Design Science Research – an engineering research approach to improve methods for engineering education research

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***Abstract**: Modelling is an engineering activity commonly used by engineers, and can be used also in engineering education research (EER). The use of qualitative research methods have in EER not always been widely accepted but have recently gained more attention (Case & Light, 2011). There are, however, also qualitative research methods in engineering research that may be used in EER (Bernhard, in press). One such approach is design science research, where the object of research is the design process, i.e. the knowledge retrieved is not always knowledge about the phenomenon, the artefact, the design, but rather knowledge about the method used.*

This paper aims at researching the method used when deriving the model "the learning of a complex concept", the LCC-model, which we developed while designing teaching sequences in a course in electrical engineering.

Introduction – overall layout

The purpose of this paper is to research the method used when deriving the model "the learning of a complex concept", the LCC-model (e.g. Bernhard & Carstensen, 2015; Bernhard, Carstensen, & Holmberg, 2011; Carstensen, 2013) which we developed while designing teaching sequences in a course in electrical engineering. To justify a methodology, to investigate whether a method can be transformed into a methodology is what has long been a research aim in design research, and particularly in design science research, so what then can engineering education learn from engineering? First we will present some literature where design research, design science research and design based research are discussed in order to introduce the field to the engineering education researcher. Then we will use methods from design science research to evaluate our model and the development of the model as a research method and finally discuss what this approach can contribute to the EER field.

Theoretical background

To design is what engineers do (Mitcham, 1994, p. 220) and to model is an engineering endeavour very often taken for granted. However, design research was already established as a research field by the foundation of "Design Research Society" in 1966 (Roworth-Stokes, 2011). The reason for this was that design seemed to have its own "theoretical base" (Roworth-Stokes, 2011, p. 419) – "Designerly ways of Knowing" (Cross, 1982) and "a designerly way of thinking and communicating" (Archer, 1979). Areas where design research have been of utmost importance are operations research and decision theory, where e.g. Bunge could identify "operational theories", which he describes as "scientific theories concerning action" (Bunge, 1967, p. 123 in Mitcham, 1994). The need for design research was thus to develop a theory for the design of manmade phenomena, artefacts, where often "the design researcher arrives at an interpretation (understanding) of the phenomenon and the design of the artefact simultaneously" (Vaishnavi & Kuechler, 2008).

There are at least two areas where traditional scientific methods are not sufficient for engineering research, the practice of engineering (e.g. Schön, 1983; Simon, 1969/1996) and the role that human values play, i.e. axiology (Vaishnavi & Kuechler, 2008) or volition (Mitcham, 1994). This leads to two characteristics of design: an artefact is always made with a purpose, and design is as well a noun as a verb, it is in action.

Furthermore, design research is a multidisciplinary field and "it is typically only in multi-paradigmatic …communities …that researchers are forced to consider the most fundamental bases of the socially constructed realities … in which they operate" (Vaishnavi & Kuechler, 2008, p. 17). Accordingly, the methods and methodologies are questioned by those who work within a paradigm (Kuhn, 1962).

Framing design research, Roworth-Stokes (2011), p.424 concludes: "Any definition [of design research] reflects the temporal nature of an evolving discipline that is increasingly being called upon to solve complex technical, social, and operational problems through the co-production of knowledge."

Already Dewey (1922/2009) recognized in his reflection on education as engineering, that the design of education requires as well specific as generalizable knowledge in practice. "Similarly, in 'design-based research' or 'design experiments' in education, insights from design and engineering are employed to address the complexity of educational activities and the need, as known from engineering, for theory as well as tinkering." (Bernhard, in press)

In a similar vein, researchers focusing on the process and design as methodology, have in education called their research "design-based research", and in information technology "design science research". Both approaches have struggled with reviewers not finding their research rigorous, but now claim: "Yes" (Kelly, 2004; Vaishnavi & Kuechler, 2008, p. 9). Furthermore the status of these approaches are shown by literature overviews such as Anderson and Shattuck (2012) in education, Roworth-Stokes (2011) in design and Vaishnavi and Kuechler (2008) in design science.

Thus, "If we are to find ways to significantly address the challenges of the twenty-first century we need an educational research field that can extend its domain of questions to those that are patently needing to be asked." (Case & Light, 2011) The questioning of qualitative research should maybe not be if it is rigorous, but rather what impact the research may have on education, a remark made by Reeves (2011).

Developing a methodology

In this research we are aiming at finding a methodology, i.e. we will use design science research to investigate the development of "the model of the learning of a complex model". This is thus a meta-study of research we have presented elsewhere. Typical results in design science research are "constructs, models, methods and instantiations" (Vaishnavi & Kuechler, 2008) and in our research the LCC-model (the learning of a complex concept) reveals all four.

Our model can be considered to be a design artefact, and the "evaluation of the artefact then provides information and a better understanding of the problem in order to improve both the quality of the product and the design process." (Hevner, March, Park, & Ram, 2004, p. 78)

The methodology most often used in design science research in information technology is the method described by Takeda, Veerkamp, Tomiyama, and Yoshikawa (1990):

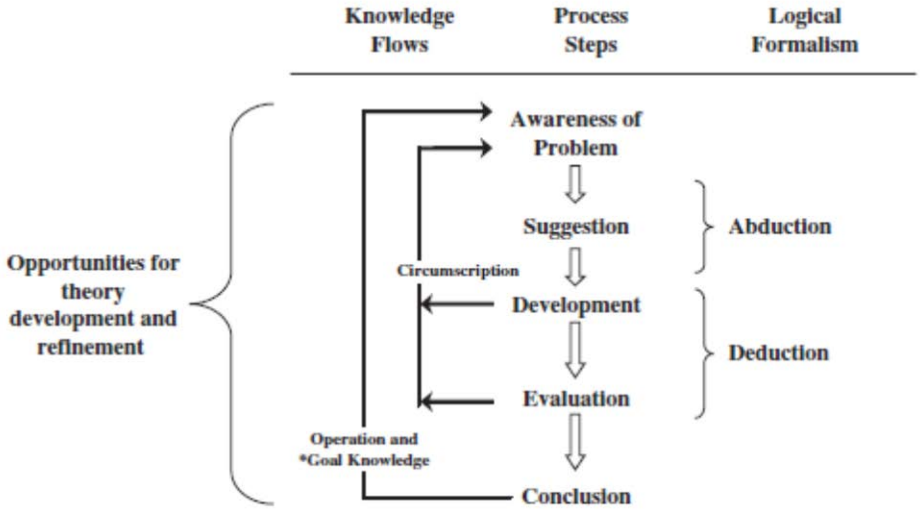

Figure 1: The design cycle originally proposed by Takeda et al. 1990 (as displayed by Kuechler & Vaishnavi, 2008, p. 493)

The iterative process gives opportunities to refine the artefacts, and models, but also for theory development (Kuechler & Vaishnavi, 2008). The theories that inform design science research belong to either of two categories, *descriptive* and *prescriptive*, where the descriptive, also called *kernel theories*, frequently have their origin within other disciplines, and the prescriptive, the *design theories,* are prescriptions of "how to do something". In this paper we will start the journey towards a theory development, but settle with the analysis of the process which led to the model. The purpose is to make the modelling process visible, and hopefully useful for other researchers to use in engineering education.

Typically the design cycle starts with the awareness of a problem (Figure 1), and an analysis of the normally wicked and complex problem. The first suggestions towards a "solution are abductively drawn from the existing knowledge or theory base for the problem area" (Vaishnavi & Kuechler, 2008), often theories from other disciplines, termed *kernel theories*. In our case we used analysis methods from pragmatism in the analysis of students' actions (Wickman, 2004) and from phenomenology in the analysis of "the intended object of learning" (Marton & Tsui, 2004).

A suggestion is then made, in our case a model was designed, and used to design new teaching sequences. As well the model as the labs were then evaluated, and especially the model has been refined in subsequent design cycles, which will be described and analysed. However the evaluation is not the last step since this is an iterative method, the circumscription is of uttermost value. When designing a car, the prototype is not the last step, there is always a new iteration of the car design starting the moment a prototype is ready to launch.

The design process – Result of the design science metastudy

First design cycle

In the first design cycle we had video-recorded students' actions in a lab course in electric circuit theory. One of the labs concerned "Transient Response". We needed a way to analyze the problems students faced when dealing with this topic, in order to design a new lab-instruction. The amount of data is very large, and thus the need for a method to condense data is necessary. Our first attempt in this was to listen to the students' discussions and look for the occasions students asked questions. We used the method of *Practical Epistemologies* (Wickman, 2004) where the researcher looks for gaps in students' conversations, when they encounter something that is new to them. Analysis of the questions showed that the questions seemed to occur when students were changing topics to discuss. For example the students started to wire up the circuit, and the first questions concerned how to connect the leads for measuring. Thus we started to draw the questions as arrows, and the discussions on a topic as nodes, “islands”, which lead us to draw the two circles called “real circuit” and “measured graph”, and although we did not write any labels on the arrows, they represented the action where the students connected the circuit to the computer-interface, and started to measure (using a computer interface measurements directly render graphs). Now the next action expected was that the students should try to make the computer draw the calculated graph in the same diagram, by use of the mathematical expression of the time function. In the first course the students were not able to do this without help from the teachers, and thus they asked “Is this good enough for the report”, showing that they did not make the links between the topics but only talked about one concept at a time.

Thus we tried to analytically draw what nodes and actions we had expected the students to talk about, what in *the Theory of Variation* is termed the *intended object of learning* (Marton & Tsui, 2004) – and draw the nodes starting with the real circuit, onto the differential equation, further to the Laplace Transform in order to calculate the solution to the differential equation by searching the inverse transform, i.e. the time function. In this first course the arrows were not actions done by the students, rather they were the path of topics in a traditional teaching sequence or text book. The gap between the measured graph and the calculated graph – which was very clear in the video recordings, thus appeared as a gap between what was taught in theory classes and what was expected actions in the lab-sessions.

According to Tiberghien and co-workers (e.g.Vince & Tiberghien, 2002) who consider the learning divide be between the theory/model-world, and the object/event world (rather than between theory and practice) the most problematic steps for students to take are those transcending the two worlds, and by studying the newly drawn model it was obvious that those passages were very small and very few.

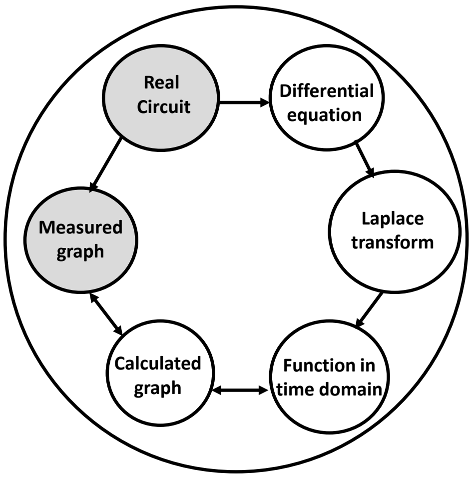

Figure 2: First Design Cycle – Intended object of learning

Our proposition thus became to try to find arrows across the circuit. One of those would be to draw an arrow from the Laplace transform, the transfer function, directly to the calculated graph, something that could be possible to make through simulations of various transfer functions in Matlab-Simulink.

Second Design Cycle

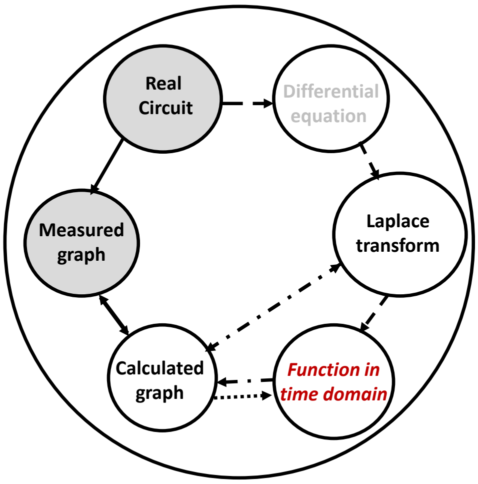

Figure 3: Second Design Cycle – Design of new teaching materials

In figure 3 the dashed arrows are showing the teaching sequence in the lectures, the dash-dotted arrows show the two tasks explicitly asked for in the new course, where problem solving sessions and labs were integrated. The students were now asked to analyze the correlation between the calculated graph and the function in the time domain, the dotted line, in order to realize what parameters in the time-function that rendered differences in the calculated graph.

Now the students worked in a totally different way than in the old course: Some students started to do the calculations, and some started to do the simulations, and the new video-recordings from the revised course rendered two different versions of the model:

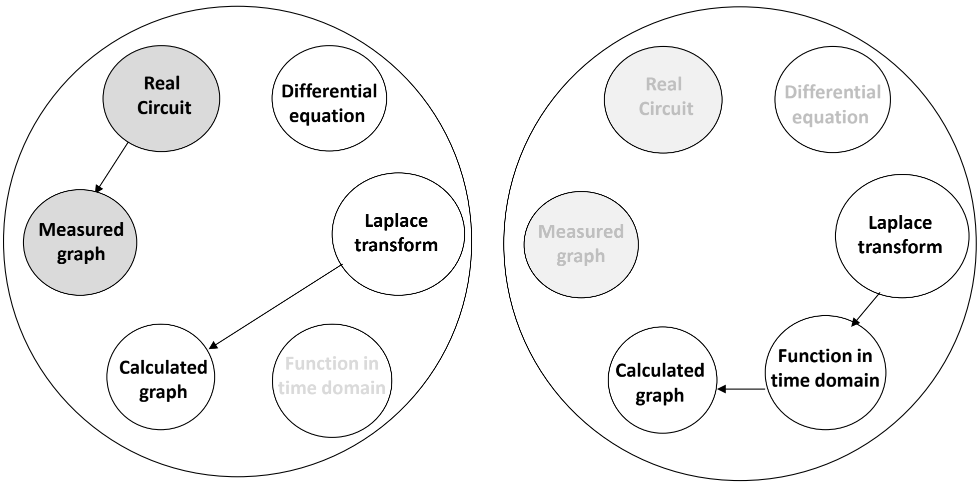

Figure 4: Two different students' paths due to different actions

The student who first measured a couple of graphs, then jumped to the simulation task without any connection to what he had measured, led to the left figure, and the student who started to do calculations made us draw the right figure. At the end of the lab both students had worked the whole lab through and made all the links in figure 5:

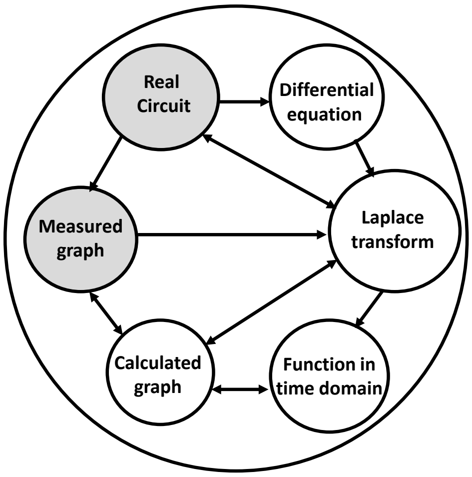

Figure 5: The students' paths at the end of the lab in the new course

In this new course not once was the question "Is this good enough for the report" asked, since now the students had made all the links that were necessary in order to understand the complex concept "transient response".

Third Design Cycle

The two first design cycles were focusing on the analysis and design of the lab instructions. Now it was necessary to start the analysis of what knowledge this designed model could bring to the engineering education research community, the phase that Vaishnavi and Kuechler (2008) call "circumscription". In Figure 6 we can see that two of the nodes have double labels. The first pair of labels were *Laplace transform* and *Function in time domain.* Of course the Transfer function is the Laplace transform of the differential equation, and thus a noun, but the Laplace transform is also the action that has to be taken in order to go from the differential equation to the transfer function. Similarly the Inverse transform is the action that transforms the transfer function into the function in the time domain, i.e. it is not a node but an arrow. The confusion here due to the word transform being as well a verb as a noun, highlighted that all nodes were nouns and all arrows verbs, as in other types of models such as concepts models or concept maps. However it also highlighted that the verbs, the actions were not just rote actions. It was necessary for the students to have both nodes in focal awareness while making the link between them. Thus the links, the arrows are not just there to learn but are actions students need to do in order to make links between concepts, i.e. to learn complex concepts is to do something that connects the islands. Here the analysis of the designed model thus leads to a new learning theory, that to learn complex concepts is to *make links.*

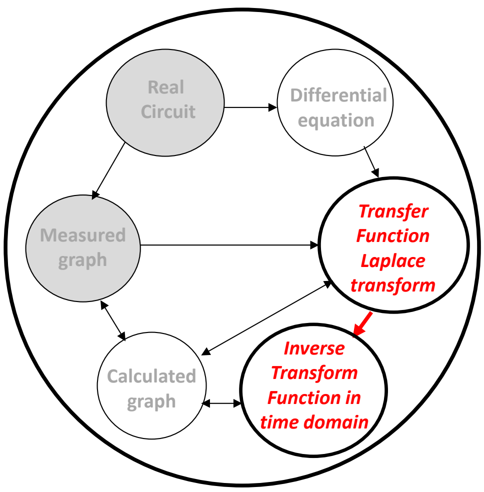

Figure 6: The model "the learning of a complex concept"

In the third cycle also the other links were explored (Carstensen & Bernhard, 2013), but are omitted in this presentation.

Conclusions and Implications for further Research

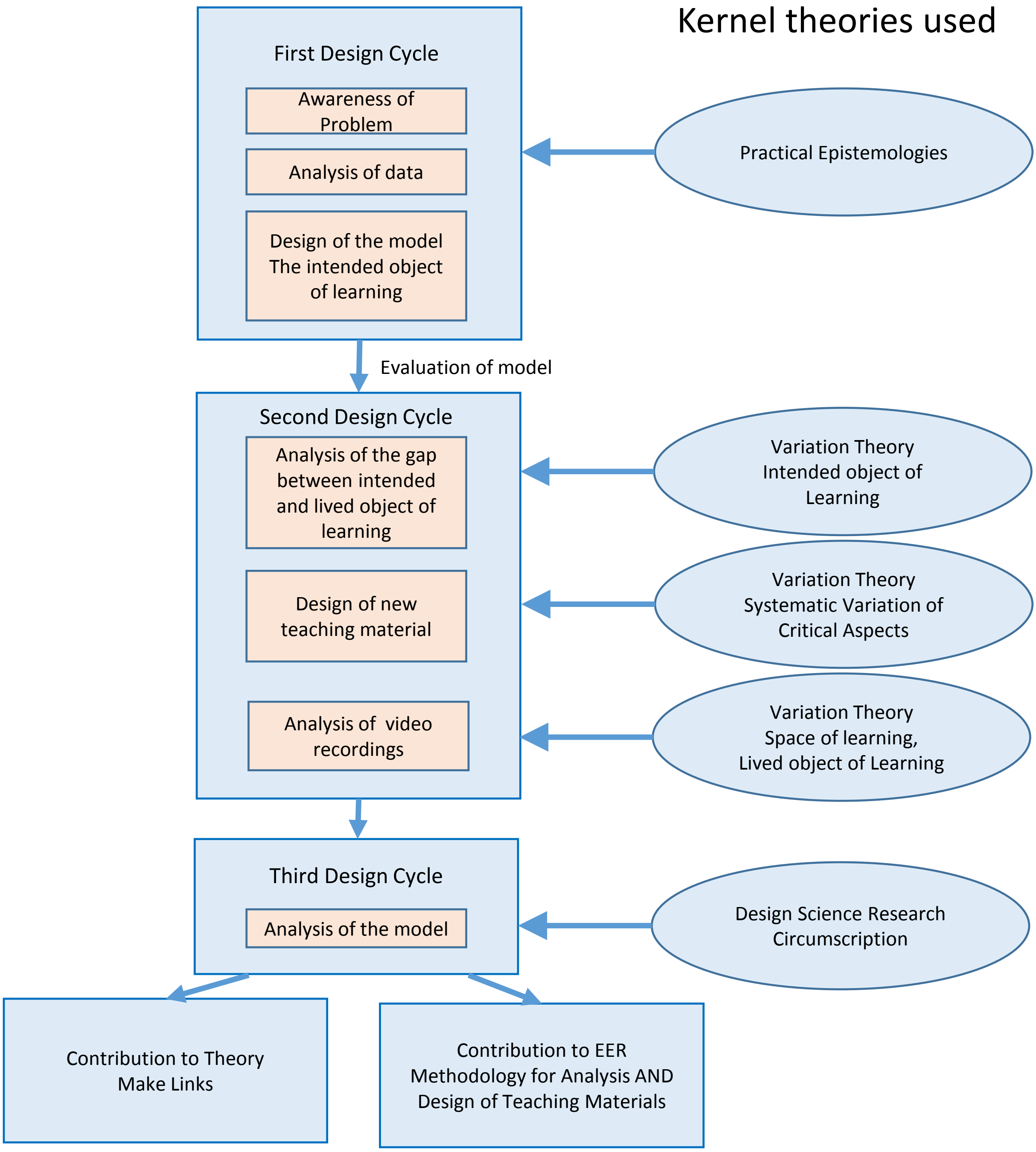

Figure 7: The Design science research process and the resulting contributions to the EER-field adopted from Takeda et al. 1990, with reference to referenced kernel theories from education

The above exploration indicates that using design science research may contribute to the understanding of learning but also to the design of learning materials. But more importantly, it also shows that design science research may inform the development of *tools* for such research. As pointed out by many researchers, a model is judged by the work it does (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003) and may be useful as epistemic tools (Knuuttila, 2011). This tool, the model of the learning of a complex concept, has already been used to analyse other lab-instructions (Bernhard & Carstensen, 2015; Bernhard, Carstensen, & Holmberg, 2009).

As already mentioned, the results from design science research are “constructs, models, methods and instantiations” (Vaishnavi & Kuechler, 2008). So far we have focused on the method and the model. To use design science research to further develop this tool and to further develop this method into a methodology seems to be a promising research endeavour.

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