PRACTICAL INTEGRATION OF SUSTAINABILITY INTO ENGINEERING

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Abstract – The broad terminology around sustainability is an excellent catalyst for discussing the technical and social impacts of projects in an engineering classroom and for improving decisions made in team-based design projects. When an exploratory hands-on methodology is applied, the introduction of the various aspects associated with sustainability allows instructors to engage students to SEE (identify) Social, Economic, and Environmental impacts and quantify the relevancy of generic criteria to specific projects. The P5™ Impact Analysis tool (GPM Global) was used to identify relevant criteria for ranking design projects. Whereas the methodology is reproducible, the decisions made by students can vary when there is no clear answer. With a range in results, the instructors can then have the students perform additional analyses to reflect on the complexity of ranking alternatives and to view the results based on various circumstances. The outcome is that the students gain a broader understanding of how SEEing different perspectives matters and adds value to the decision making process.

Keywords: sustainability, engineering design, social, environmental, economic, criteria

1. INTRODUCTION

The motivation for this paper was to help students incorporate sustainability concepts seamlessly into their engineering designs. Sustainable design is specified in accreditation requirements for Canadian engineering programs [1]. The GPM Global P5™ impact analysis tool [2] was used by students to help them systematically identify a relevant list of criteria to evaluate projects in two distinct classes.

The technique was first used in a third-year “Introduction to Mining” class with Chemical, Geological, and Mechanical Engineering students. The authors presented a realistic field scenario of an anticipated tailings dam breach to teach and practice sustainability-informed decision-making [3]. The P5 tool was applied to facilitate evaluation in a simulated fast-paced emergency situation. Due to its success, the technique was then applied in a second-year design class of Civil and Geological Engineering students to generate potential criteria to evaluate alternatives for a newly proposed, fictitious pedestrian bridge near the University of Saskatchewan campus. This latter in-class activity supplemented the typical practice of providing only a lecture to define and describe sustainability in an engineering context.

The P5 tool was developed for professionalism in project management and “provides guidance on what to measure and how to integrate P5 into project activities” [2, p. 4]. The updated v. 2.0 document includes a long list of criteria and a method of scoring of a project’s success at incorporating sustainability concepts before and after changes to an actual project. We used the same list during project design to help the design teams anticipate which impacts in the list could apply to the particular project they are assigned.

The three authors have previous experience in mining and consulting and have witnessed improvements in safety statistics related to injuries and fatalities during their careers. Part of the improvements in safety can be attributed to checklists that remind employees to look for hazards as they enter their work areas. Another common application of checklists is in the engineering review process to verify that drawings are annotated properly.

Using the P5 tool, these structured brainstorming methodologies founded on sustainable thinking allowed students to identify several applicable criteria in a short time period. The criteria were used to compare the effectiveness of alternative designs. With this list of criteria, the students could next focus on prioritizing which criteria they would use in evaluating their project. The benefit of the P5 tool is that the categories encompass all sustainability principles, and the analyses are suited to evaluations in spreadsheets.

2. LITERATURE REVIEW

First-year engineering design instructors at the University of Saskatchewan base their instruction on the book Designing Engineers: An Introductory Text [4]. The
book is well written by Canadian authors, and the second chapter describes both free and structured brainstorming approaches. Free brainstorming is described “for uninhibited idea generation, not for selection” [4, p. 130]. Structured brainstorming can also be used to generate concepts: potential solutions are evaluated against functions and constraints required of the design. Methods to compare alternatives include the Pugh method and weighted decision matrices [4, p. 151]. Section 4 of the textbook presents the concept of designing for sustainability. This book is in alignment with “Society and Environment” attribute No. 9 of Engineers Canada [4] in that it addresses concepts of sustainable design, environmental stewardship, and economic, cultural, societal, and health and safety issues.

Adams [5] provides various representations of sustainability, including Fig. 1. He writes that “Environmentalists, governments, economic and political planners and business people use ‘sustainability’ or ‘sustainable development’ to express sometimes very diverse visions of how economy and environment should be managed… In implying everything sustainable development arguably ends up meaning nothing” [p. 3].

The P5 tool [2] takes the diverse terminology of sustainability and creates a table that lists categories related to sustainability to guide project management teams. It considers the impacts to People (Social), Planet (Environment), and Prosperity (Economic) of Fig. 1 but goes beyond to consider the impacts of Process (complexity of project management, assessment, development, and operations) and Product (Fig. 2). The authors used the P5 list in two teaching case studies to facilitate brainstorming of criteria to evaluate positive and negative impacts of projects so that sustainability is broadly considered early in project design.

Peltier [6] concluded: “the mining industry has been very successful in changing the corporate culture around health and safety issues.” One way the industry improved safety was by adopting the Five-Point Safety System introduced by Neil George in 1942. All employees complete this checklist before beginning each work day. This approach was used to develop the hands-on activities described in two case studies. Case Study 2 is an extension of an earlier publication [3].

3. CASE STUDY DESCRIPTIONS

Two interactive team activities were planned as structured brainstorming to show that the P5 checklist can be used to incorporate sustainable thinking early in the design stage. The circles in Fig. 1 were rearranged (Fig. 2a) to help students remember the terminology of Social, Environmental, and Economic impacts: the goal is to “SEE” the impacts and identify criteria that encompass all three areas. The question mark is a reminder that the project management process is also important. Fig. 2a was further modified to represent the P5 categories (Fig. 2b). When brainstorming for ideas, criteria related to any of the P5 categories may be required for the final design.

3.1. Case Study 1

The objective of Case Study 1 was to introduce sustainability into design so that student final reports integrated sustainability, rather than including it as an after-thought. This second-year design class required teams of 3–4 students to develop at least three alternative solutions to open-ended problems using a systematic, design-oriented approach. No other team projects are based on bridge designs, so no advantage is conferred to any team through this problem. Written communication and the design process were emphasized over technical content. Students were provided with Fig. 3 and asked to use free brainstorming to identify potential criteria to compare alternatives for a design study for a new pedestrian bridge. They had already completed a similar exercise to develop criteria in their first year design class, where they were similarly not provided with structure. Following a lecture defining sustainability, students were provided the P5 list (Table 1 with column 3 blank) and used it to further brainstorm to develop a list of all criteria that could be used to select alternative bridge designs. The lists were combined from all teams and made available to students so that they would later have an example to follow when
performing a similar exercise on their individual team projects.

![Fig. 3. Study for new pedestrian bridge in Saskatoon [7].](image)

#### 3.2. Case Study 2

Case Study 2 was an extension of Case Study 1. With the aid of Table 1, Chemical, Geological, and Mechanical Engineering students brainstormed potential criteria and then added details by rotating through posters on the classroom walls. In a take-home assignment, they individually weighted each criterion between 1 (not important to decision making) and 10 (very important to decision making). The class average weighting was used for each criterion. Criteria with a weighting < 5 were deemed not significant to decision making and removed. Decision-making is subjective, thus it is important to document the logic used.

The objective of Case Study 2 was for at least three teams to numerically rank three alternatives independently so results could be compared with common weightings and agreed-upon criteria. The teams decided the influence of each of the five criteria in Fig. 2b and gave each alternative a final score. Those final spreadsheets were ideal for post-analyses because the students individually could reflect on why their scores/rankings differed from other teams.

| Table 1: Potential criteria generated without the checklist (black), with the checklist (blue italics), and added by the instructors (blue underlined). |
| Sub-Categories | Possible Objectives of Design | Generated Potential Criteria |
|----------------|-------------------------------|------------------------------|

#### Category: PEOPLE (Social):

| Labour Practices & Decent Work |
|--------------------------------|
| Employment & Staffing | Manual labour, Work Opportunity, Local hiring |
| Labour/Management Relations | |
| Public Health & Safety | Safety of construction processes |
| Training & Education | |
| Organizational Learning | |
| Diversity & Equal Opportunity | |
| Local Competence Development | Local hiring, Training |
| Community Support | Community support - capacity (traffic volume), Practicality/ use, Seasonality, Impact to existing traffic, Construction effect on nearby land use, Accessibility, Aesthetics, Appearance, Visual appeal, Multi-use (bikes/ pedestrians), Dimensions, Footprint, Size, Length |
| Public Policy/Compliance | Public policy and compliance, |
| Protection for Indigenous & Tribal Peoples | Treaty lands |
| Customer Health & Safety | People's safety, Design, Capacity (weight), Factor of safety (maximum load), Stability |
| Product & Service Labeling | |
| Market Communications & Advertising | |
| Customer Privacy | |
| Human Rights | Non Discrimination, Wheel chair accessible |
| Ethical Behaviour | Non Discrimination |
| - Voluntary Labour | |
| - Procurement Practices | |
| - Anti-corruption | |
| - Fair Competition | |
When teams brainstormed using Table 1, the number of categories represented (column 2) increased from 3 to 8, 6 to 10, and 1 to 2 in the people (social), environmental (planet), and prosperity (economic) categories, respectively (blue text in Table 1, column 3). This highlights that a checklist is a useful tool to avoid missing possible project impacts. Most product and process (project management) impacts were identified in the initial brainstorming activity. These relate to technical design factors that reflect the technical training of the engineering curriculum.

Each team would work on unique projects later in the course, so the goal of this activity was to teach a methodology to incorporate criteria from a sustainability perspective from the start of a project. Students were free to choose any weighting system to rank their three alternatives in their individual team projects. A total of 10% of their final design report marks were allocated to incorporating sustainably principles: with this approach, the students could discuss their final design with respect to the extensive list of criteria they originally defined. They were told that their client ultimately can choose the criteria,
4.2. Case Study 2

Through group activities, the entire class contributed to brainstorming for criteria. They furthermore also brainstormed for the alternatives to compare but the instructors reduced their list to only the 3 of discharge, flood the mine or raise the dam. 16 criteria were identified as significant to decision making (Table 2, weighting ≥ 5). However, totals differed among the six teams, depending on the scale they used to weight the criteria (Table 2 bottom). For example, the preferred option would have the lowest score if +5 denoted the most negative impact, −5 denotes the most positive impact, and 0 meant the particular criterion is neutral to the decision. Having the highest score as the worst alternative is contrary to how most people think which is an effective way to teach that everyone does rankings differently.

Alternatively, the preferred option would have the highest score if 10 denoted the most positive impact, 1 denoted the most negative impact, and 5 was neutral. Similarly, the three alternatives were ranked differently in some cases. This exercise was a great way to systematically quantify a decision with no clear “right” answer. Further, it highlighted the importance of using clear terminology when defining criteria to avoid skewing results by weighting certain concepts more than once.

Certain items affected the weighting and hence the final selection. Using the +5/−5 scale (Table 1) implies that employee safety, permitting, water contamination, and business flexibility are highly influential criteria when ranking alternatives because these had the highest numerical values (weighting × score). As a reflection exercise, the students were asked to verify whether their criteria matched the company values provided to them as background information and encouraged to adjust their numbers accordingly.

By altering scores through weightings, students were able to see how their totals were more sensitive to some categories. For example, in Table 3, the total was most-to-least sensitive to Product, Profit, Planet, People, and Process. Furthermore, all team results were shared so that students could see how teams quantified the results differently. Together, the teams all agreed on what were the most relevant criteria through brainstorming. With a chart already prepared like this, other options could be reviewed and adjusted efficiently.

Columns 1, 2 and 3 of Table 3 are a summary of the discharge results (columns 1, 2 and 3) of Table 2. That is, the italicized items in red in Table 2 form the first 3 columns of Table 3. Students were asked to change the overall weightings for the P5 categories to see how this would affect the ranking of alternatives. For example, People was based on the weightings of 8 of 16 criteria, so it was given a weighting of 50% (Table 3, column 2). Then they adjusted the scores so all categories were weighted equally at 20% (column 4), then at 60% to the planet and 10% to the other four categories (column 6). The same exercise was repeated for all three alternatives.

Table 2: Samples of rankings.

| Category and criteria | People | Planet | Profit | Product | Process |
|-----------------------|--------|--------|--------|---------|---------|
|                       | #-% of |        |        |         |         |
|                       | Criteria | Discharge | Flood | Mine | Raise | Dam |
| People 8/50%          | -10     | 15      | 5      | 25      |        |
| Hire locally          | 15      | 5       | 25     |         |        |
| Employee safety       | 35      | 14      | 0      |         |        |
| Community involvement | 5       | -15     | -15    |         |        |
| Community support     | -5      | -10     | -10    |         |        |
| Permits/compliance    | -32     | -32     | 8      |         |        |
| Customer safety       | 21      | -21     | -14    |         |        |
| Reputation            | -20     | 25      | -25    | -25     |        |
| Quality control       | -25     | -25     | -25    |         |        |
| Sutotal               | -6      | -59     | -56    |         |        |
| Planet 4/25%          |         |        |        |         |         |
| Local procurement     | 10      | -80     | 6      | -18     |        |
| Energy consumption    | -20     | 10      | 20     |         |        |
| Contamination         | -24     | 32      | 40     |         |        |
| Waste                 | 32      | -32     | 32     |         |        |
| Sutotal               | -100    | 16      | -70    |         |        |
| Profit 3/19%          |         |        |        |         |         |
| Costs                 | -15     | -15     | 25     |         |        |
| Business flexibility   | -35     | 28      | -35    |         |        |
| Local Jobs            | -28     | 21      | -21    |         |        |
| Sutotal               | -78     | 34      | -31    |         |        |
| Product 1/6%          |         |        |        |         |         |
| Outcomes              | -25     | 25      | -20    |         |        |
| Process 0/0%          | 0       | 0       | 0      |         |         |
| Total Team 1 16/100%  | -209    | 16      | -177   |         |        |
| Total Team 2 93       | 229     | 73      |        |         |        |
| Total Team 3 363      | -47     | -186    |        |         |        |
| Total Team 4 351      | 469     | 22      |        |         |        |
| Total Team 5 274      | 193     | -105    |        |         |        |
| Total Team 6 368      | 293     | -11     |        |         |        |

Table 3: Sample of adjusted scores for the discharge column in Table 2.

| Category | Weighting | Score | Weighting | Score | Weighting | Score | Score |
|----------|-----------|-------|-----------|-------|-----------|-------|-------|
| People   | 50        | -6    | 20        | -2    | 10        | 0     |       |
| Planet   | 25        | -100  | 20        | -80   | 60        | -192  |       |
| Profit   | 19        | -78   | 20        | -82   | 10        | -43   |       |
| Product  | 6         | -25   | 20        | -83   | 10        | -139  |       |
| Process  | 0         | 0     | 20        | 0     | 10        | 0     |       |
| Total    | -209      | -248  | -375      |       |           |       |       |
5. CONCLUSIONS

The P5 tool was applied in two case studies to provide the terminology to discuss the technical and social impacts of particular projects as well as a quantitative measure of the influence of decision-making based on different priorities or circumstances. This tool was designed for project managers but can be applied to any design situation. Whether looking at a project or product after the construction phase or—as shown here—in the project planning stage, this approach generates meaningful discussions regarding sustainability and influential factors in decision-making.

This mathematical method of comparing alternatives incorporates project management and product concerns and is based on SEEing the Social, Environmental and Economic impacts. If provided with company goals, the students can be asked to reflect on and discuss if the final decision is in alignment with company or client values. It can be also used to discuss how the results may differ based on another value system, for projects that are strictly focused on technical aspects, or for projects that consider community effects. That insight into perspectives is valuable because it highlights where different alternatives might be justified because decision-making is subjective.

In both case studies, the criteria were determined from input from the entire class, not individual students or teams. Going step-by-step through ranking each alternative and brainstorming different subcategories reinforced the benefits of teamwork. With more people, more concerns were identified because everyone looks at things differently. Companies and individuals have different values, and engineering problems are open-ended, so these examples clearly show that different teams will develop different solutions to similar engineering problems. Some projects may prioritize impacts on the environment while others concentrate on profit.

Decision-making is complex, but once documented, it is possible to analyze if sustainable thinking was effectively captured. The students gained so much more practical learning by experiencing how to incorporate sustainability into design and doing, rather than just hearing a lecture about sustainability.

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