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Conceptual Modelling As An Overarching Research Skill In Engineering Education

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CONCEPTUAL MODELLING AS AN OVERARCHING RESEARCH SKILL (CONCEPTUAL-RESEARCH-PRACTICE)

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ABSTRACT

Today's society is impacted by complex, fast and continuously changing problems. These need to be tackled inter-, multi and transdisciplinary. At the University of Twente, we have developed a new CBL minor *Intelligence, creativity, and responsible technological innovation in societal transformations*, (ICR&TIST), which focuses on research skills in complex socio-technological problem-solving contexts. The design of this minor has been guided by new insights from long-running research aimed at developing a *Philosophy of Science for the Engineering Sciences* and extensive experiences with engineering education in project-based learning (PjBL).

Education in scientific research tends to focus on academic contexts, while scientific research in real-world problem-contexts (e.g., sustainability) requires the ability to effectively and responsibly construct relevant, reliable and intelligible knowledge for the benefit of the concrete, local problem and possible solutions, using everything science has to offer (knowledge, methods, instruments, mathematical tools). This type of scientific research calls for a *new paradigm*, called an *engineering paradigm of science*. *Conceptual modelling* (rather than hypothesis testing) fits better the core activity of this type of scientific research and should therefore be seen as an overarching skill.

The educational design of the minor has adopted conceptual modelling as the overarching learning objective. This new concept, how to work with the accompanying conceptual modelling methodology (B&K method) and understand the underlying philosophical insights appears exciting and challenging for the multi-disciplinary educational-design team. This paper will elaborate on the educational design process, the resulting design of the minor, and preliminary findings in the pilot-phase.

1 INTRODUCTION

1.1 Conceptual modelling as research skill in socio-technological problems

Today's society faces complex and rapidly evolving problems that require interdisciplinary approaches. At the University of Twente, we have developed the *Intelligence, creativity, and responsible technological innovation in societal transformations* (ICR&TIST) minor, which focuses on research skills in socio-technological problem-solving contexts. This paper introduces conceptual modelling (CM) as a research skill suited for complex real-world problem-contexts, such as sustainability. By effectively and responsibly constructing relevant and reliable knowledge, CM enables the utilization of scientific resources. The changing paradigm of science, specifically the engineering paradigm, is discussed in relation to CM, along with the B&K method for constructing and analyzing conceptual models. The implementation of CM as an overarching research skill in engineering education is highlighted, along with the identified barriers that require further investigation.

1.2 Research in the engineering science: experiences and insights

The author's background in chemical engineering and *process optimization research in industrial bioleaching processes* (e.g., Boon 1996a, Boon and Heijnen1998) aimed at developing *sustainable technologies* has acted as a moral and epistemological concern that motivated philosophical inquiry. For example, a contribution to a book about sustainable futures raises questions about the role of (academic) scientific research:

> "In discussions about the relation between science and sustainability at least four questions come to the fore. (1) What should be the role of science in a society aiming at sustainability? (2) Is science as practised today appropriate for a sustainable society? (3) Do we have indications that point at the emergence of new methodologies and paradigms relevant for the realization of sustainability? (4) Can we come up with proposals for eliminating or creating (un)favourable conditions for the role of a new science in a sustainable society?" (Boon and Doorman 1994).

The *normative epistemological* focus in developing a *philosophy of science for the engineering sciences* (Boon since 2001) therefore primarily concerns the *quality of scientific research and education practices* in view of their societal contributions (e.g., to sustainability), where *ethics in technology* acts in the background.

Philosophical reflection during the research project, shed light on several challenges regarding the role of science, including the difficulty in integrating fundamental scientific knowledge and misaligned expectations between technologists and microbiologists. Furthermore, the lack of deeper scientific understanding in industrial research and the translation of concepts without considering scientific understanding are highlighted. The tension between publishing academic articles conforming to reductionist research methodologies and generating practical scientific understanding for industry is also discussed. These experiences contribute to the identification of a gap between fundamental and applied research, leading to the realization that expectations of scientific research do not always align with practical and societal needs.

1.3 Overview

The paper briefly explains the importance of philosophy of science for the engineering sciences in bridging the gap between fundamental and applied research. By critically reflecting on the value and relevance of scientific research for reliable, relevant and responsible knowledge production in socio-technological contexts, philosophy helps reshape research approaches and education therein.

The paper then moves on to discuss aspects of the *philosophy of science for the engineering sciences* that underpins the proposed interpretation of conceptual modelling. This includes replacing the *traditional physics paradigm* by an *engineering paradigm of science*, better suited for understanding the role of scientific research in addressing complex socio-technological problems.

The engineering paradigm of science emphasizes, among other things, the production of *relevant, reliable and useful knowledge* as a goal of scientific research. Regarding the *quality of scientific research practices*, this implies for example that, in contrast to emphasis on universal knowledge and reductionism in the physics paradigm, the focus should be on the construction of relevant and reliable knowledge (including technological and mathematical tools) for specific problems. This normative basis raises the epistemological question of what this implies for scientific research and teaching practices. The engineering paradigm emphasizes that conventional reductionist approaches are not necessarily the best, and relatedly, that applying fundamental scientific knowledge is less straightforward than the physics paradigm suggests. In addition, *interdisciplinary research* is crucial for knowledge production for real-world contexts, which is notoriously difficult and not straightforward either. Conceptual modeling aligns with this paradigm and provides a framework for effectively addressing complex problems in scientific research projects.

To further develop the quality of academic engineering education, the paper suggests conceptual modelling as an overarching learning objective that contributes to the ability of engineers in professional roles to conduct scientific research in complex socio-technological context. The B&K method, which aids in the construction and analysis of conceptual models, is explained in detail. Finally, the paper briefly discusses the educational design of the (30 ECTS) ICR&TIST minor.

2 PHILOSOPHY OF SCIENCE FOR THE ENGINEERING SCIENCES

The philosophy of science examines beliefs and views about science and their impact on research practices. Commonly, ideas about science are influenced by physics as an example of "real" science. However, it is essential to determine if these ideas are suitable for the engineering sciences or if they hinder problem analysis and solutions. Based on my experiences in the engineering sciences, I hypothesized that our current ideas about science justify research practices but may not always be productive as desired (Boon 1996a, 1996b, 2006, 2011a). Therefore, an alternative understanding of science is necessary, specifically a paradigm of science that better suits the engineering sciences (Boon 2017). Developing a philosophy of science for the engineering sciences has been a focus of my research for the past twenty years.

In typical discussions about science, the emphasis is primarily on evidence for scientific claims, which is evident in scientific articles and how they are read and taught. The content and methodologies of science education revolve around conveying proven scientific knowledge and evidence-oriented research methodologies like hypothesis testing. Students are often taught to critically assess whether the methodology and collected data sufficiently support the conclusion. The philosophy of science uses the term "context of justification" to describe this focus on evidence. The “context of discovery,” on the other hand, encompasses aspects like creative thinking, formation of concepts, understanding and conceptualization, and various reasoning processes that cannot be considered as evidence.

These discussions reveal several important assumptions about scientific research. Firstly, the normative claim that evidence for scientific claims should solely consist of objective data and logically valid arguments. Secondly, the metaphysical belief that such evidence provides certainty or proof of the (approximate) truth of scientific claims. Thirdly, the belief that the goal of science is to produce true claims about physical reality. Lastly, the epistemological belief that true knowledge about specific instances can be deduced from proven scientific claims. These assumptions are part of a paradigm of science called the *physics paradigm*.

However, contemporary philosophy of science and historical case analysis have shown that these assumptions are philosophically problematic and inadequate in representing successful scientific practices (e.g., Knuuttila and Boon 2011). The dominant physics paradigm often overlooks crucial aspects of scientific research, particularly in applied sciences like the engineering sciences. As a result, an alternative paradigm of science, termed the *engineering paradigm*, is necessary. The engineering paradigm emphasizes that the construction of knowledge is an inseparable part of understanding and justifying scientific knowledge claims (Boon and Knuuttila 2009). It challenges the unjust distinction between the context of discovery and the context of justification and proposes the “context of construction” as an alternative (Boon 2022).

Thomas Kuhn (1962) introduced the concept of paradigms and paradigm shifts in science. A paradigm encompasses symbolic generalizations, metaphysical presuppositions, values to judge theories, and exemplars (Kuhn 1970). Inspired by Kuhn's work, contrasting paradigms of science have been developed: the physics paradigm and the engineering paradigm (Boon 2017). These paradigms allow for the examination of differing beliefs about science. For example, the engineering paradigm focuses on constructing useful knowledge for specific applications, while the physics paradigm assumes the discovery of pre-existing entities and phenomena.

The engineering paradigm has implications for ideas about scientific knowledge, methodology, and education. It recognizes the roles of technological instruments and human understanding in generating and interpreting data. Scientific knowledge is seen as representations of human understanding, constructed using empirical knowledge, measurement tools, scientific concepts, theories, and mathematics. The engineering paradigm acknowledges the contributions of conceptual and instrumental resources in scientific knowledge construction, which the physics paradigm tends to ignore.

The alternative engineering paradigm of science has profound implications for conceptual modeling and provides a richer understanding of its meaning.

3 CONCEPTUAL MODELLING

The term ‘conceptual modelling’ is not new. Robinson (2008), for example, stresses the importance of conceptual modelling for (computer) simulation, while Thalheim (2010, 2012) declares that conceptual modelling is one of the central activities in computer science. It involves creating schematic descriptions of systems, theories, or phenomena using concepts to enhance the model. However, these authors also consider conceptual modelling the most difficult and least understood aspect of e.g. computer simulation studies.

There are three types of scientific models: those deduced from abstract theories, visually represented models of unobservable entities, and heuristic models used as aids. The first type aligns with the physics paradigm, where the model is derived logically or mathematically from the theory. The second type represents invisible entities or phenomena and relies on the similarity between the model and the real-world entity. The third type, heuristic models, are not intended to be realistic but serve as tools.

In an engineering paradigm, models are not literal representations but rather how researchers imagine and conceptualize the (invisible) phenomenon. These models contain essential information expressed verbally and visually, making them *thinking tools* (called *epistemic tools*) within a specific context. Models (esp. conceptual models) are thus considered *epistemic tools* that help researchers think about and interact with the phenomenon they represent, as well as the ever further development of these models (Boon and Knuuttila 2009).

To illustrate this view on models, the example of Sadi Carnot's conceptual modelling of the ideal heat engine is presented (Knuuttila and Boon 2011). Carnot's model was constructed based on already existing steam engines, aiming to understand the limits of power generation from heat (Carnot 1824). His approach involved abstracting from the technology and formulating the problem more fundamentally. Carnot's model included both abstract and practical concepts, as well as fundamental principles and existing scientific knowledge (e.g., gas-laws).

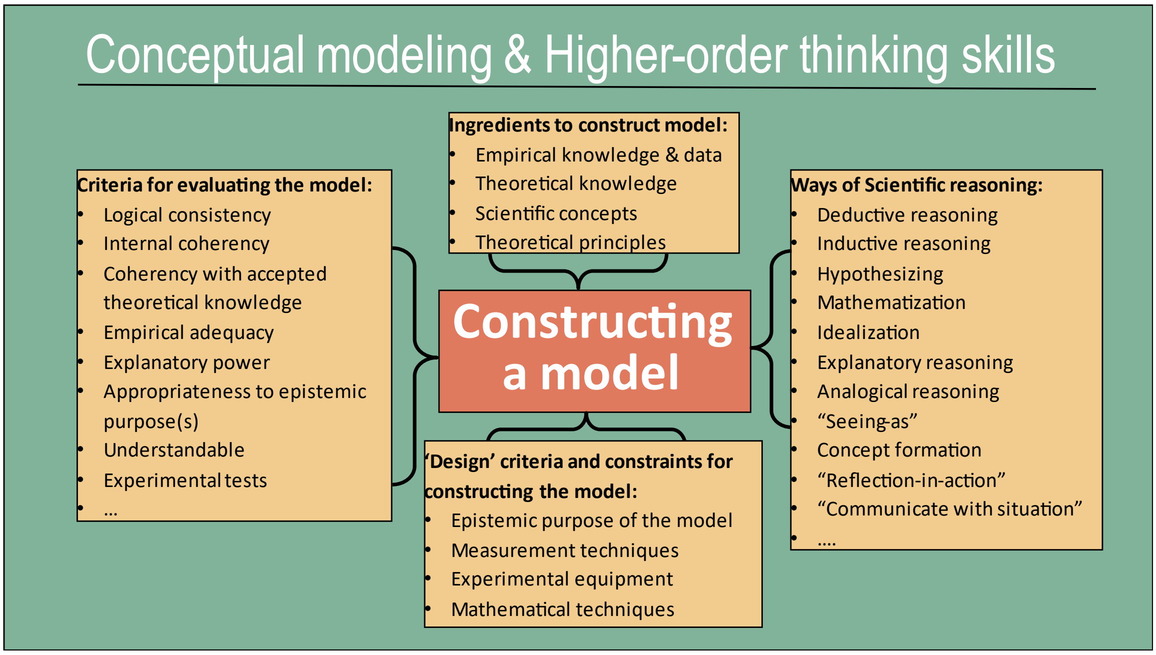

Figure 1 (Lecture slide, copy right Mieke Boon): Conceptual modelling according to an engineering paradigm of science. 'Reflection-in-action' and 'Communicate with the situation' in the scientific reasoning box (right side) refers to Schön (1983).

The B&K method, consisting of ten questions, can be used to systematically determine the aspects built into a scientific model. It helps construct or reconstruct existing models by considering relevant elements (partly listed in Fig. 1, upper and lower box). However, the B&K method is not an algorithm but a tool that requires scientific reasoning skills (Fig 1, right box) and epistemic responsibility (Boon 2020a) guided by criteria (Fig 1, left box) relevant to the intended epistemic purpose of the model.

The engineering paradigm recognizes that an algorithmic methodology for producing true or correct knowledge is not feasible. Researchers bear the responsibility of deciding which ingredients to include in the model, considering the available resources, existing knowledge, and the model's epistemic purpose (Boon and Van

Baalen 2019). This approach does not compromise objectivity and rationality but involves meeting logical, epistemic, and utility criteria (Fig. 1, box left).

“Bringing the human back into science” is an essential aspect of the engineering paradigm (Boon 2020c). It acknowledges the role of human scientific reasoning, which extends beyond logical reasoning (Fig. 1, box right). Researchers must develop higher-order thinking skills (HOTS) and engage in critical assessment of models, including the criteria used (Fig. 1, box left) and how well the models meet them.

In summary, conceptual modelling plays a central role in scientific knowledge construction. It requires intellectual skills and training in higher-order thinking for researchers. The engineering paradigm embraces the complexity of conceptual modelling and emphasizes the responsibility of researchers in constructing and evaluating models.

4 TEACHING AND LEARNING CONCEPTUAL MODELLING

4.1 Conceptual modelling interpreted from the engineering paradigm

The traditional physics paradigm of science, which emphasizes objectivity, rationality, and the pursuit of true knowledge, has influenced engineering education in unproductive ways. It limits the recognition of the human role in scientific research and overlooks the diverse ways of reasoning that contribute to scientific understanding. Academic engineering education has also adopted some of these ideas, such as the distinction between research and design and the limited roles attributed to teachers in supporting the development of HOTS by students in scientific research (Boon 2022). However, the engineering paradigm offers a different perspective, emphasizing the importance of the human ability of conducting scientific research in complex problem-solving contexts, which involves the human ability to reason in different kinds of ways (Fig 1, box right) and judge the quality (Fig 1, box left) of conceptual models thus produced.

Conceptual modelling, as interpreted from the engineering paradigm, provides a suitable approach for teaching and learning scientific research in academic engineering education. It involves understanding conceptual models as representations of researchers' understanding of a phenomenon, incorporating various contributions from technology, mathematics, and cognition, and being constructed with specific epistemic purposes in mind. Conceptual modelling serves as an overarching learning objective that involves developing other intellectual skills (Boon et al. 2022). According to the engineering paradigm, these include (non-exhaustive): problem-analysis, systems-thinking, knowledge-application, integration of heterogeneous elements, explanation, evaluation, representation, conceptualization, and logical reasoning.

4.2 Implementing conceptual modelling in academic engineering education

There are several ways to implement conceptual modelling in engineering education:

1. *Explaining abstract theory*: By reconstructing the development of a theory, such as thermodynamics or electro-chemistry, students can gain a deep understanding of its structure and content (e.g., Knuuttila and Boon 2011). The B&K method provides guidance for analyzing and identifying key components. This understanding enables students to apply the theory effectively in practical applications (Orozco et al. 2022, 2023).

2. *Analyzing scientific articles*: The B&K method can be used to analyze scientific articles, allowing students to gain insight into the content and identify important aspects of the reported research (Boon 2020a). This approach helps students overcome the challenges of reading scientific literature and encourages them to focus on the research process rather than just the conclusions.

3. *Using conceptual modelling in PjBL and CBL projects*: Conceptual modelling can be implemented as an overarching approach in problem-based and challenge-based learning (PjBL and CBL) projects (Boon 2020a). By constructing conceptual models of complex problems, students can develop a deeper understanding of the problem and the criteria for potential solutions. The B&K method provides support for students' modelling activities in these projects.

Implementing conceptual modelling in engineering education has shown positive outcomes. Teachers have observed improvements in the quality of student projects, and students have expressed an understanding of how conceptual modelling supports their research. However, students often struggle with thinking like researchers and formulating research questions. Further scaffolding is needed to develop their higher-order thinking skills, particularly in question-asking as part of the conceptual modelling proces (Orozco 2023).

In summary, teaching and learning conceptual modelling in academic engineering education aligns with the engineering paradigm of science. By implementing conceptual modelling in various educational contexts, students can develop a deeper understanding of scientific research and enhance their ability to responsibly produce relevant and reliable knowledge (including instruments and tools) for complex socio-technological problems.

4.3 Educational design of the ICR&TIST minor

The overarching learning objective of the ICR&TIST minor is to conduct trans- and interdisciplinary research. The educational design adopts a challenge-based-research-learning (CBR/L) approach in which students learn to conduct trans- and interdisciplinary research on a complex real-world problem. To this end, we have entered into a partnership with external stakeholders in the *energy-transition challenge*. Crucially, this minor is entirely skills-oriented (rather than content- oriented as in most programs focused on interdisciplinarity, see Kuiphuis-Aagten et al. 2019).

The development of so-called higher-order-thinking skills (HOTS) relevant to trans- and interdisciplinary research is promoted by eight inter-related micro-modules (1 ECTS each). The minor and micro-modules have been developed by a multi-disciplinary cross-faculty team of dedicated teachers and educational designers. The micro-modules cover conceptual modelling through the B&K method, and seven other micro-modules aimed at understanding methods and measuments in both the engineering and the social sciences, developing ‘the art of reflection’ targeting critical thinking, creativity, problem-analysis, and responsibility (also see Schön 1983), and insights into research-strategies in inter-and transdisciplinary research. For the multi-disciplinary teacher-team in our educational-design team, this new concept, how to work with the accompanying CM methodology and understand the underlying philosophical insights is exciting and challenging: "this is a completely new paradigm of what scientific inquiry is and our roles as teachers."

5 CONCLUDING REMARKS

The University of Twente recently developed a challenge-based learning (CBL) minor called *Intelligence, creativity, and responsible technological innovation in societal transformations* (ICR&TIST). This interdisciplinary program aims to cultivate scientific research skills in complex socio-technological problem-solving contexts. The educational design of the minor incorporates the engineering paradigm of science and draws on experiences with the conceptual modelling approach in project-based learning (PjBL).

The current problem is that scientific research training typically focuses on academic contexts, aligned with the physics paradigm of science. However, real-world problem-solving requires the ability to produce relevant, reliable, and understandable knowledge in concrete problem contexts, utilizing the full range of scientific resources available. Additionally, socio-technological problems necessitate trans- and interdisciplinary research, which is intellectually challenging (Boon 2020b).

The goal of the CBL minor is to foster students' trans- and interdisciplinary research skills, with a particular emphasis on interdisciplinary research skills (cf., Van den Beemt et al. 2020, Boon and Van Baalen 2019, Boon 2020b). Existing interdisciplinary PjBL and CBL education primarily focuses on scientific content and professional skills development, with limited support for promoting interdisciplinary research skills (Kuiphuis-Aagten et al. 2019). To address this gap, it is crucial to scaffold students development of higher-order thinking skills required for understanding and conducting scientific research.

A key pedagogical insight is that students struggle to apply abstract knowledge in concrete settings due to the physics paradigm's emphasis on true and justified knowledge. In contrast, the engineering paradigm highlights the application of scientific knowledge in problem-solving contexts and the understanding of how knowledge is *constructed*. Therefore, it is essential to prioritize the development of scientific thinking skills over the conveyance of scientific content. Students with these skills can acquire knowledge independently, prompting teachers to reflect on their contribution to students' scientific thinking skills.

Another insight is that both students and teachers are influenced by the physics paradigm, shaping their beliefs and attitudes about teaching and learning. Paradigm shifts, as described by Kuhn, are challenging and require time. Redesigning education using the conceptual modelling approach necessitates creating awareness of paradigms among teachers and students.

The design process of the ICR&TIST minor involved workshops with the teacher team, where strategies such as reflecting on crucial learning experiences were employed. Teachers' beliefs about scientific research and education were interpreted from the physics versus engineering paradigm to increase awareness of paradigms. This process facilitated the development of shared understandings and led to the joint creation of micromodules, aiming to promote scientific thinking skills related to research and measurement methods, including several types of reflection skills.

Educational research on the pilot of this minor is ongoing, but initial findings indicate that teachers found the approach inspiring, experiencing a paradigm shift in their understanding of scientific inquiry and their role as teachers. Students quickly adapted to the new mindset, finding it exciting and liberating. They realized the potential to develop their higher-order thinking skills actively. Scaffolding the development of scientific research and thinking skills based on the engineering paradigm proved successful, although there is room for improvement and further research is needed to identify and address students' obstacles.

In conclusion, experiences in education and insights into the scientific research required for academically trained engineers highlight the need for the development of interdisciplinary research skills to tackle complex socio-technological issues. Conceptual modelling serves as an overarching skill encompassing various other skills, and a scaffold has been developed to facilitate the learning process. The new educational approaches have shown positive results and garnered appreciation from students and teachers. However, students still face challenges in developing the higher-order thinking skills crucial for scientific research. Further research is necessary to identify and address these obstacles, ensuring the effective support of students in becoming creative and responsible researchers, thereby enhancing the quality of academic engineering education.

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