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## Exploring a simple visualization tool for improving conceptual understanding of classical beam theory

Eivind Johnsen\*, Magnus Nilsen, Eilif Hjelseth, Christoph Merschbrock

*Oslo and Akershus University College, P.O. Box 4, St. Olavs plass, NO-0130 Oslo, Norway*

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### Abstract

First year students struggle to understand the concepts in introductory engineering physics courses. Computer generated visualizations have proven their value for improving learning in tertiary education. However, it remains often unclear how visualization software can be effectively deployed in classrooms to best improve learning outcomes. In this paper we put a freshly developed educational software entitled “The virtual beam demonstrator” to a first test in a physics and mechanics lecture at Oslo University College. The intention of this work was to explore how to get the balance between technology, pedagogics, and content knowledge right to best support student learning. We evaluated student learning outcomes of our initial attempt to use the software in a classroom based on a student evaluation form. While initial results are promising, we cannot claim to have significantly improved student learning in our initial attempt at using the software. The evaluations showed only slight improvement in conceptual understanding by the students. This finding was not unexpected as we anticipated that finding the right approach for putting this software to use would take several attempts. To turn failure into success, we would need a stronger emphasis on customized pedagogic methods. Relevant theory is explored and an approach based on “Interactive Lecture Demonstrations” is proposed.

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\* Corresponding author. Tel.: +47-67238639  
E-mail address: [Eivind.Johnsen@hioa.no](mailto:Eivind.Johnsen@hioa.no)

## 1. Introduction

Several studies in the past three decades have shown that traditional lectures (“chalk and talk”, “teaching by telling”, “deductive” as opposed to “inductive” [15]) are not the best way of improving students’ conceptual understanding within engineering education. Sokoloff and Thornton claim to see no more than 5-15% learning improvements after a physics course run exclusively based on traditional lectures [1]. Similarly, a large longitudinal 10-year study (1999-2009) run at the University of Sydney showed an improvement of 13-19% in students’ conceptual understanding after a 5-week introduction physics course (Newton’s laws, velocity and acceleration) lectured in a traditional manner [13]. Inspired by such research outcomes, Sokoloff and Thornton developed a novel pedagogical approach called «Interactive lecture demonstrations» [1]. Their pedagogical approach is designed to encourage discussion, reflection and understanding. In consecutive studies they report up to 80% improvement in conceptual understanding from courses where this approach is implemented [13]. Some of the findings from these studies suggest that student learning can be significantly improved when emphasizing conceptual understanding by making use of appropriate technology [14].

Although a range of such teaching concepts are available, civil engineering courses are still typically lectured in a more traditional manner. Consequently, many first year engineering students find it difficult to obtain conceptual understanding from what is presented on the blackboard alone. Laboratory work is the typical solution to this problem. However, increasing class sizes limit the use of practical lab work in basic physics courses. In this paper, we contribute to the discussion of how virtual demonstrations of physical concepts and principles could contribute to increasing learning outcomes in civil engineering. At last year’s Creative Construction Conference, we presented an article introducing an early prototype of a software developed for the purpose of providing first year engineering students with an initial understanding of classical beam theory [2, 3]. The software features a three-dimensional view of different beam structures and their response to applied forces (e.g. deflection, bending moments, shear forces, stresses). It emphasizes visualization and ease of use to ensure that the system can be readily used in classroom settings. Following up on an initial test by ten first year students at Oslo University College in 2014, the software has been refined throughout 2015. This article picks up where its predecessor left off and we report our experiences from the first practical implementation of the system in a lecture on “Physics and Mechanics” at Oslo University College held in early October 2015 with more than 90 engineering students attending. The research question asked was: *How can the ‘Virtual beam demonstrator’ be used best in a lecture hall to support students’ conceptual understanding of classical beam theory?*

We argue that this research is important beyond the context of Oslo University College and that lecturers elsewhere may find useful ideas for teaching their students based on our work. Placing our self-made program ‘virtual beam demonstrator’ at the core of our study rather than using other commercially, available software allowed us for changing the software based on student requirements as we went along. This provided us with the some flexibility to fine-tune the technology based on emerging pedagogical and content knowledge. This was a precondition for creating a successful learning system. We made the software freely available on the web<sup>1</sup> and the two versions (e.g. 1.0 and 2.0) have been downloaded altogether more than 100 times indicating interest in our work. To understand how to best use the software in a classroom setting we ingrained our work in the Technology, Pedagogy and Content Knowledge (TPACK) framework stemming from the literature on pedagogics [12]. This framework has been developed for exploring how technology can be utilized to its full potential within education. While our work is limited in that we study a local Norwegian visualization-based teaching solution, we argue that our findings related to developing a teaching ‘system’ combining pedagogical, technological and content knowledge are relevant beyond our context. However, this would need to be verified by research into other visualization based teaching solutions elsewhere. The remainder of the article is structured as follows: first we introduce the TPACK theory informing our work, second the method is briefly presented, third the findings of the student evaluations are presented. Last, the discussion and conclusions of our work are introduced.

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<sup>1</sup> <http://www.mathworks.com/matlabcentral/fileexchange/49780-virtual-beam-demonstrator>

## 2. Theoretical lens

Duval makes an important distinction between vision and visualization [7]. Vision is the knowledge we achieve through direct access to a physical object. Visualization on the other hand, is about comprehension of the invisible – some kind of link between the physical and cognitive. In classical beam theory there is an obvious visual link between load and deformation. The eye observes that the beam deflects when a load is applied. This is however not the case for the interrelation between load and bending moments, shear forces and stresses. These are not visible (although stresses could be measured with sensors) and therefore often perceived as theoretical and complicated by students. This paper argues that visualization could contribute to make these interrelations clearer. The complicated theory is integrated into something practical to create what is called coherence.

Like most professional education, the engineering curricula consist of courses from various scientific disciplines. The overall focus is mathematics, physics and science. However, in order to fulfil the learning outcome requirements, technology and economy courses are also needed. The knowledge base is therefore relatively fragmented, meaning that there is a lack of theoretical integration throughout the studies [17]. Although there is often a natural progression from year to year in the education program, students often strive to see the relevance of the studies as a whole. Thus, coherence in the education rises mainly from knowledge about how a profession is executed in real life. Comprehensibility, manageability and meaningfulness are central concepts within the theory of coherence [8]. When students are introduced to new material, they should ideally understand it, believe in their own ability to manage it and find it meaningful. This can be obtained with support from the students' own previous knowledge and experience, the education program and/or future professional experience [9]. Due to social and demographic reasons, engineering students seem to have less relevant practical experience than earlier. Fewer students grow up in the countryside with practical tasks as natural daily activities, their parents are typically not in practical jobs, practical activities in their homes are outsourced (fix the car, refurbish the kitchen etc.). In addition, there is no longer any practice requirements in the engineering education. Hence, it is probably more important than ever that the students find relevance within their study program.

Traditionally, laboratory work is where the students get practical experience within the engineering education. Civil engineering students are shown how concrete and steel beams behave when exposed to a load, mechanical engineering students see how different machines work etc. However, there is rarely any laboratory work in the theoretical first year courses like mathematics and physics where relevance is probably most difficult to spot for the students. In addition, the ongoing trend with stronger emphasis on research and fewer educators with both academic and professional background probably leads to an increased gap between education and profession [10].

According to the above discussions, we are possibly then in a situation where both teacher and student lack practical experience. The challenge for the educational institution is then to close the gap through pedagogical methods. Lee Shulman argues that content knowledge and general pedagogical knowledge must be integrated in order to achieve what he calls «pedagogical content knowledge» (PCK) [11]. By this he means that pedagogic strategies are not universal, therefore they must be adjusted to each individual problem or subject matter. Simple theory could possibly be efficiently presented on a blackboard, while more complex problems might need more active involvement of the students in order to be fully understood. An extension of Shulmans theory was introduced by Koehler and Mishra, who argue that technology knowledge also must be integrated into the pedagogical strategies [12].

TPCK or later TPACK stands for “Technology, Pedagogy and Content Knowledge” [12]. In a wider definition, technology could also be something like a pencil or a piece of chalk. In this context however, we consider modern digital technology. Technology is not utilized to its full potential within education today for several reasons: educators tend to replicate teaching methods from their own studies, many lecturers do not feel they master the technology well enough, and it can sometimes be difficult to see the added value in student learning. In addition, lecturers are rarely trained in relevant use of technology. The model presented by Kohler and Mishra consists of three fundamental knowledge components necessary for good teaching. Knowledge about content, pedagogy and technology. Each component is influenced by the other two. New technology could change a course content (why memorize historic dates when it is all on the internet?) or facilitate for new educational methods (flipped classroom). Pedagogic knowledge could affect a course content (enables us to communicate complicated theory we otherwise could not). According to the authors of the article, the best conditions for learning arises when all three components are integrated and customized to the individual teaching situation. The interaction between technology and pedagogy (TPK) is especially challenging since there is not much software developed for education. Commercial software is designed to solve

commercial problems. Within civil engineering there are several programs designing all kinds of load bearing structures. You enter the input (loads, geometries and other essential parameters) and receive more or less finalized drawings ready to be sent to the producer. Within education however, we are interested in seeing what happens between input and output. Which physical effects determine the design of the structure? «TPK requires a forward-looking, creative, and open-minded seeking of technology use, not for its own sake but for the sake of advancing student learning and understanding» [12].

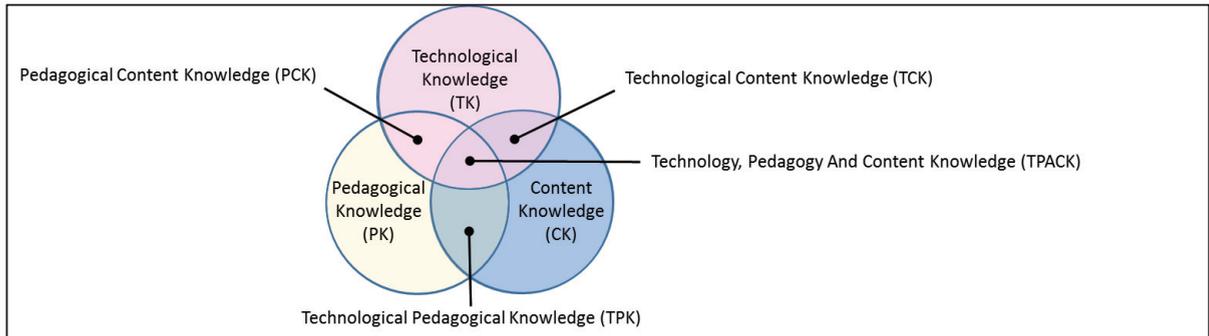


Figure 1: The TPACK framework and its knowledge components [12]

### 3. Methodology

The software was introduced in a 45 minute lecture in the course “Physics and Mechanics” in early October 2015 with approximately 90 students present where the objective was to evaluate the benefit of the visualizations in a lecture situation. The lecture was held as a traditional “teaching by telling” session where the software acted as a more sophisticated replacement for the sketches and drawings that would have accompanied the theory otherwise. To assess student learning outcomes a questionnaire was prepared in which the students could rank their learning outcomes. This questionnaire was circulated after class. In addition to the questionnaire the student learning was tested based on two tests, one circulated before class and the second after class. The students had to calculate several different examples covering the content delivered in the lecture. The tests were similar, but the last one required a somewhat deeper understanding of the theory, to be expected after the class. The design of the questionnaire and tests was guided by what Bloom suggested to be a taxonomy for learning in higher education. In the 1950s Bloom described six categories of cognitive skills relevant to higher education [4]. These are knowledge, comprehension, application, analysis, synthesis, and evaluation, where the last 3 are known as the higher-level thinking skills. Learning outcomes in higher education (knowledge, skills, competence) are typically designed to cover all these levels. In many engineering courses however, the lectures, assignments and exams focus on reaching only the application level [5]. Students might even leapfrog the comprehension level as they experience that knowledge and application skills could be sufficient to pass the often calculation-packed exams. In a basic course like “Physics and Mechanics”, reaching the analysis level would probably be an appropriate goal and a good base for reaching level 5 and 6 in design courses later in the bachelor program. It must be ensured however, that the students have obtained sufficient comprehension of the material. The lecturer has the main responsibility for giving students the possibility of reaching higher-level thinking skills. Abstract theory presented in the traditional manner often causes apathy among students, while connecting it to something real and physical typically leads to more interest and enthusiasm. Visualization tools can contribute to avoid such information overload [6]. Using self-assessment and tests in combination works well for establishing how well the students learned the content. The other two dimensions important in TPACK, namely pedagogics and technology, were assessed based on observation.

### 4. Analysis

We arranged the analysis part based on TPACK. Figure 2 provides a visual impression of the software used, the classroom situation, and the content knowledge focused.

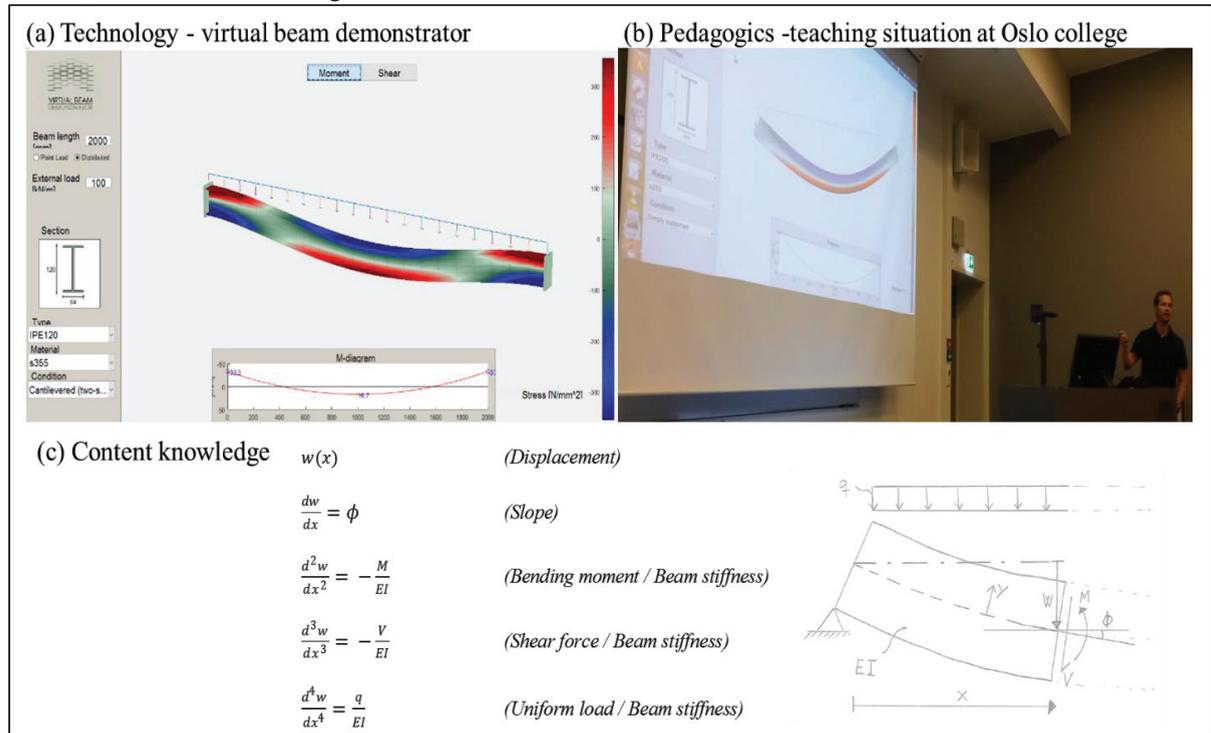


Figure 2: Virtual Beam Demonstrator 2.0 – technology (a), pedagogics (b), and content knowledge (c)

*Content knowledge* - The equations from the classical beam theory were programmed with MATLAB to visualize the different effects on a beam exposed to a load. The classical beam theory describes the interrelations between load (q), bending moments (M), shear forces (V), displacement (w) and slope (Φ) in a point (x) of a beam with given support conditions, length (L), section geometry (I) and material (E) [3]. From the bending moments and the shear forces, the bending stresses (σ) and the shear stresses (τ) can be derived at any point (y) of the cross section. An evaluation form was handed out to the students after the lecture. The students were asked to rank four different learning outcomes from the lecture. The results are shown in table 1. The students were also asked if they would like to see more use of similar software in lectures. This was scored with an average of 3,9 on a scale from 1 to 5. Added comments at the bottom of the form were mainly directed towards the following two categories: (1) the level of difficulty of the problem displayed was too high / we lacked basic understanding prior to the lecture (2) The deployment of the visualization in the lecture was too short to influence understanding.

Table 1. Student evaluations

To what degree did this lecture improve your understanding of:	Mean value
Bending moment and shear force diagrams for different constructions	3,5
The interrelation between bending moments and shear forces	3,5
The interrelation between bending moments and normal stresses	2,8
The interrelation between shear forces and shear stresses	2,9

1 = very low degree, 2 = low degree, 3 = some degree, 4 = high degree, 5 = very high degree

We ran two tests to assess whether the learning outcome was improved from using the software, one before and one after class. The tests consisted of several questions comparable in difficulty. The results of the test before and after class are presented in figure 3 below. The findings of comparing the test scores of the before and after tests show how student content knowledge has not significantly increased by deploying the system in class.

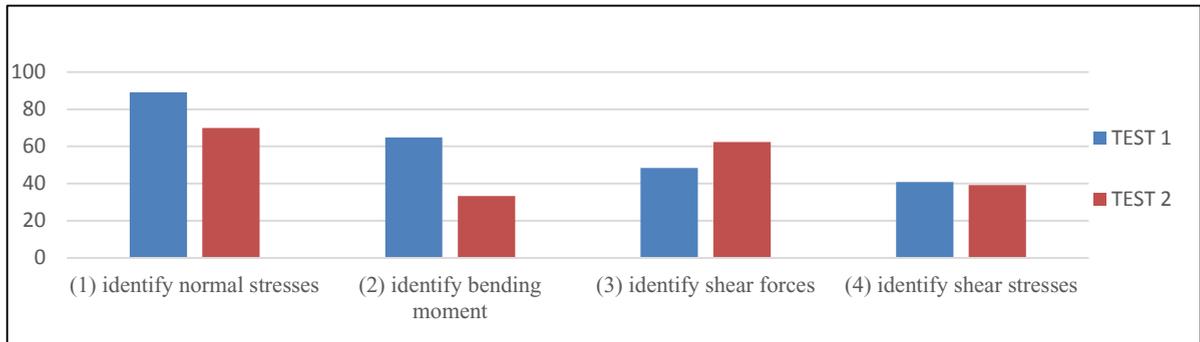


Figure 3. Test results before (test 1) and after (test 2) using the virtual beam demonstrator

*Technological knowledge* - The software was developed in 2014 by an engineering student at Oslo University College as part of his thesis work. An early beta version of the system was then assessed by ten first class engineering students. The suggested changes were then implemented in the system before deploying it in the classroom. One of the main advantages of the software is its simplicity. As soon as the properties section on the left (see fig 2) is completed (beam length, load, cross section, material and support conditions), a 3D model showing deformations and stress distribution appears along with a diagram underneath. The user may switch between two windows, moment (bending stress distribution and bending moment diagram, see fig 2) or shear (shear stress distribution and shear force diagram). The user may also rotate the 3D model in order to investigate it from other angles. This allows for interactive exploration, as appreciated by the initial test group [2]. Thus, the software can be said to be ‘good enough’ for achieving the desired goal for improved learning. However, the present version did not allow for being displayed on mobile devices which may have improved its utility for teaching.

*Pedagogical knowledge*- The students present in the experiment lecture had already been introduced to classical beam theory in previous lectures so no general introduction was given in the session. The starting point of the experiment lecture was a fixed cross section of a given material that was used in different beam setups. The idea was then to show how variations in support conditions, span width and load would cause changes in displacement, slope, bending moment, shear forces, and stresses. Finally, we would try to tie those findings to the general theory, e.g. through showing that bending moments are proportional to the first derivative (change) of slope or that shear force equals the first derivative of bending moments. These explanations were shown on a piece of paper using a document camera connected to a second screen. Most engineering students are visual, sensing, inductive and active learners [15]. This particular lecture was organized with both visual and verbal presentations of the material. However, the students were mostly passive observers, not given the opportunity to learn through active involvement.

## 5. Discussion

Based on the student evaluations we cannot conclude that the lecture using the visualization software improved conceptual understanding compared to a traditional lecture. However, the lecture was in fact held as a traditional “teaching by telling” session where the software acted as a more sophisticated replacement for the sketches and drawings that would have accompanied the theory otherwise. Based on the initial testing it can be claimed that the technology itself can be considered sufficient for teaching beam theory.

The analysis in this article shows that the pedagogical approach applied was unsuited for attaining the desired results of improved student learning. This could however be expected since this was the first time the system was implemented in a classroom setting. Based on TPACK we argue that the technological knowledge and content knowledge required for creating a successful classroom were in place. What we fell short on was pedagogical knowledge. This is where our teaching approach would need refinement. An attempt to visually express what happened in our classroom, explaining why student learning has not significantly improved, is depicted in figure 4. TPACK is a framework and not a fixed solution. An example of adaptation

can be found in a study by Hjelseth [16] about integrated building information modelling (BIM) in existing curriculum. The intersection of the aspects in TPACK was representing defined deliverables in the learning outcome.

Taking this technology further to become a classroom success would require a less traditional approach to classroom teaching. This could be done based on pedagogical concepts like “interactive lecture demonstrations (ILD)” [14]. Research indicates that an ILD based approach could significantly improve student learning. Studies report up to 80% improvement in conceptual understanding from courses where this approach is implemented. A 10-year longitudinal study at the University of Sydney shows more moderate results of an ILD approach (30-50% improvement), possibly due to a higher knowledge level at the pretest [13]. Still, several studies report considerable improvement in conceptual understanding using the ILD compared to traditional lecturing. Some of the findings from the development and use of ILD are summarized below [14]:  
 “Student learning is improved when we:

- Use peer instruction and collaborative work
- Keep students actively involved by using activity-based guided-inquiry curricular materials
- Use a learning cycle beginning with predictions
- Emphasize conceptual understanding
- Let the physical world be the authority
- Evaluate student understanding
- Make appropriate use of technology
- Begin with the specific and move to the general”

Instead of the physical experiments recommended by Sokoloff and Thornton, the software could be adjusted to execute virtual experiments as a starting point for active learning lectures. This would require less equipment and would also enable us to visualize more aspects of the classical beam theory than a physical experiment. Thus, the next step in developing this system could be done based on the following stages inspired by Sokoloff and Thornton: (1) Teacher describes and executes the experiment (input: beam length, cross-section, material, load, support). The program will show the visual implication (deformation), but no other results. (2) Students make anonymous individual predictions about the results in a questionnaire. (Various interactive learning tools such as Kahoot or Socrative, with students answering using smartphones or laptops, could help this step run smoother). (3) The results of the student predictions are shown on the screen. (4) Students discuss in smaller groups or just with their neighbor. (4) The experiment is completed; all results are shown on the screen. (5) Open discussion about the results. The software would have to be adjusted in order to fit the above procedure. The results (except deformation) should be hidden, either on a separate page or activated by command. Finally the software should be tested and evaluated in one or more sessions.

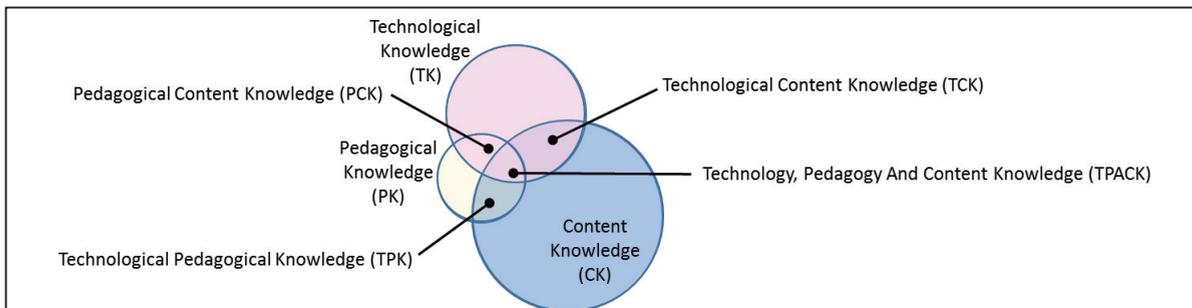


Figure 4. Dimensions of TPACK as experienced in the classroom

## 6. Conclusion

This article presents a reflection on using a self-made visualization program for teaching beam theory in a classroom setting. While we argue that the software was ripe for classroom implementation and for providing sufficient content knowledge for our students, our pedagogical approach was not. Our findings suggest that simply replicating a traditional lecture and replacing chalk drawings for digital models will fail. Thus, we would need to develop a proper pedagogical concept in addition to our program for making it a success. We will continue developing both the software and a related teaching approach to provide an overall successful learning system which then in turns may be applied by lecturers elsewhere.

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