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Experiments in learning design: Creating space for creativity and continuity in design education

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Background

Structural engineers usually start by learning static equilibrium, followed by trusses and beam theory, which lead on to indeterminate beams and frames. There is a natural progression of subjects; singly-reinforced concrete sections need to be studied before moving on to doubly-reinforced sections, shear, columns and slabs.

Defining how we learn design is more difficult, especially "design" in its broadest sense of the engineer as a problem solver who conjures up innovative solutions to problems that have not been tackled before. This involves developing a personal "toolkit" of skills through learning and experience, and working with other people who bring their own skills, experiences and opinions to the design task.

University degree programmes traditionally have courses such as "design of steel and concrete structures" that teach code and computer methods for design, but these traditional courses focus on "detailed design" calculations that are only one part of the engineer's design toolkit. The modern profession needs structural engineers who can tackle complex design, involving iteration and inspiration, conflict and compromise. Tim Ibell's article, "Virtual by design", earlier this year[1] set out the need for our education system to embrace creative design, because detailed design is becoming increasingly automated as we move through the digital revolution.

There is no obvious step-by-step method to becoming a good designer, but at the University of Edinburgh we have evolved a continuous and progressive "thread" of design skills from the first to the last year of our degrees. This has:

- creativity, compromise, complexity, confidence and confusion embedded into our design problems
- space for students to experiment, make mistakes, learn from the experience, and then to try again
- guided self-learning that builds confidence in sensibly applying new skills to solve engineering problems and so helps prepare students for a changing professional world

1st year

Civil Engineering 1
- Bridge inspection + Road design (4×2h)
- Hydropower design (6×2h)

2nd year

Tools for Engineering Design 2
- Games (Pictionary, ready-steady-design, Countdown) (1×3h)
- 15 minute design problems (1×3h)
- Upgrade of a water supply network (2×3h)
- Education masterplans in Africa (2×3h)
- Design-communciate-build-test-learn (3×3h)
- Calculation, drawing, reflection tasks (3×3h)
- Self-study tasks (AutoCAD, drawings, Excel)

Detailed Design 2 (steel and concrete sectional design, with detailed design tasks).

3rd year

Conceptual Design for Civil Engs 3
- TRADA timber design: intial concepts (1×3h)
- Restaurant cantilevered off cliff face (1×3h)
- Cable car over a dockyard (2×3h)
- TRADA timber design, themed sessions on materials, construction, connection detail concepts (5×3h)

Strutural Form, Function and Design Philosophy 3 (exploration of structural forms, materials, loads, load paths, design theorems)

Engineering Sustainability 3

Detailed Design 3 (code design of steel and concrete structures, including detailed design tasks).

Civil Engineering Construction 3

4th and 5th years

Interdisciplinary design project 4 (10×3h)
Passive house / Potable water / Hydropower (with chemical, mechanical, electrical engs.)

Civil Eng Design Project 4 (2 wks full time)
Geotechnical and transportation design.

Bridge Design Project 5 (2 wks full time)

Figure 1 Design thread at University of Edinburgh: continuity and progression through degree programme

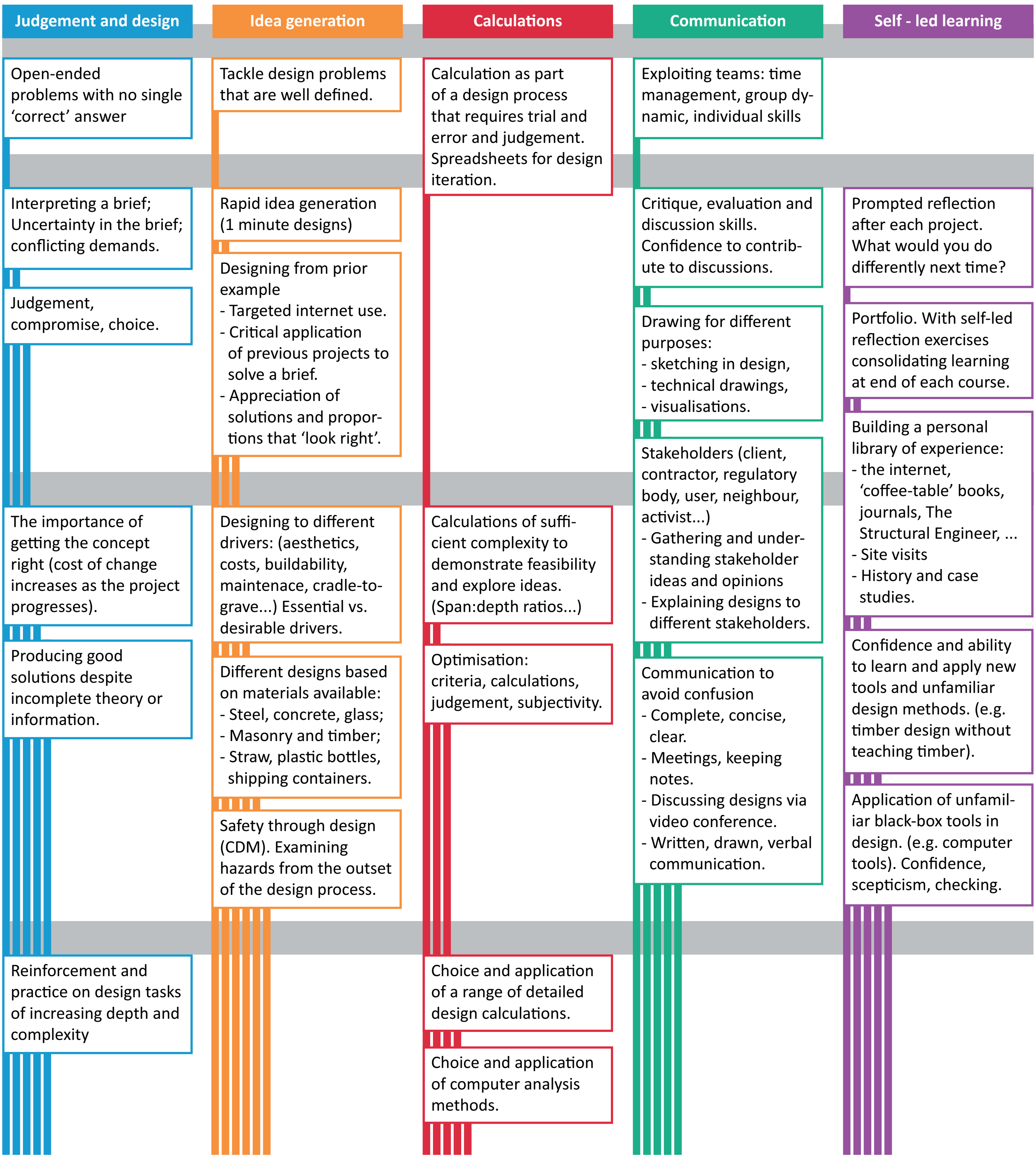


Figure 2 Examples of long and short design-and-build projects

a) Long project: trebuchet design, build and test

b) Short project: design, build and test, communicate, reflect and learn (second year)

Like any good designer, we have been experimenting with our students' design learning for several years, and not all of our ideas have worked first time. The aim of this paper is to share our experience with the other universities around the world which are also experimenting with their design teaching, and to help other universities which are perhaps just starting to realise the need for change in our education.

Need for change

Why did we change our courses?

In 2007, students at the University of Edinburgh tackled several substantial design projects. Our design projects had been tried and tested over many years. We have a five-year MEng programme in which our students designed roads and dams in the first year; steel and concrete buildings in the third year; foundations, transport and water supply in the fourth year; and bridges in the fifth year. Each of these was a substantial project that took place over several weeks, in which students identified a few design options, chose one to develop in more detail, and spent the bulk of their time doing detailed design calculations. The students were asked to incorporate issues such as sustainability, safe construction, maintenance, operation, and end-of-life decommissioning into their project reports.

We had fantastic support from a range of industrial experts; swapping to the Eurocodes had prompted us to modernise our course material; and our students were regularly winning prizes at the Steel Construction Institute's national student bridge design competition. Our design teaching appeared to be in good shape.

Three things prompted us to examine whether this was really the case:

1. In 2008, our third-year design project incorporated both steel and concrete building design. It was a group design project, and we realised that we had been encouraging half of our students to work on steel and half to work on concrete buildings. Something was clearly not right with our design teaching, although at this point we did not understand what we wanted to change.

2. Chris Wise's paper in the Centenary Issue of *The Structural Engineer*[2] explored the changing role of the 21st-century engineer, the implications of computer automation of detailed design, and the importance of conception and judgment for our graduates.

3. Despite several years experimenting with our third-year concrete and steel building project, we struggled to give our students real appreciation of the complexity of the design. Students rushed through the initial design concept selection, so that they could work on their detailed design calculations. It was not until our 2011 Joint Board of Moderators (JBM) accreditation visit that we realised that a change in approach was needed.

Stage 1: Creating space for creative design

Chris Wise[2] set out the need for structural engineers (and their education) to adapt in a digital world in which they spend far less time on detailed calculations, but in which the ability to conceive and judge design ideas is far more important.

"We do not need more engineers. We need better engineers. We need quality, not quantity. We need more thinkers, more engineering designers, more people with judgment who can conjure up something magical out of a complex world and get it out there."

Chris Wise[2]

Other studies have followed that address education for the changing engineering profession, such as the ASCE Structural Engineering Institute's *Case for change*[3], Andrew Phillips' examination of engineering leadership development[4], the Royal Academy of Engineering's report *Thinking like an engineer*[5], and Tim Ibell's message as Institution President about the vital importance of creativity in our design teaching[1]. All of these studies have reinforced the need to change our design education to prepare structural engineering for the future.

The first stage in changes to our design curriculum was to create the space to foster creative conceptual design. By 2012, we split our third-year design course into two deliberately distinct parts: Detailed Design (concrete and steel code methods assessed by exam) and Conceptual Design (group design coursework). At the same time we created a new second-year course called Tools for Engineering Design, to give students the space to develop a creative toolkit of skills. These two courses in the second and

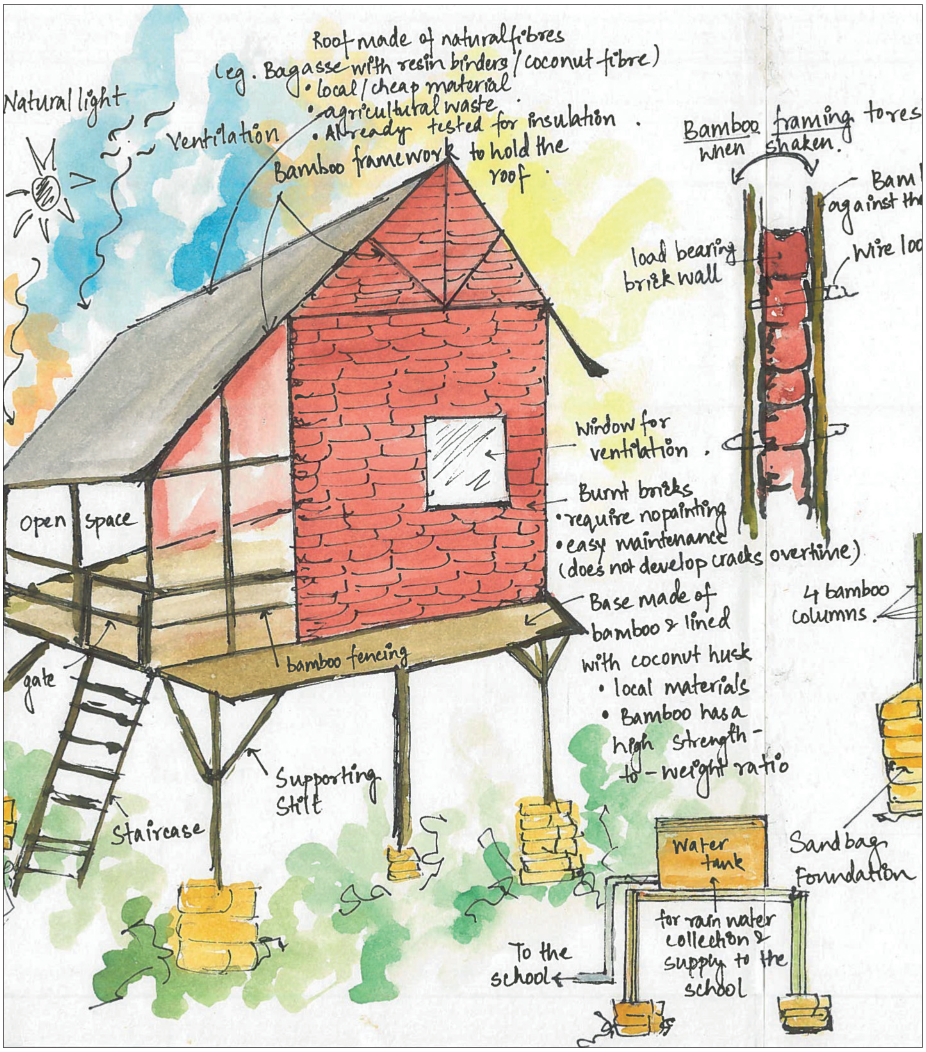
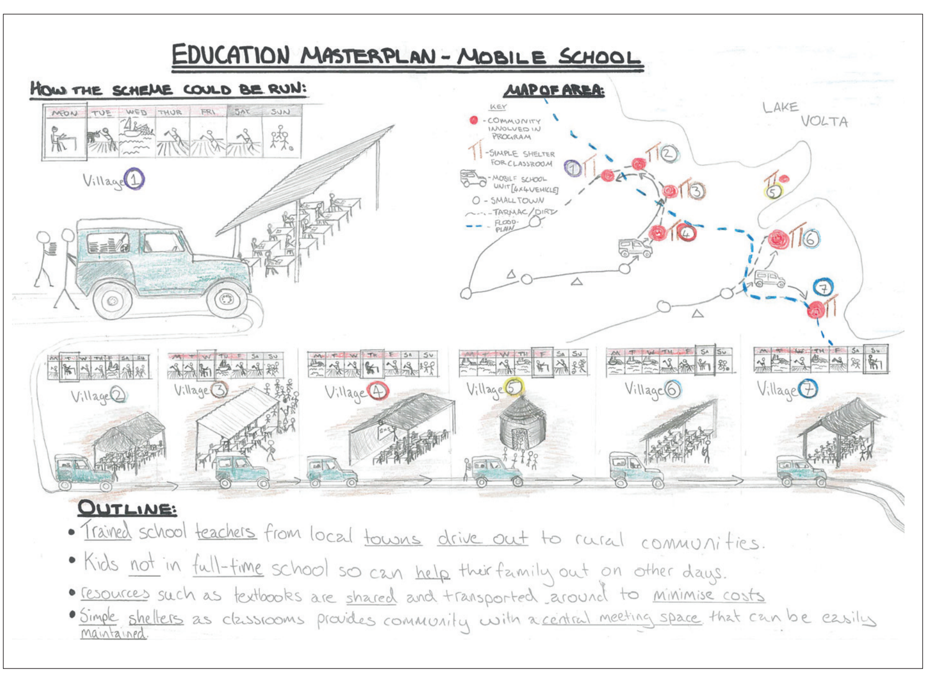


Figure 3
Extracts from two submissions for our Education Masterplan project (second year)



third years allow students to develop design tools (communication, sketching, calculation) and skills (creating concepts, coping with uncertainty, confusion and conflict, tackling problems outside their comfort zone and training). The philosophy behind these courses is described by Gillie *et al.*[6].

Stage 2: Progressive development of design skills

Creative conceptual design skills cannot simply be learnt in a single course; they need to be introduced gradually and reinforced and practised. In 2014, all of our design courses were still running independently. A fourth-year structural engineering course would not have "static equilibrium" as one of its learning outcomes, and yet our fourth-year design project listed learning outcomes of "team working skills", "encourage questioning and creative thinking", and "project planning issues". These did not match the rich complexity of design skills that students should have developed by the fourth year. The logical next step was to join our design courses up to ensure design skills were introduced consistently and progressively, reinforced from course to course, and increased in complexity from year to year. Figure 1 is an overview of the design thread that we have developed by 2016.

Design thread

The complexity and diversity of design and the need for a "design thread" is set out by the JBM Annex B[7], but this document only emphasises that there is not an obvious sequential way to learn how to be a good designer. The thread that we have developed at the University of Edinburgh deliberately develops students' manner of thinking[5], and provides the context and inspiration for all of our other teaching[1]. It addresses all parts of civil engineering design, but with a particularly strong structural engineering component to it. The version of the thread shown in Fig. 1 is idealised, and in reality it is more blurred with overlap courses and deliberate repetition to remind, practise and reinforce.

The thread develops five broad skills: judgement and design, idea generation, calculations, communication, and self-led learning, with the complexity and richness of each skill augmented and reinforced progressively through the degree programme (indicated by the vertical lines in Fig. 1). Our core design subjects are highlighted in boxes on the left side of the figure, which shows details of the design tasks within them and the time spent on each design task. For example, Conceptual Design for Civil Engineers 3 takes place one afternoon (three hours) per week, and among the design tasks is a cable car design project that takes two weeks. Other courses listed in Fig. 1 (such as Engineering Sustainability 3) are woven into our design thread, even though they are not central to it.

The majority of our design skills are introduced within Years 1–3 of the programme, but note that we deliberately use only the simplest possible calculation methods (span-to-depth ratios, load paths, basic equilibrium etc.) up to the end of Year 3. There is plenty of complexity to be explored in choosing and optimising design solutions without opening a design code or using a computer analysis package. Detailed design calculations and computer methods are merged into the design thread in our fourth- and fifth-year projects.

Short or long projects?

We use a series of short design tasks in Years 2 and 3, which are usually only one afternoon, or two afternoons in consecutive weeks[6]. These short projects allow students to keep sight of the conceptual design process, to make mistakes and learn from them, to practise creativity, choice, compromise, and coping with confusion. Students work in groups of four, and we move them from group to group for each project, so that they do not work with the same person twice.

Longer projects take substantially greater effort on behalf of both the student and the academic, but with comparatively little learning. We used long projects in our early attempts to foster creative design, but students spent too long on the project to learn from the fact that they made the wrong concept choice at the beginning. For example, we previously ran week-long full-time projects in which students designed, built and tested large model trebuchets or bridges[8,9]. While great fun for all involved, the amount of time spent building and testing these structures (Figure 2a) meant that students struggled to relate the structural failures back to their original design decisions, and the learning opportunities were lost. By contrast, we now run a much simpler design-and-build exercise as part of Tools for Engineering Design (Fig. 2b), which is an exercise in communication, where the contractors are a different team to the designers. Most importantly, it is a rapid exercise in which the designers get to learn from their mistakes and have a second go to improve upon their original design.

By Years 4 and 5, students have developed sufficient appreciation of the design process to tackle extended projects, but even then this requires careful guidance to ensure they do not lose sight of the important design decisions and learning points. The class dynamic can lead to each

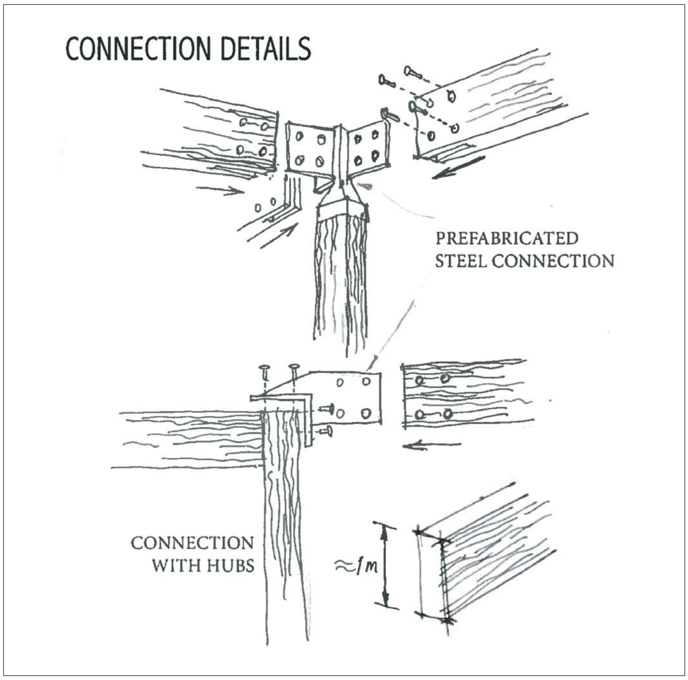


Figure 4 Extracts from two submissions for timber design project (third year)

group trying to outdo their classmates, and the long project format can result in groups functioning as four individuals, who only compare notes and allocate tasks once a week and who work individually between the project sessions.

Guided, self-led and black-box learning
Setting a series of short design projects creates space for our students to learn about design; *what* the design brief asks for is not important as long as the task gives space for students to explore *how* to tackle design problems. We use a "guided learning" approach; our design problems are given to the class with little guidance on how to approach them. We do not teach our students how to tackle the problem, but neither do we leave them to their own devices. We circulate around the groups to understand how they are progressing, and periodically hold a whole-class discussion, sometimes asking them some targeted questions that steer them to think about things they have missed, sometimes pointing them towards some internet resources, or sometimes getting them to review other groups' progress part way through the exercise.

Figure 3, for example, shows two solutions from our Education Masterplans project about developing an education strategy for a rural part of Ghana that is prone to flooding. The brief for this project is deliberately vague and ill-defined because the client is a non-expert who is not sure what they want. The class start by thinking in terms of physical buildings and classroom floorplans, but we gradually lead them through the idea of a broad masterplan, funding sources that might be available to the client, the timescale for works, the implications for the local community (impact on way of life, social inclusion etc.) and the effects of regular flooding. They generate a wide range of options, some of which require physical buildings, but many of which do not.

Alongside the guided learning, we set self-led learning tasks. For example, we no longer have a formal course teaching computer-aided design (CAD); instead, we point the students towards AutoDesk's AutoCAD tutorials, warning them that they will need to use CAD to produce two-dimensional engineering line drawings. We similarly use the Expedition Workshed[10] sketching and drawing resources to develop hand drawing skills. The ability to learn new tools is a key design skill, due to the rapid pace of change within the profession. Consequently, we want our students to struggle to learn new tools and then use them to solve problems without being told how to do this. We use the TRADA national student timber design competition[11] in our third-year course (Figure 4), but we do not have a taught course on timber design. We use targeted discussions to guide the class to learn about timber as a structural material, connection details, construction methods etc., but deliberately do no traditional teaching on timber structures.

This approach makes many academics and engineers very uncomfortable. We traditionally say that "we must teach students about shape functions before we let them use a finite-element package". If we are going to exploit the digital revolution

"This approach makes many academics and engineers very uncomfortable"

and apply the latest computer technology, we need to move away from this way of thinking and become comfortable using black-box tools that we do not necessarily understand. Our aim in our design thread is to help students apply black-box design tools in a self-critical way and to develop the awareness and intuition to know when they do something that is not sensible.

Developing conception and judgement
Designers need to be able to think up a wide range of solutions to problems, spanning from conventional sure-to-work solutions, to slightly out-of-the-box, to completely wacky but worth-having-a-go. A key part of our design thread is to break students out of the mould of single correct solutions, which is encouraged by our theory courses.

The successful approach that we now use is to prompt students using a range of design "drivers". For example, when setting a bridge design, we start by asking them what bridge design is best if the client wants a landmark structure. Then, what would be best for an economic structure, or if the river is prone to scour, or if construction safety is the biggest driver etc.? We give the class a new driver every 15 minutes, and work through perhaps six drivers, then ask them to develop an "optimal" solution at the end of the session.

This approach leads into explorations of judgement, using judgment aides (such as multi-constraint analysis/weighting tables), by asking groups to rank each other's designs (tackling subjectivity in assessment), and the fact that the "correct" choice depends upon the project drivers, whether those are explicitly staged in the brief or not. We use the design driver idea several times through the thread, but dressed in different ways, such as generating designs using different materials, or asking students to role-play different stakeholders (client, user, activist etc.) whose opinions generate "drivers" for a range of design concepts.

Exploring judgment with our students links directly into how we assess their work. Whereas in 2007 we had a very formulaic mark scheme where we awarded marks for ability to design a steel beam, a steel column, a concrete beam, a concrete column etc. (all based on calculations), we now tie our assessment to a multi-constraint analysis that might be used to assess design solutions. We assess each project on a small number of categories, such as "range of concepts" or "communication of design". We send our students out to look at university buildings (and rail stations, airports etc. that they know) and ask them to tell us where they lie on a scale of "fail"–"pass"–"good"–"excellent". This links directly into the way we assess their work.

Judging success of thread

Student design ability
There has been a notable change in the ability of our students to tackle open-ended and complex design at the conceptual stage. Our students are exposed to a far wider range of design challenges that develop a wide palette of skills. They are producing design work that demonstrates ability in conceptual and creative design; Fig. 4, for example, shows work from the third-year timber design project, and Figure 5 is part of a submission for our fifth-year bridge design project.

Making a fair comparison between our 2007 graduates and our 2016 graduates is not straightforward because of the number of things that have changed during this period; however, we now ask students to produce a single-page reflection upon what they have learnt. Figure 6 shows two example extracts from these reflection exercises. Fig. 6a is a reflection on the general design process from a second-year student, while Fig. 6b is a more targeted reflection upon a specific bridge design brief made in Year 5. The majority of students demonstrate depth of understanding of the conceptual design stage through these reflection exercises.

We still have some students who quickly jump into detailed design calculations with a fundamentally flawed design concept. They thrive on equations and analysis, and in the terms of Wise[2] they are destined to become specialist specialists, not specialist

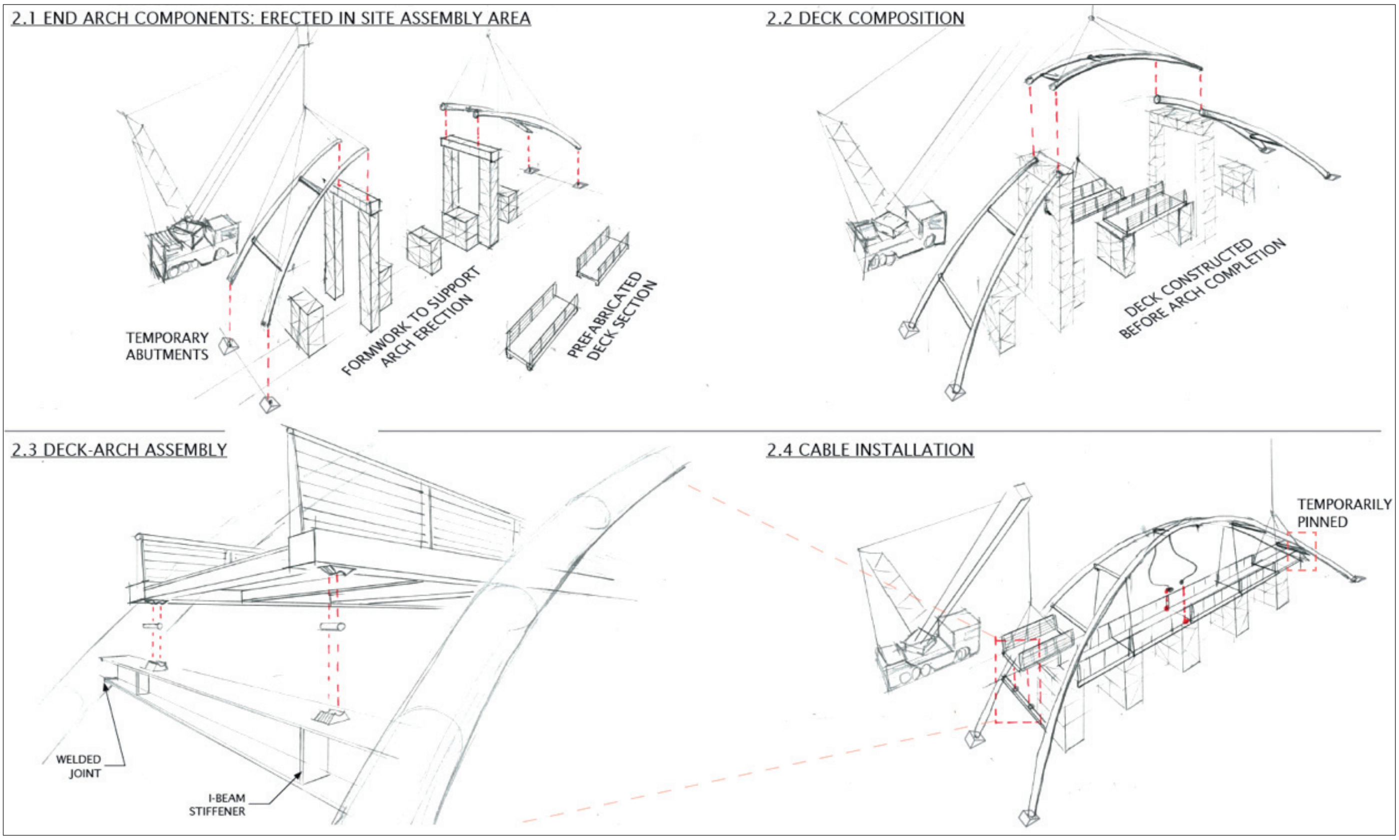


Figure 5
Extract from bridge design project submission (fifth year)

generalists. They will certainly become good technical engineers, but will likely lack the flexibility to adapt to the future needs of the profession.

What do students think?

Students appreciate the chance to tackle design problems, and welcome the break from theory courses. The second-year design course, however, is not always well received and there are several challenges that require very careful handling to help students get the most out of it. We do not always get these right.

- Tools for Engineering Design is very different to any other course they have met in Year 2. The open-ended problems and the assessment method both mean there is no step-by-step method that they can use to get good marks. We struggle with dissatisfaction at the end of the course when the marks are released. The careful explanations about what a "pass" and "excellent" mark mean in a design context are forgotten, and everyone thinks they deserve a higher mark.

- Students paying tuition fees have been forthright, telling us that they expect to be taught, not guided to learn from the internet (e.g. for AutoCAD tutorials). The manner in which we use guided learning (e.g. guiding the class to search for examples of African education projects) is quite subtle and not the direct teaching style that second-year students expect.

- One problem we did not anticipate stems from the fact that the traditional mode of design teaching is still the norm elsewhere. Our students talk to friends at other universities where "design" teaching remains focused on detailed design codes. They come back from industrial placements reporting that their hosts were surprised that we are not teaching them CAD, or that when they were at university they would have been taught steel design to the code by now.

To address these points, we have learnt the hard way how vital it is to explain the course, its aims, its philosophy, and why it is very different to other courses. Frequent reminders are needed of this message, and next year we will spend even more time explaining the wider changes in the profession[2,3]. Change is inevitably difficult to make and a large amount of self-belief is required to see it through, but it is also important to recognise that the student dissatisfaction tells us that we need to improve the way we communicate the aims of the course.

Barriers or excuses?

Established practice in a university can appear to have a huge inertia that makes it difficult to change any course. The University of Edinburgh is no different to anywhere else, and it took several years for us to adapt our design courses. In making these changes, we have learnt that each of the supposed "barriers" to change can be easily overcome if there is the will to change.

Sacred courses: "There isn't enough space in the curriculum"

We spent several years telling our students that there was no design in their second year because there was a lot of theory that they needed to learn before they could apply it to design things. This is clearly not defensible: creative design is absolutely essential within our degree programmes[1]

To find space in a degree programme, we examined supposedly "sacred" courses and asked whether they were really needed. To create our second-year design course, we removed our "computer tools" course that taught CAD and computer programming. To create our third-year design course, we reduced the amount of steel and concrete design that we teach. This steel and concrete design would almost certainly be "sacred" subject material to many of us, but we are convinced that the creative design exposure is more important.

Administrative challenges: "Open-ended design doesn't fit our course structure"
Open-ended, ill-defined design challenges do not easily fit into the university's neat view of courses that cover particular learning outcomes and assessment criteria, and we struggled with university procedure and the need to explain what we were trying to do in each individual course. The structure provided by Fig. 1 has allowed us to have far easier conversations with other colleagues, and also allows us to have meaningful conversations with our students beyond their individual course.

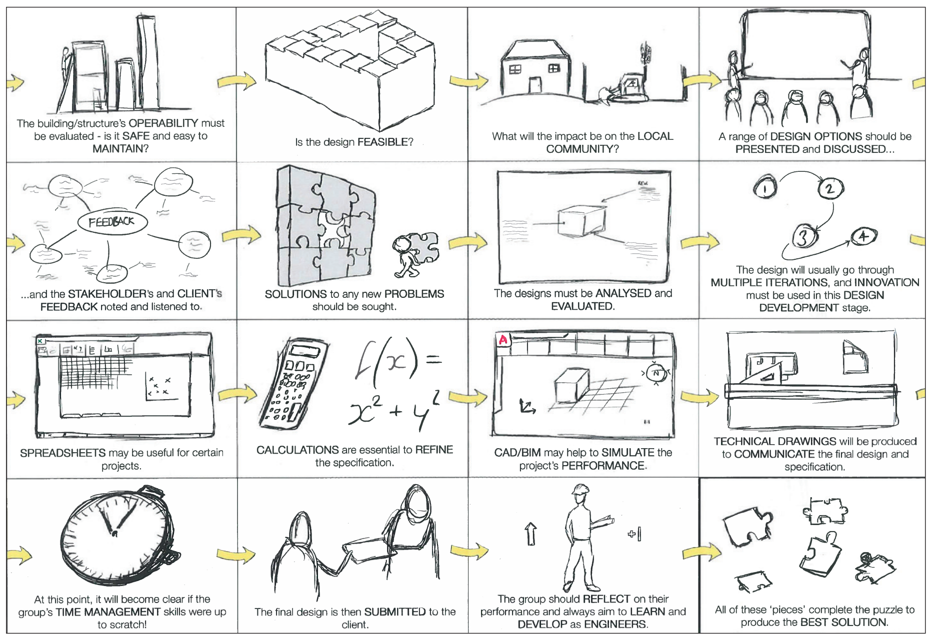
A second challenge is the time needed to teach design project courses; however, one of the joys of teaching open-ended design is that with a bit of practice and a few notes on what you want students to get from the session, it is easy to guide a challenging three-hour design session. Providing written feedback on every short project is certainly time consuming, but this can be avoided by more creative approaches to feedback; for example, by giving a verbal critique to each design group, and asking the students to keep meeting notes. The final course assessment at the end of the semester takes no longer than marking an equivalent theory exam.

Ability to teach design: "Academics are not recruited for design experience"
Some variation of "my university recruits researchers who cannot design" is often heard. At the University of Edinburgh we have an excellent mixture of academics from all backgrounds, each with our own strengths and skills. Real-world design experience within the academic team is undoubtedly vital; however, design experience does not necessarily translate into an ability to teach design.

Creative design is about the ability to conjure up solutions to open-ended problems, to cope with complexity and confusion, and to create ideas and judge whether they will work or not. The demands of good research are very similar, and a consequence of shifting the focus of our design education from detailed design to creative design is that researchers are very well placed to engage with and lead our design teaching. Enthusiasm for solving complex problems and time spent fixing things in a shed or testing things in a lab are surely more important than whether someone has applied a design code or not.

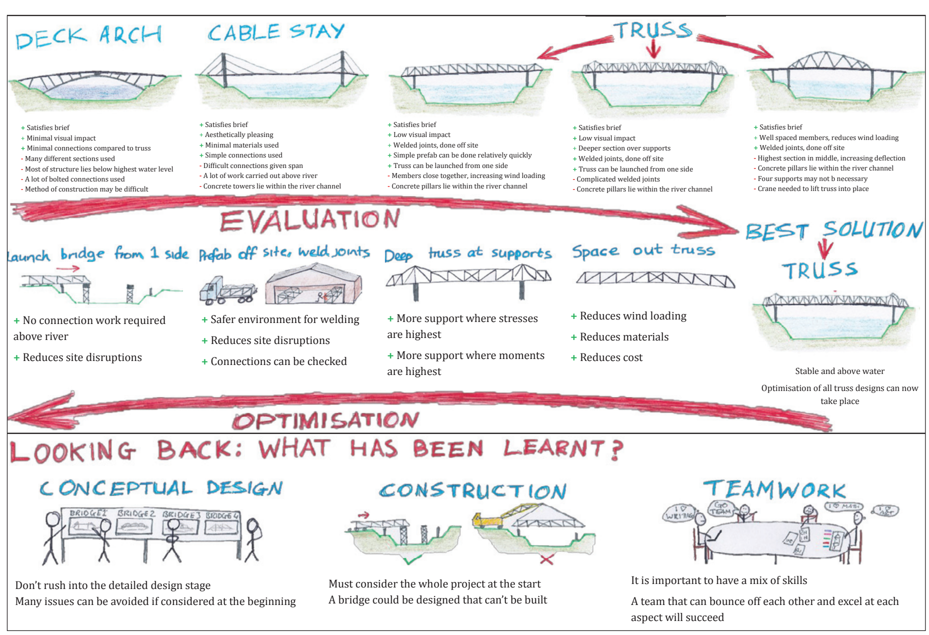
What do we plan to do next?
There is one piece in the jigsaw that we have not directly addressed, and which remains a conundrum. We need to update our education to launch the profession into an age where digital engineering takes over the burden of detailed calculations, enabling engineers to focus on conception and judgment, and engineers will need to shift their skills into creative design[1]. Our design thread thinking, however, does not embrace digital engineering.

We use spreadsheets to aid rapid design exploration, and we give an overview of the capabilities of BIM. We do not, however, set tasks that exploit the power of digital engineering to handle complex information and aid the creative design process. This is deliberate, because when we have experimented with even simple computer analysis within design projects, students have been distracted by the details of the model and have lost site of the wider design choices. The aim of our design thread is to develop the engineering maturity



a) Second year

Figure 6
Two example extracts from end-of-course reflection upon learning



b) Fifth year

(engineering judgement, engineering intuition) necessary for creative design, and digital engineering can be used within the design context once these skills have been learnt.

A future challenge for us is to integrate digital engineering into the fourth or fifth year of our degrees, with a project where software is exploited to assist the creative conceptual design process, rather than software for detailed design analysis (which is already part of our fourth- and fifth-year design projects).

Conclusions

The design thread in Fig. 1 looks very logical. In 2016, it seems obvious that we should nurture our students' design skills by progressively increasing the richness and complexity of design learning from Year 1 to Year 5, in much the same manner as static equilibrium belongs at the start of a degree programme, and shells, prestressed concrete etc. belong at the end. What seems obvious now, however, was far from obvious 10 years ago. It has taken us this time to realise, develop and experiment. Our thread is not a single "correct" way to do things, and other universities may have better ways to do this; however, hopefully by explaining our experience and the thinking behind our design teaching, others will be able to benefit from the changes we have made so far.

Acknowledgements

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