# Whole System Mapping for Sustainable Design for Senior Engineering and Non-Engineering Students

Mehrube Mehrubeoglu
Department of Engineeirng
Texas A&M University-Corpus Christi
Corpus Christi, Texas, USA
ruby.mehrubeoglu@tamucc.edu

Lifford McLauchlan
Department of Electrical Engineeirng and Computer Science
Texas A&M University-Kingsville
Kingsville, Texas, USA
lfllm00@tamuk.edu

Stefanie Koehler
Green Crane Innovation, LLC
Portland, Oregon, USA, and
Minneapolis College of Art and Design
Minneapolis, Minnesota, USA
stef@greencraneinnovation.com

***Abstract*—This innovative practice full paper presents the implementation of whole system mapping for sustainable design thinking in engineering and non-engineering courses. Sustainable design has gained substantially more attention in both academia and industry as increasingly designers of products and services are expected to consider the longevity and sustainability of their products and services. Whole system mapping entails consideration of the resources, users, product life cycle, environment, and the interconnections of a product or service idea during design. Using the open educational resources, whole system mapping exercises were incorporated in senior engineering Project Management and senior Electrical and Computer Engineering Project Lab courses with engineering students, and a Gulf of Mexico Studies course for non-engineering students as a method to introduce the students to the idea of sustainable design. In this paper, we compared the students' utilization of whole system mapping to help them demonstrate sustainable design thinking in their proposed project ideas. This innovative practice assisted the students with determining resources needed to create their product or service, and whether more sustainable materials/ options could be chosen. The exercise assisted the students in considering the product life cycle from ideation to disuse of the product/service, and how they could incorporate reuse/ repurposing/recycling to extend the life of the product or its parts. The students considered the interactions based on the purpose of the product to incorporate useability in their design. Finally, the students also established connections to the users and where the product/service outputs or outcomes may end up, impacting their environment. Creative ideas were generated both in the interdisciplinary engineering and single-discipline engineering courses at two institutions. Non-engineering teams also brought fresh perspectives to the process with alternative project ideas in one course. This case study represents part of a wider study that includes additional cohorts to study whole system mapping and students' skills development in sustainable design.**

***Keywords—sustainable design, whole system mapping, engineering design, product life cycle, problem-based learning, introduction to sustainable design principles, interdisciplinary collaboration, systems thinking training, life cycle assessment (LCA)***

## I. Introduction

Sustainable design is gaining more attention in both academia and industry as increasingly designers of products and services are expected to consider longevity and sustainability of their products and services. Whole system mapping (WSM) entails consideration of the resources, users, product life cycle, environment, and the interconnections related to a product/ service/process during design. Using the open educational resources (OER) put together by VentureWell [1], whole system mapping exercises were incorporated in senior engineering Project Management (Fall 2023) and senior Electrical and Computer Engineering Project Lab (Spring 2024) courses with engineering students, at two institutions, and a Gulf of Mexico Studies (Spring 2024) course for non-engineering students. These courses were chosen due the requirement of a project in the course outcomes.

In this paper, we compare the students' utilization of whole system mapping to demonstrate sustainable design thinking in their proposed project ideas. This innovative practice, as it is incorporated in senior capstone design projects, and gulf impact projects practice, assisted the students with determining resources needed to create their product or service, and whether more sustainable materials/options could be used. The exercise encouraged the students to consider the product life cycle from the ideation to the disuse of the product or service, and how these students could incorporate reuse/repurposing to extend the life of the product/service or its parts. The students examined the potential interactions based on the purpose of the product to help them incorporate useability in their design. Finally, the students also established connections to the users and where the product/service outputs or outcomes may end up, impacting their environment and therefore fostering critical thinking for sustainability and sustainable design.

## II. Background

### A. Literature Survey

System mapping has been used to help plan and implement action to promote physical activity [2] in a less structured system mapping model. Whole system mapping has been applied in non-design contexts and considers five steps including: 1) internal environment, 2) human factors, 3) tool application, 4) lived process cycle, and 5) external environment [3]. Green design tools have been developed in the whole system design process to support sustainable thinking in design. Faludi et al.

investigated the tools we incorporate here to determine green design activities and mindsets that drive innovation and sustainability and found that whole system mapping was well received by students [4]. In an earlier work, sustainable design was introduced to interior design/architecture students through studio experiences resulting in increased awareness among students to sustainable design as "a multidimensional concept that requires critical thought processes", as well as recognizing environmentally responsible design [5].

A survey of almost 7000 students found that most of the surveyed students were concerned with sustainability as well as environmental impacts resulting from climate change [6]. There is a growing concern to incorporate more information about sustainability into engineering curricula utilizing innovative practices so that students learn the skills necessary to incorporate sustainability practices into their engineering designs. For instance, Engineering for One Planet (EOP) strives to ensure that students learn the skills required to incorporate sustainability into engineering design and associated processes [7]. As part of the ABET engineering accreditation process, engineering programs need to include content as well as design projects and/or assignments in which students learn to "…produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors," (outcome 2) [8] and content that instills in students the ability to address "…the impact of engineering solutions in global, economic, environmental, and societal contexts" (student outcome 4) [8]. These particular open educational resources (OER) were chosen since they directly contributed to the course and student learning outcomes in engineering, and are also relevant to non-engineering application scenarios.

As systems become more complex, methods to visualize or analyze these system-of-systems are needed to facilitate working with these complex systems. System maps enable visualizing a complex system with its associated subsystem relationships as a whole. Flores looked at a capstone course's use of system methods and concepts to improve student coordination and students' application of system methodologies to a project [9]. Schimpf and Olewnik studied differences between an instructor's and student's system mapping for a system of systems and the inherent relationships among the systems; the instructor's mapping incorporated more structure and aspects that a student or novice did not include [10]. Ghadiri *et al.* studied complex food systems using system maps [11]. Faludi et al. conducted workshops and surveyed professionals about sustainable design methods, such as Whole System Maps [12].

The comparison of WSM ideas, approaches and connections by engineering vs. non-engineering students is unique to this project. We discovered that even though the non-engineering students' project ideas differ significantly from engineering design projects (Gulf of Mexico related summer camps, informational brochure, tagging sports fish, vs. traditional engineering design solutions to identified engineering problems, including building prototypes), sustainable design ideas can be incorporated equally successfully in both engineering and non-engineering disciplines through innovative practices to engage the students in the process.

## III. Student Cohorts and WSM Exercises

Whole System Mapping exercise was conducted in a Project Management (Senior Design 1) course at Texas A&M University-Corpus Christi (TAMUCC) ($n_1$ = 29), and Senior Design 2 at Texas A&M University-Kingsville (TAMUK) ($n_2$ = 5). In addition, Whole System Mapping exercise was introduced to Gulf Scholars Program (GSP) students composed of junior/senior science students (biology and environmental science), psychology, pre-mechanical engineering and pre-nursing students ($n_3$ = 13). These students were chosen because they were enrolled in courses that had a project and design component.

At TAMUCC, In Senior Design 1, students performed the task within their capstone team using their capstone project idea for the WSM exercise. In GSP, students formed teams of two or three, picked a topic of interest, and applied WSM and analysis to their chosen project topic. At TAMUK, The Senior Design students applied WSM to their team's capstone project, but individually.

### A. WSM Exercises

The exercise conducted was adapted from Venture Wells' Design and Sustainability resources available online [1]. The general concept and considerations for whole system mapping as used in the courses is summarized in Figure 1.

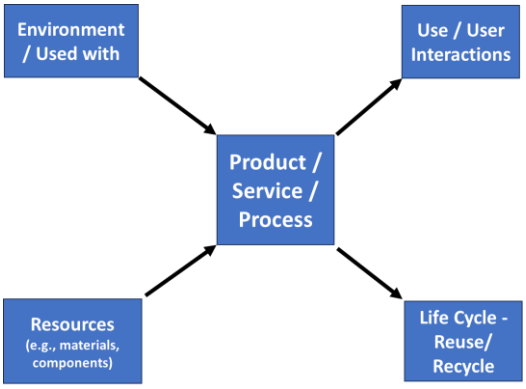



Fig. 1. Conceptualization and interconnections relaed to whole system mapping.

The four steps of whole system mapping adapted from [1] is listed below:

- **Step 1.** Visually map the product's (or service's or process') system.
- **Step 2.** Use estimated product life cycle assessment (LCA) to set environmental priorities, then balance with business or other priorities.
- **Step 3.** Brainstorm further on the system map to generate additional ideas.
- **Step 4.** Choose winning idea(s) based on the identified priorities and expected idea performance.

At TAMUCC, engineering students used steps 1-4 as an in-class exercise during a laboratory period. The students were first presented with a PowerPoint presentation covering the main concepts of sustainable design and whole system mapping (see Appendix), and then shown a short video with an example that

highlighted the concept of sustainability in design where the whole system must be considered to devise the optimal solution. In sustainable design, therefore, it is not enough to consider only one part of the whole system, or subsystem. Students were asked to consider two alternatives, and compare these alternatives to select the best solution for sustainable design.

At TAMUK, the entire exercise was implemented as a take-home assignment, as posted on the OER Website [1], as an individual assignment.

### *B. WSM With Engineering Students*

At TAMUCC, engineering students typically chose tangible projects whose focus was a product, or engineering-related service. These included the creation of a basic utility vehicle, an unmanned aerial system for firefighting, an autonomous rover, a tank for sinkhole simulation and modeling, conversion of a gasoline truck to a hybrid truck, and a weather balloon.

At TAMUK, the students implemented whole system mapping for an infrared mapping system, an automated lighting system, and an autonomous robot for material transport. Students on the same capstone project were asked to attempt whole system mapping individually, so multiple perspectives were possible for the same project idea.

### *C. WSM With Non-Engineering Students*

A very different set of projects emerged from the Gulf Scholars Program students, including creating high-impact business cards, informational brochure, a summer camp, sports fish tagging, and beach (debris) comber.

## IV. Results

Figure 2 depicts an example whole system map [13] developed as a student team in Project Management (Fall 2023), and included in the Capstone Project Final Report (Spring 2024).

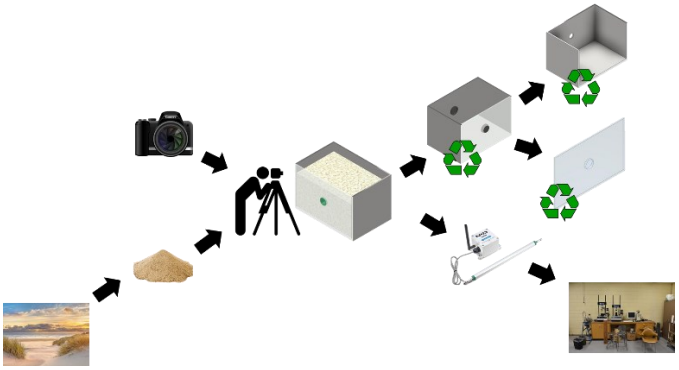


Fig. 2. Sample Student work of a whole system map (soil tank for sinkhole simulation and modeling, an engineering senior capstone design project team) [13].

## V. Preliminary Assessment of Student Work

### *A. Instructors' Assessment*

During whole system mapping in-class exercises at Texas A&M University-Corpus Christi, the students demonstrated creativity, teamwork, and ideation as a group. The students were able to adapt the concept mapping exercise to either their capstone projects, or to a project idea of interest to them or their discipline. The students made strong connections between their product/service idea and raw materials, its user interactions, life cycle, and its environment. They were able to show how the product and system could be created using alternative materials; they demonstrated how their brochure could be turned into a sustainable product by generating a QR code, and updating brochure content on the Internet so it would not be outdated. They successfully investigated the reusability and recyclability of materials when the product life cycle reached its end. On a scale of 1-poor to 5-excellent, all student teams performed at a level of 5-excellent in this assignment.

At Texas A&M University-Kingsville, students demonstrated individual understanding of the concepts in a more extended version of the assignment, completing the entire exercise that provides a 360 viewpoint for whole system mapping for sustainable design ($n = 5$), performing at a level of excellent.

### *B. Student Opinions*

Students were asked to complete an optional survey assessing the Whole System Mapping in-class exercise in engineering Project Management (Senior Capstone Design 1) course. Figure 3 shows the survey results based on average scores for each question.

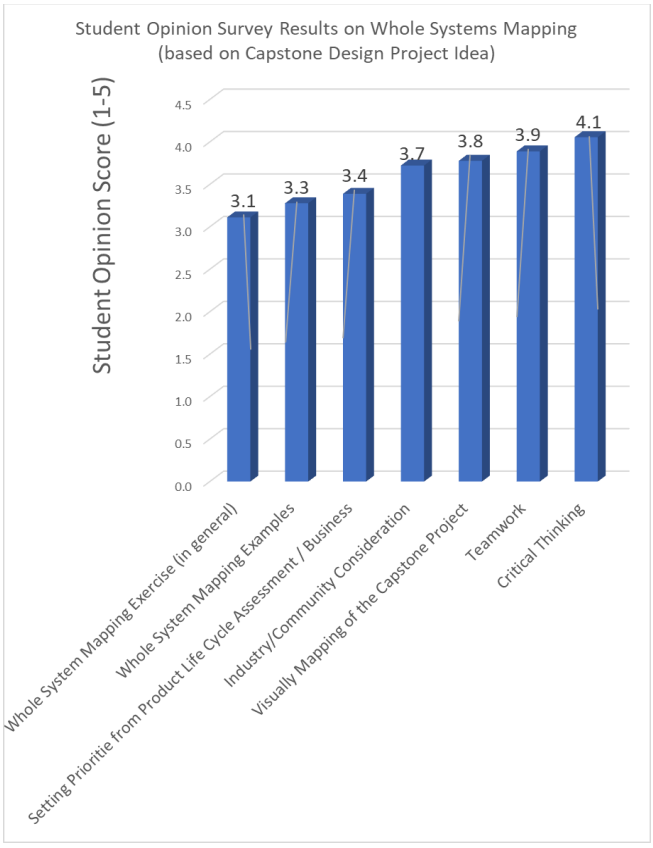



Fig. 3. Student opinion survey results in Project Management (Capstone Design 1) class. 1 – Poor, 2 – Fair, 3 – Neutral, 4 – Good, 5 – Excellent ($n = 18$)

Based on the average scores of 18 students who responded, students ranked all Whole System Mapping exercise related survey questions above 3.0. The WSM exercise, in general, had mixed reviews and received the lowest score of 3.1. Anecdotally, some students mentioned that there was not enough time to complete the exercises in 2-3 hours during the lab time. Some students also mentioned additional examples could have been helpful, as whole system mapping was a new concept for them. The students in this course scored "Setting Priorities from Product Life Cycle Assessment and Business" at 3.4. This exercise excelled in "Critical Thinking" and "Teamwork." The students expressed that this exercise engaged them in critical thinking (score of 4.1) by requiring them to make connections using their knowledge and research results. The majority of students who responded also enjoyed working in teams (score of 3.9), expanding their knowledge through peer-learning. Visually mapping the capstone project was rated at 3.8, suggesting the students found visually displaying the whole system map of their capstone project idea valuable. Making industry/community connections received a comparable score of 3.7, suggesting students were able to make these connections but there is always room for improvement. Surveys in the other two classes were not completed during class.

## VI. Conclusions

Based on the observations and student performance, and student opinion results, whole system mapping was successfully completed by both engineering and non-engineering students, and both in teams and as individual student exercises.

The project ideas categorically varied among engineering and non-engineering students. Some service projects appeared among non-engineering teams' project ideas, whereas among capstone teams, the project ideas centered around the development of a prototype.

Students successfully compared the sustainability of their design and design options, appropriately selecting the optimal solution for their application. Interdisciplinary teams produced more diverse solutions than teams composed of same majors.

OER as external resources developed by VentureWell to conduct whole system mapping that foster sustainable design thinking were successfully incorporated into three courses as innovative practice where the students in these courses had not experienced or covered relevant topics, or achieved relevant objectives, before. The team looks forward to expanding this work to other courses as well as new cohorts in these courses using EOP and other OER.

## Acknowledgment

The work presented here is an extension of work supported in part by an Engineering for One Planet (EOP) Grant awarded to Texas A&M University-Corpus Christi by ASEE and Lemelson Foundation titled "Incorporating Practical, Socially Aware, Sustainable Engineering Solutions in Engineering Coursework," 2023. The authors thank the students who allowed their class work to be shared as successful examples of whole system mapping exercises.

## References

[1] Tools for Design and Sustainability, https://venturewell.org/tools_for_design/introduction/

[2] N. Cavill, D. Richardson, M. Faghy, C. Bussell, and H. Rutter, "Using System Mapping to Help Plan and Implement City-Wide Action to Promote Physical Activity," J. Public Health Research, 9(3), 2020. doi:10.4081/jphr.2020.1759

[3] M. N. A. Nasir, A. N. A. E. Efendi, "Arguing for the Neo-Biopsychosocial Agenda: How Does Human Rights Fit In And Which Political Paradigm To Use," South East Asia J. Contemporary Business, Economics and Law, 18(5), 2019. ISSN 2289-156.

[4] J. Faludi, A. Agogino, S. Beckman, and A. Isles, "What Green Design Activities And Mindsets Drive Innovation And Sustainability In Student Teams?" 21st International Conf. Engineering Design, 21-25 August 2017, The University Of British Columbia, Vancouver, Canada, pp. 88-97, 2017.

[5] M. Ö. Gürel, "Explorations in Teaching Sustainable Design: A Studio Experience in Interior Design/Architecture," Int. J. Art & Design Education, vo. 2, issue 9, pp. 184-199, 14 June 2010. https://doi.org/10.1111/j.1476-8070.2010.01649.x

[6] "Students, Sustainability and Education: Results from a survey of students in higher education around the world," Students Organizing for Sustainability International, SOS Report, pp. 1–122, February 2021.

[7] V. Matthew, C. Anderson, C. Cooper, S. Lipkin-Moore, "Integrating Sustainability into Engineering Education: Building a Pathway to Scale," Annual ASEE Conference and Exposition, Baltimore, MD, USA June 25-29, 2023.

[8] ABET, Engineering Accreditation Commission, Criteria for Accrediting Engineering Programs, 2024 – 2025, pp. 1-56, Nov. 2023. https://www.abet.org/wp-content/uploads/2023/05/2024-2025_EAC_Criteria.pdf

[9] B. Flores, "A Systems Engineering Capstone Course that Makes a Difference," 2012 ASEE Annual Conference & Exposition, San Antonio, TX USA.

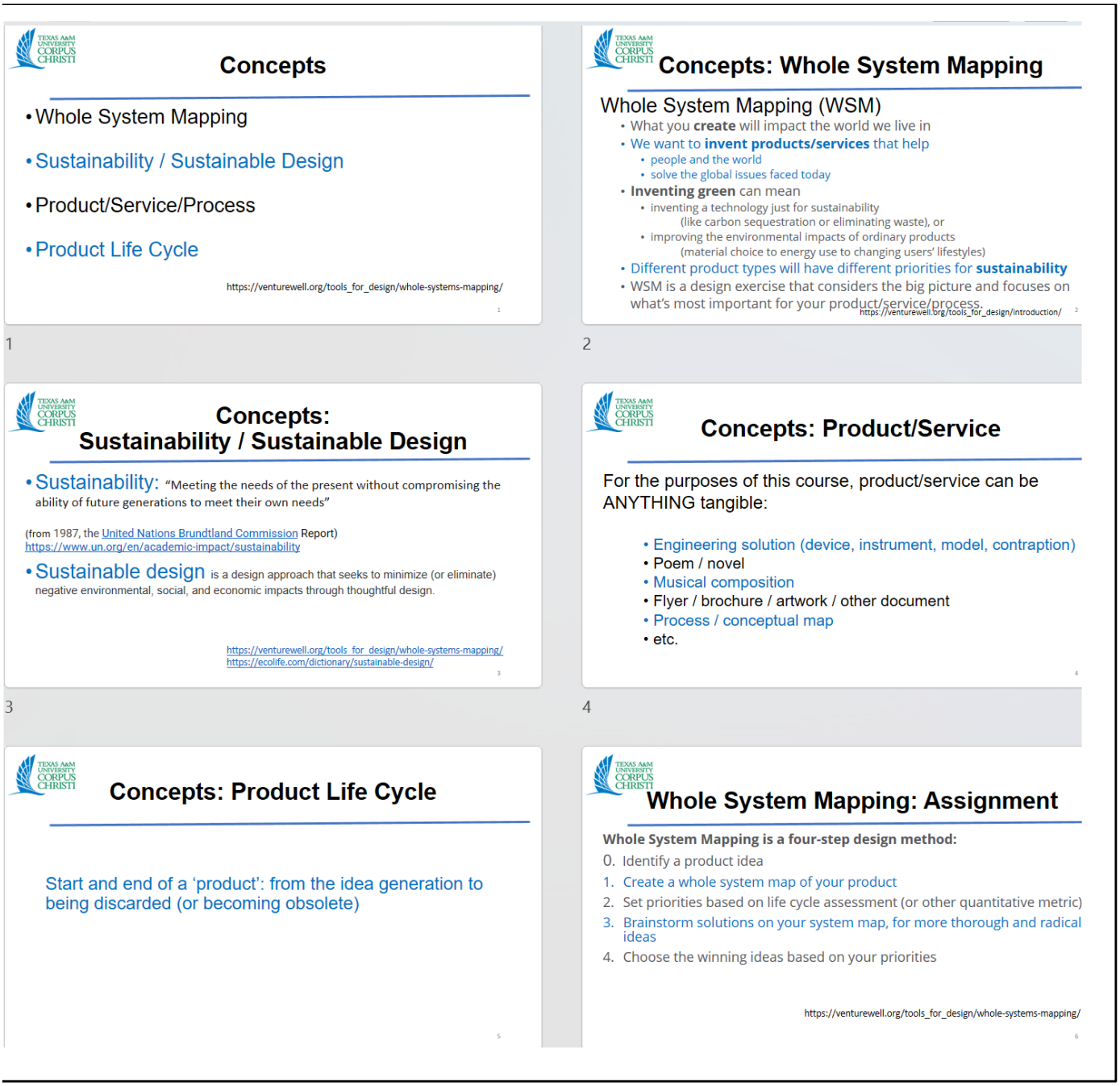
[10] C. Schimpf and A. Olewnik, "Surfacing Students Design Problem Understanding through System Mapping: A Novice-Expert Comparison," 2022 ASEE Annual Conference and Exposition, Minneapolis, MN, USA.

[11] M. Ghadiri, R. Newell and T. Krawchenko, "Participatory System Mapping for Food Systems: Learned from a Case Study of Comox Valley, Canada," Challenges 2024, 15, 22.

[12] J. Faludi, F. Yiu, and A. Agogino, "Where do professionals find sustainability and innovation value? Empirical tests of three sustainable design methods," Design Science, 6(e22), Article e22, 2020.

[13] B. Alaniz, V. Castaneda, B. Loya, A. Nawaz and P. Puebla, "Sinkhole Simulation and Measurement Tank (SSMT)" Capstone Projects Final Report, Texas A&M University-Corpus Christi, p. 27, May 2024.

APPENDIX


Concepts
• Whole System Mapping
• Sustainability / Sustainable Design
• Product/Service/Process
• Product Life Cycle
https://venturewell.org/tools_for_design/whole-systems-mapping/
1
Concepts: Whole System Mapping
Whole System Mapping (WSM)
• What you create will impact the world we live in
• We want to invent products/services that help
• people and the world
• solve the global issues faced today
• Inventing green can mean
• inventing a technology just for sustainability
(like carbon sequestration or eliminating waste), or
• improving the environmental impacts of ordinary products
(material choice to energy use to changing users' lifestyles)
• Different product types will have different priorities for sustainability
• WSM is a design exercise that considers the big picture and focuses on what's most important for your product/service/process.
https://venturewell.org/tools_for_design/introduction/
2
1
2
Concepts:
Sustainability / Sustainable Design
• Sustainability: "Meeting the needs of the present without compromising the ability of future generations to meet their own needs"
(from 1987, the United Nations Brundtland Commission Report)
https://www.un.org/en/academic-impact/sustainability
• Sustainable design is a design approach that seeks to minimize (or eliminate) negative environmental, social, and economic impacts through thoughtful design.
https://venturewell.org/tools_for_design/whole-systems-mapping/
https://ecolife.com/dictionary/sustainable-design/
3
Concepts: Product/Service
For the purposes of this course, product/service can be ANYTHING tangible:
• Engineering solution (device, instrument, model, contraption)
• Poem / novel
• Musical composition
• Flyer / brochure / artwork / other document
• Process / conceptual map
• etc.
4
3
4
Concepts: Product Life Cycle
Start and end of a 'product': from the idea generation to being discarded (or becoming obsolete)
5
Whole System Mapping: Assignment
Whole System Mapping is a four-step design method:
0. Identify a product idea
1. Create a whole system map of your product
2. Set priorities based on life cycle assessment (or other quantitative metric)
3. Brainstorm solutions on your system map, for more thorough and radical ideas
4. Choose the winning ideas based on your priorities
https://venturewell.org/tools_for_design/whole-systems-mapping/
6