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# Implementation of empirical-mathematical modelling in upper secondary physics: Teachers' interpretations and considerations

## Abstract

*This paper reports on the implementation of an upper secondary physics curriculum with an empirical-mathematical modelling approach. In project PHYS 21, we used the notion of multiple representations of physical phenomena as a framework for developing modelling activities for students. Interviews with project teachers indicate that implementation of empirical-mathematical modelling varied widely among classes. The new curriculum ideas were adapted to teachers' ways of doing and reflecting on teaching and learning rather than radically changing these. Modelling was taken up as a method for reaching the traditional content goals of physics teaching, whereas goals related to process skills and the nature of science were given a lower priority by the teachers. Our results indicate that more attention needs to be focused on teachers' and students' meta-understanding of physics and physics learning.*

## BACKGROUND: MODELLING IN PHYSICS AND THE PHYS 21 PROJECT

Models and modelling receive increasing attention from the science education community as important components of a contemporary science education (Gilbert, 2004; Gilbert & Boulter, 2000; GIREP, 2006; Greca & Moreira, 2002; Hestenes, 1987). This paper concerns how PHYS 21, a project developing a modelling approach to upper secondary physics education, was interpreted and implemented by physics teachers in Norway.

In PHYS 21, we argued for modelling from two main perspectives. The first concerned the nature of physics as models of reality and the task of physicists to construct and apply models, and this perspective was seen as implying that students should develop a view of the nature of physics as a modelling enterprise and that physics education should train students to become competent modellers and interpreters of models. To become competent modellers students need practice in performing reasoning processes. Scientific reasoning with coordination of ideas and evidence has proven difficult for students to learn (e.g. Leach, 1999). An important component in a modelling approach to physics education thus would be to give students an understanding of *reasoning* as an essential mediator between experimental observations and theory/model.

The second perspective concerned modelling as a powerful tool in the teaching and learning of physics. We believe that a modelling approach may develop students' understanding of the relationship between mathematics and physics and of the role of experiment in physics. Also, the PHYS 21 approach was designed to give students practice in handling multiple representations (experiments, graphs, verbal descriptions, formulae, pictures/diagrams) of physical phenomena (Angell, Henriksen, & Kind, 2007; Angell, Kind, Henriksen, & Guttersrud, 2008; Dolin, 2002). According to Prain and Waldrip (2006), a focus on multiple representations may contribute to effective science learning by catering for students' individual preferences and promoting active engagement with ideas and evidence.

The *empirical-mathematical* modelling approach of PHYS21 entails activities where students employ multiple representations of physical phenomena to conduct experiments and construct and evaluate mathematical models of the phenomena. We are concerned not to promote "discovery teaching", where students reinvent physical laws. Rather, our modelling approach is based on empirical-mathematical model building of specific phenomena using established theory. In the modelling process students identify relevant variables, based on the theory, and use experiments and mathematical tools to determine a relationship (the model) between them. For details on the PHYS 21 approach, see Angell et al. (2007; 2008).

### **IMPLEMENTATION – NOT AN EASY TASK**

Physics teaching is generally known to be 'conservative'. Angell et al. (2004) found that teaching approaches in Norwegian physics classrooms were largely 'traditionalistic' and that students were quite happy with this state of affairs. Carlone (2003) described how 'prototypical physics' (physics envisioned as difficult, hierarchical, objective, etc.) was maintained and reproduced even in an allegedly 'reformed' physics course. In an extensive literature review, Powell and Anderson (2002) found that implementation of any reform requires a transformation in teachers' ideas about and understanding of subject matter, teaching, and the learning of science. They also point to the relationship between teachers' knowledge and beliefs and reform-oriented classroom practice. Similarly, Roehrig, Kruse and Kern (2007) emphasized that implementation of the curriculum was strongly influenced by the teachers' beliefs about teaching and learning, and the presence of a supportive network at their school sites. The importance of involving teachers in curriculum innovation has long been recognized, and if teachers feel some sense of ownership of an innovation they will more effectively carry it out in the classroom (Pinto, 2004). Teachers might also believe that local and external barriers impede their ability to implement educational reforms (Haney, Czerniak, & Lumpe, 1996).

In this paper, we look at how the PHYS21 curriculum approach was received and implemented by project teachers in the classrooms, more specifically:

1. How was the intended empirical-mathematical modelling curriculum (PHYS 21) interpreted and adapted by project teachers?
2. How did the PHYS 21 philosophy fit into the existing 'culture' of physics teaching?

## METHODS AND SAMPLES

PHYS 21 was a slightly adapted variety of the regular, optional physics course in the second-last year of Norwegian upper secondary school. The project took place over a period of three years: An introductory year with teacher workshops and design of learning activities; a 'pilot year' and a full implementation year (2005-2006). 10 schools and about 20 physics teachers participated in the initial phases of the project, whereas 6 schools, 13 teachers and 289 students (17-18 years old) took part during the full implementation year, employing the PHYS 21 course material and activities involving empirical-mathematical modelling along with a focus on multiple representations and scientific reasoning. Teachers had a large degree of freedom regarding the implementation of PHYS 21 and were invited to contribute with their own ideas and suggestions. However, some modelling activities were strongly recommended for all PHYS 21 classes (but it was up to the teacher to decide the context in which they were carried out).

Three workshops and several regional meetings for project teachers were arranged. A teacher booklet introduced the view of physics applied in the project, aspects of scientific method and scientific reasoning, examples of scientific models and the modelling process, and suggestions for student modelling activities. A similar booklet was produced for students. The booklets were compiled by the research team, but reflected issues discussed in the workshops held with the teachers.

Researchers visited all project schools during modelling activities. After the full implementation year, a short, online questionnaire was administered to the 13 teachers who had been actively involved in teaching PHYS 21. 12 teachers responded. The questionnaire comprised both open questions and closed questions with a 4-point Likert scale.

Semi-structured interviews with 6 teachers were conducted during the pilot year. Interviews were transcribed and analysed qualitatively with special attention to teachers' interpretation of the project's purpose, their descriptions of actual implementation in the classroom, and their views on physics and on teaching and learning. Interpretations were discussed among the researchers, and the transcripts were reread to check preliminary interpretations until a consistent account was constructed and agreed upon.

## RESULTS FROM THE TEACHER QUESTIONNAIRE

Indications of the degree of teachers' dedication to the project may be extracted from the questionnaire. Responses showed that the majority of teachers had conducted the recommended modelling activities in their classrooms. When asked to indicate the percentage of classroom time where the 'modelling idea' was prominent in their teaching, eight of the 12 teachers gave answers in the range 15 % - 30 % and four teachers answered less than 15 %. Most of the teachers answered 'to some extent' when asked to what extent they felt that PHYS 21 had changed their teaching practice. The teachers were also asked to what extent they thought PHYS 21 had improved students' understanding of physics, of the nature of science and of the role of experiment in physics. The majority responded 'to some extent'. On the question of whether PHYS 21 had increased students' motivation and interest, answers were more varied.

All teachers expressed that they would continue to employ the material and the philosophy from PHYS 21 in their future teaching to a great or to some extent. On an open question about which elements from PHYS 21 they wanted to continue using in their teaching, teachers mentioned central ideas and themes in the project, such as the modelling approach in general, the individual modelling activities, and the emphasis on scientific reasoning. For example: '*...change the practical work so it will include more about modelling*', '*the experiments will be more open ended and I will not give the answers first*' and '*More focus on modelling, and the model's good and not so good qualities*'.

On the open question of what they considered most successful in PHYS 21, teachers mentioned the emphasis on experiments and the modelling process and the explicit use of multiple representations of phenomena. What teachers found least successful in PHYS 21 was some uncertainty on their part

concerning the goals and progress of the project, and difficulties to get students to adopt the way of thinking and working with physics employed in the project.

### **RESULTS FROM TEACHER INTERVIEWS**

Although project teachers were in general committed to the project and mainly followed project guidelines, the project also illustrates clearly how curriculum ideas are interpreted and adapted to individual teachers' 'identities' and personal backgrounds. To illustrate this point, examples will be given of how teachers' specific interests 'merged' with the modelling ideas and led to particular foci. Names are fictitious.

#### **Peter: Modelling in physics history**

Peter expressed two main aspects in his 'philosophy' for physics teaching: having an experiment-based teaching and including historical perspectives. Practical experiments were seen as a way of engaging students and making them motivated for learning physics, but also crucial to their understanding of the physics phenomena. The historical element stemmed from a long and personal interest:

..I think historical physics, the way ideas have developed in physics, is very exciting. It has always been exciting to see how things started. How accidental events have caused progress, but mainly because the scientists have been well prepared.

When getting involved in PHYS21, Peter immediately saw possibilities for incorporating activities he previously had used in his teaching. These were based on Galileo Galilei's experiments when modelling the laws of motion. Peter developed a teaching sequence on 'force and motion' in which the students modelled physical motion through a stepwise series of activities, starting by dropping metal balls and timing them with a stopwatch. The teaching approach made use of graphs and regressions and the final outcome was the equations of motion as found in physics textbooks.

Peter did not start his course by teaching about models and modelling in physics before introducing the equations of motion; rather, he did this the other way around. Having finished the experimental approach to introducing the motion equations he had the students read about modelling.

I was dubious about starting with something as theoretical as this [the student text about modelling] without having done something practical first. When reading the text, students recognised the methods they had used in the experiments.

Peter's focus was on modelling as a teaching method, allowing students to follow a historical route, simulating the process when physics laws were first developed. Using the historical example was seen as having a double effect: students got to know an interesting piece of physics history and they could observe how physics equations were developed in a modelling process. Peter found it very difficult to include modelling in other physics topics, due to not having any stepwise routes as in his 'Galileo-approach'. However, when teaching other topics he could use the 'Galileo-approach' as a reference to say that similar processes had taken place and 'this is why we trust physics formulas'.

#### **John: Modelling as discovery teaching**

John claimed that participating in PHYS21 had triggered a small revolution in his way of teaching physics. This change related to the order in which he introduced physics theory and did experiments. Before, he had always introduced theory first and conducted experiments after this to 'prove' the theory. With the modelling approach, he rather made students 'discover' the theory on their own.

All experiments we have had so far I have tried to do before introducing the theory, when the student did not know much about the topic. This is what I have called modelling.

Contrary to Peter, he therefore saw modelling experiments as strictly open-ended tasks:

They [the students] are supposed to find out something, and I give a very clear message about what the task is all about, but I do not tell them what they are expected to find.

John's way of reflecting on modelling has much in common with Bruner's *guided discovery teaching* (Bruner, 1960). As in this literature, John drew parallels between physics learning and physics method, and he therefore much stronger than Peter defends explicit teaching about science methods.

John, however, met a similar problem as Peter, in that he found it difficult to design modelling activities. For John this should be activities where students can 'discover' the physics formula by themselves, and he soon found that few physics topics actually allow themselves to be 'discovered' by students.

I have been looking at 'Electricity'. There I see problems in doing any modelling activities, because a lot of time is devoted to introducing the concepts of current and voltage. Before you know these concepts you can not model anything. And [when you know them], Ohm's law is obvious.

### Henry: Modelling as a science method

Henry expressed an interest in the nature of physics and had some experience with teaching *about* physics before participating in PHYS21. He often included small class discussions about science methods and evidence in science. Sometimes he used contemporary examples from media to make students reflect on such issues and more generally the role of physics in society:

I try to emphasize the difference between 'ideal' and 'real science'... and maybe what reality you meet as a scientist (...) power structures, funding, money, aspirations, climbing the career ladder..

Henry's reflective attitude towards the nature of science made him see modelling both as teaching *about* science and as a skill. He was opposed to the idea that modelling activities should make students 'discover' the laws of physics:

There is an issue that some [teachers] think you may just make students do experiments and learn for themselves. I have told my students, there is no reason to try finding Newton's laws again.

Henry also claimed that the modelling approach to physics teaching had advantages in the teaching of physics knowledge, but this benefit was related to students' 'meta-reflection' on physics rather than a discovery process:

*Interviewer:* Do you think modelling is an important element in physics teaching?

*Henry:* Yes...as I have said before...it is open what the results will be, so they [the students] are forced to reflect more on physics. This is the way I see it. And you got the ways of presenting results .. with graphs and mathematics combined with physics. All this is... trying to see connections.

### **Roger: Modelling with Modellus is perhaps not a very good idea**

Roger has participated in the project from the start, but he did not teach a project group every year. He expressed somewhat uncertainty concerning the project's main goals, but he has conducted some modelling activities in his classroom. However, he also expressed doubt about the students' outcome:

.... They have used the formula  $s = v \cdot t$  very often, but it is .... but they have only used the formula to computing. They have not understood that it is a model.

Roger has used computer based equipment such as data logger and the program Modellus in his class. (PHYS 21 teachers were encouraged to use the program Modellus, which is a modelling and simulation software). But also here were the experiences not too good. His students seemed to not taking the modelling task seriously.

.... What we do in the datalab (the students) perceive as something we do in addition to the real subject.

Roger and his colleague were the only teachers within the project who tried out the Modellus software, but they did not seem to be convinced of its potential. Their judgement was that it was time consuming and that their students did not appreciate it.

Roger's students had not worked very much with open ended practical activities and he had not put much emphasis on any aspects of the nature of science (NOS). He said however, he had used the student booklet a bit.

In spite of Roger's somewhat uncertainty about how to involve himself and his students in the project, he had some positive experiences. For example he said:

Now we are touching scientific reasoning and methods and so on. There is a big step from making formulas to making science, ... but when they (the students) see that they can make something by themselves they might get some understanding of how things are made. And I believe that they are closer to it now ... to make something themselves than they were before.

### **Kenneth: Less committed to the project**

Kenneth came late into the project and he had for the most part inherited Peter's ideas and his activities based on Galileo Galilei's experiments (see above). However, Kenneth seemed not to be very motivated and he had neither introduced his students into the modelling ideas nor into open ended activities. But using the activities from Peter he had introduced at least some modelling aspects. Based on that experience he expressed his own view in this way:

I have the feeling that we should do it the other way around. We should have taken the theory first. That means that we should have taken the relations between distance, speed and acceleration either on a horizontal or on an inclined plane. And then made a model for a real incident. I felt it was somewhat unclear .. without anything for the students to put it on.

### **Mary: Practical work is important**

Mary had also to a less degree than for example John grasped the idea of modelling in our project. She had neither used the teacher booklet nor the pupil booklet very much. But she is convinced that practical work is important, and that the subject should not be too theoretical. She said she had not used open ended experiments with her students this year, but some years earlier. She said:

...and some students are very clever, ... they are in fact able to propose their own hypotheses .. and their own experiments as well.

The interviewer commented that the experiment he had observed in her class earlier the same day was quite open. But Mary was thinking of much more open ended tasks. However, she had some reflections about students' abilities to proposing hypotheses:

... and if you can get your students to proposing a hypothesis ... then they either get it verified or rejected ... and that, I believe, gives more to the students themselves. It becomes more reasonable for them that way, if they manage. But it's a matter of practice ... to get them thinking like this.

Mary and her colleagues were quite often working with data logging in their classes, but didn't make explicit connection to the idea of modelling, and she said that they probably could have been more aware of it.

Some aspects of NOS (the nature of science) were to some extent topics in her class. In particular she was using historical examples in her class. But she said it was difficult to engage students in discussions, and that it was of little help if only one or two students participated in a discussion.

## DISCUSSION

### Adapting to – or transforming - the culture of physics teaching?

The examples above indicate that new curriculum ideas are adapted to teachers' ways of doing and reflecting on teaching and learning rather than radically changing these. All the teachers found a place for modelling in their personal rationale for teaching physics. Similarly, Stein et al. (1999) claimed that teachers interpret new ideas and practices through the lens of their existing habits of practice and filter information about new ways of teaching through their prior experience as students as well as through cultural images of what teaching should look like. Like other researchers (e.g. Roehrig et al., 2007) we found that even if teachers stated that they were implementing the model-based curriculum, observations and interviews revealed a wide range of implementation practice.

A main observation from the classroom visits as well as the questionnaire, teacher interviews and workshop discussions was that the implementation of the PHYS 21 curriculum varied widely both in form and extent from classroom to classroom. For instance, the topic 'Forces and motion' was by all teachers introduced through modelling activities; however, interviews and observations indicate that the activities were conducted in quite different manners in different classrooms.

As already mentioned, physics teaching is generally seen to be 'conservative' and the main focus in a traditionalistic physics instruction is on physics as a body of knowledge to be learned. Teachers present new theories and laws in lectures followed by practical experiments to confirm, or 'test', these. All teachers in the PHYS 21 project referred to such 'traditional teaching', and some expressed that a motivation for being involved in a research and development project was to break out of this pattern. However, what the teachers saw as a main problem of physics teaching was the way it is presented, and not the *content* of the subject.

In PHYS 21, we saw modelling as important both because it reflects the nature of physics and because modelling activities were considered useful for learning physics. Classroom observations and teacher interviews show clearly that the last perspective – modelling as a method to teach physics content - was found most attractive by the teachers. This dimension seemed to most closely match the teachers' needs and ideas for renewing physics, as is apparent from the section on John's teaching (above).

Like the other teachers in the project, John's main focus was on the 'modelling activities' and the way these serve as ways of introducing conceptual knowledge. Although several of the activities were designed to teach 'modelling' rather than concepts, John and the other teachers assessed their quality in the perspective of conceptual learning.

The strong focus on the concept-teaching dimension does not mean that teachers are unable to understand the other two dimensions. During the workshops, for example, there often occurred fruitful and interesting discussions about the priority of aims in physics teaching, but back in their classrooms teachers keep to the priority of their traditional teaching. This problem was brought up and discussed in the interviews and the teachers generally agreed that learning skills and learning 'about physics' were important, but that they had few strategies for handling these dimensions in their teaching. John related this to his own learning of physics at the university:

I myself have been bred the same way as the students.. right? When I was at university we never had any discussions [about the nature of science]. It was more like just describing a phenomenon and using the rule.

Simply put, this background and the way it is kept alive in the existing culture of school physics twisted the outcome of the modelling project into a matter of modelling tasks as an alternative to 'chalk and talk' teaching. Teachers found the modelling tasks attractive because they challenged the ordinary teaching and forced students to be more reflective:

What they [the students] have said, and what I like most about the modelling activities, is that they are not traditional - that one should not just confirm a theory. The point is more openness and that there is not a final answer. They have to use their heads. I guess this is the point - and sometimes I think it has worked. Not always. (*Henry*)  
It is a tremendous change for me, [away] from going through the theory first and [then] in a way confirming.... (*John*)

To the extent that PHYS21 teachers did teach modelling as a skill, physics knowledge as models or physics as a modelling activity, this happens implicitly rather than explicitly. It is seen as a side effect generated from doing the modelling activities and not something that needs attention in itself. This attitude is not unique, but well known as a problem in practical work generally (Millar, 2004). To make more fundamental changes to the physics curriculum, a comprehensive change in teachers' priority of aims is needed.

Traditionalist, or conservative, attitudes towards physics teaching are held not only by teachers. Physics teaching is embedded in a more general 'school culture' where also the attitudes of students, parents and society at large are involved. Some teachers in PHYS 21 reported difficulties to get students to adopt the way of thinking and working with physics employed in the project:

...it is clear that they [the students] have a quite clear expectation of what they are going to learn and how they are going to learn it.

Other studies have documented that students have certain expectations concerning how 'proper physics teaching' is conducted. Such expectations are often influenced both by school culture (and school physics culture in particular (Carlone, 2003)), but also by parents, peers etc. (Geelan, 1997). These expectations also seem to be aligned with students' beliefs about the nature of the subject and about what they see as appropriate teaching and learning. For instance, Angell et al. (2004) remarked that upper secondary physics students were conservative in their views on physics teaching and learning; students viewed the subject matter as relatively fixed and the instruction methods as largely determined by the nature of the subject matter.

Similarly, it has been indicated (Brass, Gunstone, & Fensham, 2003), that there is a relationship between physics teachers' views of the nature of physics and the value they put on various instructional strategies in the physics classroom. Thus, it appears that the relationship between views on the nature of physics and choice of teaching/learning strategies needs to be addressed both for teachers and students. Interview data indicate that this was not given sufficient attention in PHYS21. Some project teachers seemed not to have 'internalised' the view of physics as models that was underlying the project – some might not agree to this view, and some might not have given it sufficient thought. The six teacher interviews confirmed the uncertainty about the ideas forming the foundation of the project; particularly, some of them expressed weak understanding of the nature of science and how to teach:

*Interviewer:* Do you talk about science making models.. and how science makes models?

*Teacher:* I have not worked much with that part. Maybe because I don't quite know where I'm going with it. I suppose I know relatively little about it myself.

Our approach to teacher/research team cooperation in this project was inspired by 'design research' (Kelly, 2003), pursuing at the same time design of well-functioning teaching approaches and strategies, and research (or understanding). However, in hindsight it appears that the terms for the cooperation may have been interpreted differently by the different participants in the project. Teachers expressed that they experienced the goals and progress of the project as somewhat unclear, whereas the research team on their part experienced teachers as contributing less than expected to discussing the project and developing course material. The researchers' agenda was that the teachers should actively contribute to developing the project, both its philosophy and concrete teaching material, whereas the teachers favoured to be given readymade material and a clearer agenda. Carlone and Webb (2006) describe the complexities of university/school collaboration projects and point out how such projects may easily end up as a 'top-down' enterprise despite the best intentions of true 'collaborative labour'. In their study, researchers were found to have 'global' goals for the project (including transferable knowledge to enlighten future curriculum or professional development projects), whereas the teachers in the team had 'local goals' (planning the teaching sequences for their class). This tension between the particular and the universal was found to disturb project team work. Also, Stein, Smith and Silver (1999) suggested that teachers who are accustomed to workshops that feature lectures and 'take-away' materials for tomorrow's lesson may feel uneasy when asked to construct a plan for long-term collaborative work with outsiders.

## CONCLUSIONS

In this paper, we have drawn on experiences from the PHYS 21 project to investigate how a modelling approach may be implemented in upper secondary physics and how the modelling idea is interpreted and adapted to each teacher's interests and teaching style.

We have pointed out some possibilities and some challenges connected with implementing this modelling approach. In promoting modelling in physics teaching, it appears important to focus not only on teaching materials, but also on the views on the nature of science and on physics learning that underlie teachers' practice. Indeed, without teachers seeing modelling skills and methodological and epistemological perspectives as equally important as conceptual knowledge, it is doubtful if these topics will ever become established in the implemented curriculum. It takes long-term work, both with teachers and with students, to adopt and internalize new views on the nature of physics and what it means to teach and learn it.

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