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Authors	Froese, Thomas M.;Bristow, David N.;Rankin, Keagan
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Towards a Sustainability-Centred Design Curriculum in Civil Engineering

Thomas M. Froese[1], David N. Bristow[1] and Keagan Rankin[2]

[1]Department of Civil Engineering, University of Victoria, Victoria, B.C. Canada

froese@uvic.ca

[2]Department of Civil Engineering, University of New Brunswick, Fredericton, New Brunswick, Canada

Abstract

To improve the green engineering and active learning of the civil engineering program at the University of Victoria, Canada, we are developing a design spine: a series of courses running throughout the program with major design activities based on a sustainability-centred design approach. This paper describes our design spine approach and presents a conceptual framework for sustainability-centred design that we are developing. The framework organizes both the subjects of design and of sustainability into four high-level categories: 1) foundations, 2) frameworks, 3) tools and techniques, and 4) application areas. We have piloted the design spine approach in a second year course on sustainability.

1 Introduction

A new civil engineering program was created at the University of Victoria, Canada, in 2012 with the goal of being the greenest civil engineering program in Canada. Since that time, we have established a new department of 16 faculty members and graduated several cohorts of civil engineering students. So, although it is still a relatively recent curriculum, there is already enough evolution of faculty members and experience with delivering the program to warrant a strategic curriculum revision, which we call our "Curriculum 2.0". Two broad strategic objectives are central to these curriculum changes:

1. to excel in green civil engineering and
2. to embody progressive teaching and learning practices such as problem-based learning or other appropriate active learning styles.

The department carried out several strategic planning activities to develop an approach to these objectives, considering alternatives from instructor development only with no changes to the overall program, to wholesale changes that delivered the majority of the program in non-traditional formats. The resulting strategy is between these two extremes. The focus on green civil engineering in anchored by a theme of sustainability-centred design: an approach to engineering design that places sustainability firmly at the centre of the design process. The focus on active learning involves programmatic changes, but it concentrates these changes into a "design spine": a program curriculum that will add a major design project into one existing "anchor" course in each term, with integrative links into several other courses in each term and with a coordinated body of design content and project-based teaching and learning practices that provide the scaffolding to link these anchor courses throughout the program.

Several others have explored a design spine approach (Carrick and Czekanski, 2017; Frank et al., 2013; Gary et al., 2013; Lulay et al., 2015; Sheppard and Gallois, 1999). Our implementing of a design spine strategy involves three main elements:

1. an overall approach and set of learning activities for delivering the design projects in a consistent way throughout the program,
2. a body of content relating to engineering design that can run throughout the program, and
3. a curriculum map that identifies the design anchor course and the supporting courses in each term, suggests how the learning activities will integrate with the existing course content and formats, and lays out how the design content is distributed across these courses.

This paper first describes these elements, and then describes our first pilot implementation of a design spine course. While much work has been done to date, we are still in early development stages and have yet to complete fully-detailed curriculum development or research studies of the results.

2 Features of the Design Spine

In the 4-year civil engineering undergraduate program at the University of Victoria, the first year is common to all engineering students, the 2nd and 3rd years are mainly core courses, and the 4th year includes many technical electives and a final year capstone course. In keeping with the focus on green civil engineering, the program includes green courses that are less traditional in civil engineering programs—such as sustainable development, environmental policy, and building science and energy—as well as more traditional civil engineering courses that have been adjusted to have emphasis on green engineering issues.

Within this overall program, the objectives for the design spine initiative are to include more substantial active learning and problem-based activities, and improve learning of engineering design with an emphasis on sustainability. The approach is to include one major team design project in an "anchor" course in each term. Some of the other courses in each term will play supporting roles to these design activities (for example by using the same scenarios or case studies in their assignments), but these will be fairly "loosely-coupled" relationships so that the courses do not become too highly interdependent. The design projects will aim to have a number of smaller submissions that require team collaboration and discussion, rather than a large submission at the end of term that encourages teams to divide the work and complete it individually. Activities will be developed to promote teamwork, project management, and other targeted graduate attributes. The projects will involve the application of the technical material of the host course, but they will also involve the explicit application of sustainability-centred design, based on a body of content that is introduced in the first year and is expanded and reinforced in each cycle of the design spine course.

The following section introduces our approach to the content while Section 5 provides an illustration of the overall approach by describing a pilot implementation.

3 Sustainability-Centred Design

3.1 Development Approach and putting sustainability at the Centre of the Design Process

In addition to a plan for implementing the design spine as a series of learning activities across a range of courses, we also required a foundational body of knowledge, or course content, to be delivered throughout the design spine courses with some degree of consistency, repetition, and scaffolding from the beginning of the program through to the end. Both design and sustainability are topics that arise frequently through our civil engineering curriculum, yet neither is a major traditional sub-discipline of civil engineering with well-establish curricular content. During the summer of 2019, we conducted an undergraduate research project to collect and organize ideas for this content. This project identified a wide range of topics and organizational approaches relating to engineering design and to sustainability.

For design, one topic of particular interest was design-thinking and the way that this body of thinking suggests both conceptual and specific techniques for putting users at the very core of the design process (as opposed to being just one of a long list of considerations in a "design for-X" approach (Dym, 2005; Roe et al., 1969). We adopted an approach of taking a similar position, except that we wanted to find ways of bringing sustainability to the core of the design process: hence, *sustainability-centred design* rather than user-centred design.

For sustainability, we grouped the wide range of topics into four high-level categories: 1) foundations—knowledge from other disciplines that are important for understanding sustainability issues, 2) frameworks—key conceptual models or perspectives for understanding and addressing sustainability, 3) tools and techniques—specific practices or analysis related to sustainability, and 4) application areas—topics related to sustainability applied to a specific field or discipline.

After many cycles of collecting and organizing both design and sustainability topics, we found that these four high-level categories can apply not only to sustainability knowledge, but to design knowledge as well. This lead to a central model that provides an underlying structure for organizing a very broad range of topics related to both design and sustainability, the *sustainability-centred design model*.

3.2 Sustainability-Centred Design Model

Figure 1 depicts the sustainability-centred design model. The model is used as a high-level structure for organizing the wide range of topics that make up design and sustainability.

1. Foundational Sciences and Systems: The foundational sciences and systems are topic areas that are not themselves design or sustainability, but they provide the critical background understanding necessary for sustainable design, similar to the way that mathematics and physics provide critical foundational sciences for many areas of engineering. For design, the foundations emphasize the engineering science and design required to understand and solve the particular problems at hand. For sustainability, foundation include topics like ecology (as a science based on "holistic" or systems models as opposed to sciences such as physics that tend more towards "reductionist" models). Sustainability foundations also include the key systems related to planetary boundaries (Steffen et al., 2015): climate, water, energy, biodiversity, etc.
2. Frameworks: Ways of thinking about and approaching problems and solutions. For design, key frameworks include design processes and design principles. They address concepts such as convergent and divergent thinking, prototyping and iteration, etc. For sustainability, core frameworks might include approaches such as systems thinking, lifecycle thinking, etc.

3. Tools and Techniques: The "toolbox" of practices that can be used during design and sustainable engineering. Examples relating to design include requirements-capture techniques, rapid prototyping approaches, analysis of cost, risk or other "design for X" considerations. Examples relating to sustainability include life cycle assessment, LEED and other sustainability certification systems, etc.
4. Implementation Areas: The final layer includes topics that are not general to design and sustainability, but are rather unique to specific application areas. For design, these could include disciplinary codes and regulations, or contracting and other project delivery practices. For sustainability, these could include techniques used in high-performance buildings, energy systems modelling, or any other application area.

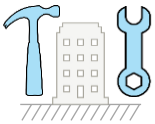
	Design	**Sustainability**
Foundational Sciences and Systems 	Engineering Science and Design.	Ecology, Biology, Chemistry, Key constituent systems of: climate, water, energy, biodiversity; the social dimension.
Frameworks 	*The Design Process and Design Principles:* Convergent/ divergent thinking, iterative loops, etc.	*Ways of Approaching Problems:* Systems engineering, life cycle thinking.
Tools and Techniques 	*Design Activates:* Requirements capture, rapid prototyping, design for X, etc.	*Modeling, Analyzing, Assessing Solutions:* Sustainable Rating Systems/Codes, Cradle to Cradle, LCC/LCA, etc.
Application Areas 	*Application of design to specific disciplines*: Codes and regulations, project delivery practices, etc.	*Sustainability Application Areas:* Green buildings, clean energy, sustainable software, etc.

Figure 1: Sustainability-Centred Design Model.

4 Positioning the Design Spine within the Program Curriculum

The design spine is being implemented in one main host course within each term of the civil engineering program. The tentative plan for these host courses is as follows:

- Terms 1A and 1B: First year engineering design courses
- Term 2A: Engineering graphics course
- Term 2B: Sustainability in civil engineering course
- Term 3A: Environmental engineering course
- Term 3B: Steel and timber design course
- Term 4A and 4B: Capstone design course

While each term will refer to the overall sustainable design framework, different terms will have a particular emphasis on portions of the framework. Figure 2 illustrates the framework portions that will be of primary and secondary emphasis in different terms.

Semester 2A

	Design Thinking	Sustainability
Foundational Sciences and Systems	Innovation and Creation	Foundational sciences
Frameworks	Design Process and Guiding Principles	Ways of Approaching Problems
Tools and Techniques	Design Activities	Modeling, Analyzing, Assessing
Application Areas	Broad Fields of Study	Green Application Areas

Semester 2B

	Design Thinking	Sustainability
Foundational Sciences and Systems	Innovation and Creation	Foundational sciences
Frameworks	Design Process and Guiding Principles	Ways of Approaching Problems
Tools and Techniques	Design Activities	Modeling, Analyzing, Assessing
Application Areas	Broad Fields of Study	Green Application Areas

Semester 3A

	Design Thinking	Sustainability
Foundational Sciences and Systems	Innovation and Creation	Foundational sciences
Frameworks	Design Process and Guiding Principles	Ways of Approaching Problems
Tools and Techniques	Design Activities	Modeling, Analyzing, Assessing
Application Areas	Broad Fields of Study	Green Application Areas

Semester 3B

	Design Thinking	Sustainability
Foundational Sciences and Systems	Innovation and Creation	Foundational sciences
Frameworks	Design Process and Guiding Principles	Ways of Approaching Problems
Tools and Techniques	Design Activities	Modeling, Analyzing, Assessing
Application Areas	Broad Fields of Study	Green Application Areas

Semester 4A

	Design Thinking	Sustainability
Foundational Sciences and Systems	Innovation and Creation	Foundational sciences
Frameworks	Design Process and Guiding Principles	Ways of Approaching Problems
Tools and Techniques	Design Activities	Modeling, Analyzing, Assessing
Application Areas	Broad Fields of Study	Green Application Areas

Semester 4B

	Design Thinking	Sustainability
Foundational Sciences and Systems	Innovation and Creation	Foundational sciences
Frameworks	Design Process and Guiding Principles	Ways of Approaching Problems
Tools and Techniques	Design Activities	Modeling, Analyzing, Assessing
Application Areas	Broad Fields of Study	Green Application Areas

Figure 2: Scaffolding the sustainability-centred design model across the four-year program. Within each semester, the darker shaded topics are a primary focus area and the lighter shaded topics are a secondary focus.

5 Implementation

The pilot host design-spine course was the summer 2019 offering of our core course in sustainability in civil engineering. This course introduces additional foundational sciences of sustainability, such as ecology, planetary boundaries, socioeconomic metabolism and the fundamentals of resource extraction, by expanding on knowledge from an earlier core course in earth systems science (climate, geology, etc.). Systems thinking is introduced as the core framework for examining issues of sustainability. With a systems

lens, tools and techniques of sustainability assessment are studied, such as basic thermodynamics, life cycle assessment, material flow analysis, and various footprinting techniques.

The revamped design-spine version of the course resulted in several changes. This includes revisiting generic design processes and design activities, building on courses from first year. The design aspects of the course are framed within the context of a new group-based design project and the inclusion of group-based exercises. The exercises and project work in tandem.

The exercises provide in-class problem-based use of the sustainability frameworks, tools and techniques, in order to progress student learning in advance of each stage of the design project. The group-based project, conversely, centres on the use of the design thinking frameworks and techniques to deliver a suite of design alternatives to an applied sustainability challenge. In the prototype offering of the design project the ask is to first assess and then propose low impact neighbourhood designs for a re-development area in Vancouver, Canada. The project includes several features designed to meet our curriculum change objectives: realistic problem-based coursework that is broken-up throughout the term and is supported by providing students with pre-existing engineering materials and data with which to create their designs.

The term project is divided into five assignments distributed throughout the term. The first three assignments concern the use of sustainability tools within the application area of green buildings. From CAD drawings and additional supporting data for a real building students are required to (1) calculate the use of energy over the supply-chain; (2) conduct a partial quantity take-off estimate for use as inputs to (3) a detailed life cycle assessment. In assignments four and five, the students first create high-level design alternatives for the re-development area using details of archetypal buildings from the 2011 National Energy Code of Canada and then they evaluate the sustainability outcomes of their designs using a decision matrix approach. The five assignments are graded and submitted throughout the course. For the fifth submission, all the previous assignments are compiled into a single report along with recommendations to a hypothetical client. The project concludes with group presentations, a group reflection and an individual peer review of group members.

This prototype also involves changes to support the concept of a design-spine hub course loosely integrated with other core courses offered within the same term. The integration in this offering occurs with our building sciences fundamentals course and our civil engineering materials course. The connection with the building sciences course is through the systems-based framework. In this course the students assess energy flows and balances of buildings. The building science course also provides students with a view to how techniques in that course are used to arrive at greener building designs. For the materials course the linkage is made through life cycle assessment and the neighbourhood design. While students conduct an LCA of buildings in the sustainability course, they conduct an LCA of pavement alternatives in the materials course. This affords an opportunity to consider alternative pavements within the neighbourhood design, though the project stops short of requiring this consideration formally. Instead, this consideration is examined through the final reflection in the design-spine course. The reflection also requires students to adapt methods from the building science course to further reduce buildings' environmental impacts on neighbourhood designs. In this way, the design-spine offering connects learning across three disciplines to further support a systems-based mentality.

This first design-spine course has been assessed at a high-level by the students (Figure 3). The students rank the project as a core aspect of the course they think should be kept. Interestingly, in this regard, the

project was second only to the in-class exercises (when the feedback related to projects is added – see items with an * in the figure). In effect this means the two largest changes made to support the design-spine – the project and the exercises – are the most favoured aspects of the new version of the course. In future design spine offerings we plan to formalize our student feedback assessment by focussing survey questions in terms of the relationship of lectures, assignments and tests to the students' own perceived effectiveness in design and sustainability.

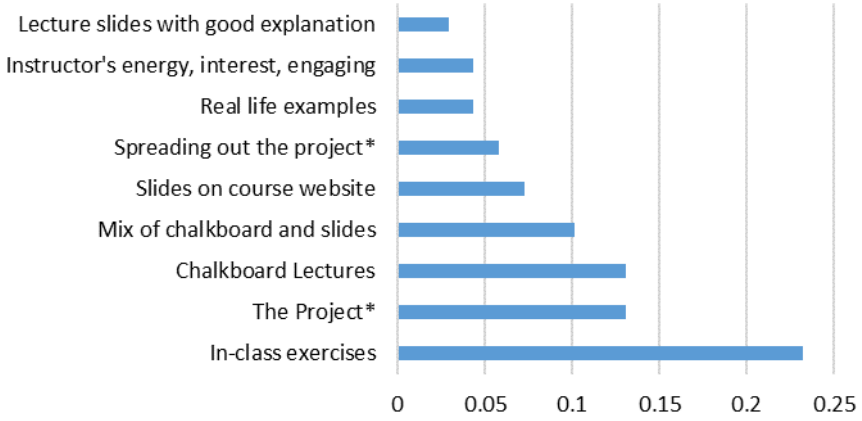


Figure 3: Frequency of Student Replies to the Question "What should the instructor keep doing?"

6 Conclusions

We have developed a design spine strategy as a program-level curriculum improvement approach motivated by two primary drivers: a desire to improve our sustainable design content, and a goal of improving our active learning practices. The design spine will implement one major design activity within a host course in each term of our civil engineering program. We are developing a sustainability-centred design model as a anchoring framework for the sustainability and design content that we will be including in the design spine courses. The model is based on four high-level categories of foundations, frameworks, tools, and applications. We have completed a pilot implementation of our design spine approach, and found that students had a very favourable reaction to the design activities. In future work, we will continue to refine the design spine activities, develop the sustainability-centred design content, and implement the strategy in a number of other courses through our civil engineering program.

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