# TEACHING ENGINEERING AS A DESIGN SCIENCE

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## ABSTRACT

In this paper, we take the position that teaching engineering itself is a design science. Engineering educators worldwide creatively design, implement, and evaluate new ways of teaching to facilitate the learning of their students and to respond to various societal challenges. Sadly, their teaching and course design discoveries often remain with them. By representing successful experiences in engineering education as structured pedagogical patterns, we could develop this vital professional knowledge collectively into a so-called *pattern language*. The pattern language method acknowledges the complexity of instructional design and divides it into smaller and more understandable pieces. One piece is called a ‘pattern’. This paper aims to set the argument of why and how to develop a pedagogical pattern language for engaging and activating engineering education. In Delft, we see this pedagogical language as a part of TU Delft’s so-called ecosystem approach toward learning and teaching. TU Delft recognizes the need among students for impact-driven education that matches the way this generation learns and what our society needs. Successful ecosystem pedagogies will be the core of the intended pedagogical pattern language. It is our idea to develop this pattern language in close cooperation with the teaching communities of TU Delft, that is the TUD Teaching Academy, the 4TU Centre of Engineering Education, and CDIO.

## KEYWORDS

engaging engineering pedagogy, eco-systems communities for teachers, pattern language, scholarship of teaching and learning, Standards: 8, 9, 10

## MOTIVATION FOR A SHARED PEDAGOGICAL LANGUAGE FOR ENGINEERING EDUCATORS

Today's and tomorrow's global socio-technical challenges ask for many new ideas, sustainable solutions, and smart transition strategies. The world is particularly looking at engineers who should play an important role in 'solving' these challenges. And those technological solutions need to be seen in the context of global limits, moral decision-making, societal and environmental justice, (inter)national legal procedures, and (local) political forces. Engineers will need to be able to adapt to those changing societal contexts to stay valuable professionals over time (Moravec, 2013).

The future generations of engineers need to be guided into this complex society. That is why university teachers should look at education (and their teaching in particular) from a societal perspective, get out of their bubbles regularly by connecting with colleagues and industry, and share and discuss teaching practices and experiences. Besides, the changing world has an enormous impact on engineering pedagogies. Teaching engineering is no longer 'simply' about passing on technical knowledge from lecturer or professor to student, or 'just' doing a project to apply technical knowledge and gain more engineering skills, experience, or expertise. Education of today is also – and more and more – about higher-order and transversal skills and critical thinking in order to better understand the world, develop a professional position, and intervene in reality.

Engineering educators at universities have to cope with and teach in that fast- and ever-changing, complex environment (Kamp, 2016; 2020; Kavanagh, 2019). Accordingly, learning about engineering does not only mean learning technology fundamentals and more specialized engineering skills, but also learning to adapt to this changing and uncertain society in an entrepreneurial, responsible, and healthy way (4TU.CEE, 2021). And more and more, engineering students not only want to learn about engineering, but also want to engage with and have a positive impact in society during their studies (Dierckx, Zaman, & Hannes, 2022; Sociologie magazine, 2022; Loosbroek, 2021).

In this paper, we take the position that teaching engineering itself is a design science. Engineering educators face the challenge of developing pedagogical formats. So, every day, colleagues worldwide creatively design, implement, and evaluate new activating and engaging ways of teaching to facilitate the learning of their students. Sadly, their teaching and course design discoveries often remain with themselves (and their students), or at best within their local, departmental environment. By representing and communicating successful experiences in activating and engaging engineering education as structured *pedagogical patterns*, we could develop this vital professional knowledge collectively into a so-called *pedagogical pattern language* (Laurillard, 2012; Bergin et al., 2012; Bennedsen, 2006; Sharp, Manns & Eckstein, 2003). This can lead to more understanding and internalisation among teachers, allowing education to adapt more quickly to change and thus better match society's and students' needs and expectations.

A pattern language is – by nature – open-ended and dynamic (Rooij & Dorst, 2020). In due time, new patterns can be added to and outdated patterns could be removed from the language. A pattern language can be adjusted (and re-published) anytime. In this way, a pattern language is an invitation to educators all over the world to translate their teaching experiences into one or more pedagogical patterns and integrate them into the language. In each pattern description, credits are given to the original authors as "the origin or provenance of a pedagogical pattern is as important as citations are in research" (Mor & Winters, 2007). It is our position that twentyfirst-century engineering education needs university teachers who work collaboratively to design effective, relevant, up-to-date, agile, challenging, and innovative teaching formats.

## GOAL AND STRUCTURE OF THE PAPER

This paper aims to set the argument of why and how to develop a pedagogical pattern language for engaging and activating engineering education. The argument is supported by (the review of) a variety of literature with pedagogical, design, and societal perspectives. The paper can also be read as a kind of research proposal, as it presents our motivation, ambition, intended outcomes, and action plan for the coming years.

We will organize our thinking into five additional sections. First, we will deepen the teaching-engineering-as-a-design-science thinking, Then, we look at some important lessons for instructional design from more traditional fields of design. Thirdly, we elaborate on the value of pedagogical patterns for engineering education/educators and we present and argue what a pedagogical pattern could look like. Fourth, we explore in what ways we could organize and structure this potentially endless set of patterns in a coherent, accessible, and communicative way. Fifth, we will present our view on how to co-create this pattern language with engineering educators from all over the world; in particular, in cooperation with our communities at TU Delft and with CDIO.

## TEACHING AS A DESIGN SCIENCE

Designing is at the core of what educators do[1]. Akker (2013) presents the elements that educators have to integrate into their instructional design in the format of his 'curriculum design spider web' (Figure 1). Together they cover a full spectrum of contents, pedagogy/didactics, and organization. However, the spider web does not say much about *how* to do the instructional design; that is the design approach or design process.

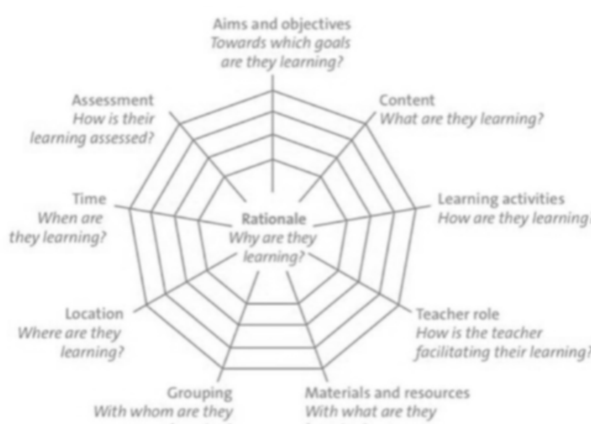


Figure 1. Curriculum Design Spider Web (Akker, 2013)

[1] Here we use the word 'educator' for both 'university teachers' and 'education coordinators'. University teachers are academic staff members, like lecturers and (assist./assoc./full) professors, with teaching responsibilities. Education coordinators are academic staff members, like lecturers and (assist./assoc./full) professors, program directors, and (vice-)deans of education, with coordination and/or leadership responsibilities such as course, program(s), or department coordination.

We distinguish here three main levels at which instructional design activities take place:

- program/curriculum level;
- subject/course/module level;
- classroom/session level.

At the **program/curriculum level,** an instructional design needs to be made for the full program, e.g. a bachelor of science undergraduate program, or a master of science graduate program. Usually, programs at universities are 1-5 years programs and they are developed in interaction with the teacher and student communities; sometimes even together with other institutes and/or industry. At this level, we consider what kind of engineer we are educating (e.g. the technical domain) and how the educational environment, including the role of the teacher, can support the professional and personal development of the student.

At the **subject/course/module level,** educators (or teaching teams) design the set-up of one 'unit' within a program/curriculum: a subject/course/module with its constructive alignment of learning contents & objectives, learning & teaching activities, and assessment strategy. An important instructional design challenge here is to make the subject/course not only coherent in itself, but also within the learning trajectory of students; e.g. taking into account prerequisite knowledge and follow-up subjects/courses. Courses very often last a few weeks or months (quarter, trimester, semester).

At the **classroom/session level,** teachers design the teaching approach for one 'lesson'. An important instructional design challenge here is the very concrete organization and planning of the session, teaching & learning activities, interaction formats (student-teacher, student-students), feedback approaches et cetera. The duration of a classroom/session 'normally' is about 1 to 4 hours.

## LEARNING FROM DESIGN FOR DESIGN

It is interesting to bring into play here how design fields with a long design tradition, such as architecture, urban design, and product design, view this question of how to design and how to become a better, more professional designer. These fields developed a rich body of writings about it, from which we will emphasize 'just' two: Lawson & Dorst (2009) *Design Expertise* and Dooren (2020) *Anchoring the design process*. Lawson and Dorst (2009) make clear that there is not a single overarching definition of such a thing that we call design, as it is and/or can be…:

…**a mixture of creativity and analysis**: 'When steeped deeply in your design activity you just keep switching between analysis and creativity, between 'problem' and 'solution' without any effort.' (p. 30)

…**problem-solving**: 'pose – search – generate – evaluate – choose' (p. 30)

…**learning**: 'As a designer, you gradually gather knowledge about the nature of the design problem and the best route to take towards a design solution…' '…You propose, experiment, and learn…' (p. 32)

…**evolution**: 'A creative event occurs as the moment of insight at which a problem-solution pair comes together.' (p. 38)

…**the creation of solutionS to problemS**: important when talking about 'underdetermined' and 'overdetermined' design problems (p. 42), that is with (too) few requirements, constraints, and/or starting points, or (too) many.

…**integrating into a coherent whole**: 'Well integrated and coherent designs are characteristically simple, elegant and give the feeling that everything (RR: important) has been taken into consideration, and is as it should be. There is a glimpse of perfection in an integrated design.' (p. 44)

Additionally, Lawson and Dorst (p. 98-99) point out (based on Dreyfus, 2003) that design expertise is something that grows over the years of doing design, getting more experience and proficiency, and being a reflective practitioner. In brief, **beginners** tend to follow certain rules. The **advanced beginner** is much more context-sensitive. The **competent performer** has learned to develop and use certain design strategies. **Proficiency and expertise** are achieved when the performer automatically and immediately follows an appropriate design approach. And the **master and visionary** designers even go beyond. Masters display a deeper involvement in the field and visionaries consciously strive to extend the domain of operation of that design field.

From a pedagogical point of view on design teaching and learning, Dooren (2020) presents five generic elements via which the essential basic designerly skills are described. These elements are not meant as a formula for a good design or a good design process. Rather, they are anchor points to express the designerly ways of reasoning.

**Experimenting, exploring, reflecting, and deciding**: designers have ideas, evaluate them ex-ante, improve them, implement, evaluate ex-post, and improve again. Instructional designers have a reflective attitude toward their teaching ideas, exploration process, and instructional design decisions.

**Bringing focus**: during the design process, designers tend to look for and find the essence of their design that guides them, their ideas, and the sub-solutions; the educational vision behind the concrete design.

**Working within domains**: each design discipline has its domains. In instructional design, the domains relate to contents (learning and teaching vision, learning objectives and contents, sources and materials), pedagogy (learning and teaching activities, roles of teachers, assessment strategy), and organization (group approaches, learning environment, time). Decisions in one domain usually have consequences for other domains.

**Using references**: design ideas can come to the mind of the designer in many ways; for example by talking to people such as students, teaching staff, education management, learning developers, etc). Designers tend to learn and take a lot of inspiration from references, cases, and other concrete examples. They explore proven design principles and see if it makes sense to adapt them to their context.

**Speaking the language of design**: designers imagine possible, desirable futures and they communicate accordingly. Seeing opportunities and defining ambitions is their first nature as well as representing these via drawings, schemes and other visual strategies besides using words.

## THE VALUE AND LOOKS OF A PEDAGOGICAL PATTERN[2]

Christopher Alexander recognized the complexity and dynamic quality of design. He developed a method to deal with this complexity; making the relation between the recurring nature of a problem and the process of designing a 'solution' that 'solves' that problem (Alexander, 1964, 1979; Alexander et al., 1977). This method acknowledges the complexity of design, and at the same time divides this reality into smaller and more understandable pieces. One piece is called a 'pattern'. On the one hand, the pattern is underpinned by theory, while on the other hand, the pattern is discussed in pragmatic terms and societal value, and clarified with a sketch, photo, illustration, or example. In one 'simple' overview a pattern presents a bridge between a problem and a solution.

So, a pedagogical pattern bridges a pedagogical problem and a pedagogical solution. Laurillard (2012) reasons that pedagogical patterns should be made by and for the instructional design community itself, that is the educators. One can see such a building block of this pattern language as teaching or course/curriculum design principle: a pedagogical problem-solution unit. For experienced educators, (some/several) patterns might be 'normal, 'logic, 'obvious', perhaps even 'trivial', because they have used them so often. For those newer to teaching or newer to certain ways of teaching, the patterns offer a way for experienced teachers to pass on their pedagogical experience and knowledge (Bergin et al., 2012).

In our view, a pedagogical pattern for engaging and activating engineering education should consist of an attractive and informative title, a hypothesis on the problem-solution relation, a deeper explanation of the context of and forces behind a pattern, a theoretical backing from scientific research and literature, its societal value, its practical implications, its relations to other patterns, and one or more communicative visuals. The patterns enable constructive and solution-oriented discussions amongst the people designing or teaching a course without either bringing down the richness of a topic or losing oneself in details (Rooij & Dorst, 2020). Furthermore, the patterns are not prescriptive. The involved people, e.g. the course design team, have to decide whether or not to use (or adjust) certain patterns in their institutional context.

> *In our view, a design pattern is a semi-structured description of an expert's method for solving a recurrent problem, which includes a description of the problem itself and the context in which the method is applicable, but does not include directives which bind the solution to unique circumstances. Design patterns have the explicit aim of externalizing knowledge to allow the accumulation and generalization of solutions and to allow all members of a community or design group to participate in discussions relating to the design.*
> From Yishay Mor & Niall Winters (2017)

Patterns can be more or less concrete and/or more or less context-specific. An example of a more generic pedagogical pattern for engaging engineering education is 'DESIGN EDUCATION'; a more concrete one is 'ASSESSING INDIVIDUALS IN TEAMS ' (see Figures 2 and 3).

[2] The first part of this section is based on and partly derived from Rooij and Dorst (2020).

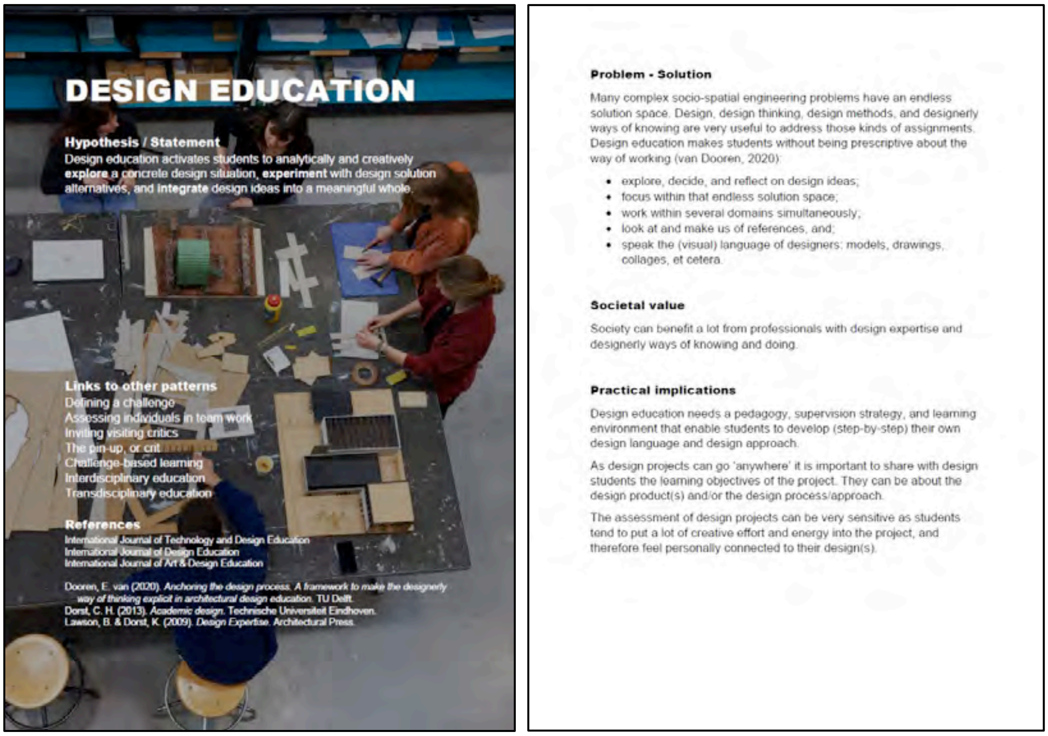


Figure 2. More generic pedagogical pattern example
'DESIGN EDUCATION'

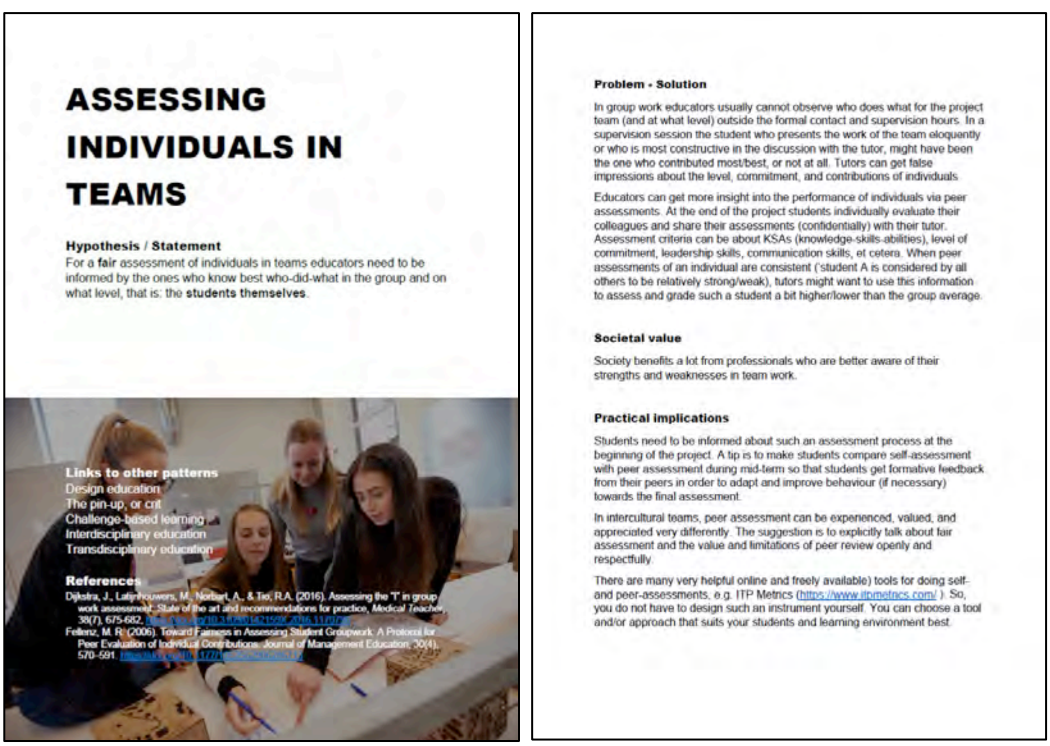


Figure 3. More specific pedagogical pattern example
'ASSESSING INDIVIDUALS IN TEAMS'

## ORGANIZING AND STRUCTURING PATTERNS

One pattern is 'simple'. Complexity kicks in if one starts relating patterns to other patterns. Pattern languages can consists of tens or hundreds of individual patterns. Every pattern usually links up to several other ones, very often in different ways (e.g., thematically, or via stakeholders). A pattern may even conflict with another pattern. If the relations between patterns are sketched out, we get a so-called 'pattern field' (Figure 4), which can easily be(come) as complex as a real design or planning assignment (Dorst, 2005).

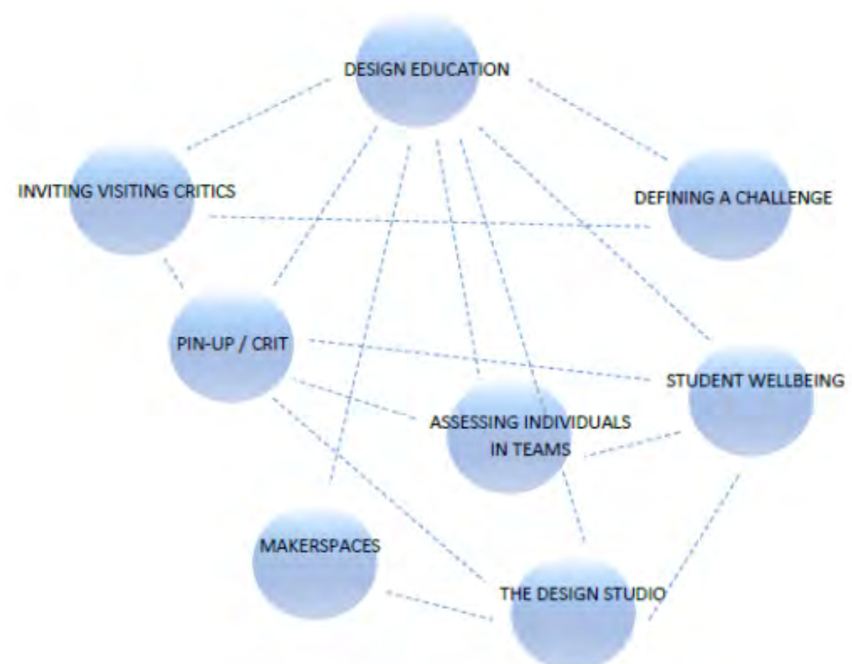


Figure 4. Example of a (relatively) small pattern field on 'DESIGN EDUCATION'

As the number of patterns in a pattern language can (drastically) grow over time, the accessibility of both the language as a whole and individual patterns become crucial. A smart way to get an overview of all patterns is by (re-)organizing them in one or more meaningful ways. Organizational principles can be:

- from abstract/generic to concrete interventions;
- from small-scale to large-scale interventions, e.g. classroom level, course level, program level;
- thematically, e.g. domains of contents, pedagogy/didactics, organization;
- from short-term to long-term interventions;
- stakeholder-oriented, e.g. individual students, student groups, partners from industry or engineering practice, lecturers, coordinators, and educational management;
- from engineering education-specific patterns to more general and holistic patterns about learning.

At the level of individual patterns, we should aim for a presentation format of a pattern that is both (visually) attractive and informative. It is our view that each pattern should contain a certain (visual) design quality itself in order to reach a large audience. So, besides clear explanatory texts and clear descriptions of examples, we should not forget to stick to a consistent structure with repeating headings and/or subtitles, but also develop an appealing sheet mirror with enough white space, and room for photos (from concrete teaching settings), schemes, or icons illustrating and emphasizing the main concepts addressed in a pattern.

Furthermore, depending on the objective of how you would like to use the patterns, certain ways of organizing and representing the pattern field might be more or less useful:

- as an **analysis** tool – to systematically analyze, review, evaluate, assess (the presence or lack of patterns in) a certain learning environment or pedagogical context;
- as a **(co-)design** tool – to catalyze the instructional design process of a course or degree program (within a teaching team) with inspiring, 'proven' principles;
- as a **communication** tool – to develop a shared language among various stakeholders;
- as a **co-creation** tool – to facilitate the inter- or transdisciplinary co-operation between various stakeholders;
- as a **learning** tool – to document, further develop, and share knowledge acquired. This function is not to be underestimated as society asks for continuous professional development and lifelong learning, also within universities, so also of educators.

## CONCLUSIONS AND STEPS FORWARD: CO-CREATING A PATTERN LANGUAGE

This paper presents the argument why we – as engineering educators – should collectively develop a pedagogical pattern language on engaging and activating engineering education. It is our responsibility to organize future-proof engineering education and educate future-proof engineers. So, we need to not only develop but also share our insights into successful engineering pedagogies. At the same time, we understand that institutional contexts differ a lot in higher (engineering) education and nobody needs directives from others about what and how to teach. The bundling of teaching principles (the so-called pedagogical patterns) gives room to the instructional designers locally to assess if certain patterns are valuable in their local contexts.

In Delft, we see this pedagogical language as a part of TU Delft's ecosystem-learning approach that we develop together with other learning-level institutions and various partners from within the public and private domains and civil society. In ecosystems, university and vocational education students and lecturers learn and work together with stakeholders on societal challenges. This brings interesting pedagogical insights to teachers and we see teachers learning from each other's approaches. TU Delft recognizes the need among students for impact-driven education that matches the way this generation learns and what our society needs. TU Delft promotes a distinctive approach to education that inspires students and connects our students, teachers, and researchers to the wider world: an educational and/or campus ecosystem that accelerates innovation.

Ecosystem partnerships facilitate ownership for students as they come face-to-face with the real challenges of the 21st century, apply theoretical knowledge, generate new insights, find solutions or transition strategies, and develop professional skills. As students begin to recognize the long-term value of engaging with societal partners, they can better contextualize general engineering principles. Ecosystem learning and teaching reinforce the idea that engineering students and teachers can respond directly to the actual needs of society while simultaneously accelerating innovation and change. As a result, educational quality will rise, learning with societal impact by students is stimulated, and educators become more flexible and faster (and every time better) to adapt their pedagogies. Successful ecosystem pedagogies and patterns will be the core of the intended pedagogical pattern language because they improve and refresh our teaching language continuously.

It is our idea to do all of this (and learn!) in close cooperation with the teaching communities of TU Delft, that is the TUD Teaching Academy, the 4TU Centre of Engineering Education, and CDIO. We will organize workshops in all these communities in the coming years to share views and experiences on a pedagogical pattern language. Furthermore, we will set up an ecosystem learning and teaching environment so that we can experiment with how it works and how it can accelerate innovative teaching practices. During the workshops, teaching practices of participating engineering educators are shared and 'translated' into one (or more) pedagogical patterns (to be added to our pattern language). Our intended overall outcome of this pedagogical pattern language endeavor is therefore twofold:

- An online, open-source environment that presents a pattern language for engaging and activating engineering pedagogies. Ideally, it will not only share all kinds of patterns but also tell the stories and experiences of engineering educators who made and/or used them.
- A digitally and online freely available serious card game that will help and support curriculum and course leaders, teachers, and teaching teams to playfully develop (or analyze/assess) their class, course, or curriculum design.


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## BIOGRAPHICAL INFORMATION

***Remon Rooij*** is an Associate Professor at the Department of Urbanism and TU Delft's institutional CDIO leader. Since July 2023, Remon has been chair and scientific director of the 4TU Centre for Engineering Education, the national platform in the Netherlands that promotes innovation and pedagogical research in engineering education. Remon is a passionate lecturer, coach, course and curriculum designer, education innovator, and researcher in engineering education. Remon has over 25 years of experience in teaching and coordinating a large variety of design and planning courses and programs within the faculty of Architecture & the Built Environment. He is particularly interested in engaging engineering pedagogies that stimulate the intrinsic motivation and responsibility of students (such as design education, CBL, and inter- and transdisciplinary learning environments) and the kind of academic and professional skills that come with these. He has been in many leadership roles for the Urbanism department, the Architecture & Built Environment faculty, the TU Delft institute, and the Dutch 4TU alliance.

***Linette Bossen*** is an Educational Advisor at the Department of Education and Student Affairs in the faculty of Mechanical, Maritime, and Materials Engineering. She engages in the development of contemporary engineering education so that engineering students can take responsibility for their learning and personal development in line with their ambition. The starting point of this approach toward engineering education is society at large with its challenges and where technological solutions no longer stand alone. Within curricula, she searches for the best-fitting learning environment supported by deploying different teacher roles. Currently, she is exploring eco-learning systems for a society where students and teachers with different learning levels work and learn together with stakeholders and citizens.

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