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WIP: Integrating Sustainability into First-Year Design through a Junkyard Band Project

Dr. Benjamin Emery Mertz, Rose-Hulman Institute of Technology

Dr. Benjamin Mertz received his Ph. D. in Aerospace Engineering from the University of Notre Dame in 2010 and B.S. in Mechanical Engineering from Rose-Hulman Institute of Technology in 2005. He spent 7 years as a lecturer at Arizona State before returning to Rose-Hulman teach at Rose-Human in 2018. His academic interests focus on clean energy, specifically wind turbine design, and has developed curriculum and projects that integrate sustainability into his classes. He also enjoys employing flipped class structures to improve active learning and improving the way teamwork is taught in undergraduate engineering programs.

Dr. Kelley E Dugan, Rose-Hulman Institute of Technology

Kelley E. Dugan is an Assistant Professor in the Department of Mechanical Engineering at Rose-Hulman Institute of Technology. Her research interests are at the intersection of engineering education and design including topics such as sustainable design, systems thinking, community-engaged learning, and open-ended modeling problems. They focus on how social dimensions can be recognized and integrated into engineering pedagogy on problem solving processes by studying project-based courses. They earned their B.S. in Mechanical Engineering from The Ohio State University and their M.S. and Ph.D. in Mechanical Engineering from the University of Michigan.

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Abstract

This work-in-progress (WIP) paper describes ongoing efforts to integrate sustainable design concepts into a first-year engineering design course. In spring 2022, a sustainability related project was developed for a first-year introduction to design course for mechanical engineering majors. The course project was inspired by the Paraguayan community, featured in the "Landfill Harmonic" documentary, who formed a children's orchestra that performs with instruments made of our materials recycled from a local landfill. While having student teams design musical instruments made of trash to form a "junkyard band" with their classmates, instructors cover design concepts such as stakeholder analysis, requirements and specifications development, design process modeling, mathematical modeling, and technical communication. In addition to covering traditional design concepts, the project topic enables coverage of several sustainable design concepts including: the UN Sustainable Development Goals, assessment of a product's carbon footprint and embodied energy, and connections between sustainability and ethical engineering practice. Sustainability considerations, in turn, tie back to best practices in design related to having a holistic process to increase the likelihood of producing a successful solution. We also present our work towards a more formal assessment of these interventions using both quantitative and qualitative techniques to understand what students are learning about sustainable design from the course. We hope to increase student awareness of sustainable design concepts so that they can build upon this introduction to the topic in future courses and projects.

Introduction

Most engineering programs require a first-year introductory engineering course and many researchers have shown that such courses can have a positive impact on a student's identity as an engineer, skill development (e.g. technical, communication, teamwork, among others), and retention [1-5]. While the content and objectives of first-year introductory engineering classes can vary significantly between institutions and even sections within an institution [6], according to McAlister et al., most introductory engineering course syllabi that they looked at emphasized teamwork, communication, problem solving, design, engineering technology/tools, and ethics [7].

In first-year engineering design courses, open-ended design projects that emphasize practicing an iterative design process to solve a relevant problem typically play a critical role in achieving course learning objectives though the details, scope, duration, and problem vary widely [8-10]. Interest in the topic of the project has been shown to increase student engagement and learning [10-12]; hence the choice of the project is important. Those who have developed musical instrument-based projects before suggest that these projects can produce a novice mentality [13] while still being tractable for modeling purposes [13-14] and promote the mingling of arts with STEM [13,15]. It has also been shown that certain design projects can also support developing broader beneficial mindsets such as an Entrepreneurial Mindset [16-17] and Sustainable Thinking [18-21].

Sustainable design has been highlighted by accrediting agencies (ABET) and professional societies (such as ASME and NSPE) as a professional obligation that students ought to be trained in [22-23]. Sustainable design frameworks, such as Engineering for One Planet (EOP), have created helpful sustainable design competencies/learning outcomes that can be implemented across an engineering curriculum [24]. First-year design courses play an important role in introducing sustainable design concepts early in an academic career so that they can be built upon or used in later classes [20-21].

The goal of this paper is to describe the development of a first-year design project that aims to strengthen the sustainable design concepts introduced in an introduction to design course. This was done by leveraging the benefits of instrument design projects from literature and using The Landfill Harmonic documentary [25] as inspiration and motivation to build familiarity with sustainable design concepts by upcycling materials considered as waste in their own environment. We will also propose assessment techniques we plan to employ to understand what students are learning about sustainable design from the course.

Course and Project Background

An analysis by our colleagues classified Introduction to Design as a C-Tier sustainability-related course which are courses where a major component of the course is a project and sustainability could be applied to the course through the project [26]. This required course is offered in the spring quarter of each year and is summarized in Table 1. We have small class sizes (capped at 24 students), so we end up having many (8+) sections of this course. This leads to variation in instructors who teach the course from year to year as well as variation in the projects offered over time as different instructors have bandwidth to develop and revise the project(s) they run in their sections. Projects created by instructors are sometimes adopted by other instructors and materials are regularly shared and adapted by those teaching the course. Projects are often being refined, or new projects are developed to give students different experiences. Since the project was first implemented in AY22-23, four different instructors have run the project with over 360 students across 17 sections. Most students have been first-year mechanical engineering students, however every year there are several students from other majors (refer to Table 2).

Table 1. Introduction to design course details

Title: Introduction to Design (EM 103) **Credit Hours:** 2 **Prerequisites:** None **Structure:** Meeting for 2 hours 2x per week over a 10-week quarter.	**Catalog Description:** Introduces the engineering design process including problem definition, analysis, alternate solutions, specifications of final solution, and techniques of oral and written communications. Stresses the importance of teamwork through group design efforts.

Table 2. Summary of Junkyard Band Project use

Academic Year	AY22-23	AY23-24	AY24-25
No. of Instructors	2	3	2
No. of Section	5	7	5
No. of Students	110	141	113
Student Majors	Mechanical Eng., Optical Eng., Computer Sci., Civil Eng., Electrical Eng., Eng. Physics, Physics	Mechanical Eng., Optical Eng., NanoEngineering, Computer Sci., Civil Eng., Physics	Mechanical Eng., Optical Eng., NanoEngineering, Computer Sci., Biomedical Eng., Civil Eng., Chemical Eng.

Junkyard Band Project Development

Project Overview

The motivation to develop a new project for the Introduction to Design class at Rose-Hulman Institute of Technology was two-fold: to increase the number of different project options given to students across different sections of the class and to implement more sustainable design concepts into the class. A musical instrument design project for an online first-year design class was a helpful starting point [27] as it highlighted some of the key modeling and design process learning objectives we wanted to teach in our course. However, it did not explicitly address sustainable design concepts. The Landfill Harmonic documentary [25] provided additional context for which to highlight different relevant Sustainable Design Goals (SDG) [28]. The Landfill Harmonic documentary documents a youth orchestra in Paraguay which plays instruments created by citizens of a city that derives most of its income by harvesting materials from a local landfill. Their instruments are made mostly out of trash which helps motivate our students to identify and choose materials from waste streams on campus to create their instrument (hence the “Junkyard Band” project name). The documentary also allows us to highlight issues of poverty, quality education, and responsible production and consumption which correspond to SDGs 1, 4, and 12.

Unlike the “band-in-a-box” project from literature, each team is randomly assigned to one of three different types of instruments: a tonal percussion (e.g. xylophone), wind (e.g. recorder or flute), or string (e.g. guitar or harp). As a class, the teams make up a “band” and are tasked with performing the school’s fight song together at the end of the academic term. They are provided with mathematical models for frequencies (focusing on fundamental frequencies) of vibrating strings, bars/tubes, and standing waves in air columns and are expected to use the provided models to aid in making design decisions. They test their instruments using tuning apps like Tonal Energy Tuner on their phones. Student teams must track all material costs as well as quantify the amount of trash, recyclable, and compostable materials used in their design.

The instruments are assessed based on the range of notes their instrument can play, the number of distinct notes that can be played, the loudness of their instrument (while adhering to standards that limit how loud they can safely be played), the percentage of the instrument made out of trash (or compostable, recyclable, or reusable materials), the total cost of the instrument (if new materials are bought or parts with useful life are scavenged and assigned a cost), and their ability to develop and assess a "special feature" that adds value to a particular subset of potential stakeholders. A breakdown of the grading rubric for instrument performance can be found as Appendix A (Table 5). Most of the quality metrics and targets were set by the instructors so the "special feature" rubric item was added as an opportunity for students to conduct interviews with potential stakeholders and identify an opportunity to add value for a particular stakeholder based on what they learn from those interviews. They are required to define what measurable metrics can be used to prove that value is added and then test their final design based on those metrics.

Some students have not studied music or played an instrument before but are taught through lectures and videos enough modeling and music theory concepts to be able to create their assigned instrument type. Even those who have played instruments before might not have played the type of instrument they were assigned or at least have not had a lot of previous experience designing their own instrument, thus encouraging them to adopt a "novice mindset" and apply the design skills we teach in class. This may help them avoid some design fixation issues common in novice designers [29], although in practice these kinds of issues are still observed.

Project Modifications

In AY23-24 the project was aligned more formally with the Engineering for One Planet (EOP) [30] learning outcomes by adding in lectures on different definitions and frameworks for understanding sustainability, discussions of sustainability as a professional obligation, and adding an EcoAudit module that has students do a preliminary life-cycle analysis of different designs to estimate and compare the embodied energy and CO2 footprint of the designs. No new course learning objectives (CLOs) related to sustainability were added to the course because of the need to maintain consistency of CLOs between different sections/project offerings. However, when possible, current CLOs were mapped to EOP framework learning outcomes to help students connect sustainable design principles with the design skills. This mapping can be found in Table 3. Note that certain CLOs are grouped together in the mapping as there are often overlaps between multiple EOP LOs and CLOs. We have also included other EOP LOs that are not directly tied to current CLOs but would be relevant to some of the added modules and the nature of the Junkyard Band Project as the last row of Table 3. The CLOs are assessed through various reflections, presentations, and reports as the students work through the design process described later in this paper. The EOP LOs are largely used to help frame the conversations around different parts of the design process but are currently not formally assessed. We are hoping to get a better understanding of what students are learning about sustainability by implementing the proposed assessments described later in this paper.

Table 3. CLOs mapped with EOP framework learning outcomes [30]

CLOs	EOP LOs
• Determine the needs of stakeholders and translate these into qualitative and quantitative objectives. • Describe and compare various engineering design process models presented in class.	• Define problems comprehensively with consideration of consequences, unintended and intended. • Identify issues and actions of environmental and social priority. • Implement stakeholder user experience/participatory studies (e.g. design thinking, human-centered design) and social impact assessments to meet user needs in responsible, novel, improved, ethical, and sustainable ways.
• Develop several alternative design concepts that meet given evaluation criteria within the context of an engineering problem. • Employ mathematical modeling and solid modeling to communicate, refine, and establish the feasibility of a design concept.	• Execute technical analyses to choose strategies that maximize the positive and minimize the negative environmental and social impacts in order to achieve design goals. • Design for the environment and society based on discipline-specific technical skills (e.g. light-weighting, design for repairability and durability, design for upgradeability, design for disassembly, flexibility, and reuse, design for part or whole recovery, etc.).
• Effectively communicate the goals, methods, and outcomes of a design project using oral presentations and written reports.	• Recognize that every person has a role in sustainability and has the right and need to be informed about the environmental/social/economic impacts of the products they purchase, consume, and discard. • Communicate through audience-specific written, graphical/visual, oral, and interpersonal communication skills.
• Explain the relevance of professional ethics within the practice of engineering design.	• Recognize and be empathetic to ethical implications relative to the social impact of their work. • Critique complex ethical and values-based choices, employing empathy when evaluating conflicts of interest, trade-offs, and uncertain knowledge and contradictions within problem constraints.
• Recognize and exhibit behaviors that contribute to effective teamwork.	• Demonstrate ability to work within and function well on teams and across disciplines.
Additional EOP LOs	
• Explain whole life-cycle and closed-loop systems thinking as related to the impact of their work (e.g. understanding of life-cycle burdens of design alternatives) • Identify the United Nations Sustainable Development Goals (SDGs) • Explain high-level environmental impact assessments (e.g. basic Life-Cycle Assessments (LCAs) and life-cycle hazards (i.e. how they work, what information they require, how to incorporate their findings into their work). • Identify potential impacts of materials (e.g. embodied energy, emissions, toxicity, etc.) through the supply chain – from raw material extraction through manufacturing, use, reuse/recycling, and end of life – with a focus on minimizing negative impacts to the planet and all people (i.e., especially those who have been intentionally marginalized). • Design with lower impact, natural materials (e.g. earth, bamboo, agro-waste, etc.) with an aligned degree of knowledge of industrial materials (e.g. iron, steel, aluminum, etc.) • Weigh trade-offs that guide selection of design-appropriate materials (e.g. technical considerations including strength, weight, cost, toxicity, extraction impacts, material compatibility, and thermal properties, among others) • Report being self-aware and reflective practitioner with values, empathy, and guardianship of one's environment.	

Based on experience gained by running the project over multiple years, one important modification to the project in AY24-25 was providing students with the ability to "buy" certain materials from a manicured list of stocked items that would be helpful to produce good tones. This lessened the anxiety of having to find the "right" piece of trash, but they still had to balance this with the cost and trash content hits that would result from using these materials. It was helpful in getting the students to weight design trade-offs. More definitions were provided for what counts as trash (for example old/reused fasteners or discarded 3D printed parts) as well as providing opportunities to increase the sustainability of their designs by having them consider recyclability and composability for the end of their design's life. We also gave more opportunities to our campus community to talk with the teams about their designs at the end of the project. This was done through a reception where students would stand by their instruments and talk with visitors (including classmates) about their design. This gives students the opportunity to present their work in something more like a poster session or elevator pitch while also spreading awareness of sustainability on campus.

Many different types of instruments have been created by students including pan flutes, whistles, trombones, xylophones, glockenspiels, harps, guitars, hurdy-gurdy. The first year this project was run there was a major renovation of the academic buildings on campus that was happening and so students were able to find an abundance of construction materials to use in their instruments. Since then, the focus has been on incorporating more common sources of trash around campus such as cardboard, soda cans, plastic bottles, or sources of otherwise unusable machine shop scrap. The goal is to keep the spirit of the Landfill Harmonic documentary by having students use trash materials that are around their living environment.

Design Process Implementation

In alignment with research that emphasizes the importance of using multiple design process models in novice design instruction [31], on the first day of class students are introduced to a variety of design process models. Models introduced include problem-solution co-evolution, decomposition / recombination after VDI 2221, French's engineering design process, and Agogino's design, build, test [32]. We also share a socially engaged design process model [33] and certainly see alignment between our efforts to emphasize stakeholder considerations and sustainability considerations broadly and a socially engaged design process.

Student teams begin by learning about stakeholder interviewing, conducting background research on their assigned instrument type, and setting goals for which notes their instrument will be able to play. They soon identify people to interview and are introduced to the NSPE Code of Ethics [34] as well as ethics specific to interview conduct as they develop interview protocols. Students experience firsthand design as consisting of multiple efforts in parallel as they start learning about ideation strategies and work through individual—and then group—ideation for portions of their instrument design while they are still gathering information (e.g., conducting interviews). As students move into concept development, they are introduced to the importance of being able to justify their design decisions. Models (e.g., mathematical, functional, and solid) and analysis (e.g., eco-audits) are framed as iterative activities during refinement of ideas.

Prototyping is introduced multiple times in the course. Early on (Day 6 of 20), students are introduced to a purposeful prototyping tool adapted from [35-36] and encouraged to build the simplest prototype and smallest collection of prototypes possible with the focus of communicating their ideas to their teammates. Later (Day 11 of 20), students are introduced to proof-of-concept prototypes as being specifically focused on feasibility and encouraged to focus on evaluating provided tech specs step by step rather than building the entire instrument all at once. In parallel, students are developing stakeholder needs and technical specifications for their "special feature" while drawing on the information they gathered from interviews. As the project progresses, students are introduced to the ethics of communicating results and transition to spending a significant portion of class time on building their instruments. The final few classes are focused on evaluating the performance of their instrument and reporting their results.

Rather than presenting a single process model for students to adhere to, the project introduces design as a flexible and customizable experience while providing several key deliverables for novice designers. Halfway through the project, individual students complete a design process modeling activity where they are tasked with using principles of effective graphics [37] to describe the design process as they have experienced it up to that point. For the end of quarter report, teammates update their models and synthesize them into a single descriptive model.

Planned Assessment of Effectiveness

The Junkyard Band project will be the focus of two sections of Intro to Design in AY25-26. We plan to leverage the benefits of having a smaller student enrollment to do a mixed methods study focused on evaluating the effectiveness of the Junkyard Band project in supporting students' understanding of sustainability and sustainable design practices. In Intro to Design we care more about students developing a solid foundation with design processes than their design outcomes. Therefore, our investigation will focus on foundational sustainable design concepts that support process and sustainable design as a process. Our mixed methods study will be a partially mixed concurrent equal status design [38] where we are collecting both quantitative and qualitative data at the same time. The main form of data collection will be pre-/post-surveys that are completed on the first and last day of class. These surveys will consist of three parts. Part 1 consists of the construction of a concept map addressing the question: "What is sustainability?" and draws directly from [40]. Part 1 serves as both a primer for Parts 2 and 3 questions and a source of data for tracking student coverage of various aspects of sustainability, e.g., social, environmental, and economic, and understanding of the complexity of sustainability—through number of concepts identified and overall connectedness. Parts 2 and 3 are adaptations of our colleagues' investigation of introducing sustainable design principles in civil engineering design [39]. Following a partially mixed concurrent equal status design [38], our analyses will consist of both quantitative (Part 1 and 2) and qualitative (Part 1 and 3) approaches and implications will be inferred from the mix after both types of data have been analyzed separately. The pre-/post-survey content and analysis types are summarized in Table 4.

Table 4. Summary of pre-/post-survey content and type of analysis

	Part 1	Part 2	Part 3
Description	Directed to create a concept map on the focus question: “What is sustainability?”	Multiple choice questions covering basic sustainable design concepts in engineering design.	Qualitative questions that dig into explanations of sustainable design concepts.
Example	N/A	The three aspects of the triple bottom line in sustainable design describe impacts on [environment, society, economy] [39].	Define sustainability/sustainable design [39].
Analysis	Relational scoring assessing the correctness of propositions [41] and categorical scoring assessing category coverage and complexity [40].	Quantitative investigation of statistically significant differences in percentage of students who answer questions correctly.	Qualitative thematic analysis of explanations.

Conclusions

In this paper we have documented the development of a Junkyad Band project that merges the design of musical instruments with sustainable design concepts. Various instructors have been able to run this project in a first-year design class and iterate towards a project that we believe effectively promotes the learning objectives of our class. The next step is to do a more formal assesment of the student learning experience to better understand how introductory design students approach problems that inherently requires consideration of sustainability. We hope to present this work in future publications.

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Appendix A: Grading Rubric for Instrument Performance

Table 5. Rubric used to assess the performance of the instruments

Objective	Poor (1)	Marginal (2)	Good (3)	Excellent (4)
Number of notes that can be played	2 distinct notes can be played	3 to 6 distinct notes can be played	7 to 10 distinct notes can be played	Distinct notes that can be played > 10
Percent weight of materials that satisfy RRC[1] criteria	RRC Weight % ≤ 50%	50% < RRC Weight % ≤ 70%	70% < RRC Weight % ≤ 95%	RRC Weight % > 95%
Amplitude of notes played (measured 5 ft away)	Decibel level < 20 dB or > 140 dB	Decibel level between 20 dB and 75 dB	Decibel between 76 dB and 85 dB	Decibel between 86 dB and 100 dB
Accuracy of notes (up to 4 notes will be tested at random)	Within 20 cents of all tested notes	Within 10 cents of all but two tested notes	Within 10 cents of all but one tested notes	Within 10 cents of all test notes
Weight	Weight > 20 lbf	Weight 10 lbf – 20 lbf	Weight 5 lbf – 10 lbf	Weight < 5 lbf
Range (distance between lowest and highest note)	< 1/2 octave range	½ to 1 octave range	1 to 1 ½ octave range	> 1 ½ octave range
Special feature	Tried to pass off an expected/required feature as a "special feature" or only used technical specifications already defined to evaluate special feature.	An attempt is made at a special feature, but it is not well executed. Unclear who the intended target stakeholder is or how it is evaluated.	A strong attempt is made at a special feature, but there is some room for improvement. Mostly clear who the intended target stakeholder is and how it is evaluated.	Special feature(s) is impressive, insightful, and well executed. This feature targets a specific subset of potential stakeholders and is evaluated based on a specific set of metrics.
Total project cost[2]	Project cost is more than $14.99	Project cost is between $14.99 - $8.00	Project cost is between $7.99 and $2.00	Project cost is less than $2.00

[1] RRC criteria stands for Recyclable, Reusable, or Compostable. For this class, we consider it recyclable if it can be recycled in the standard City of Terre Haute recycling program (note that adhesives like hot glue or epoxy can make part or all of the material unrecyclable), we consider it reusable if can be returned in a condition that could be provided to future EM103 students (this only applies to materials that were sourced through the ME department), and it is considered compostable if it could be composted in a residential compost process (note that PLA used for 3D printing, while compostable using industrial process, is not considered compostable in residential processes). Your instructor has the final word in determining if the RRC criteria is met.

[2] Total project cost includes the cost of all materials used throughout the project (even for prototyping when they do not appear as a part of the final design). Items sourced from the ME department will have associated marked costs that you must track as a part of your budget even though you do not spend your own money on them. Post-consumer waste materials pulled from the trash/recycling stream do not count towards your costs. Fasteners provided by the ME department are priced at $0.02/fastener but glues provided by the department do not need to be tracked for cost.