Design science research – a powerful tool for improving methods in engineering education research

Anna-Karin Carstensen\textsuperscript{a} and Jonte Bernhard\textsuperscript{b}

\textsuperscript{a}School of Engineering, Jönköping University, Jönköping, Sweden; \textsuperscript{b}Department of Science and Technology (ITN), Engineering Education Research Group, Linköping University, Norrköping, Sweden

\textbf{ABSTRACT}
Modelling is a central activity in practical engineering and something that is also useful in engineering education research (EER). Additionally, qualitative research methods have found important applications in engineering research, although their use in EER has not always been widely accepted. Design science research is a qualitative research approach in which the object of study is the design process, i.e. it simultaneously generates knowledge about the method used to design an artefact and the design or the artefact itself. This paper uses techniques from design science research to analyse the method used when deriving the ‘learning of a complex concept’ (LCC) model, which we developed while designing teaching sequences for a course on electrical engineering. Our results demonstrate the value of design science research in EER and suggest that the LCC model is generally applicable in this field.

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\section*{Introduction}

Usually, in their professional careers, engineers are often involved in design projects. Their training prepares them to approach design problems in a systematic way. In most cases they learn to apply a systems approach … analyzing the objectives and planning alternative solutions to reach the desired goal … Surprisingly, engineers seldom put their design skills into practice when they are faced with the task of curriculum design in engineering education. (Rompelman and De Graaff 2006, 215)

As engineers and engineering professors, we have, indeed, followed Rompelman and De Graaff’s (2006) plea, and we have used our design training when developing engineering education (Bernhard 2010; Carstensen 2013; Carstensen and Bernhard 2009). For more than two decades, we have been involved in the systematic, research-based, design of learning environments, primarily in mechanics and electric circuit theory. Engineering education research (EER) was an emerging field when we started this process, and we thus faced many challenges. To guide the design and redesign of labs in mechanics and electric circuit theory, we wanted to follow the students’ processes of learning process during these labs. At the time, pre-testing followed by post-testing based on a conceptual instrument was the most common research method. This method, however, treats a lab as a ‘black box’ and gives no information about what happens during it. The method is, thus, of limited value in guiding the design of learning environments. We wanted to open the black box and to systematically follow the interactional work that students carried out, and examine the resources they used to collaborate and to complete tasks.
For this reason, we started to record videos of students’ actions in lab exercises on electric circuit theory. This yielded a huge amount of data (approximately 250 hours of video recordings for the whole lab course, and approximately 80 hours of video for two sets of labs that are discussed in this paper – one set dealing with transient responses and one set dealing with alternating current (AC) electricity). Analysing this huge video dataset was a major challenge. We found some guidance for the transcription and analysis of video in methods such as interaction analysis (IA: Jordan and Henderson 1995) and conversation analysis (CA: e.g. Hutchby and Wooffitt 1998; ten Have 2007). However, most studies using IA or CA analysed only short episodes and it became apparent that transcribing complete labs would be too time-consuming. Furthermore, it was difficult to obtain an overview using this method. Yet, given our interest in understanding what students actually do during labs, it was important to be able to analyse students’ activities during complete labs in what the students experienced as normal settings. Thus, we were faced with the task of developing a method for analysing and representing the complexity we saw in students’ actions in labs, i.e. to develop a method for modelling their learning. We have tentatively named this method the ‘learning of a complex concept’ (LCC) model (e.g. Bernhard, Carstensen, and Holmberg 2011; Carstensen 2013; Carstensen and Bernhard 2004). This method has been used not only to analyse, model and represent students’ learning but also to guide the design of new lab instructions (Carstensen 2013; Carstensen and Bernhard 2009). The LCC model will be described below.

The purpose of this paper is to discuss the method used to develop and design the LCC model. As already mentioned, designing is a very common task in engineering, but the designing and modelling that engineers carry out are often taken for granted (Mitcham 1994). There is, however, a field of research known as ‘design science’ that is devoted to their study. Not only Rompelman and De Graaff (2006) but also Dewey (1983), Artigue (1988), and Bernhard (2015) have pointed out many similarities between educational design and engineering. Thus, we propose that it is important that engineering research education study engineering research methods such as design science.

The following discussion begins with a literature review covering some important findings in design research, design science research and design-based research. This introduces readers with a background in engineering education to these fields. We then use methods from design science research to evaluate our model and its development as a research method. Finally, we apply the LCC model in a new context and discuss ways in which the approach presented here can be applied more generally in EER.

**Design science**

The aim of the work presented here was to identify a methodology by using design science research techniques to study the development of the LCC model and the iterative refinement of the labs’ design in order to improve the students’ understanding of transient responses in electric circuits. Mitcham (1994), for example, has pointed out the importance of design in engineering, and that modelling is a central activity in both engineering and the design process. While design is often taken for granted, design research was established as a field of study as early as 1966, when the ‘Design Research Society’ was founded (Roworth-Stokes 2011). The society’s founders explained the need for this new field of study by noting that design seemed to have its own ‘theoretical base’ (Roworth-Stokes 2011, 419) – ‘Designerly ways of knowing’ (Cross 1982) and ‘a designerly way of thinking and communicating’ (Archer 1979) – which merited investigation and analysis. The main purpose of design research in its original form was to develop a theory for the process or phenomenon of designing man-made objects and artefacts (Vaishnavi and Kuechler 2008).

There are at least two areas of engineering research in which traditional scientific methods are of limited usefulness: the practice of engineering (Schön 1983; Simon 1996), and the role of human values in engineering (which is called ‘axiology’ by Vaishnavi and Kuechler (2008) and ‘volition’ by Mitcham (1994)). This is important because of two key aspects of design: an artefact is always made with a purpose, and design is both a noun and a verb – that is to say, it is an action.
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 and Kuechler 2008, 17). The typical outputs of design science research are ‘constructs, models, methods and instantiations’ (Vaishnavi and Kuechler 2008). It will become evident that all four were produced during our analysis of the development of the LCC model. A major strength of design science research is that the underlying theory is based on the same kind of iterative process as that used in the development and evaluation of artefacts. The refinement of the designed artefact is thus aligned with the development of the theory, in a process known as ‘circumscription’. Our LCC model can be regarded as a designed 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 et al. 2004, 78).

The most commonly used methodology in design science research is that described by Takeda et al. (1990). It is summarised in Figure 1.

The iterative process provides opportunities to refine the artefacts and models, and for theory development (Kuechler and Vaishnavi 2008). The main theories that influence design science research are either descriptive or prescriptive. Descriptive theories (also known as kernel theories) frequently originate from other disciplines, while prescriptive theories (also known as design theories) provide instructions for ‘how to do something’. Design theories use and refine kernel theories. This paper describes the first step in the development of a theory, and analyses the process that led to the construction of the LCC model. Its purpose is to make the modelling process visible.

The design cycle starts with the awareness of a problem (Figure 2), which is typically large and complex. The first suggestions towards a ‘solution are abductively drawn from the existing knowledge or theory base for the problem area’ (Vaishnavi and Kuechler 2008), and frequently make use of theories from other disciplines, termed kernel theories. The kernel theories we used were ‘practical epistemologies’ (Wickman 2004), a method that has its roots in pragmatism, and ‘variation theory’ (Marton and Tsui 2004), a theory that has its roots in phenomenology.

A suggestion is then made (in our case, this entailed designing a model) and used to design new teaching sequences. Both the model and the labs were then evaluated, and the model was refined in subsequent design cycles. The method is iterative, and thus the evaluation is not the final step: circumscription is an extremely valuable step that occurs after evaluation. Similarly, the prototype is not the final step in the design of a new car: further iteration of the design process starts as soon as a prototype is launched.

As briefly mentioned previously, the similarities between engineering, engineering design and educational development have been noted by educational researchers such as Dewey (1983).
essay ‘Education as engineering’ shows that the design of education requires both specific and generalisable knowledge. In a similar vein, several non-conventional approaches to designing innovative curricula have emerged in the learning sciences (Brown 1992; Collins 1992). These approaches have been described as ‘design experiments’ (DE) (Brown 1992; Cobb et al. 2003) or as ‘design-based research’ (DBR) (Barab and Squire 2004; Design-Based Research Collective 2003; Fishman et al. 2004). Cobb et al. (2003) also made the connection to engineering and described DE in these terms:

Prototypically, design experiments entail both ‘engineering’ particular forms of learning and systematically studying those forms of learning within the context defined by the means of supporting them. This designed context is subject to test and revision, and the successive iterations that result play a role similar to that of systematic variation in experiment.

According to the Design-Based Research Collective (2003), DBR has the following five features:

First, the central goals of designing learning environments and developing theories or ‘prototheories’ of learning are intertwined. Second, developments and research take place through continuous cycles of design, enactment, analysis, and redesign … Third, research on designs must lead to sharable theories that help communicate relevant implications to practitioners and other educational designers … Fourth, research must account for how designs function in authentic settings. It must not only document success or failure but also focus on interactions that refine our understanding of the learning issues involved. Fifth, the development of such accounts relies on methods that can document and connect processes of enactment to outcomes of interest. (Our emphasis)

Clearly, the complexity of educational activities is addressed in an iterative manner when DE/DBR is applied to education. Such work aims to improve educational practice and develop educational theory at the same time. Our approach could very well be described as DE/DBR. However, engineering ‘design science’ complements and extends the DE/DBR approaches in educational research by providing tools that can be used to describe and analyse the content of the design process and the design cycle (and the steps of the process) (Figures 1 and 2).

Interestingly, the DE/DBR approach in education and the design science approach in engineering were both initially criticised for lacking rigour, but have been subsequently accepted as important fields of study (Kelly 2004; Vaishnavi and Kuechler 2008, 9). The growing recognition of their merit is demonstrated by a number of recently published reviews of work in these fields, such as those published by Anderson and Shattuck (2012) in education, Roworth-Stokes (2011) in design, and Vaishnavi

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**Figure 2.** Processes in the design cycle, adapted from Kuechler and Vaishnavi (2008, 493), based on the original proposal of Takeda et al. (1990).
and Kuechler (2008) in design science. Moreover, it has been noted that ‘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 and Light 2011). We propose that insights from design science research can extend the domain of EER.

Setting and data collected

This study is part of a larger project on the development of active-learning conceptual labs in engineering mechanics and electric circuit theory for engineers (Bernhard 2010). The associated investigations have included studies spanning several academic years on lab work performed in introductory and intermediate courses in electric circuit theory for engineering students (e.g. Bernhard and Carstensen 2002; Bernhard, Carstensen, and Holmberg 2009; Carstensen 2013; Carstensen and Bernhard 2009). This study uses previously reported data and can be regarded as a meta-study. The original data consist of video recordings of two sets of labs, one set on transient response and one set on AC. During these labs, a computer-based system is used to control a signal generator and to collect and present data.

The video recordings analysed in this work were acquired using a digital camcorder with a wide-angle lens. The camcorder was mounted on a tripod and adjusted to provide a good view of one group of students’ activities during labs. Additionally, a table-mounted microphone was used to capture their conversations. It should be noted that the recordings were made during regular labs, so the setting is naturalistic. Prior, informed consent was obtained from the students in accordance with standard ethical procedures.

In the transient response lab, the students studied the response \( y(t) \) of a second-order system (specifically, the \( RLC \) circuit shown in Figure 3(b)) to an input signal \( x(t) \) featuring a voltage step (Figure 3(a)). The measured response \( y(t) \) consisted of the resulting current \( i(t) \) through the circuit and the voltage \( v_C(t) \) across the capacitance. Figure 4 shows the current responses for different resistances. The transient response lab and the three design cycles it went through are discussed in more detail below. The video recordings from the transient lab were used to develop the LCC model.

The LCC model was later tested in the analysis of the AC lab recordings. This lab was divided into two parts, each four hours long. In the first part of the AC lab, the students measure stationary (i.e. steady-state) AC and voltages in \( RC \), \( RL \), and \( RLC \) circuits. Figures 5 and 6 show an illustrative task involving an \( RL \) circuit and some associated measurements. Because of the inductance \( L \), the voltages \( u_R(t) \), \( u_L(t) \) and \( u_{in}(t) \) and the current \( i(t) \) are not in phase (Bernhard, Carstensen, and Holmberg 2013). The students must therefore use complex numbers and phasors in graphical form in their calculations and their attempts to model the circuit’s properties. In the second part of the AC lab, the frequency of the input sinusoidal voltage is varied and the frequency dependency and transfer functions for the \( RC \), \( RL \), and \( RLC \) circuits are determined.

These measurements are displayed on the computer screen (Figure 6).

Figure 3. (a) A general model of a system, and (b) the system studied in the transient response lab – an \( RLC \) circuit.
First design cycle

The first design cycle used the video recordings of students’ actions in a lab course in electric circuit theory, from a lab that dealt with transient responses. We needed a way to analyse the problems that students encountered when dealing with this topic, so that we could come up with a new lab design. The video recordings constituted a huge quantity of data, which needed to be condensed during analysis. Our first attempt at doing this involved listening to the students’ discussions and searching for occasions on which they raised questions about the lab. This approach is based on the method of practical epistemologies (Wickman 2004; Wickman and Östman 2002), in which the researcher looks for gaps in students’ conversations that arise when they encounter something unfamiliar while learning. According to Wickman (2004, 328), gaps occur ‘when people encounter something … during talk or in action … noticing that a relation is needed … to go on’. Gaps are explicitly manifested ‘when students express a question or hesitation’ (Wickman and Östman 2002, 616). Our analysis of the students’ questions during the labs revealed that they most frequently asked questions when the topic of discussion was changing.

Figure 4. Experimental current curves for different values of $R_{res}$ ($L = 8.2$ mH, $C = 100$ μF, using a coil with an internal resistance of 6 Ω).

Figure 5. An experiment conducted in the AC lab to investigate the validity of Kirchoff’s voltage law. The interface generates a sinusoidal voltage $u_{in}(t)$ with a frequency of 100 Hz and an amplitude of 2 V, and measures the signal generator output voltage $u_{\text{out}}(t)$, the current $i(t)$, the resistor voltage $u_R(t)$, and the inductor voltage $u_L(t)$.
One such occasion was when the students first started to wire up their circuits and had questions about how the circuits should be connected, as demonstrated by the excerpt below:

Excerpt 2002_Group_13_Tape1_00:11:47

1. Jack: John! ((The lab-instructor))
2. John: Yeah ((Moves towards the group))
3. Jack: What does this mean (.). ‘Connect across the whole circuit’
4. John: What
5. Jack: It says connect the output across the whole circuit
6. John: Well, then you should =
7. Jack: = How do you do that
8. John: Then you have in and outputs where you should have one if you have an RLC-circuit then for example if you include the 10 ohm-resistor, then this is across the whole circuit ((demonstrates his point by connecting the resistor))
9. Jack: OK, it was a little cryptical, hard to understand which one to use
10. John: There was a headline that
11. Jack: Yeah, it said that we shouldn’t use this one
12. John: No, not in the first one, there are others.
13. Jack: But this one is connected here ((Points to the 10 ohm-Resistor))
14. John: No, no if this is the first step, you should is it only this one then we have the R in this=((Points at the inductor)) Here the R should be the internal R in the inductor
15. Jack: ((Jack interrupts John once he understands which R to use))

In this excerpt, we can see that Jack initially voiced the lab group’s hesitation because it did not know how ‘to proceed’, i.e. a gap existed (Wickman 2004; Wickman and Östman 2002). After investigating several similar episodes captured by our video recordings and the related transcripts, we found it useful to model the students’ conversations and actions by representing the students’ topics of discussion as nodes or ‘islands’. These became connected by arrows once the students’ questions were answered and they understood how to proceed. Thus, the situation presented in the excerpt is represented by a pair of nodes (drawn as circles in Figure 7), which we have labelled ‘circuit diagram’ and ‘real circuit’. At first, the students did not know how to proceed; this state is represented by Figure 7 (a), where there is no connection between the ‘circuit diagram’ and ‘real circuit’ nodes. These nodes
are connected in Figure 7(b), indicating that the students now understand how to proceed. Although we did not label the arrow in this instance, it represents the actions taken to resolve the students’ uncertainty, allowing them to proceed to the next stage of the exercise. For the case presented in the excerpt, the arrow represents the point at which the students successfully connected the circuit to the computer interface and began to make measurements. This method for condensing, i.e. modelling and representing the students’ courses of action, was tentatively designated the ‘LCC model’. An important object of learning in engineering education is that students should understand and learn to use theories and models, and link them to objects and events. Indeed, Tiberghien and co-workers (e.g. Vince and Tiberghien 2002) have proposed that the ‘worlds’ of theories/models and objects/events should be seen as the main analytical categories in the analysis of knowledge (rather than theoretical and practical knowledge). Using the terminology of Tiberghien, the shaded real circuit node is categorised as belonging to the object/event world (shaded), while the unshaded circuit diagram belongs to the theory/model world.

In this case, the intended object of learning was that students who participated in the lab should gain a deeper understanding of transient responses in second-order systems. The intended object of learning (Marton, Runesson, and Tsui 2004) is the subject matter, along with the skills and values that the teacher or curriculum planner expects the students to learn. In particular, they were expected to learn that an RLC circuit can be modelled as a second-order system. The step response of the current through the circuit (RLC circuit can be modelled as a second-order system. The step response of the current through the circuit diagram unshaded real circuit nodes is shown in Figure 4 for the circuit shown in Figure 3.

The students were then expected to try to model the step response by making the computer draw a graph on the same diagram as the measurements, using the mathematical formulation of the time function. This required the students to identify possible time functions and manually optimise the coefficients to achieve good fits to the experimental data. The students were then asked to use this fitting to estimate the values of $R$, $L$, and $C$.

Despite the fact that there are only two possible types of function (as discussed above; Table 1) and this material was also covered in lectures and described in the course textbook, the students

![Image of a circuit diagram]

Figure 7. The ‘complex concept’ corresponding to (a) the first part of the transcript excerpt, and (b) the second part of the excerpt.

| $R_{\text{tot}}$ (Ω) | $L$ (mH) | $C$ (μF) | Roots of $s^2 + \frac{R_{\text{tot}}}{L}s + \frac{1}{LC}$ | $i(t)$ (A) | $(t > 0)$ |
|---------------------|----------|----------|-----------------------------------|-----------|----------------|
| 0                   | 6        | 8.2      | $-366 + 1042j$  | $-366 - 1042j$ | $0.1170e^{-366}\sin(1042t)$ |
| 10                  | 16       | 8.2      | $-976 + 517j$  | $-976 - 517j$ | $0.2357e^{-976}\sin(517t)$ |
| 33                  | 39       | 8.2      | $-272$          | $-4484$     | $0.0290(e^{-272t} - e^{-4484t})$ |
| 100                 | 106      | 8.2      | $-95$           | $-12,832$   | $0.0096(e^{-95t} - e^{-12832t})$ |

Note that the frequency, $\omega_n$, of the damped system changes with $R$ and is not equal to $\omega_r$. 
(in the first iteration of the course) generally needed the teacher’s help to determine which function they needed to use to achieve a good fit to the experimental data. The students were unable to determine what kind of function a graph represented by inspection, i.e. to go from a graph to the corresponding mathematical expression. Therefore, they worked in a rather random and unorganised way when trying to fit curves to the experimental graphs. A common question was ‘Is this good enough for the report?’, showing that the students had not drawn connections between the topics targeted in the lab and were only considering one concept at a time.

Our next step as researchers and designers of the lab exercise was to analyse the intended object of learning (Marton, Runesson, and Tsui 2004) by using the LCC model to identify the nodes and actions we had expected the students to talk about. Figure 8 shows our analysis, where we draw nodes that start with the real circuit, pass on to the differential equation, and continue 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 design of the lab course, the arrows did not correspond to the students’ actions but to the circular sequential path of topics in a traditional teaching sequence or textbook. The gap between the measured and calculated graphs (which was clearly demonstrated by the students’ actions captured in the video recordings) thus reflected a gap between what was taught in theory-focused classes and the actions expected in the lab sessions. Additionally, because the lab instructions asked the students to perform the tasks described above, there also appeared to be a gap between the intended and lived object of learning.1

The model presented in Figure 8 clearly shows that in the first iteration of the lab, the connections (represented by arrows) between the ‘worlds’ of theories/models and objects/events were small and few in number.

**Second design cycle**

In the first design, the learning path and task structure followed the circumference of a circle as shown in Figure 8. As discussed above, a major disadvantage of this structure is that it is only possible for the students to make two links between the theory/model and object/event ‘worlds’. Our objective thus became to redesign the task structure of the lab to create new connections that extend across the circle rather than just run around the perimeter. One way to do this is to create an arrow that passes from the Laplace transform, the transfer function, directly to the calculated graph. This could be achieved by having the students simulate various transfer functions in the Matlab-Simulink software package.

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**Figure 8.** First design cycle – intended object of learning.
The dashed arrows in Figure 9 represent the teaching sequence in the lectures, and the dash-dotted arrows represent the two tasks assigned to the students in the new design of the lab course (Table 2). This cycle integrated problem-solving and practical exercises. The students were now asked to analyse the correlation between the calculated graph and the function in the time domain, the dotted line, in order to better understand which parameters in the time function gave rise to specific features in the calculated graph.

The most important new task in the redesigned structure was the introduction of simulations of step responses for systematically varied transfer functions using Simulink. These simulations generate graphical outputs. Three forms for the denominator were used: \( s^2 + 2s + 5, \ s^2 + 2s + 1 \) and \( s^2 + 2s + 0.75 \). These polynomials have complex-conjugated roots, a double root, and two real roots, respectively (Table 3). Figure 10 shows the step responses for the transfer functions given in Table 3. In the initial trials, two numerators were used (5 and \( 3s + 5 \)), giving six combinations of numerator and denominator. In subsequent revisions, \( 3s \) was added as a third numerator. This task created a direct link between the Laplace transform and the calculated graph (Figure 9), which made it possible for students to establish a triangular route between the transfer function, problem-solving lab/Lab

![Figure 9. Second design cycle – design of new teaching materials.](image)

Table 2. An overview of the task structure and organisation in the transient response lab according to the new and old designs.

| Scheduled time | A brief description of the task                                      | Second design | First design |
|---------------|-------------------------------------------------------------------|---------------|--------------|
| Lecture       | Class (problem-solving)                                           | 4 h           | 4 h          |
| Problem-solving lab/Lab |                                                            | 2 × 4 h       | 4 h          |
| 1a.           | Using Simulink to simulate the step response for six systematically varied second-order transfer functions. Results are displayed in graphical form. | •             | –            |
| 1b.           | Obtain ‘by hand’ the mathematical function in the time domain for the six step responses in task 1a. | •             | –            |
| 2.            | Obtain the expression for the transfer function of an RLC circuit with \( R = 100 \Omega, \ L = 100 \text{ mH and } C = 100 \mu \text{F} \). | •             | –            |
| 3.            | Calculate the step response \( y(t) \) for some values of \( R, \ L \) and \( C \) that correspond to the values of the real circuit (to be used in coming tasks). | •             | –            |
| 4.            | Measure the step responses \( i(t) \) and \( V_c(t) \) for a real RLC circuit. \( R \) is varied while \( L \) and \( C \) are kept constant. | •             | –            |
| 5a.           | Fit a mathematical function to the four different experimental curves for \( i(t) \) obtained in task 4. | •             | –            |
| 5b.           | Use the fits obtained in task 5a to calculate the values of \( R, \ L \) and \( C \). | •             | –            |

Note: Some tasks not discussed in this paper are excluded from the table (see Carstensen and Bernhard 2009, for more details).
time function, and the calculated graph, i.e. to make links between these. It should be noted that the graphs in Figure 10 correspond to ‘calculated graphs’, whereas the mathematical expressions for the step responses in Table 3 correspond to ‘functions in the time domain’; this distinction is important.

Classroom observations and video recordings revealed that the students taking the second version of the lab course worked in a completely different way from those who had participated in the first version. For example, some students began by working on the calculations, while others started with the simulations. Figure 11 shows the different courses of action taken by these students in terms of the LCC model.

The left-hand side of Figure 11 represents the actions of a student who first acquired a few measurements and plotted some graphs of the experimental data, and then immediately began to work on the simulation task without connecting it to his measurements in any way. Conversely, the right-hand side represents the actions of a student who started by working on the calculations. As the lab progressed, the students made more and more links, generating a triangular route between the ‘Laplace transform’, ‘Function in time domain’ and ‘Calculated graph’ nodes (which was the intended result of introducing the new simulation-based task). Interestingly, however, the new tasks also created another triangular route that linked the ‘Laplace transform’, ‘Measured graph’ and ‘Calculated graph’ nodes, and thus involved a transition between the theory/model and object/event ‘worlds’. Although the students had not established a full set of links between the different nodes at the start of the lab (as shown in Figure 11), both students had completed the exercise and made all of the links shown in Figure 12 at the end of the lab session.

Table 3. Some transfer functions used in the Simulink simulations and the corresponding step responses.

| Transfer function | Roots of the denominator (poles) | Step response \( (t > 0) \) |
|-------------------|----------------------------------|-----------------------------|
| \( G_1 = \frac{3s}{s^2 + 2s + 5} \) | \(-1 \pm 2j\) | \( y_1(t) = \frac{3}{2} e^{-t} \cdot \sin(2t) \) |
| \( G_2 = \frac{\frac{3s}{s^2 + 2s + 1}}{s^2 + 2s + 1} \) | \(-1, -1\) | \( y_2(t) = 3t \cdot e^{-t} \) |
| \( G_3 = \frac{\frac{3s}{s^2 + 2s + 0.75}}{s^2 + 2s + 0.75} \) | \(-2, -2\) | \( y_3(t) = 3 \cdot (e^{-1/2t} - e^{-3/2t}) \) |

Figure 10. Step responses for the transfer functions presented in Table 3.
Students taking this new course were never observed to ask ‘Is this good enough for the report?’ because all the conceptual links required to understand the complex concept of a ‘transient response’ were made.

**Third design cycle**

The first two design cycles had focused on the analysis and design of the lab instructions. It was now necessary to analyse the knowledge that this newly designed model provides to the EER community, in the phase that Vaishnavi and Kuechler (2008) call ‘circumscription’. Two of the nodes in the model have been given double labels in Figure 13.

The first pair of labels is **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 must be performed 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 both a verb and a noun led us to realise that all the nodes are nouns while all the arrows are verbs. This is the case also in other model types such as concept models or concept maps. However, we also realised that the verbs do not just correspond to rote actions; when making a link between nodes, the students needed have both nodes in ‘focal awareness’ (Marton and Booth 1997), i.e. to maintain a focus on both of them simultaneously. Consequently, the links (i.e. the arrows) correspond to actions that students must take to forge connections between concepts. We conclude that learning complex concepts requires taking an action that connects isolated islands of understanding. The analysis of the model thus led to a new theory of learning based on the idea that to learn complex concepts is to make links.

Additional links were explored in a third design cycle (Carstensen and Bernhard 2013, 2016), but are not discussed here for the sake of brevity. Figure 14 depicts the three cycles, and the kernel theories used in each one, in terms of the ideas presented by Takeda et al. (1990) and Vaishnavi and Kuechler (2008).

**Validation cycle**

We performed a fourth cycle of iteration that focused on students’ learning in other lab exercises, in order to investigate the feasibility of applying the LCC model to objects of learning other than the transient lab. The fourth cycle also allowed us to validate the LCC modelling procedure. In this iteration, we studied video recordings of one lab group (comprising two male engineering students, Adam and David) from two AC electricity labs. The topic of the first lab was how to use phasors (the \( j \omega \) method) to analyse and represent currents and voltages in AC circuits. The topics of the second lab were the frequency dependency of currents and voltages in AC circuits and ways of representing them using transfer functions and Bode plots. These labs are completed at an earlier stage in the students’ studies than the transient response lab, but all three labs use the same computer-based system to control signal generation and to collect and present data.

The analytical procedure in this case was slightly different to that adopted when developing the LCC model and studying the transient response lab. In this case, the labs were initially analysed using the LCC model and the transcripts were subsequently analysed to verify the results of the first analytical step. This contrasts with the analysis of the transient lab, which began with a review of the video recordings, to be followed by analysis of transcripts and the lab’s task structure in order to develop new approaches for modelling students’ actions. The first author was primarily responsible for transcribing the recordings, while the second author took overall responsibility for the project and
checked the first author’s interpretations to ensure there was a consensus. For the AC electricity labs, the roles were reversed; the second author did the modelling using the LCC model, while the first author served as the ‘quality checker’. Another difference is that in the case of the AC labs, the modelling was done on the basis of notes taken directly while watching the video recordings; it wasn’t until a later stage that the videos were transcribed to facilitate a comparison between methods (see for more details Bernhard and Carstensen 2015).

This paper does not discuss all the steps and courses of action taken by Adam and David in the two AC labs. Instead, Figure 15 presents the links established at the end of each lab based on our analysis of the video recordings. For example, Figure 15(a) shows that differential equations emerged as a ‘single concept’, but the students did not make links to it (and were not requested to do so). However, functions in the time domain does not even appear as a non-linked ‘single concept’ in our representation, even though the lab instructions called for the students to make links to such functions. Similarly, in the LCC model for the frequency dependency lab (Figure 15(b)), calculated graphs in the time domain and functions in the time domain appear as unlinked...
single concepts, even though the lab instructions call for links to be made between these subjects. The LCC method thus facilitates direct comparisons between the intended object of learning, as expressed in the instructions for a class or lab, and students’ lived object of learning during the lab. This makes it possible to identify points at which students experience significant ‘learning difficulties’ because such points correspond to gaps, especially lingering gaps, and non-established links. Figures 15(a and b) also demonstrate the difference in complexity of learning between the first and second AC electricity labs.

As mentioned above, the students’ conversations captured in the videos were transcribed according to the conventions of CA (e.g. Hutchby and Wooffitt 1998; ten Have 2007). The transcript of the first (four-hour long) AC lab consists of 3046 turns detailed in 87 pages (with a line spacing of 1.5). The more condensed format of the LCC model provides a better overview of the learning process than transcripts (in which the bigger picture can be lost in the details). This is illustrated by Figures 15(a and b), which provide much clearer overviews of Adam and David’s learning during the two labs than 6000 lines of transcripts.

**Conclusions and implications for further research**

The analysis presented above strongly suggests that techniques from design science research can significantly enhance our understanding of learning in technical subjects such as engineering. These techniques can also help to improve the design of learning materials. This is compatible with the results of Lo et al. (2004), who noted that the main ‘benefits of design experiments [in education] are that [they] will … contribute to theory development, and improve practice at the same time’. Figure 14 summarises the design and research process discussed in this paper.

As should be the case in engineering design, an educational design process informed by design thinking draws on different theories. Dewey (1983), for example, has pointed out that it is not fruitful to take the approach of ‘blindly trying one’s luck or messing around in the hope that something nice will be the result’ (p. 326). Variation theory (Marton 2015; Marton and Tsui 2004) was a major influence on our way of working as we designed and redesigned the learning environment. Despite this, our first design for the transient response lab did not allow our students to achieve the desired level of learning. This confirms Dewey’s (1984) statement that ‘no conclusion of scientific research can be converted into an immediate rule of educational art’ (p. 9). Instead, ‘design [is] a reflective conversation with the situation’ (Schön 1983). Variation theory, developed by Marton and co-workers (Bowden and Marton 1998; Marton and Booth 1997; Marton and Tsui 2004), provides an explanatory framework that describes the conditions required for learning.
Central to this theory is the idea that we learn through the experience of difference, rather than the recognition of similarity. The process of opening up to learning should be understood in terms of discernment, simultaneity and variation. One of the main themes of variation theory is that the pattern of variation inherent in the learning situation is fundamental. In the words of Marton, Runesson, and Tsui (2004):

What we believe is that variation enables learners to experience the features that are critical for a particular learning as well as for the development of certain capabilities. In other words, these features must be experienced as dimensions of variation.

However, variation theory does not identify the ‘critical’ features. We identified these features by means of a ‘reflective conversation with the situation’. In this conversation, it was necessary for us to be aware of the problem, i.e. the discrepancy between our intended object of learning and students’ lived object of learning, but it was also necessary that we make decisions about which problems should be addressed first, as described in the model of the design cycle presented in Figure 1 (Takeda et al. 1990). Engineers always use modelling as a tool in their ‘reflective conversation’ when designing; in accordance with this practice, we used the LCC model as a tool when we redesigned the transient response lab. This shows that designing is not ‘deterministic’ – the designers’ ideas and values all play a role – reflecting the difference between engineering and science.

The output of the design-based research presented in this paper was not just the design and redesign of a lab dealing with transient responses in electric circuits but also the design of the LCC model, i.e. a contribution to learning theory. The LCC model demonstrates that learning can be understood as a process of establishing more and deeper links between individual areas of knowledge and understanding (Carstensen and Bernhard 2013, 2016). More importantly, it also shows that design science research can inform the development of tools for such research. The LCC model was developed alongside our efforts to try to understand and represent students’ activities and learning in the transient response lab. As pointed out by Trevelyan (2014), ‘the knowledge of practice is created by practice’. Furthermore, as noted by many researchers, models are judged by the work they do (Cobb et al. 2003) and may be useful as epistemic tools (Knuuttila 2011). This tool, the model of the learning of a complex concept, was originally developed to describe learning in the transient response lab. However, as noted in the section on the validation cycle, it has already been used to analyse students’ learning in other labs (Bernhard and Carstensen 2015; Bernhard, Carstensen, and Holmberg 2009).

In the introduction of this paper, we stated that the outputs of design science research are ‘constructs, models, methods and instantiations’ (Vaishnavi and Kuechler 2008). In this paper, we have focused on the development of the LCC model that can be seen as a method as well as a model. The analysis of this model thus led to a new theory of learning based on the idea that to learn complex concepts is to make links (Carstensen and Bernhard 2013, 2016). The results obtained using the LCC model and the analysis presented herein suggest that using design science research techniques to further develop this tool and the associated method into a methodology would be a very productive research endeavour.

Note

1. The lived object of learning is what the students actually learn, i.e. the way they see, understand, and make sense of the object of learning and the relevant capabilities that they develop (Marton, Runesson, and Tsui 2004).

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Notes on contributors

Anna-Karin Carstensen, Ph. D. is a senior lecturer at the department Computer Science and Informatics at Jönköping School of Engineering. Her research interest is Engineering Education Research, mainly concerning learning in engineering and computer science. She teaches courses in the program Embedded Systems within Computer Engineering. She is also responsible for the Industrial Placement Course at her department.

Jonte Bernhard is professor in Engineering Education Research at Linköping University and Deputy Editor of European Journal of Engineering Education. He has an M Sc (Engineering) and a PhD (Engineering) from Uppsala University with specialization in material science. His research is mainly focused on the design of learning environments and on engineering students' collaborative learning in labwork and design projects. He teaches courses in electrical engineering and in engineering and science education.

ORCID

Jonte Bernhard http://orcid.org/0000-0002-7708-069X

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