KUL2021 — EXTENDED ABSTRACT

Architectural design methods used in engineering Master's thesis projects

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Short summary

By letting structural engineering thesis students explore questions using architectural design methods, they creatively and systematically addressed holistic questions while maintaining a technical depth. The approach may serve as a model to increase engineering students' ability to insightfully contribute to solutions for complex societal problems.

Extended abstract

Technological development propels a need for technical specialisation reflected in higher engineering education as requirements for a depth within field-specific knowledge and skills. There are also requirements for general competence regarding judgement and attitudes, but these often weigh lightly when, for example, assessing degree projects. This imbalance also characterises the taught methods and tools, where an emphasis is put on mathematical models for problem solving.

Design oriented educations, such as architecture and industrial design, have developed in another, more holistic tradition. The aim of the methods taught is the ability to process complex and compound challenges and requirements and to develop reflected and well-debated deign proposals.

Today many calls for curriculum development in higher education aimed at the development of professionals with both such abilities, that is, a depth in discipline-specific knowledge and skills and broad boundary-crossing competencies by some called 'T-shaped professionals' [1]. How can we, as a technical university, contribute to the educations of such 'T-shaped engineers'?

Upon comparing the examination criteria from the engineering cultures with those of the design cultures, the differences become evident. The differences are needed to provide technical expertise and multiple perspectives to solve the challenges at hand. However, they also constitute a source of friction, making collaboration between professionals a challenge. This challenge is not new and has, at least within the built environment, been discussed ever since the 18th century when scientific progress led to a division of the traditional master builder role into the roles of architects and engineers. For example, architect Eugene-Emmanuel Viollet-le-Duc concluded in the late 1800s that 'the interests of the two professions will be best saved by their union' [2]. More recently, renowned structural engineer Peter Rice noted that 'engineers are associated with unimaginative dull solutions' and argued for exploration and innovation as keys for engineers to contribute to the work of architects [3]. Educational initiatives at Chalmers such as the Tracks courses [4] address this challenge within specific topics, whereas the dual degree Architecture and Engineering (AT) program has a focus on the entire built environment [5].

Since the start in 2006, the AT program has established an educational tradition that includes an awareness of the different professional cultures reflected in learning objectives and corresponding evaluation criteria for the two degrees. Besides being a growing ground for 'T-shaped professionals,' this environment offers a platform for educational experiments, also including students with a traditional engineering background.

By letting engineering students explore questions using well-established methods from the architectural design culture, we believe they creatively and systematically can address holistic questions while maintaining a technical depth. This paper presents and discusses an experiment where structural engineering students applied such methods in their Master's thesis project. The outcome was not only an engineering Master's thesis report [6] but also the design and construction of a wooden pavilion with intricate geometry and complex structural behaviour (fig. 1). While the project meets all engineering degree criteria, it also tangents some of the architectural degree criteria.

Figure 1: A seminar taking place in the Wood Fusion Pavilion during the Trä & Teknik fair 2018.

The making of a high-quality built environment

The built environment is complex and forms an undivided whole, larger than the constructions that constitute it. In a lack of a better wording in English, the Davos Declaration 2018 discusses this undivided whole as *baukultur* [7]. Baukultur is the result of existing and contemporary construction as well as the processes involved in its creation. Existing construction, including cultural heritage assets, provides an important baukultur reference for the future design of our built environment. All activities with an impact on the built environment, from detailed craftsmanship to the planning and execution of infrastructure projects that have an impact on the landscape, are expressions of baukultur.

The Davos Declaration furthermore introduced 'high-quality baukultur' as an expression for the idea of an improved, high-quality built environment [7]. The idea relies on the 'application of conscious, well-debated, high-quality design to all building and landscaping activities, ensuring that cultural values are placed centre-stage and human social and cultural needs are satisfied.'

The role of architects and engineers

Although several professionals are involved in the making of baukultur, architects and engineers have through their involvement in the design process a special influence on it. The design process is usually lead by an architect who organises matter into spaces whilst balancing essential components of architectural qualities, by Vitruvius summarised as *utilitas* (functionality), *firmitas* (strength), and *venustas* (beauty) [8, book I, ch. III]. Engineers support with their specialist knowledge by designing objects and systems that fulfil objectives and requirements while considering the limitations imposed by, for example, practicality, regulation, safety, and cost.

Peters [9] argues that architects use synthetic and qualitative approaches to explore options and assemble details into a holistic whole, whereas engineers mainly use logic and quantitative methods to address specific aspects of the project. Furthermore, engineers use, in general, the notion of mathematics to develop their design, whereas architects employ visual language and graphic notation. In line with the 'T-shaped' metaphor [1], Peters further sorts their methodologies, noting that architects use a non-categorical lateral system allowing for infinite possibilities based on empiricism and associations while, in contrast, engineers use a vertically stacked analytical or hierarchical system allowing for the systematic derivation of an answer based on logic.

As a result, architects and engineers tend to have different perceptions of the same reality making successful collaboration a challenge [10]. In addition,

> 'structural engineers are critical of architects' lack of structural understanding, their seeking structural advice too late for optimal structural solutions, and request that architects in general improve their standards of collaboration. Architects are disappointed by engineers' lack of innovation and poor engagement with architectural design ideas.' [10]

This challenge is sometimes referred to as a 'gap' that needs to be bridged [11], with conceptual design as one of the most important and powerful activity to do so [12].

The role of education

From an educational perspective, the reasons for this challenge may be understood by studying the learning objectives for architects and engineers respectively. On the one hand, the objectives reflect a societal need, and, on the other hand, they are part of a self-enforcing prophecy. This has led to the conclusion that the coverage and delivery of structural education at schools of architecture deserves attention [10]. Similarly, architecture should be addressed in the training of engineers [13].

Another way to understand the challenge is to study the examination criteria for the degree project: a scientific report for engineers and a well-debated design proposal for architects. Though the exact formalities vary from institution to institution, an attempt to summarise these criteria is made in table 1.

Most higher educations within the built environment teach in either of the two traditions. Nevertheless, there are exceptions, with entire educational programs [14]–[16] devoted to the development of the student' attitudes, knowledge, and skills based on the core of the two professional cultures of architects and engineers. At Chalmers, this is done through the dual-degree Architecture and Engineering program [5] and manifested in learning activities where form and technology are inseparable such as the bachelor project [17], workshops [18], [19], and Master's thesis projects [20]–[22].

The pavilion

In 2016, students in architecture designed and exhibited a small wooden pavilion at the Trä & Teknik fair [23]. Based on the 2016 success, a new collaboration with the fair was initiated, who suggested a much larger project: a spectacular wooden seminar pavilion. Discussions started in summer 2017, and by the end of the year, ownership of the project

Table 1: Core elements of examination criteria for degree projects.

Master of Science in Engineering	Master of Architecture
1 Subject	
Depart from a subject and perform deepened studies within the subject.	Identify/formulate a societal relevant and complex challenge/question.
2 Context	
Scientifically correct relate to the subject's research and development work.	Contextualise the question and thereby shed light on its various aspects/layers.
3 Limitations	
Depart from clear/limited questions/objectives.	Be able to identify specific values ('concepts') which can be created through the architect's knowledge and processing, and guide the design choices.
4 Execution	
Choose and motivate method(s) and within the main subject of the education create, analyse, and critically evaluate different solutions.	Perform an iterative and explorative architectural design process which, based on informed design choices, results in a design proposal.
5 Communication	
In written and oral clearly account for and discuss the conclusions, and the knowledge and arguments from which the conclusions are drawn.	In written, oral, and graphics communicate points 1-3 and motivate and argue for the design proposal.
6 Reflection	
Critically reflect upon the work and the result.	

had gradually been transferred to two students studying the structural engineering track within the Structural Engineering and Building Technology Master's program.

The complete design process is illustrated in fig. 2. Stages A-C were executed by the students in spring 2018 (points 1-4 in table 1) who then described the work in a report [6] which they successfully defended (5-6 in table 1). Stage D was performed after their successful thesis defence and the pavilion was exhibited at the fair in August 2018.

Stage A: Conceptual design

Conceptual design is important to develop integrated qualitative architecture and sound engineering solutions [12], [24]. This is, for example, evident in the way structural engineer Jörg Schlaich works [25, p. 284]. Following the methods used in the *Matter Space Structure* architecture studio at Chalmers [26], the conceptual design stage was divided into three phases: *intuitive*, *intentional*, and *evaluation* (fig. 2). The phase transitions were supported by a *crit* [27] and by qualitative evaluation matrices. At the crits, experts and stakeholders participated and helped to point out qualities and weaknesses of the proposed concepts.

In the intuitive phase, ideas for spatial and structural ideas were generated resulting in ten improvised concepts. Simple physical models of the concepts were made, and structural and spatial qualities were discussed and evaluated qualitatively.

During the intentional phase, the number of concepts was reduced to three. Digital and physical models were developed to investigate spatial and structural aspects of each concept as well as construction-related issues.

In the evaluation phase, a final concept was developed based on the spatial qualities of possible concept 1 and the structural idea of possible concept 2. The final concept consisted of actively bent plywood laths tracing curves on several sweeping surfaces that together defined the seminar space. Thin shell structures are susceptible to bending, so to increase its resistance against bending, post-tensioned cables were to be attached along the laths.

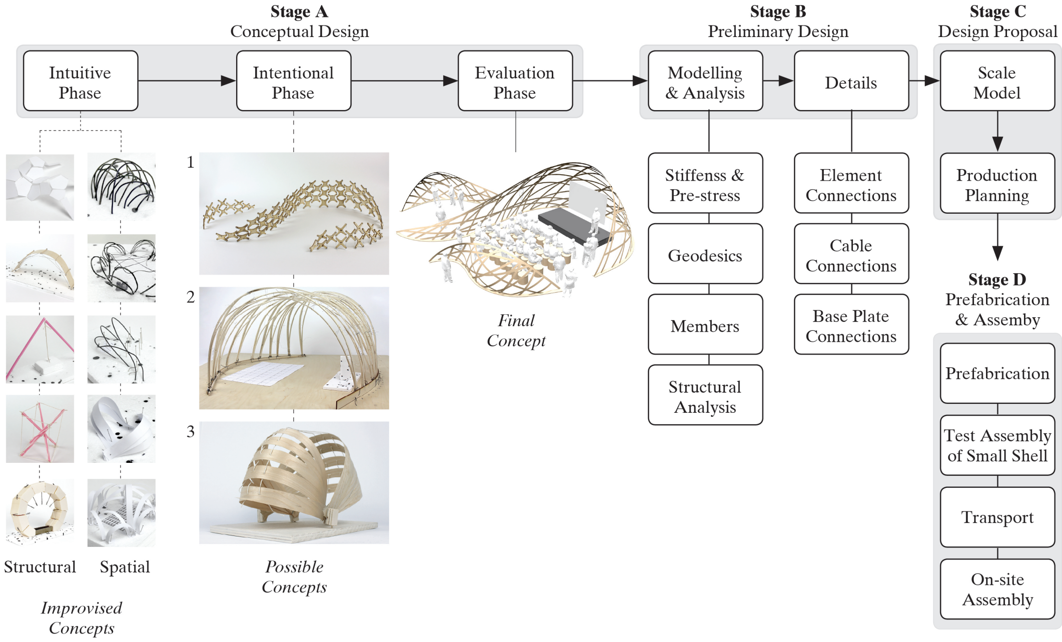


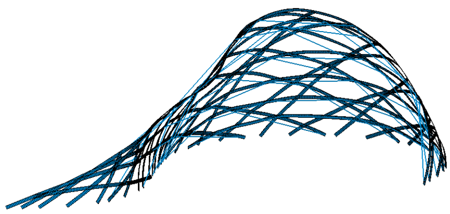
Figure 2: Design process.

Stage B: Preliminary design

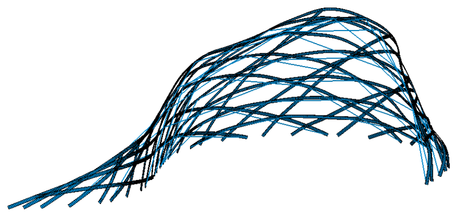
The final concept was developed into a design proposal. Several activities were setup to provide knowledge to iteratively make necessary design choices. Geodesics [28] were explored and decided upon to find curves on target surfaces which could be materialised by bending straight flat laths of plywood. The stiffness and prestress needed to get acceptable deformations of the shell were investigated qualitatively by building several cable-stiffened models and quantitatively by computing the eigen modes and the canonical stiffness [29], [30] of different setups, first in two dimensions and then in three (fig. 3). Choice of material, member sizing, and development of connection details were done using physical testing and code checks [31] bearing in mind that the laths should have sufficient strength while be flexible enough to be bent into shape by hand. The results were used to refine the stiffness of the element connections in the full three-dimensional finite element model, which in turn was used for final verification and code checks.

Stage C: Design proposal

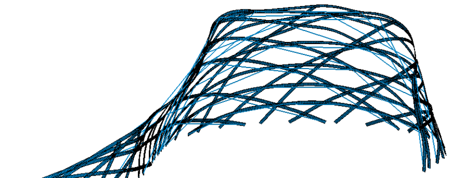
The design proposal was tried out by building a physical model (fig. 4) where both geometry and stiffness was scaled to be able to explore the true behaviour of the shell. The exercises provided valuable knowledge regarding the assembly process and the model later worked as a ‘drawing’ during the full-scale assembly at the fair (Stage D).



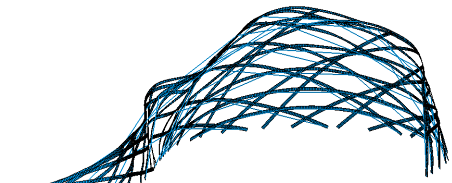
(a) Deformation pattern 1: $\lambda^0 = 1.22$ vs. $\lambda^P = 2.04$.



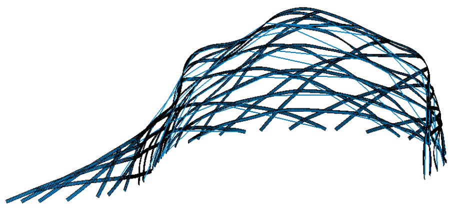
(b) Deformation pattern 2: $\lambda^0 = 1.29$ vs. $\lambda^P = 2.50$.



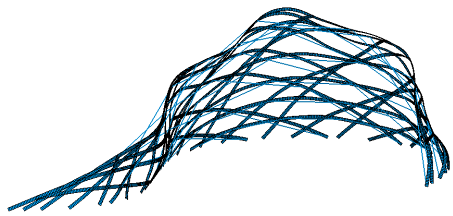
(c) Deformation pattern 3: $\lambda^0 = 1.45$ vs. $\lambda^P = 2.69$.



(d) Deformation pattern 4: $\lambda^0 = 1.57$ vs. $\lambda^P = 2.78$.



(e) Deformation pattern 5: $\lambda^0 = 1.72$ vs. $\lambda^P = 2.91$.



(f) Deformation pattern 6: $\lambda^0 = 1.74$ vs. $\lambda^P = 2.98$.

Figure 3: The first six deformation patterns $\mathbf{x}$ of the pavilion with post-tensioned cables. The canonical stiffness is given without prestress (λ^0) vs. with prestress (λ^P).

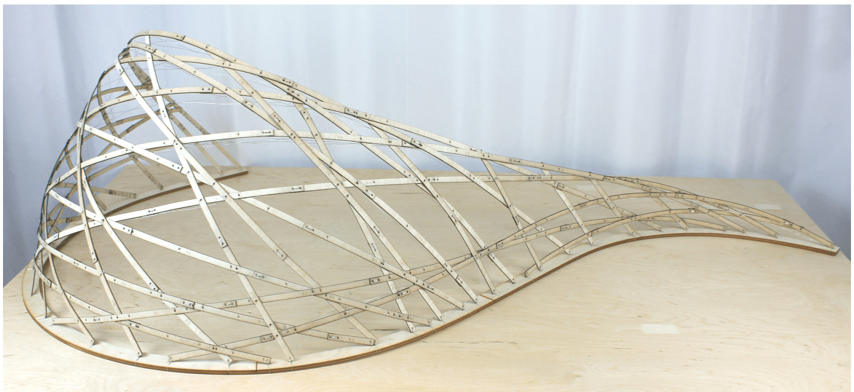


Figure 4: 1:10 scale model of the main shell of the pavilion where both size and stiffness properties were scaled.

Discussion and conclusion

How can universities contribute to the education of engineers possessing both a discipline-specific technical depth and a holistic breadth? By letting engineering students address their tasks using architectural design methods, we hypothesised that they creatively and systematically could address holistic questions while maintaining a technical depth. This was explored by letting two structural engineering thesis students take on a broad design task requiring specialist technical knowledge and skills.

The students' Master's thesis was assessed and approved according to the learning objectives and evaluation criteria for students within the engineering programs at Chalmers [32], [33]. The core elements of the two educational traditions of engineering and architecture are shown in table 1 and an evaluation of the project according to these are shown in table 2.

With the departure in the engineering tradition and with the scientific report as format, we have shown that students in structural engineering were capable of solving broader questions than the usual engineering scope demands by processing the questions arising during the journey through the use of methods from the architectural design tradition. Nevertheless, the students were able to fulfil the examination criterion for the Degree of Master of Science in Engineering. Meanwhile, the students gained valuable experiences of conceptual design and dealt with open-ended problems, skills they most likely will need throughout their entire professional career, regardless of where it might take them.

In conclusion, there is no contradiction between the two sets of criteria. On the contrary, they may indeed strengthen one another and thereby equip the students with tools and attitudes to better contribute to solutions for complex societal problems. The project may serve as a model for how technical universities may develop their curricula targeted to develop 'T-shaped engineers.'

Table 2: The pavilion thesis project in relation to the core elements of examination criteria for degree projects listed in table 1.

Master of Science in Engineering	Master of Architecture
1 Subject	
A deepened study of prestressed wooden shell structures.	Design of an attractor that creates a welcoming and exciting seminar space and enhances the wood and technology theme of a national fair.
2 Context	
Find relevant theories and methods for design, analysis and testing, as well as methods for construction and assembly.	Find references of existing shells, pavilions, and seminar spaces.
3 Limitations	
Successively refine the limitations to increase the precision of the investigations undertaken.	Exploration concepts that balances openness (by-passers can see, listen, and join seminars with ease) and enclosure (well-defined space for undisturbed speaker-audience interaction).
4 Execution	
Iteratively refined design informed by analysis (Stage B-C in fig. 2 including static eigen modes FEM, physical models and testing, member sizing, connection details, code checks). Refinements done using qualitative and quantitative evaluation matrices (c.f. syllabus for BOM170 Structural design [34]).	Iteratively explore and develop design concepts balancing structural and spatial aspects (Stage A in fig. 2 using physical and digital models for analysis including geometry and structural behaviour).
5 Communication	
A written report [6] describing the design process in detail, divided into succeeding stages including successive refinements of subject, context, limitations, and execution.	Communicate a design proposal for a pavilion which was well-debated and argued in a written report [6] .
6 Reflection	
Successively done via the intermediate crits [27]. Documented throughout the report as each choice of method or design choice were made.	

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