

Work in progress: Integrating sustainability assessment at the planning phase in capstone design projects

Dr. Ada Hurst, University of Waterloo

Ada Hurst is an Associate Professor, Teaching Stream and Associate Chair, Undergraduate Studies in the Department of Management Science and Engineering at the University of Waterloo, where she teaches engineering design to management engineering students. She is a passionate design educator and researcher, with interests in engineering and software design cognition, management, and education. She is a co-founder of the Canadian Design Workshop, a biennial conference series to promote design education research in Canada. She also serves as Associate Editor for the Studies in Engineering Education journal, and co-chair of the Design Society's Special Interest Group on Cognitive Design Science.

Prof. Christine Moresoli, University of Waterloo

Christine Moresoli is a Professor in the Chemical Engineering Department at the University of Waterloo in Canada. She obtained a Bachelor's and Master's in Chemical Engineering from McGill University (Montreal, Canada), and a PhD from Ecole Polytechnique Federale de Lausanne (Lausanne, Switzerland). Her research and teaching expertise are in chemical, biological and food processes and products and sustainability. Current research activities focus on the integration of sustainability in engineering undergraduate and co-operative education programs and in the assessment of environmental impacts by life cycle analysis of food products. She was Associate Dean Co-op Education & Professional Affairs in the Faculty of Engineering at the University of Waterloo where she coordinated the Canadian Engineering Accreditation Board (CEAB) accreditation activities of engineering undergraduate programs and supported the development of processes for the assessment of graduate attributes in the Faculty of Engineering. She participated in the creation of the Waterloo Experience Accelerate (WEA) program to assist first work term undergraduate students with the development of their job search and transferable skills. She has developed online resources to support experiential learning of leadership skills for the Canadian Engineering Grand Challenges, a set of six Grand Challenges built on the UN SDGs for the Canadian context. She has received the University of Waterloo Outstanding Performance Award and the University of Waterloo Faculty of Engineering Teaching Excellence Award. She is a member of the Canadian Engineering Accreditation Board (CEAB) and has served on numerous NSERC grant selection committees.

Mr. Christopher Rennick, University of Waterloo

Chris Rennick, PhD P.Eng. received his B.A.Sc., Honours Electrical Engineering in 2007 and his M.A.Sc. in Electrical Engineering in 2009, both from the University of Windsor, in Windsor, Ontario, Canada. Chris' PhD from the University of Waterloo investigated how knowledge and personal epistemology of novice designers relate to their design behaviours. Chris is currently an Engineering Educational Developer with the Pearl Sullivan Engineering Ideas Clinic at the University of Waterloo. Chris is a fellow of the Canadian Engineering Education Association.

Reem Roufail, University of Waterloo

Reem Roufail is a materials engineer that is interested in engineering teaching and applying new technologies to engage students in class. Reem believes that learning is a continuous process that does not end with earning a degree. This explains her willingness to explore different fields of engineering as opportunities to learn. She explored mechanical engineering, environmental engineering, petroleum engineering, systems design, and biomedical engineering in her career paths from an academic perspective. Recently she has successfully led and supported Biomedical engineering and Systems Design engineering programs at the University of Waterloo to apply the Canadian Engineering Accreditation Board (CEAB) graduate attribute and continuous improvement approach to the programs. That intrigued her to dig deeper into teaching-learning pedagogy. The abrupt changes that the pandemic brought to the education system, were a trigger for her to realize that change is coming to how we do things. However, before we jump into applying a change, we should understand the impact of the change from all stakeholders' perspectives.

Work in progress: Integrating sustainability assessment at the planning phase in capstone design projects

Abstract

This work-in-progress paper will discuss an initiative to better integrate concepts of sustainability in upper-year engineering design courses, including 4th-year capstone design course. Sustainability encompasses diverse concepts such as environmental, social, and economic sustainability dimensions, the United Nations Sustainable Development Goals (UN SDGs), and circularity principles. The range of sustainability representations adds complexity for educators wishing to define sustainability knowledge and values. Programs often face challenges in selecting appropriate content and approaches to integrate sustainability in programs that are already content heavy and subject to strict accreditation requirements. Moreover, instructors may not feel adequately prepared with knowledge and tools to discuss and assess the factual and value-based dimensions of sustainability in their teaching. In the context of engineering design, sustainability should be an integral part of the entire design cycle and anchored as one of the main objectives of the product – from its planning phase up to and including the end of life of the product. To understand how sustainability is currently included (or not) across capstone design courses, the authors have conducted semi-structured interviews with instructors to obtain an environmental scan of sustainability concepts taught in capstone design courses across programs. Based on the results of these interviews, the authors have identified and adapted two existing tools that can be easily integrated in the existing course delivery for the analysis of sustainability in the design cycle. Both tools provide ways to semi-quantitatively assess the initial design based on a list of criteria describing sustainability. This paper will provide an overview of the results from the instructor interviews, discuss why these two tools were selected, and how the two tools were adapted and integrated in third and fourth year design courses in two Engineering programs at the University of Waterloo.

1. Introduction

Sustainability is a broad term that can refer to a wide range of concepts, including environmental, social, and economic sustainability dimensions, United Nations Sustainable Development Goals (UN SDGs), and circularity principles or life cycle thinking, among others. It has been a topic of discussion in multiple contexts and disciplines, including politics, engineering, economics, and policy-making - since the 1990s. The growing importance of sustainability is also associated with the development of technologies aimed at addressing complex societal problems and transitioning to a more sustainable future.

The range of sustainability representations adds complexity for educators wishing to define sustainability knowledge and values (Nickel, et al. 2021), underscoring the need for resources and tools to support them. Efforts to integrate sustainability into curricula can take many forms, including the creation of dedicated courses, the integration of sustainability in existing disciplinary courses, or establishing specialized sustainability credentials (Thürer et al, 2018). One example is the Engineering for One Planet initiative (<https://engineeringforoneplanet.org/>) which provides resources, grants and support and represents a step forward to address gaps in sustainability education. The success of such initiatives will be influenced by the instructors' comfort level with sustainability concepts and their ability to engage students in a meaningful

way. Research highlights a strong relationship between instructors' beliefs about sustainability and the significance of the integration of sustainability in classroom instruction (Brown et al, 2014). For example, instructors' expectations about sustainability concepts had a major impact on the sustainability content in 43 senior capstone design projects of civil engineering programs at two different institutions (Dancz et al, 2017). While some resources exist, programs may face challenges in selecting appropriate content and approaches to integrate sustainability in programs that are already content heavy and subject to strict accreditation requirements and instructors may not feel adequately prepared with knowledge and tools to discuss and assess the factual and value-based dimensions of sustainability in their teaching (Thürer et al, 2018).

Sustainability has an essential role in engineering design and should be considered throughout the entire design cycle, from the planning stage, where it is established as one of the main objectives of the product, up to and including the end of life of the product. A recent study analyzed the sustainability content of ninety-eight engineering capstone design projects across six engineering disciplines (Alhawamdeh et al, 2024). The analysis was based on a rubric with eight specific criteria including content, dimensions, cognitive levels, relationships, quantitative or qualitative representation of sustainability. The study found that the economic dimension of sustainability was the most common, while the environmental and social dimensions were not as prominent. Additionally, the relative presence of sustainability dimensions varied across programs. Other differences across programs related to the quantitative and qualitative tools and the cognitive level of the sustainability components contained in the projects.

Sustainability is an important element in the accreditation of engineering undergraduate programs. In Canada, the Canadian Engineering Accreditation Board (CEAB) requires that institutions demonstrate that their graduates can analyze societal and environmental aspects of engineering design activities. Another requirement is that Engineering curricula must incorporate engineering design content that considers sustainability in design constraints and solutions, along with complementary studies content related to the impact of technology and/or engineering on society and sustainable development and environmental stewardship (Engineers Canada, 2023).

These studies and accreditation requirements support the need to establish best practices for the integration of sustainability in engineering capstone design projects. This paper reports on an ongoing project that aims to operationalize the integration of sustainability in engineering design education, firmly grounded in the disciplinary and institutional needs and context of the educators.

1.1. Scope and aims

The Faculty of Engineering at the University of Waterloo offers 14 engineering undergraduate co-op programs. Each program includes a senior capstone design course taking place over two to three terms (12 weeks each term) with an average student enrolment of 100 students but that can range from as low as 50 students to more than 300 students. Each course has designated instructors that act as coordinators. The course organization, application of the design cycle and deliverables vary widely across programs. Most courses have scheduled contact hours with the class but few – or no – structured lectures. Some courses will include workshops (mandatory or optional). All courses have a design symposium open to the public where students present their designed solution with a poster and physical and/or digital demonstrations (as applicable).

Students self-select their team members (typically three to five students), project topic based on their interest, and typically a faculty advisor with expertise in the project topic. All projects include project ideation and scoping, assessment of user needs, solution generation, selection and iteration. The time given to each phase and feasibility and expectations regarding a physical prototype differ depending on the engineering discipline. For example, a physical prototype is common in Mechanical Engineering and Biomedical Engineering while in other disciplines (e.g., Civil Engineering and Chemical Engineering), the design artifact may take the form of a model representation.

This study was initiated to identify best practices, tools, and resources for including sustainable design practices in each phase of the engineering design cycle in capstone design courses. This work-in-progress paper will report on the results of the first two stages of this project:

1. An environmental scan of methods currently used in the Faculty of Engineering at the University of Waterloo and elsewhere (Section 2).
2. A curation (and adaptation) of methods into an open-access toolkit tailored to capstone design instructors at the University of Waterloo (Section 3).

2. Environmental Scan

2.1. Approach

To perform an environmental scan of methods used in the Faculty of Engineering at the University of Waterloo, 1-2 members of the research team conducted semi-structured interviews with capstone design instructors from across the Faculty. The research team aimed to understand:

1. The degree to which capstone design courses incorporate principles of sustainability
2. Whether individual instructors utilize approaches to incorporating sustainability that can be shared with other capstone instructors
3. The extent to which additional instruction on sustainability can be integrated into capstone design courses

The interviews took place in the fall of 2023 and the winter of 2024, and so the 2023-2024 capstone course offerings were the subject of discussion, though older offerings came up several times as course changes were discussed by the interviewees. The interviews were typically 45 minutes long and included 9 questions (some with multiple parts). The first question in the interview prompted the instructors to provide an overview of the structure of their capstone design course before transitioning to a targeted discussion on sustainability in that discipline. These latter questions asked the instructor how they define sustainability, the relative importance of the topic in their discipline, and how the instructor had (or hadn't) learned about sustainability. From there, the instructor was asked a series of questions to better understand how sustainability training was (or was not) currently being provided to their students, and to what extent students were incorporating sustainability in their capstone design projects, and how. This was useful to capture methods that might be shared with other capstone instructors, as well as to appraise the strengths, weaknesses, and opportunities for improving the instruction of sustainability in the course/program. This interview protocol was approved by the University of Waterloo ethics review board.

2.2 Findings

In total, 11 engineering capstone design instructors were interviewed (representing 12 out of the 14 engineering programs offered at the University of Waterloo). All capstone design courses described in this paper are two-term courses in the fourth year of their respective program, though four of the programs have a design course in the second term of third year where the capstone design projects are initiated. These third-year pre-capstone design courses include regular lectures on design and typically require students to form their capstone team and identify a shortlist of project topics (in one case, the students are expected to have their project chosen by the end of third year). For most programs, these third-year courses are the last opportunity to deliver lectures on design. Table 1 summarizes the format of the capstone design courses, as well as any sustainability-related content, for each program.

Table 1: Capstone design courses format and sustainability content and assessment, by program

Program (P)	Format of senior capstone design courses			Sustainability content			
	No lectures	Few (<6) lectures	Modules/workshops (<5)	No formal instruction on sustain.	Lecture on sustain.	Assessment of sustain.	Prior formal instruction on sustain.
P1	✓			✓			
P2		✓	✓	✓		✓	✓
P3		✓		✓		✓	✓
P4	✓		✓	✓		✓	
P5	✓			✓		✓	
P6		✓	✓	✓		✓	✓
P7	✓			✓			✓
P8		✓	✓		✓	✓	✓
P9		✓	✓		✓	✓	
P10		✓	✓		✓	✓	
P11	✓		✓	✓		✓	✓
P12	✓			✓		✓	

Of the 12 programs surveyed in this research, six have no lectures of any kind in fourth year; the remainder have fewer than six designated lectures, all of which are in the first term of fourth year; and seven programs include a limited number of modules/workshops on specific topics (typically fewer than five). The primary means of instruction in these courses is mentorship, informal advice, or feedback to student teams through assessment(s). Across all 12 programs, the primary means of assessment are written reports and formal presentations by the student teams, most frequently at the middle, and end of each term, though regular meetings in between these major milestones are not uncommon.

Three of the 12 programs surveyed include at least one lecture/module on sustainability in the capstone course, the other nine programs include no formal instruction on sustainability in either of the two terms in fourth year. Ten of the 12 programs include sustainability as part of at least one of the assessments in the course. In these cases, it is typically included as part of the

evaluation of the impact of the project (CEAB Graduate Attribute #9 – Impact on society and the environment), and so is combined with topics like project safety, adherence to regulations, ethics, or health. This means that in many cases, the three dimensions of sustainability (environment, economic, social) carry only minimal weight in assessments. Only two of the programs surveyed in this research expect significant attention to be paid to sustainability by the capstone teams. Six out of the 12 programs include prior formal instruction on sustainability to their students. There is no prior formal instruction for the remaining six programs.

Interestingly, the course instructors often had quite different views of what “sustainability” meant and what sustainability frameworks were incorporated in the context of their discipline, as summarized in Table 2.

Table 2: Views on sustainability and its operationalization, by program

Program (P)	What does “sustainability” mean in your discipline?				What sustainability frameworks are incorporated in your discipline?				
	Environment	Social	Economic	Other	UN SDGs	Sustainability dimensions	Sustainability building standards	Life-cycle thinking	Other
P1			✓						✓
P2		✓	✓			✓			✓
P3		✓		✓	✓		✓		
P4				✓		✓		✓	✓
P5		✓				✓			✓
P6	✓							✓	✓
P7	✓				✓				✓
P8				✓	✓		✓		✓
P9				✓	✓				✓
P10				✓	✓				✓
P11	✓	✓	✓		✓	✓		✓	✓
P12	✓	✓	✓		✓	✓			

In two cases, the three dimensions of sustainability were mentioned specifically. In one other interview, two dimensions of sustainability were specified while in five other interviews, just one of the three dimensions was mentioned. In the three programs where projects were predominantly (or entirely) software in nature and/or where projects have an emphasis on human wellbeing, social concerns were typically emphasized over environment or economy. Two other instructors viewed sustainability purely through the lens of environmental sustainability. When asked to comment on the perceived gaps in student training on sustainability, three instructors mentioned economic sustainability as an area which could be improved on, three instructors specifically mentioned systems thinking was an area for additional development, one mentioned social sustainability, one mentioned environmental sustainability, and two mentioned their students would benefit from more instruction on sustainability, broadly, early in the curriculum.

When asked what frameworks are used to incorporate sustainability in the course, the UN Sustainable Development Goals came up most frequently (seven programs), followed by the three dimensions approach to sustainability (five programs), life cycle thinking (three programs) and sustainable building standards (e.g. LEED, passive house, Rick Hansen accessibility analysis) (two programs). The other frameworks were only mentioned by one program and included the Canadian Engineering Grand Challenges, design for reusability/recyclability, and embodied energy. The program that incorporated design for reusability/recyclability includes it as part of a department-level initiative to collect useful components/materials at the end of the capstone project for future offerings of the course. This is an interesting example of circularity within the department (which houses two engineering programs) but had challenges in implementation (e.g., components were often returned damaged, recycling levels vary team to team and year to year). Reference to the UN SDGs in capstone projects was driven by the course instructor in some programs, and by the students in others; but in most cases it was catalyzed by the recent creation of a faculty-wide capstone competition that rewards sustainability based on the UN SDGs content of the projects.

3. An open-access toolkit for sustainability instruction in capstone design courses

3.1 Modification of two instructional tools

3.1.1 Requirements

The results from interviews with instructors provided some insight into potential tools for incorporating sustainability in capstone design projects. These interviews also directly informed the requirements for an open-access toolkit to facilitate the integration of sustainability considerations in capstone design projects. The instructor interviews revealed that most students had received little to no instruction in sustainability prior to the capstone design course. Even in cases when students may have received some prior training, it may have been focused only on one of the sustainability dimensions (e.g., environment), revealing a need for a broader training that include other aspects of sustainability in the curriculum. In other cases, the tools provided to students were highly discipline-specific (e.g., the Rick Hansen Foundation Accessibility Certification for buildings) and so were not appropriate to share with instructors in other disciplines.

Additionally, as the capstone design projects in each program move at different paces across two to three academic terms, tools need to be flexible in how – and when – they are deployed in the design process. Ideally, the identified tools would be flexible enough to be used as teams identify suitable problems for their capstone project, complete their initial conceptual designs, refine their detailed designs, or reflect on their project outcomes.

Finally, instructors also expressed that there was little to no time to add additional instruction on sustainability once the capstone course started, and the instructors were generally uncomfortable or unaware of one or more of the three dimensions, making their inclusion in the course challenging.

Clearly then, to achieve maximum buy-in in the Faculty of Engineering at the University of Waterloo, the ideal tool(s) would:

- be easy to understand (for students and instructors),
- assist with the incorporation of all three dimensions of sustainability,

- be flexible in when and how they are applied in the design process, and
- be flexible in application across widely divergent engineering domains.

3.1.2 Tool(s) description

Once several instructor interviews had been completed, and the authors had a rough outline of the requirements for desirable sustainability tools, a recently graduated PhD student was hired as a research assistant (RA) to scan the available literature and identify potential tool options. This search was conducted during the winter and spring of 2024 and ultimately identified several tools which were viable options to pursue further. Through a series of meetings with the project team, the RA experimented with the tools, generated a summary of their strengths and weaknesses, including where in the design process they were best suited for. This search identified several possible tools that were ultimately not pursued by the project team, including the Product Sustainability Index (ProdSI) (Shuaib et al. 2014), the Sustainability Compliance Index (SCI), Hallstedt, 2017), and the Method for Sustainable Product Development (MSPD) (Byggeth et al, 2007). Driven by the criteria listed in the previous section, the project team ultimately selected two options to pursue in detail: Green Project Management (GPM) and The Circular Pathway (TCP). Each tool provides a distinct representation of sustainability and consists of an Excel worksheet format.

The Green Project Management (GPM) tool is based on the triple bottom line: people, planet, and prosperity. It was developed for project managers to assist with the review and analysis of the activities of the project and to identify ways to mitigate negative impacts of the project. Each component of the triple bottom line is articulated in categories, sub-categories and elements. The relevance and potential impact of each element is to be examined and described with potential response if relevant to the project. The circular pathway tool (TCP) is an educational tool based on the value chain of a product, examining material selection and product and component design, use, reuse, repair, recycle, recovery and end of life. It was developed at Maastricht University and used with students in the business engineering program. Its goal is to expose students to the complexity, linearity and the importance of systematic change across the value chain of a product. In our research, both tools were simplified to align with the needs of the design process of the program.

3.1.3 Modification process

The TCP tool includes 6 Excel worksheets for students to work through:

- Brief of requirements – summarize project details, requirements, context, etc.
- Value chain analysis – analyse the input materials and end of life recovery of materials used in the project
- Linearity analysis – analyse the circularity of material inputs and end of life recovery
- Brainstorm – create “visions” for improving areas with low circularity scores
- Creation of visions – update circularity scores for iterations identified in “visions”
- Scenarios – compare different visions to select one to pursue

These multiple worksheets assist students with the analysis of circularity as a standalone tool for iterating on a design to improve its circularity, however, in the context of the capstone design courses described in this research, students will have completed many of these steps in other assessments in the capstone design course. As a first modification then, the researchers isolated

the value chain analysis and linearity analysis for further testing and refinement. To iterate further on the TCP tool, an undergraduate student was asked to apply the tool to a course design project that they completed in their prior term. Through this testing, the tool was further simplified to streamline its use by students. This included removing references to product retail packaging, removal of discussion of logistics (e.g. transportation) that were outside the scope of the capstone design courses, as well as simplifying the columns on product reuse to be clearer to students with limited knowledge.

The GPM tool has a similar excel worksheet format for students to work through:

- Instructions – provide information on the use of the excel worksheets
- Examples – illustrate the use of the tool
- People input tab– analyze the project according to categories and elements related to people, e.g., health and safety
- Planet input tab – analyze the project according to categories and elements related to planet, e.g., GHG emissions
- Prosperity input tab – analyze the project according to categories and elements related to prosperity, e.g., financial analysis
- Scoring – generate tables of the scores for each input tab
- Graphs – generate figures of the scores for each input tab

The purpose of the multiple worksheets is to assist students in applying the GPM tool as a standalone tool for examining the sustainability of their design project. With this in mind, the original tool, developed for organizations and their activities, was modified to align with the needs of students and their capstone design projects. The most important modifications were simplifications of the tool. The approval worksheet was removed, the scope of information needed in the people, planet and prosperity input tabs was reduced and clarification for the analysis of the project, problem statement and proposed solution of the capstone design project was added.

3.2 Pilot implementation

In this section, we report briefly on some early implementations of the tools in two engineering programs. These implementations inform our collective reflections on the tools which are provided in Section 3.3.

Third-Year Design Course

The TCP (The Circular Pathway) tool was integrated into the sustainability analysis assignment for a third-year engineering design course in Systems Design Engineering. The course focuses on engineering analysis, the generation of alternative solutions, and prototyping. The course includes lectures, and a term-long design project completed in small groups, developing hands-on experience with electromechanical prototyping.

One of the project milestones was the sustainability analysis of the initial design before the physical prototype phase. The sustainability analysis required the mapping of the initial design against the UN SDGs. The key concepts of the modified TCP tool were presented in a workshop. Students were then required to conduct the value chain and linearity analysis of their initial design using the modified TCP tool. The students were encouraged to iterate their design choices based on the outcomes of the sustainability analysis and before building their prototype. Groups

were asked to submit the analysis and a summary of the findings that led to their design iterations. This assignment accounted for 10% of the course grade. Students were asked to conduct a second sustainability analysis with the modified TCP tool, post-prototyping and testing, identifying the changes that could have been made because of a lack of material or access to fabrication method initially considered. The sustainability analysis included in the final report accounted for 2% of the course grade.

Fourth-Year Capstone Design Course

The fourth-year capstone design course in Systems Design Engineering is split into two consecutive courses over two terms. The first term focuses on needs analysis and formulation of the design problem statement, and the building a low-fidelity prototype when feasible. It is in the first term that students were introduced to the two tools in a lecture format. Students were asked to complete and submit a sustainability analysis addressing the social, environmental, and economic dimensions of sustainability. The social dimension included the impact on stakeholders, community, and potential risks or benefits. The environmental and economic dimensions included resource consumption, waste generation, cost implications, financial sustainability, and economic benefits to the community. Students were encouraged to consider how their design could be improved from a sustainability perspective for a final iteration before prototyping. The sustainability analysis made up 3% of the course grade. The sustainability analysis influenced the design choices made by the teams. For example, some teams adopted a multi-component product such that some components could be modified rather than adopting a single component product obtained by 3D printing. Other teams considered sustainability in the material selection, e.g. wood rather than polymer materials. During the second term, teams continued working on their project, building and testing the prototype while iterating the design. Teams had to complete a sustainability analysis of their design by week 9, with the expectations that one or two iterations had been completed. Teams were encouraged to use both tools but not mandated. Teams submitted a final report and had to complete peer evaluations observing how to how others approached sustainability in their project. The final report represented 12% of the course grade.

Third-Year Pre-Capstone Design Course

The modified GPM tool was also piloted in a third-year “pre-capstone” course in the Management Engineering program. The course was intended to provide broad instruction on engineering design methods, focusing on the early stages of design, including need finding (information gathering and synthesis), problem formulation, and conceptual design. The students formed teams at the beginning of the term and using a divergent approach, they identified potential needs, progressed through multiple milestones to converge into a need, from which they formulated a suitable management engineering design problem. One week in the term was dedicated to formal instruction on assessing the impact of engineering design projects. Instruction included both a formal lecture that covered key sustainability concepts, as well as a brief introduction to the modified GPM tool and a demonstration of its application in a previous capstone design project. Students were then expected to use the modified GPM tool to conduct a sustainability analysis of their design and submit a summary of the key findings. This activity accounted for 10% of the course grade.

3.3. Evaluation of the Tools: Lessons Learned from Pilot Implementations

The comprehensive and systematic nature of the modified TCP and GPM tools offers benefits and challenges for students and instructors which are detailed below.

3.3.1 Benefits

The modified TCP tool offers a systematic approach for assessing the sustainability of design choices from the perspective of circularity and product life cycle. It encourages critical reflection on environmental and economic impacts and helps students identify areas for improvement, fostering a deeper understanding of life cycle and circularity principles.

The modified GPM tool is effective in providing a systematic and accessible means for students to evaluate the impact of design projects on a broad series of sustainability factors. The task of evaluating how each category and sub-category can be applied (or not) to the project encourages students to critically reflect on the people, planet, and prosperity dimensions that their design project (including both activities related to the project execution and its outcomes) might interact with, and the nature of those interactions.

3.3.2 Challenges

Both tools require thoughtful reflection and significant time and effort for the students. Therefore, instructors should align this effort in the assessment of the course, ensuring that the time and efforts of the activity is reflected in the components of the overall grade of the course. Instructors adopting these tools should also ensure that guidance is provided to address potential challenges that students may be facing on various aspects of each tool:

The modified TCP tool is applied at each phase of the value chain during a design project. Therefore, instructors adopting this tool should ensure that guidance is provided to address the following potential challenges that students may be facing on various aspects of this activity:

- The potential ambiguity and misunderstanding by students of the different phases of the value chain in the worksheets. Instructors need to provide clear guidance to assist students navigate the complexities of the tool and make informed judgments relevant to resource, use and end of life phase.
- The potential ambiguity and misunderstanding by students of the description of different phases. Instructors should encourage students to refer to the detailed descriptions within the TCP tool and accompanying resources.
- The ability of the students to accurately define and assess the impacts at each phase.

The application of the modified GPM tool in a design project is done across each category and sub-category. Therefore, instructors adopting this tool should also ensure that guidance is provided to address the following potential challenges that students may be facing on various aspects of this activity:

- Supporting students in making their own judgements about whether a sub-category is relevant or not, and whether an impact score needs to be provided. Making this judgement can be difficult for some students who may hesitate to leave rows “blank”, fearing mark deductions. Instructors need to provide guidance and reassurance to encourage meaningful completion of the assessment.

- The potential ambiguity and misunderstanding by students of the description of the sub-categories. Instructors should encourage students to refer to the accompanying report that explains each category in more detail, as a “manual” for using the tool.
- The ability of students to define the various stages of their project and to identify the relevant people, planet, and prosperity dimensions that can be impacted at each design stage for the entirety of the design project, from the impact of the project that brings about the design solution to the impact of the design solution itself once implemented/delivered in its intended environment.

In summary, while these two tools scaffold student thinking of sustainability in the context of engineering design projects, the sustainability analysis requires strong technical and critical thinking skills to assess impacts, model scenarios, and develop sustainable solutions. Students may need additional training and support in these areas.

4. Conclusion

In this paper, we have provided an overview of recent efforts in the Faculty of Engineering at the University of Waterloo to more meaningfully integrate sustainability in engineering design education. The project began by establishing a baseline understanding of how sustainability is currently addressed across the Faculty’s 12 engineering programs. This was followed by an environmental scan of existing sustainability tools and frameworks, which informed the development and pilot implementation of two adapted tools: the modified TCP (The Circular Pathway) and the modified GPM (Green Project Management) tools.

These tools provide a comprehensive framework for evaluating design projects' impact along the social, environmental and economic dimensions, equipping students with skills necessary to develop sustainable designs. This holistic approach exposes students to sustainability principles and is a pathway to promote sustainable design practices. By embedding TCP and GPM into the curriculum, educational institutions can promote sustainability in the design activities. TCP tool enables students to apply circularity principles, focusing on resource efficiency, waste reduction, and the lifecycle of materials. On the other hand, the GPM tool emphasizes the importance of environmental and social responsibility throughout the design lifecycle. The success in the effective application of these tools will require access to background knowledge. Accurate and objective data are crucial to avoid subjective assessments that undermine the sustainability analysis. Ensuring that students have access to credible sources and are trained in critically evaluating information is essential to effectively apply TCP and GPM. Next steps in this project include further iterations in the tools’ design and the accompanying instructions provided to students and more evaluation of instructors’ and students’ experience using the tools and impact on design projects.

Acknowledgements

This work was supported by a University of Waterloo Learning Innovation and Teaching Enhancement (LITE) Seed Grant “Sustainability Toolkit for Engineering Design Instructors”. The authors would like to acknowledge the significant efforts of Marian Boktor in conducting the search for existing sustainability tools.

Bibliography

- Alhawamdeh, B., & Muchson, M., & Al-Bodour, A. M. R. (2024, March), *Sustainability Components Assessment of Engineering Design Capstone Projects* Paper presented at 2024 ASEE North Central Section Conference, Kalamazoo, Michigan. 10.18260/1-2—45637
- Ansys Granta EduPak, <https://www.ansys.com/products/materials/granta-edupack>, accessed 1/7/2025
- Brown, S., Bornasal F., Brooks S., Martin JP. 2014. J. Prof. Issues Eng. Educ. Pract. 141 (2): C4014005.
- Byggeth S, Broman G, Robert KH. 2007. A method for sustainable product development based on a modular system of guiding questions. *Journal of Cleaner Production* 15: 1-11. <https://doi.org/10.1016/j.jclepro.2006.02.007>
- Dancz, C.L.A., Ketchman, K.J., Burke, R.D., Hottle, T.A., Parrish, K., Bilec, M.M., and Landis, A.E. (2017). Utilizing civil engineering senior design capstone projects to evaluate students' sustainability education across engineering curriculum. *Advances in Engineering Education* 6. 10.18260/3-1-370.620-31325.
- Engineering for one Planet. <https://engineeringforoneplanet.org/>, accessed 1/7/2025
- Engineering Deans Canada, Canadian Engineering Grand Challenges 2020-2030 – <https://engineeringdeans.ca/en/project/cegc>, accessed 1/7/2025
- Engineers Canada. Canadian Engineering Accreditation Board. 2023 Accreditation Criteria and Procedures. Revised October 2023. https://engineerscanada.ca/sites/default/files/2023-12/Accreditation_Criteria_Procedures_2023.pdf, accessed 1/7/2025
- Garcia-Saravia Ortiz-de-Montellano C, Ghannadzadeh A and van der Meer Y (2023) The CIRCULAR pathway: a new educational methodology for exploratory circular value chain redesign. *Front. Sustain.* 4:1197659. doi: 10.3389/frsus.2023.1197659
- Green Project Management. GPM P5 Standard for Sustainability in Business Practice. <https://www.greenprojectmanagement.org/gpm-standards/the-gpm-p5-standard-for-sustainability-in-business-practice>. Adapted from P5 Impact Analysis Version 5.0.2, accessed 1/7/2025
- Hallstedt SI. 2017 Sustainability criteria and sustainability compliance index for decision support in product development. *Journal of Cleaner Production.* 140: 251-266. <https://doi.org/10.1016/j.jclepro.2015.06.068>
- LEED (Leadership in Energy and Environmental Design): <https://www.usgbc.org/leed>, accessed 1/7/2025
- Nickel, J., Duimering, P. R., & Hurst, A. D. A. (2022). Distilling sustainable design concepts for engineering design educators. *International Journal of Engineering Education*, 38(1), 44-55. Passive House Canada, <https://www.passivehousecanada.com>, accessed 1/7/2025
- Rick Hansen Foundation Accessibility Certification, Guide to RHF Accessibility Certification v4.2 (June 2024) <https://www.rickhansen.com/accessibility-advisory-services> accessed 1/7/2025
- Shuaib M, Seevers D, Zhang X, Badurdeen F, Rouch KE, and Jawahir IS. 2014. Product Sustainability Index (ProdSI), *Journal of Industrial Ecology.* 18 (4): 491-507. <https://doi.org/10.1111/jiec.12179>
- Thürer, M., Tomašević, I., Stevenson, M., Qu, T., Huisingh, D. (2018). A systematic review of the literature on integrating sustainability into engineering curricula. *J Cleaner Production.* 181, 608–617. 10.1016/j.jclepro.2017.12.130
- United Nations. Sustainable Development Goals, <https://sdgs.un.org/goals>, accessed 1/7/2025