 *The new learning objectives for the courses*

In 2010, Aalto University started requiring that all course learning objectives must be formally defined and described in the study catalog. For both CGT courses, the new objectives were defined as understanding how scientific principles are applied in the design and operation of combustion and gasification systems, recognizing how different types of technical solutions are related to the underlying scientific principles, and being aware of changes and development trends to be anticipated as a result of new fuels, fuel processing technologies and combustion technologies. CGT1 concentrated more on mass and energy balances, while CGT2 proceeded into calculations of chemical equilibrium and rate calculations. In all activity, the goal was in achieving a deep understanding of the technology and its scientific basis, and in encouraging critical thinking and independent assessment of situations.

Based on the formally defined learning goals, it was decided that the focus should not be so much on learning new facts but more on activating the skills needed to utilize facts learned in previous studies. Very heavy emphasis was put on independent thinking and in working as a member of a team. The students were encouraged to look at the problems from many different points of view, including environmental and societal considerations in addition to technical and economical matters. Opportunities to practice teamwork and effective communication were built into the courses.

4.3 *Implementing a design-based learning approach*

To reach the newly defined learning objectives on both courses, continuous development efforts were made in small steps during 2010–2012. In the following chapters, we provide a synthesis of the incremental changes conducted on the two courses and their connections with the design-based learning model.

4.3.1 *Interactive lectures*

It was decided to concentrate on a few selected topics and to analyze the related problems on a more fundamental level instead of just presenting superficial descriptions of many different processes and equipment or show how to mechanically perform some simple calculations. Processing new materials was supported mainly with class discussions. Thus, activating the students became an important part of the lectures. The students were encouraged to work together on solving a practical problem and the theory was developed along the way. All discussions ended with a session in which the different ideas and solutions were shared with and evaluated by the whole class.

The great emphasis on class discussions had several consequences. For one thing, the pre-planning of lectures had to remain rather sketchy. The discussions often led to unforeseeable directions, and it would have been a waste just to abruptly drop interesting topics. Consequently, the unfinished topics had to be left to the next lecture or as a reading assignment for the students. Often the discussions continued during the next lecture with new insights based on data collection and analyses carried out in the meantime both by the teacher and the students. Further, Power Point presentations were often replaced with ad hoc sketching with chalk and blackboard, which provided a degree of flexibility quite impossible to achieve with presentation slides. Third consequence was that the laptops and smart phones of the students could be converted from distractions into assets. During class discussions, the students were encouraged to search for additional or more up-to-date information from the Internet. On many occasions we found that the information in the Internet actually proved to be more up-to-date and accurate than the information in textbooks.

4.3.2 Weekly homework supported with workshops

In the first implementation, the students were given two homework problems each week. The number of homework sets was six. The first problem aimed at enhancing the technical skills and ensuring that the students mastered certain fundamental techniques related to quantitative calculation of combustion and gasification processes. The second problem was very open thus giving the students a chance for independent thinking. Defining the problem and finding the initial data was always an important part of the homework problems. In fact, some problems solely consisted of defining the problem and listing what kind of information would be needed to proceed in solution. Some other problems consisted of searching several different literature sources for some specific information, comparing the results, and commenting on possible discrepancies. All solutions had to include justifications.

For each set of homework, a voluntary 2-hour workshop was held for supporting the students in producing their own solutions. The course staff was instructed to facilitate the problem solving process instead of merely giving ready answers to the students. The students were strongly encouraged to co-operate in solving the problems. It was required, however, that each student hands in an individual, hand-written solution for each problem. Many students worked in pairs or in teams until a rough solution had been reached, and from that point on, they worked individually to fill in the details and to develop the solution further towards more generality.

4.3.3 Design-based learning project

In addition to improving the lectures and homework practices, a design-based learning project was introduced in Fall 2010. At the first time, the project was voluntary and was carried out during a single 4-hour session after all other activities had been completed. The first and second author discussed the possible ways and benefits of executing a DBL project as a part of the ADF Teaching Partner mentoring program. After planning the project together it was implemented at Aalto University Design Factory and evaluated collaboratively. Even though the first project was voluntary, majority of the students took part in it. As the student feedback was very positive, the DBL project became an essential part of both courses after 2010.

After the first implementation, two or three 4-hour ADF sessions in each course implementation were devoted exclusively to the DBL project. Typically the first session was held two or three weeks after the course had started and the students had three or four weeks time to complete the project. To keep the total workload reasonable, the number of homework sets was decreased from six to three.

The DBL project typically included an introduction to a certain field-specific, open real-life problem from various viewpoints. It could consist of, for example, the design of a biomass-fired boiler or a gasifier. The students had to participate in defining the problem and its connections to areas outside combustion and gasification technology. In the case of boiler design, this would mean, e.g., that the students were not given fuel specifications; instead, they had to define the fuel specifications themselves. A set of questions was always provided to help the students understand what kind of issues they are expected to handle, but the list of questions was incomplete and left plenty of room for student initiative. To illustrate the design task given to the students, an example is shown in Appendix 1.

The DBL project was conducted in teams of three to six people. The students themselves formed the teams and developed many team working solutions, including cloud-computing and social media applications for discussions and file sharing. The assignments were designed so that the team results were interdependent and co-operation between the teams was unavoidable. The required outcomes varied from a poster to a physical model. Written reports and Power Point presentations were sometimes required. Often the students produced also some additional material, such as computer animations and live performances.

The first DBL session started with a warm-up part, during which the Design Factory concept and facilities were introduced. The warm-up continued with a brief lecture on the principles of the project and teamwork, sometimes including team building exercises. After the warm-up part, the tasks and expected deliverables were explained to the students and the student teams were formed. The final part was devoted to working on the tasks. If an interim session was held, the students were requested to present their work-in-progress in order to receive and provide feedback on the unfinished work. In addition, peer evaluation was used for providing feedback on the working process and commitment of the team members so far. The evaluation did not concern the students' expertise on content-related issues or affect the final grades.

During the final session, the teams presented their deliverables. Presentations typically followed an exhibition walk procedure [see e.g. 24], which enforces all team members to present the complete work of their team to the other students. Finally, a peer evaluation exercise was carried out. If peer evaluation had already been practiced during the interim session, then the second exercise affected the final grading of the students. However, the peer evaluation did not concern the students' expertise on content related issues.

4.3.4 Assessment and grading

Before 2010, the evaluation of students' learning had been based solely on final exam. As the course development was started, it was decided that final exams are to be discontinued and replaced with continuous assessment. It was felt important to show the students from early on what will be required from them and also to give them continuous feedback on how well they are performing. At first the assessment was based on having six sets of homework, each one of them having an equal weight in the forming of the final grade. As the course progressed, the students from early on had a fairly good idea on the grade they could be expecting. It was noted, however, that majority of the students had such high motivation and ambition levels that they continued working on the homework problems even after they had already ascertained a passing or even the highest grade.

The first assessment method was implemented only once in Fall 2010. After the DBL projects were implemented into the courses, the workload was balanced by decreasing the number of homework sets into two or three, and the assessment was based on homework by 50% and on the design project by 50%. To ensure continuous feedback, the performance of the student teams was also graded during the interim session at the Design Factory; thus, the weight given to the final grading of the design projects was only 33% of the total. The grading scale was fixed and the score limits for each grade were published before the beginning of the courses.

4.3.5 Course development in relation to design-based learning

The course developments described above were motivated by the need to change the emphasis of learning from passive reception of information to active creation of knowledge. Introduction of the design-based project affected all elements of the course: lectures, homework, workshops, and assessment of the students work were designed to support the project work. In Table 2, we summarize the renewed course elements in relation to the typical steps of a DBL model.

The design-based learning reform reflected also many the design thinking skills portrayed by Hassi and Laakso [12]. For example, the interactive lectures, workshops supportive of solving the homework problems, and DBL project enabled a collaborative working style. Holistic view and working with open problems provided a framework for reflective reframing and ambiguity tolerance. The lecture discussions guided the students in abductive reasoning. In addition to discussions, visualization exercises were an essential part of the lectures. The DBL project was based on thinking by doing and enabled an experimental, explorative approach to learning.

Table 2. Course developments in relation to the elements of the DBL model

DBL element	Course element
Defining the problem and identifying the need	Fundamental discussions around open problems during lectures Interpreting and specifying open homework problems DBL project based on an open problem
Collecting information	Searching for data and discussing its reliability during lectures Collecting information and analyzing it in terms of completeness and consistency in homework problems Collecting and analyzing information for the DBL project
Introducing alternative solutions	Alternative ways of solving technical problems discussed during the lectures Presenting and trialing alternative ways to solve the homework problems Evaluating the validity of alternative solutions during DBL project
Choosing the optimal solution	Discussing the strong and weak points of each alternative during the lectures Choosing the most promising candidate for solution and justifying the decisions made in homework and DBL project
Designing and constructing a prototype	Visualizing abstract concepts and ideas with photographs, drawings, and demonstrations during the lectures Hand-made drawings of the conceptual design of plants, unit processes, pieces of equipment, etc. requested in homework solutions Illustrative posters, animations, and physical models as DBL project deliverables
Evaluation	Continuous evaluation of presented arguments and solutions during the lectures Peer evaluation on the working process and possibility for iteration Both peer and teacher evaluation on the DBL project deliverables

5. Outcomes of the design-based learning course development

In order to illustrate the effects of the course reform reported in this paper, we explore the results from two sources: the statistics of student grades and the feedback gathered from Aalto University's course feedback system "WebOodi". During 2010–2012, both GCT courses were offered three times. The results from all six implementation rounds are merged to reduce the fluctuations in the statistics; it should be noted, however, that no signs could be observed of significant deviations in the results of any particular implementation.

Of the 244 students who registered in the courses during the 2010–2012 implementations, 201 passed the courses (82%). Of the remaining 43 students, 25 never handed in anything nor produced any other signs of activity and 18 participated at least for some time but then dropped out and consequently failed the course. In the previous implementation rounds in 2008 and 2009, roughly 55% of the registered students passed the courses in the end-of-semester exams and an additional 20% during the following spring. Thus, 75% of the registered students had passed the course within one year of registration. Compared to the previous implementations, a clear improvement in the course completion was achieved with the design-based learning reform.

Another change in the statistics was a shift in the distribution of grades. In the new style implementations in 2010–2012, 65% of the students participating to the final exam obtained the highest or second highest grade. In the 2008 and 2009 implementations, the corresponding percentage was 39%. The improvement is statistically significant. The distribution of student grades in 2010–2012 is illustrated in Table 3.

Approximately 50% percent of participating students, altogether 106 persons, provided anonymous feedback after each course between 2010 and 2012. The feedback data partly consist of quantitative data collected on a Likert scale, partly of qualitative data collected as answers to open questions. The number of mentions in the qualitative data is more than 106, because the same respondent could provide more than one answer for each question. In this paper we mostly concentrate on the qualitative data, which was analyzed thematically. We explore the reported effects of each course development element on student learning. Finally we present the division of the reported learning outcomes in relation to disciplinary knowledge and professional skills. The findings are enriched with quotes from the open feedback data. Most of the quotes presented in this paper are translated from Finnish to English.

Table 3. Distribution of grades

Grade	Number of students*	%**
5 (excellent)	89	44
4 (very good)	42	21
3 (good)	37	18
2 (very satisfactory)	22	11
1 (satisfactory)	11	5
Total	**201**	**100**

* The 201 students who passed the courses represent 82% of the registered students.

** The individual percentages do not add up to 100% due to rounding.

From the 106 students who participated in the feedback survey, 87 students "strongly agreed" or "agreed" with the statement "The teaching arrangements facilitated my learning process". Altogether 16 students "disagreed" or "strongly disagreed" with the statement. In Table 4, we present the division of student feedback related to each course element and their reported effects on learning. In order to illustrate the reported effects further, we present quotations from the open feedback data related to each course element below.

A total of 45 feedback comments on the course arrangements were related to continuous assessment based on homework exercises instead of a final exam. 34 of the comments were positive: "*The course had no final exam, but there were exercises and Design Factory work that were much better for learning*". These students thought that "*the teaching methods enhanced learning better than the traditional courses where one sits quietly and studies for final exam*". However, according to 11 comments the lack of a final exam was eliminating learning: "*Lack of a final exam eliminates learning effectively*". On average, the students were rather content with the decision to replace the exam with continuous assessment based on homework.

In order to promote critical, independent thinking among the students, the level of interaction was increased during lectures. Altogether 31 mentions in the open feedback data were related to these

Table 4. Reported effects of course elements on learning

Course element	Supportive of learning	Hindering of learning	Total
Continuous assessment	34	11	45
Interactive lectures	22	9	31
Design-based learning project	29	–	29
Teamwork	17	1	18
Open problems	7	5	12
Total	**109**	**26**	**135**

changes. 22 comments concerned the positive effects of the interactive teaching style. As one student put it: "*[The discussions] motivated to think independently rather than repeating knowledge from books.*" However, there were also nine negative comments related to the change. Some students stated that they "prefer traditional lecturing". As one student put it: "*The lectures did not really teach me anything, it was more of a discussion.*"

The hands-on design-based learning project conducted at Design Factory was the most appreciated part of the course. Altogether 29 comments were made about the supportive effect of the project on learning. As one student put it: "*Project work was educational and interesting, definitely the best part of the course. It was great to be able to work freely.*" None of the students criticized the project. However, there were some negative comments about abandoning the traditional way of attending lectures and studying for final exam: "*There could have been some teaching in the course instead of just fiddling around*".

According to 17 comments, "the new team working methods were great". There was only one comment in the data against working with other students: "*Independent working just happens to be the best way to get things into one's head at once. It just takes a lot of self-discipline.*" However, the view of the student was implicit in some other comments as well; the traditional ways of teaching were considered more efficient and less time consuming than the new method of encouraging the students to cooperate in solving the problems.

The design-based reform was grounded on a holistic perspective to the course topic. Instead of a narrow question with only one correct answer, the student was presented with an open problem typical of the field. The division of the negative and positive comments was quite even. Seven comments were made about the positive effects of having an open problem as the basis of the course, such as: "*Emphasizing the fact that there are no right or wrong answers to problems but possible, better, or worse released some inner energy for me.*" The students thought that "*the open problem homework was motivating and very informative*". Five of the comments implied that holistic perspective hinders learning. One student was concern about the effectiveness of learning, because "*the tasks were very abstract, mostly seeking for information, analyzing, and making own conclusions*".

In general, the open feedback comments on the course arrangements were very emotional and dispersed. Some of the students reported enjoying the new approach and would not have changed anything: "*The teacher facilitated the learning process—I learned a lot*". On the other hand, some of the students reported that they did not like the changes or learn anything: "*I did not learn ANYTHING about combustion and gasification technologies*". The strong reactions of the students imply that design-based learning was rather new approach in their studies. As one student put it: "*The implementation of ideas beyond reports and presentations and into a physical model was a refreshing change for the rest of my Master's program. Even though the theoretical workload was slightly less than on other technical courses, the culmination of realistic and practical ideas into a model made the course enjoyable.*"

As indicated in Table 4, most students considered that the design-based approach supported their learning: "*The approach was activating and enabled critical thinking as well as creative solutions*". The majority of the students thought that "*theory and application were well balanced and the discussion facilitated understanding*". There were altogether 109 positive mentions about the effects of design-based model on learning in the feedback data. The number of negative comments was only 26. In addition, there were 20 mentions in the feedback data about unclear, irrelevant, or poorly focused course content. These comments were not attached to any of the specific course elements. There were also 15 comments about uneven or too heavy workload especially during the first years of the course reform in 2010 and 2011: "*For me the relation between the learning outcomes and the time spent on studying within this model is much worse than in the traditional model where time is spent on lectures and studying for the exam*".

The course reform was based on an assumption that design-based learning can enhance the learning of theoretical disciplinary knowledge as well as the development of design thinking skills." In the feedback system, the students were asked to mention one to three most essential issues they had learned in the course. The resulting data reveals reported learning outcomes from both courses between 2010–2012. Majority of the learning outcomes were related to technical knowledge in the field of combustion and gasification technology. From a total of 135 mentions, 100 represented this category. In addition to the disciplinary learning outcomes, the students reported learning design thinking and working life skills related to group working, knowledge seeking, source criticism, critical thinking and project working. A total of 35 mentions represented this category. The reported learning outcomes are in line with the formally defined learning objectives, such as deep understanding of the technology and its scientific basis, critical thinking from various viewpoints, and team working. The reported learning outcomes are presented in Table 5.

Table 5. Reported learning outcomes

Technical knowledge	**Number of comments**
Combustion and gasification technology in general	19
Mass and energy balances, adiabatic combustion temperature	18
Practical disciplinary knowledge	17
Fuels and fuel properties	12
Combustion chemistry, chemical equilibrium and reaction kinetics	10
Pollutant formation and reduction	8
Processes in flames	8
Disciplinary concepts, terminology	8
Total	**100**
Design thinking and working life skills	
Knowledge seeking	9
Group working	8
Source criticism	7
Critical thinking	6
Project working	5
Total	**35**

6. Discussion

The design-based course development efforts described in this paper aimed at encouraging the students to achieve a deep understanding of the scientific, technical and societal issues related to combustion and gasification, to enhance critical thinking and independent assessment of situations, and to provide opportunities to practice teamwork and effective communication. To reach these objectives, the course content was refocused away from numerous technical details into a fewer number of more fundamental topics. The lectures were enriched with discussion around open problems, the final exam was replaced with several sets of homework and facilitated workshops, and a design project was introduced into the course. The learning results reported by the students were well aligned with the contents and learning objectives defined by the teaching staff as well as with the performance observed during the contact teaching. Design-based learning resulted in a good balance between theoretical and practical knowledge and skills as well as the design thinking skills desired by the industry. The design project provided the students with a real-life engineering context where the new information could be applied and discussed. In comparison to theoretical lectures, building a tangible prototype provided a natural setting for intensive teamwork and communication. The students could better understand how and where the different pieces of information are associated with each other and how they can be used to construct a useful system of knowledge. Motivated by the project, majority of the students continued working on the homework problems even after reaching the best possible grade level. On top of what was required, they also built additional project deliverables. The good learning results can be at least partially attributed to the continuous feedback that provided the students with an opportunity for self-assessment. These findings are in line with previous research on the effects of DBL on middle-school level [see e.g. 18, 24].

Majority of the students liked the course changes. It seems plausible to assume that the group of students who reported achieving good learning results was also mainly responsible for the positive comments on the teaching methods, although this cannot be confirmed due to the anonymity that has been built into the feedback system. There was also a small group of students who disliked the changes and appeared to prefer the traditional teaching style with teacher-centered lectures and assessment based on final exams. The statistics for the Likert scale feedback questions suggest that the size of this group was less than 15% of all students. Extremely negative verbal feedback was only received once for CGT 1 in 2012 and due to the anonymity of the feedback system it is not possible to tell how many students provided the negative comments.

It is possible that the students who criticized the new teaching style were not used to the design-based learning approach and the emotional change resistance might have affected their judgment on the learning outcomes. Also Boaler [25] observed a group of students at middle-school level who felt uncomfortable with mathematics teaching based on open problems and self-guiding student activity. Overcoming the resistance towards the design-based learning method is crucial for engaging all students into the learning process. Even though design projects are becoming an increasingly used method in engineering education [19], majority of the first two years of the engineering curriculum continue to be devoted to the foundational lecture-based courses in mathematics, physics, and chemistry [26]. The longer the students are exposed to the passive repetition of information, the more challenging it is for them to apply various knowledge in complex open tasks. Providing the students multiple opportunities to practice their skills on authentic complex tasks already in the beginning of their studies would better prepare them for the design-based learning approach [19, 27].

As stated by Kolodner et al. [24], supportive environment in which to practice the teaching of DBL is critical for implementing the approach. The flexible spaces for teaching, teamwork, and building of physical prototypes at Aalto University Design Factory enabled establishing the DBL project. ADF Teaching Partner program lowered the threshold for experimenting with DBL model, provided ideas for implementation of the model, and supported developing the courses further.

7. Conclusions

Design-based learning has several advantages when compared with teacher-centred deductive teaching. Firstly, engineering students often tend to be more interested in practical problems than in abstract theories. Motivated by the task at hand, the students are likely to achieve good grades, commit to the course work, and perform beyond the course requirements. Secondly, introducing a practical problem usually suggests very natural ways of expanding the analysis into important areas outside of technology, such as the economical, environmental, societal and ethical issues related to the problem. Thirdly, design-based learning is an excellent tool for encouraging the students to present and discuss their ideas. Building a concrete deliverable provides a common language between various disciplines thus lowering the threshold for interaction between both students and the course staff. Pedagogical mentoring and flexible spaces that enable teamwork and building of physical prototypes support the use of design-based learning model in engineering education.

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Appendix 1. An example of Design-Based Learning Project briefing

Ene-47.5120 Combustion and Gasification Technology I / Fall 2011

Teamwork at the Aalto University Design Factory on 29th Sept–20th Oct. 2011

Tasks

Designing a biomass-fired heating plant to Otaniemi

As the subway system will be extended to Otaniemi in the near future, a significant number of new buildings are planned in the area and it is anticipated that the demand for district heating will grow substantially. There is already a heating plant in Otaniemi, nowadays fired with natural gas, but strong political pressure is being felt to develop Otaniemi as a model area for environmentally progressive and sustainable development policies. Thus, the building of a biomass-fired heating plant seems an attractive choice.

A preliminary study has now been launched. The design parameters have been chosen as:

Thermal output:	4 MW
Annual operating hours:	5000 h
Number of cold starts:	1/year
Number of warm starts:	4/year
Plant lifetime:	30 years

A number of teams have been assembled to carry out the study:

Team	Task
A	Chief design team, coordination of other teams
B	Plant location
C	Fuel procurement and transportation to Otaniemi
D	Fuel reception, storage, treatment, feeding to the boiler
E	Boiler (especially the firing system)
F	Emission control technology
G	By-products
H	Economy

Each team shall study the field designated to the team and present the findings to the other teams. Please make sure that your work is all the time coordinated with the other members of your team and the work of other teams. Communication and co-operation between teams is allowed and, in fact, required!

Instructions on practical matters are given in a separate document “Arrangements”.

The following is a brief listing on topics to be studied by each team. This list is intended to get you started, you should by no means restrict yourself to the topics mentioned here. Please observe that all teams are required to study their field in a quantitative sense, that is, the teams are expected to show some numbers based on estimates and calculations. It will not be sufficient to just present verbal evaluation of different possibilities.

A Chief design team, coordination of other teams

The main task of this team is to supervise the work of all other teams, to make sure that information is communicated effectively between the teams, and to find a way to solve any technical questions, which affect the work of several teams.

B Location

Where in Otaniemi should the plant be built? Why? What (if any) existing buildings/structures need to be relocated? Where?

C Fuel procurement and transportation to Otaniemi

What biomass fuels are available? Where? What fuel should be chosen? Why? What would be the best way to transport the fuel to Otaniemi? Why? What additional infrastructure (if any) is needed for the fuel transportation?

D Fuel reception, storage, treatment, feeding to the boiler

What technologies/facilities are needed for receiving and storing the fuel? Is some kind of additional treatment needed? What? Why? What systems are needed for feeding the fuel to the boiler? What fuel analyses are needed to ensure good and constant quality?

E Boiler (especially the firing system)

What kind of boiler should be built? Which firing technology should be used? Why? What auxiliary equipment will be needed?

F Emission control technology

What kind of emission regulations apply to this kind of a plant? What kind of emission control equipment will be needed? Why?

G By-products

What by-products (ash etc.) will be produced? How much? Are the by-products something that can be sold or are they something that needs to be disposed of?

H Economy

What will be the investment costs and annual operating costs of the plant? How do they compare with the expected value of the heat sales? Would it make sense to upgrade the plant to a combined heat and power plant (CHP plant)?

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