Iterative development of engineering in Danish schools

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Abstract
We have developed and performed a Teacher Professional Development (TPD) programme for introducing and implementing engineering in primary and lower secondary school in Denmark. Engineering is a newcomer in Danish schools, and we only had fuzzy ideas about how to introduce it when we started. We therefore designed the TPD with an initial development and test phase where teachers acted as co-developers of teaching materials and didactic models. We monitored the process by teacher surveys and interviews, classroom observations and students surveys. The overall project design helped us to optimize didactic models, teaching materials and TPD activities through two iterative cycles before upscaling dissemination and teacher training.

Key words: Engineering in school, teacher professional development, iterative approach, design based learning.

Introduction
Engineering is gaining momentum as a significant part of the Science, Technology, Engineering & Mathematics (STEM) agenda worldwide. This impetus is especially strong in the United States, and the introduction of engineering has a longer history here than other places (Carlsen, 1998; Cunningham, 2018). The movement gained political momentum with the report ‘A Framework for K-12 Science Education’ (National Research Council, 2012), that recommended a radical change of existing K-12 science education to put larger emphasis on engineering and technology.

In Denmark, the STEM-agenda reached a recent climax with the new national strategy for STEM-education (Ministry of Education, 2018). The preparatory review for the strategy addressed - amongst other issues - the didactic-pedagogical potentials of engineering (Nielsen et al., 2017), e.g. that engineering problems can be designed so they are suitable challenges for novices in science and enable students to train their modelling and inquiry competencies. In the TPD we focused on science teachers’ implementation of engineering in their teaching, as engineering provides options for motivating students, and for training their problem solving skills and inquiries into natural phenomena (Cunningham, 2018; Nielsen et al., 2017). However, there are challenges in implementing engineering in the school curriculum, the largest being the integration of STEM-subjects in interdisciplinary science teaching. The main cause for this challenge is teachers lacking interdisciplinary Pedagogical Content Knowledge (PCK) (Kurt & Pehlivan, 2013). A second challenge is how to connect engineering design learning approaches with a high level of learning science concepts (van Breukelen, van Meel & De Vries, 2017).

More or less simultaneously with this general STEM review, a dedicated review regarding engineering was published in Denmark (Daugbjerg et al., 2017). This review
looked into the potentials of engineering as a pedagogical practice in schools in Denmark. The review departed from research performed in the US on engineering, and highlighted educative elements of engineering in schools. One of them being the significance of training teachers prior to their teaching engineering. The review also provided examples of how teachers engineering-PCK (Hynes, 2007) can be developed according to the experiences gained in the US, with elements of action learning being one of the most promising strategies (Aubusson et al., 2009).

This paper presents how we iteratively developed teaching materials, didactic models and training activities for an engineering TPD-programme for primary and lower secondary schools. We struggled with the classical challenges of designing an effective TPD-programme:

a) developing efficient procedures to translate the innovative ideals into concrete instruction;

b) making the proposed change fit the participating teachers current practice and aims; and

c) performing the implementation of the innovation with limited investment, and still ensure that the expected benefits are substantial (van Driel et al., 2012).

We were challenged by engineering being a novel idea in Danish schools. For this reason, we only had fuzzy ideas about how to introduce it. We therefore designed the TPD project with an initial development phase and test phase where we, in collaboration with teachers, iteratively refined our TPD activities, teaching materials and didactic models before we started on the first dissemination and training phase (figure 1). The research question that guided our investigations of the entire TPD process is: What changes can be traced in the iterative and collaborative development of didactic models and teaching materials? The following reflections will focus on factors that hindered or promoted successful improvement of the didactic models.

Figure 1. The overall project design with the four phases: a development phase, a test phase and two consecutive disseminations phases.
Research context

In 2017 an engineering teacher training programme was developed in a nationwide TPD project “Engineering in School” (EiS) for primary and lower secondary school teachers. The project is based on principles of design research with iterative development of solutions to problems in educational practices (The Design-Based Research Collective, 2003). Teacher trainers and teachers collaborated to analyze the problems being addressed as they developed and iteratively refined solutions. The design process is continuously informed by formative assessment during the development and test phases (Mckenney & Brand-Gruwel, 2018). The aim of the EiS-project was to - simultaneously and coordinated - develop the TPD-programme in conjunction with didactic models and teaching materials and to disseminate these to schools.

The development phase was a collaboration between twelve teachers and seven teacher trainers. The aim was to create a “design laboratory” where teacher trainers acted as initial curriculum developers, but clearly presented materials and didactic models as prototypes that needed improvement based on teaching experimentation by the participating teachers. The intention was to engage the teachers as co-developers. From the outset, the curriculum developers developed prototypes of different didactic models and teaching materials (Didactic 1.0 in figure 1). The materials consisted of:

- An engineering design process model,
- A rubric for assessing students learning,
- A rubric for students’ degrees of freedom in the engineering design process,
- Engineering characteristics

Figure 2. The interchanging workshop and school based action learning model used during all the phases in the engineering project (Nielsen & Daughbjerg, 2014).
Alongside these didactic models, the curriculum developers provided five online engineering prototype activities for teacher experimentation. The TPD was organized with interchanging workshops and school based experimentation: The teachers collaboratively experimented with engineering prototype activities and didactic models in workshops. They then subsequently experimented with it in their own teaching practice, and finally engaged in collective reflections upon actions to share elements of good teaching practice (Nielsen & Daugbjerg, 2014) (figure 2). Between the development phase and the test phase the didactic models and teaching materials were revised (Didactic 2.0 in figure 1) in accordance with feedback from the participating teachers.

The test-phase included more teachers from more schools. The teachers engaged in TPD-activities that strictly followed the TPD-model depicted in figure 2, where the teachers worked with the revised didactic models and teaching materials. As in the development phase, teachers and teacher trainers engaged in action learning on the teaching experiences that provided rich data for improving the didactic models.

Between the test-phase and the dissemination phase 1 all materials were revised in accordance with feedback from the participating teachers (Didactic 3.0 in figure 1).

![Figure 3. Faded guidance and transfer of responsibility in educative contexts (van der Pol et al., 2010, p. 274).](image)

The dissemination phase 1 was divided in two steps, a first step where the teacher trainers planned and performed the workshops and a second step where teachers experienced faded guidance by the teacher trainers with the intention to transfer responsibilities for continuous professional development to local school based learning communities. The notion of faded guidance is inspired by van der Pol et al. (2010) with the intention to sustain engineering activities in school based learning communities (figure 3).

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1 [https://astra.dk/engineering/forl%C3%B8b](https://astra.dk/engineering/forl%C3%B8b), Visited 28.02.2019.
In both steps in dissemination phase 1, the interchanging rhythm of action learning was applied (figure 2).

Dissemination phase 2 is a repetition of Dissemination phase 1 in new schools. In these schools we will provide support in step one and in step two fade guidance in order to transfer responsibility for TPD activities to the local school based learning communities.

Methods

We have collected data from multiple sources to inform the development of various materials and processes. The following data was collected:

Surveys

Pre and post-surveys to teachers.

The aim of these surveys was to get an overview of the participating teachers approach to and implementation of engineering in their teaching, we further wanted to map changes in their attitude towards engineering as a teaching strategy and assessment of their use of teaching materials, didactic materials and students learning outcome. In the test phase, there were 35 responding teachers in the pre-survey and 37 in the post-survey. In the dissemination, phase 1, 68 responding teachers in the pre-survey and 74 in the post-survey.

Post surveys to students.

The aim of this survey was to map students’ self-assessment of learning outcome and motivation and attitudes towards engineering activities. In the test phase, 680 students responded in the post-survey. In the dissemination phase 1 1339 students responded in the post-survey.

Observations and interviews

Field notes, video and still photos documented a number of teachers’ classroom actions with engineering activities in the project:

- Four during the development phase,
- Ten during the test phase,
- Three during the dissemination phase 1.

A few of these were supplemented with teacher interviews focusing on clarification justification of their enactment of engineering activities. The aim with the observations and interviews was to validate surveys and further elaborate our understanding of these teachers’ experiences with engineering in science education.

Teacher produced products were collected during the workshops.

Image stories of their performed engineering teaching and lesson plans from their performed engineering teaching.

The data collected using the above-mentioned methods were analysed using Nvivo 12. The survey gave us overview of the participating teachers’ experiences with the elements in the TPD and the interviews gave us nuanced insight into the individual teachers’ experiences with engineering in primary and secondary school. In this study,
we particularly focused on the development in teachers understanding of engineering as a teaching strategy.

**What we learned from the participating teachers**

We have chosen two examples that illustrate how the data analysis changed our thinking and lead to modifications of the didactic models and teaching materials. According to the teachers’ assessments of the presented didactic models (figure 4) the most and the least useful models are ‘The Engineering Design Process model (EDP-model)’ and ‘The Learning Assessment rubric (Assessment rubric)’. We will present iterations of these prototype models.

*Figure 4. Teachers experienced usefulness of presented didactical models, data from test phase post-survey. 1 = not useful. 2 = A little useful. 3 = Useful. 4 = Very useful.*

**Engineering design process (EDP) model**

We developed an EDP-model based on our literature studies (Daugbjerg et al., 2017; Cunningham, 2018; Nielsen, 2017) (figure 5). The model included an initiating problem identification phase and some elements of prototype construction and testing and ended with an assessment of process as well as prototype. The intention of this model was to guide the teachers in their planning.
The teachers in the development phase clearly found such a model very useful.

- I could easily relate the students work to the model, and thereby guide them in their process.
- The elements in the model was also recognisable in relation to other models about design-processes and project-organised work.
  (Teacher quotes from workshop 3 in development phase)

These quotes show how the teachers included the EDP-model in their teaching. Generally, the teachers found the model useful in order to communicate the intentions to students and to organise activities in an engineering process.

It was evident during both the development and the test phases that the teachers used the model for communicating with their students and not just for planning their teaching as we had intended. We therefore reconsidered the purpose of the model and made it more into a model that could communicate the engineering design process to students. After some intermediary models, we ended up with a more organic layout (figure 6). The teachers acknowledged the importance of such a model during the test and dissemination phase 1.

- We worked with the engineering design model, so that it became a frame for the students
- I told the students about engineers and showed them the model. I presented the processes and a work plan where the processes were included.
  (From teacher post-survey in after the test phase)
The basic idea of the more organic model is the same as the one in figure 5, but this is more detailed concerning the five activities in the centre of the engineering process. These five are exactly the activities where the students work more autonomously. Furthermore, the model does not prescribe a particular order of the activities. This was a point that the teachers stressed in their feedback. We observed the same during our observations of engineering activities in the classes. The students did not do the activities in a prescribed sequence. The students jumped between the activities as they worked with their prototype and solution, not necessarily being aware of what kind activity they were doing. The latter observation is somewhat disturbing, and we will return to that in the discussion.

**Assessment rubric for students learning**

For the development phase, we had developed a rubric with emphasis on the students’ work with engineering (table 1). The intention with the rubric was for the teachers to assess students’ competencies in the various activities that constitute the engineering design process according to the preliminary EDP-model (figure 5). This assessment is then used formatively to inform students about their learning potentials. This rubric did however not achieve much attention from the participating teachers as seen in figure 4. Apparently, it was not a relevant tool in its presented form. The participating teachers made their own aims for the students work with engineering.

In the teaching sequence there is the following aims
- I was very focused on the way to work, that they should learn. Meaning the process. Moreover, working in groups. This was the assignment [building a tower] very good at addressing. It was harder with the subject matter aims, but indirectly they learned much about making stability.
- I can in collaboration with others make a brainstorm with ideas to solve the problem
- I can in collaboration with others work with prototypes of a parachute
- I can collaborate on the final model

(From teacher post-survey in the development phase)
Table 1. The initial learning assessment rubric focused on competencies.

<table>
<thead>
<tr>
<th></th>
<th>Starter</th>
<th>In transit</th>
<th>Completed</th>
<th>Exemplary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Express problem</strong></td>
<td>I can distinguish different problems</td>
<td>I understand my problem</td>
<td>I can explain my problem</td>
<td>I can relate my problem to general societal issues</td>
</tr>
<tr>
<td><strong>Plan and perform inquiries that investigate the problem</strong></td>
<td>I can recognize an investigation that say something about my problem</td>
<td>I can independently choose and perform an investigation of my problem</td>
<td>I combine independently several investigations of my problem</td>
<td>I can critique the investigation I have performed</td>
</tr>
<tr>
<td><strong>Discuss, negotiate and test ideas</strong></td>
<td>I contribute with a point of view about an idea to a solution</td>
<td>I understand how different ideas address the problem differently</td>
<td>I can combine different ideas to a practicable solution</td>
<td>I include versatile external contributions in my test of ideas and include these contributions in my solution</td>
</tr>
<tr>
<td><strong>Design a prototype</strong></td>
<td>I can make an outline for a prototype</td>
<td>I can design a prototype that shows principles in the solution</td>
<td>I design a prototype that shows essential function in the solution</td>
<td>I design a prototype that shows advantages and disadvantages in different choices in the solution</td>
</tr>
<tr>
<td><strong>Construct, test and evaluate final solutions</strong></td>
<td>I can based on my outline talk about my solution</td>
<td>I can construct a prototype, that shows principles in the solution</td>
<td>I construct a prototype that shows essential functions in the solution</td>
<td>I construct a prototype that shows advantages and disadvantages in different choices in the solution</td>
</tr>
</tbody>
</table>

The surveys from the test phase clearly indicate a shortage of assessment in the engineering activities. The most frequent assessment was teachers oral dialogue with the entire class, the objective for these oral dialogues was the prototypes and solutions produced and presented by the students, meaning that the assessment was made in direct relation to the students’ work.

One teacher describes to have made questionnaire about how the model was supporting the students in their work. Some teachers write that they found it hard to evaluate, they note that it likely will take several years before it will be easy to assess engineering in science education.

Based on this feedback we decided to refine the assessment rubric. We did this over several iterations, but finally ended up with a form where learning outcomes is understood as competencies. This choice was because the Danish science curriculum generally is formulated in accordance with competence-based aims (table 2).


<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Understand challenge</strong></td>
<td>I can sufficiently understand simple parts of the challenge</td>
<td>I have an uncertain understanding of the challenge</td>
<td>I have a good understanding of the challenge and its context</td>
<td>I understand the challenge completely and its relation to the societal context</td>
</tr>
<tr>
<td><strong>Develop ideas</strong></td>
<td>I can develop simple ideas for the prototype</td>
<td>I am uncertain about developing ideas and discussing possible solutions</td>
<td>I am confident about combining ideas to a feasible solution</td>
<td>I am very confident about combining ideas from others in my contribution for a possible solution</td>
</tr>
<tr>
<td><strong>Explore</strong></td>
<td>My knowledge about the challenge is limited and I can do simple investigations</td>
<td>I am uncertain about doing investigations about parts of the problem</td>
<td>I have good skills and knowledge about investigating my problem</td>
<td>I can with certainty investigate my problem and analyse data with a critical perspective</td>
</tr>
<tr>
<td><strong>Plan</strong></td>
<td>I can primitively outline for solving the challenge with material choices for the prototype</td>
<td>I am uncertain about choosing and processing materials for the prototype</td>
<td>I am certain that I can choose and process materials for the prototype</td>
<td>I can with great confidence choose between different materials for the prototype and argue for pros and cons of my choices</td>
</tr>
<tr>
<td><strong>Create</strong></td>
<td>I can construct a simple prototype which does not work very well</td>
<td>I am uncertain about making a prototype that only solves the challenge partially</td>
<td>I am good at constructing a prototype that almost solves the challenge</td>
<td>I can certainly build a prototype that solves the challenge and shows pros and cons in my choices during the design-process</td>
</tr>
<tr>
<td><strong>Improve</strong></td>
<td>I can make a simple assessment of my prototype suggest simple improvements</td>
<td>I am uncertain about testing my prototype</td>
<td>I can combine test procedures to test my prototype using given criteria</td>
<td>I can certainly test my prototype and discuss possible improvements with peers</td>
</tr>
<tr>
<td><strong>Present solution</strong></td>
<td>I can incoherently present my solution and use scientific and technical language to explain functionality</td>
<td>I am uncertain about presenting my solution. I alternate between everyday language technical and scientific language when explaining the functionality</td>
<td>I can coherently choose between different presentations formats that are optimal for presenting the solution. I alternate between everyday language and technical and scientific language when explaining the functionality</td>
<td>I can make a well structured presentation using formats of my own choosing. I alternate with certainty between everyday language and technical and scientific language when explaining the functionality</td>
</tr>
</tbody>
</table>

When we look at the teacher post-survey from the end of the first step in the dissemination phase it is clear that very few teachers look specifically for students learning in relation to the engineering activities. Actually, we can only identify such assessment for ten of the 74 responding teachers and only five of these have identifiable aims: typically, whether or not the product solves the problem.

Only one teacher tried to evaluate the students experience with working in the different engineering activities (process oriented assessment). Therefore, our attempt to provide a more structured guideline in the learning outcome assessment rubric have failed severely or more precisely our intention to see these guidelines put into practice has
failed. The type of assessment the teachers performed was oral assessment. In these the students expressed, that the higher degree of freedom in the work is rewarding.

**Discussion**

Design of a TPD-program can benefit from addressing six features: *focus, active and inquiry-based learning, collaborative learning, duration and sustainability, coherence and school organisational conditions* (van Driel et. al., 2012). Generally, we tried in our overall design to take these features into account. Our *focus* was engineering as a new approach to science teaching. We planned the workshop and the intervals between so that they included *active, inquiry-based and collaborative learning* at the participating schools. We asked the teachers to structure this work as action learning and provided them with guidelines to do so. In the development phase, the *collaboration* included teachers, curriculum developers and researchers. In the following phases, the focus was on *collaboration* between the participating teachers and their colleagues at their schools. The workshops in themselves were three days in the development phase and four days in the test and dissemination phase, the school based experimentation intervals between the workshops varied in *duration* from two weeks to six weeks – shortest in the development phase. The interchanging TPD design (figure 2) was intended to support implementation and secure *sustainability* of engineering in the learning communities at the schools. However, the local sustainability was subordinated the local school *organization*. Local school cultures made the conditions very different – varying from impossible to exemplary.

The reviews regarding engineering referred to in the introduction gave us reasonable arguments for integrating engineering in science teaching, but also some elements of how to include it. Furthermore, the science curriculum in Denmark includes integrated elements that address topics such as sustainability, technology and environmental issues. These topics are assessed in year nine through a competence-based, project-organised cross-curricular oral and practical examination. The idea of implementing engineering in science teachers practice seems to be in *coherence* with the cross-curricular examinations and the national reviews on engineering. Not all the teachers accepted the idea, that engineering was a mean to meet the cross-curricular aims. Looking specifically at the supporting elements presented above - the EDP-model and the assessment rubric we learned some important points.

**The EDP-model**

Generally working with student’s learning and innovation skills is gaining momentum in primary and secondary education. The framework for 21st century competencies addresses five such skills: problem solving, creativity, critical thinking, communication and collaboration (P21, 2018). This means that a contemporary EDP-model for primary and lower secondary school shall include options for the students to develop such skills, but also to reflect on their learning of such skills.

Learning by design processes is not a new approach in science education (Capobianco et al., 2018; Carlsen, 1998). Within technology education, learning approaches is inspired by how professionals work with design (Kolodner, 2002). The intention is that students learn about science phenomena by designing and building constructions, that lift or move objects or keeps soil from eroding.

The need to make one’s design ideas work provides opportunities and reasons for students to identify incomplete and poor conceptions of science content and to debug those conceptions; the iterative nature of design provides opportunities to
apply and test new conceptions; and the collaborative nature of design provides opportunities for team work and the need to communicate ideas and results well. (Kolodner, 2002, p. 3)

This approach is very similar to our and other engineering design approaches (e.g. Capobianco et al. 2018). However, Kolodner stress how the learning of science can be integrated into the application of engineering-like design processes. When performing engineering inspired science teaching it is important for the teacher to keep track of how they emphasize or minimize the different engineering activities (figure 6), and of how they make disciplinary connections to science and design and what instructional and classroom organisational strategies they employ during different activities in the EDP-model (Capobianco et al., 2018). It was aspects like these that we learned and had contextualised in collaboration with teachers during the development phase, and based on these experiences we transformed the original EDP-model (figure 5) into the final one (figure 6) as it made it easier for the teachers to perform instructions and to organise the classroom. This evolution created a model that made transfer from workshops to classrooms more coherent. The way we worked with the EDP-model thus actively addressed the feature of collaboration and coherence in professional development programs (van Driel et al., 2012). However, we do in classrooms observe students that are not fully aware of the characteristics of the different engineering activities. Therefore, even though the final EDP-model provided options for the teachers to address directly what kind of activities the students were conducting and more easily support the students’ reflection on their own working and learning process. There still is some work to do regarding our instruction of the teachers regarding their scaffolding of their students’ awareness of the characteristics of the different engineering activities in our EDP-model (figure 6).

**The learning assessment rubric**

Assessment of science education by use of rubrics is not new (Haury 1993; Luft, 1998; Ryoo & Linn, 2015). Rubrics has been used in primary science education (Haury, 1993; Uyeda et al., 2002) as well as in science teacher education (Luft, 1998). Rubrics can be used for assessing specific content knowledge (Ryoo & Linn, 2015) but also for assessing problem-based work (Uyeda et al., 2002). Typically, rubrics are designed like ours with increasingly more clear, comprehensive and detailed students’ skills and knowledge in handling the problem (Uyeda et al. 2002). Especially when applying approaches where the students have more control of their own learning, it is important to have clearly expressed assessment criteria e.g. in the shape of the rubric (Uyeda et al., 2002).

However beneficial a learning outcome assessment rubric (table 2) might be, it has to be activated and brought into focus of the participants during the workshops, otherwise they don’t remember it and don’t apply it (figure 4). It seems we failed in relation to the feature of focus (van Driel et al., 2012) in order to make it active in our professional development program. When it slips out of focus the rest of the features becomes irrelevant, as it is never a significant part of the teachers’ collaboration or of the coherence to other aspects of their science teaching.

**Conclusion**

Alongside our intervention, we were interested in learning how changes could be traced in the iterative, collaborative development of didactic models and teaching materials. In this paper, we have only addressed the didactic models. We planned the overall
intervention with a developing phase as a first iteration that included collaboration between teachers and teacher trainers. The teachers’ action learning was fruitful for the further development of the didactic models. The second iteration of our didactic models occurred during the test phase, which was an upscaling in numbers of participating teachers from the developing phase. Again, inspiring recommendations for adjustments were collected during this phase. Our overall design has helped us to focus the design process and more importantly, to refine the didactic models, so they support active, inquiries and collaborative learning in the TPD activities in the dissemination phases. We have found it very rewarding to engage teachers as co-developers of engineering teaching activities and its supporting structures and we will continue to do so in the further development of Engineering in school in Denmark, but also in other implementation projects.

Acknowledgement

We would like to thank first the participating teachers in this project, they are the true heroes of the development of Engineering in school in Denmark, without their enthusiasm and flexibility we would never have been able to keep the pace in this project. Furthermore, we would like to thank our dear colleague senior lecturer PhD Lars Brian Krogh, VIA UC for developing, managing and analysing the surveys we present data from in this paper.

References


