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Integrating Sustainability Issues into a Materials Science Course using Universal Design for Learning Principles

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Abstract

This paper summarizes the evolving integration of sustainability issues into a materials science course taught within a multidisciplinary engineering program over the previous four years at the University of Colorado Boulder. Integrating sustainability topics was hoped to bridge the sociotechnical divide that is common in engineering education. The course worked to achieve the overarching learning goal "Think about the broader implications of materials, such as the triple bottom line for sustainability over the life cycle (cradle to grave or cradle to cradle) including environmental impacts, social impacts, and economics." The teaching methods included assigning the textbook chapter on environmental and societal issues during the first week of the semester, integrating sustainability topics into lectures consistently throughout the semester, and requiring students to consider social and environmental issues as part of two open ended projects. Sustainability-related topics were worth about 6% of the overall course grade. Teaching and assessment methods in the course were intentionally selected to provide students choice and flexibility, aligned with Universal Design for Learning (UDL) principles which are intended to create a neuroinclusive environment. Examples of UDL practices included: (1) allowing students the choice of whether to work alone or in self-selected groups for the course projects; and (2) allowing students the option of how to communicate their knowledge on the projects (written report, website, or recorded video). The quality of the students' knowledge about sustainability as revealed through the projects was highly uneven, and on average weaker than their scores on the more traditional technical portions of the project. It is hoped that the examples and lessons learned will help others integrate sustainability topics into materials science courses. However, it appears difficult to instill a sociotechnical mindset and overcome the engineering culture which preferences technical topics.

Introduction

It is important that engineers work to create products and infrastructures that are sustainable. Sustainability encompasses environmental, social, and economic factors, considering both current and long-term impacts. There is an opportunity to create our products, structures, and infrastructure out of a variety of materials, and these decisions have impacts on human safety, environmental pollution, global equity, and lifecycle costs. An engineer has the challenging task of selecting materials that balance functionality under a range of conditions (e.g., mechanical forces, temperature, moisture, chemical exposure) with broader impacts (e.g., human impacts and air, water, and soil pollution during raw material extraction, refining, and processing) and cost. It is crucial that engineers are trained to consider these broader impacts along with more traditional constraints. In a study published by Theil et al. [1], 99% of the faculty members of the Materials Research Society believed that sustainability should be incorporated into the curriculum. Interestingly, geographically disaggregating survey results they found that the United States had the lowest percentage of students who indicated that they had been exposed to sustainability during their higher education experience [1].

Sustainability knowledge and attitudes are increasingly important for engineers. Sustainability topics relate to the ABET Engineering Accreditation Commission (EAC) requirements of Criterion 3, student outcomes 2 ("…design… with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors") and 4 ("ethical and professional responsibilities … must consider the impact of engineering solutions in global, economic, environmental, and societal contexts") [2]. International accreditation requirements are more explicit in requiring sustainable development knowledge and attitudes, e.g., WA3 "design… with appropriate consideration for public health and safety, whole-life cost, net zero carbon as well as resource, cultural, societal, and environmental considerations as required" and WA6 "analyze and evaluate sustainable development impacts to: society, the economy, sustainability, health and safety, legal frameworks, and the environment" [3]. Within the NCEES *Fundamentals of Engineering Exam Handbook* [4] sustainability is included within the ethics and professional practice section (page 12), as well as formulas to quantify sustainability impacts within the environmental engineering section (page 356). Sustainability is stated to be a topic included within the NCEES FE exams for chemical, civil, environmental, industrial and systems, mechanical, and other disciplines [4].

Sustainability falls squarely within the realm of socio-technical considerations [5]. Previous research has found that engineering students often prioritize technical issues and fail to recognize broader social implications [6],[7]. This can be considered a culture of engineering or mindset of engineers. To develop a sociotechnical perspective in engineering students it is important to take an across-the-curriculum approach [8] rather than teaching these ideas in only a single course or a few modules. It is also important to recognize that there are different definitions of sustainability [9]. The Engineering for One Planet (EOP) framework offers a holistic view of sustainability tied to tangible and proven teaching practices in engineering [10], [11]. Systems thinking is at the heart of the EOP model which also includes a set of knowledge and understanding domains (i.e., environmental literacy, responsible business and economy, social responsibility), technical skills (i.e., environmental impact assessment, materials selection, and design), and leadership skills (i.e., critical thinking, communication & teamwork). The EOP materials selection skill includes 6 core learning outcomes and 8 advanced learning outcomes. For example, core learning outcome 1 is to "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) [10, p. 18].

Materials science is a required course in many engineering curricula [12],[13]. It is also a required topic included on the NCEES Fundamentals of Engineering (FE) Exams [4] in the disciplines of chemical (materials science, 4-6 questions), civil (materials, 5-8 questions), electrical (properties of electrical materials, 4-6 questions), mechanical (material properties and processing, 7-11 questions), and other disciplines (materials, 6-9 questions). The integration of sustainability topics into materials science is therefore an opportunity to promote a sociotechnical mindset among students and might be part of a large curriculum wide effort.

A number of examples of sustainability integration into materials science courses have been previously published. Ruzycki embedded sustainability into a laboratory-based materials course, including case studies, life cycle analysis, and the Granta CES software [14], [15]. Dr. Jordan's materials science course at Baylor University incorporated two modules with sustainability integration [16]. Both modules were taught incorporating active learning in team settings. One module centered on the analysis of different materials used in baseball bats and the second was centered on metal corrosion and recycling.

Przestrzelski et al. [17] described four modules that they introduced into a materials science course at the University of San Diego. The modules were generally focused on waste and included a personal look at student's own waste generation, a field trip to a city recycling facility, a guest speaker on waste disposal, and an assessment of the materials used in a commercial product. The modules each included a student reflection, and the authors report that students were generally interested in the content.

Interesting cases related to the conflict minerals used in electronics and recycling electric vehicle batteries are being developed for circuits courses but are equally applicable for materials science [18]. There were also examples of sustainability topics integrated into materials courses for construction engineering and civil engineering via projects on green concrete [19], [20]. Beyond a single course, Lesar et al. described how sustainability topics were being integrated into the materials science undergraduate curricula at Cal Poly, Worcester Polytechnic Institute, and Iowa State University [21].

A large study was conducted to benchmark where sustainability topics had been integrated in 100 mechanical engineering programs [22]. The data source was information submitted by institutions to the American Association for Sustainability in Higher Education (AASHE) in pursuit of certification under the Sustainability Tracking, Assessment & Rating System (STARS) program [23]. Evidence of sustainability integration into materials science courses was found in 5 of the programs. Three of the 5 were international institutions, one-third of the 9 international institutions in the data set. The specifics from those programs are shown in Table 1. In only one course was specific information provided about how sustainability topics were integrated into the course (Santa Clara University). At two institutions the information appeared to be a brief mention in the catalog description of the course. In two cases there was no tangible evidence provided by the institution as to why the course was classified as including sustainability topics.

Table 1. Materials courses counted by institutions as including sustainability under STARS

Institution	Course	Sustainability Descriptors
Santa Clara University	MECH 163 Materials Selection	Case studies and discussions on process economics, life-cycle thinking and eco-design. Use CES EduPack software to select a combination of appropriate material and manufacturing method that optimizes cost, performance and sustainability for a specific application
University College Cork – National U of Ireland	ME1001 Engineering Materials	Environmental and ethical issues Mapped to the United Nations Sustainable Development Goal 7 affordable and clean energy and 9 industry, innovation, and infrastructure
University of Queensland	Science and Engineering of Metals Materials Selection	… corrosion, recycling, future directions Principles & practice of materials selection in mechanical design. … Economic aspects. … Concurrent and compound objectives. Selection of materials for a practical application (project).

Institution	Course	Sustainability Descriptors
Universidad San Francisco de Quito	IME 3101 Materials Science and Engineering Lab	*(counted by the institution in STARS but nothing specific evident in the course description in the catalog)*
Seattle University	MEGR-3500 Materials Science	*(counted by the institution in STARS but nothing specific evident in the course description in the catalog)*

Increasingly engineering education is moving beyond a focus on topics that need to be taught to exploring how best to facilitate student learning to reach desired learning goals. While the effectiveness of different educational strategies varies, it is generally believed that student centered teaching approaches yield better learning outcomes [24], [25]. Universal Design for Learning (UDL) acknowledges that both our teaching practices and assessments of learning can be designed to enable all students equitable access to education [26],[27],[28]. UDL explicitly acknowledges that some educational practices are incompatible with particular dis/abilities and that students have individual strengths for particular learning modalities.

Many college students are neurodivergent, with brains that function differently than the "typical norm". Under the medical model, conditions such as Attention Deficit Hyperactivity Disorder (ADHD), Autism Spectrum Disorder (ASD), dyslexia, and others are considered neurodivergent. However, from a theoretical perspective, neurodiversity rejects the medical model that frames atypical neurotypes as deficits [29]. Rather, neurodiversity recognizes that individuals may be afforded advantages and disadvantages based on particular social systems. Further, due to the limitations and variability of medical diagnosis among demographic groups, the neurodiversity framework allows individuals to self-identify as neurodivergent (ND). Many ND individuals have a range of conditions, and these overlapping effects may mask typical 'symptoms' used for diagnosis. Studies have found that as many as 37% of engineering students may be ND [30], contrasting with earlier studies finding a small percentage of ND students in engineering (3-5%) [31]. One should not assume that the accommodations process typical at most universities will 'level the field' for ND individuals. Faculty can design their courses to provide education that is neuroinclusive [32]. These aspects fall within the UDL paradigm.

Goals of the Paper

This research explored the extent to which the integration of sustainability topics into a materials science course using UDL principles for assessment seemed successful. The sections below first provide an overview of the course, followed by details of the teaching methods used to integrate sustainability topics into the course. The direct assessment of the student projects is used as evidence of student learning related to sustainability topics. The paper concludes with suggestions for improvement.

Course Context

This intervention was conducted in a 3-credit materials science for engineers course offered as part of a multidisciplinary engineering program at the University of Colorado Boulder. The Integrated Design Engineering (IDE) program has students select a technical emphasis in aerospace, architectural, civil, environmental, electrical, or mechanical engineering. The course was one option to fulfill the materials science requirement in the IDE major, as well as counting as an option to the traditional materials science courses taken by mechanical and aerospace engineering students. The course met three times per week with a 50-min class on Monday and Friday plus a 2-hour lab on Wednesdays. Most weeks a topic was introduced via lecture on Monday (with embedded iclicker questions to encourage active student engagement), a related lab was done on Wednesday, and Fridays were primarily devoted to problem solving (often worksheets distributed and students encouraged to work with a partner or table group).

The course was largely structured around the topics in the textbook by Callister and Rethwisch, *Materials Science and Engineering: An Introduction* [33], with one to two chapters grounding the topics covered for the week. Students purchased the WileyPLUS 10th edition of the book, giving them access to the additional online materials (practice problems and solutions, muddiest point videos, etc.). Each week students were given a list of textbook problems that they were encouraged to complete on their own; solution sets written up by the instructor and/or Teaching Assistant (TA) were provided for those problems via the Canvas course management system.

Most of the weeks in the semester the students completed an online quiz that provided a series of multiple-choice questions related to concepts and short quantitative problems. Quizzes were worth 20% of the overall course grade. The students could use their notes or resources to complete the quizzes but were encouraged to try using only the *NCEES FE Reference Handbook*. This would prepare the students for the final exam (worth 15% of the overall course grade) which was styled off the FE Exam where students were only allowed to use the FE Reference Handbook. Solution sets were provided for each quiz. Students were allowed to take a second quiz on the same content and only the higher score was retained for their grade. Most of the students completed both quizzes and typically did better on the second. The timing of the quizzes was generous to allow students to consult the textbook and their notes if they hadn't prepared for the quiz in advance. The instructor considered the quizzes via the course Canvas system as an efficient alternative to grading weekly assignments. The quiz would provide quick feedback. The quizzes were modified each year to try to cut down on cheating. In 2024 there were 9 quizzes across the semester. The average time students spent on the first attempt for the quizzes ranged from a low of 16 minutes to a high of 54 minutes, with a median of 35 minutes.

The labs in the course illustrated specific mechanical, thermal, and electrical properties. Many labs utilized two Universal Test Machines, such as for tension tests on specimens of metal and polymer and compression tests on wood specimens. Torsion and hardness tests were also conducted. The students completed a short pre-lab assignment with a video and introduction to the test procedures. After collecting data, the post lab required calculations and short answers on observations. Students did not complete formal lab reports. The labs were graded for participation, and along with class attendance comprised 15% of the overall course grade.

The final component of learning and assessment activities in the course were three projects, worth 50% of the overall course grade. The first two projects were literature studies of a particular material, including sustainability aspects. Students were provided with a detailed rubric that outlined the content requirements. More details on these projects are discussed later in the paper. The third project required students to design their own materials testing experiments.

The course primarily enrolled sophomore and junior students, with 21 to 34 total students per term. The course instructor and author began teaching the materials course in spring 2021 and made iterations on how sustainability topics were integrated during this time. A previous instructor at the institution shared their course materials but had not integrated sustainability topics. The discussion below primarily focuses on the spring 2024 course, except where noted.

Course Topics and Objectives

The description of the course in the university catalog and included in the syllabus was:

> Examine structure, properties, processing and uses of metallic, polymeric, ceramic and composite materials; topics include perfect and imperfect solids, phase equilibria, transformation kinetics, mechanical and electrical behavior and failure modes.

This description is very similar to the multiple versions of the materials science course at the university (i.e., nearly identical to the mechanical engineering version of the course). Three additional goals were included on the syllabus:

- Apply materials science information in the engineering process to select appropriate materials, with broad considerations of the primary and secondary effects.
- **Think about the broader implications of materials, such as the "triple bottom line" for sustainability over the life cycle (cradle to grave or cradle to cradle) including environmental impacts, social impacts, and economics**.
- Be prepared for the types of materials science questions on the NCEES Fundamentals of Engineering (FE) exam.

Students earning a degree in the Integrated Design Engineering program are required to take the FE exam prior to graduation, so the final objective helps prepare them for the style of questions and format of the exam (given that some of the materials science equations in the NCEES Reference Handbook are not identical to the textbook).

In-Class Lecture

From the start of the semester, the instructor made a concerted effort to embrace the sociotechnical nature of engineering and the real-world importance of materials science. On the first day of class, students were asked to think about their favorite project that they had designed and built in a previous course (e.g., the required first-year design course) or personally. They were asked how many different materials were in their favorite project (which for many would have been over 20 if their project included an Arduino Uno board). Students shared their guess using an embedded classroom response system (i-clicker). Then they were asked what factors impacted materials selection for their project. Five choose all-that-apply options were provided: cost, availability, compatible with equipment in the campus manufacturing center, social and environmental factors, or didn't think about it. During the discussion it was clear that almost no students had considered social and environmental factors. Rather they were focused on quickly making a low-cost gadget that would survive through the end-of-semester expo or creating a functional product for future use. This often involved using materials readily available (such as the 3D printing filament provided by the university, sometimes scrounging materials they could get for free like cardboard from a recycling bin). This simple discussion was intended to raise their awareness for future class projects, and more broadly their decisions when purchasing products as consumers.

Chapter 22 in the Callister and Rethwisch [33] textbook focuses on sustainability topics, including environmental and societal considerations and recycling issues. The location of this topic at the end of the book seems to position it as an afterthought, and many instructors may not even reach this chapter. Therefore, this content was moved to the second lecture of the semester. The two learning objectives stated at the start of that lecture were:

- Diagram the total materials cycle, and briefly discuss human safety, health, and environmental issues that pertain to each state
- Understand quantitative metrics that can be used to evaluate human and environmental effects

Figures 22.1 and 22.2 on lifecycle impacts from the textbook [33] were shown and discussed. Students were also directed to information in the NCEES FE Reference Handbook [4] on societal considerations (page 12), safety (page 13), safety data sheets (page 18), and toxicology (pages 21-24). Qualitative and quantitative information on human health impacts were presented, including information from lead as a specific example (see lecture slide in Figure 1). The goal was to illustrate the importance of the topic and provide interesting, concrete examples.

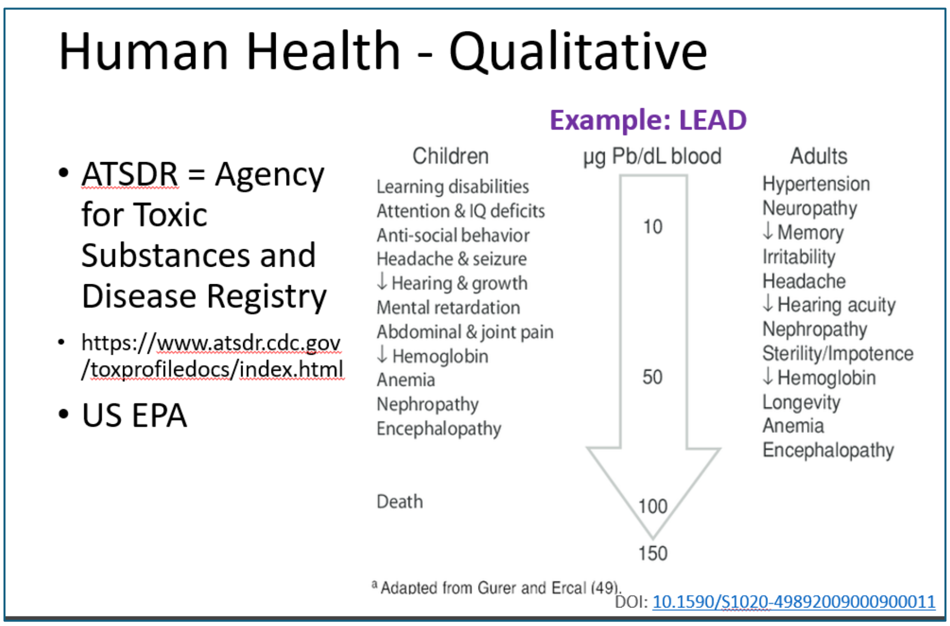

Figure 1. Example slide illustrating human health effects [34]

Contemporary sustainability issues were integrated into the lecture throughout the semester (examples in Table 2). These topics were updated each year and often generated questions and discussion, with the real-world context interesting at least some students. Links to more information were embedded into the modules in Canvas. Common topics related to renewable energy, the processes used to extract the raw materials from the earth, and end-of-life issues. For example, in week 5 the Canvas module included a link describing the process to convert toxic aluminum production waste into steel [35]. Week 7 on polymers described how plastic is made from crude oil [36] and nanoplastic concerns [37]. In 2024 there was an inadvertent gap between the initial focus on socioenvironmental context in week 1 and returning to these topics in lecture. In contrast, in 2023 there was better integration across the semester.

Table 2. Examples of sustainability-related topics integrated into lectures

Book Chapter	Topic	Reference(s)
22	Economic, environmental, and societal issues in materials engineering; Wind power example	Callister and Rethwisch [32]; [38] Wind turbine blade materials [39]
2	Rare earth elements - mining	[40]
8	Safety, testing – faked submarine material tests	[41]
14	Plastic pollution during its lifecycle	[42], [43], [44]
14	Nanoplastics prevalence and health concerns	[45]
15	Road made of recycled plastic	[46]
12, 13	Ceramics, carbon footprint, water usage, recycled fraction	Bubble charts [47]
17	Corrosion of lead pipe and Flint	[48]
17	Biodegradable plastics? PLA	[49]
18	Generate energy from roads	Piezoelectricity [50]
18	Solar energy and materials	[51]
16	Composites: carbon footprint of construction materials	[52], [53]

Class Projects

The primary integration of sustainability issues was conducted and assessed via open-ended projects. The goal of the projects was to allow students to do a deep dive into a particular engineering application (product) and explore the materials concepts in this applied context. This linked materials science to engineering applications. Allowing the students the freedom to select product was intended to spark their interest and motivation. This was also important because the students represented a range of technical emphasis areas – aerospace, environmental, and mechanical engineering, for example. Thus, their project topic could be more related to future products and materials of importance to their technical specialty area.

The first project required students to conduct an in-depth study on a metal. The second project was similar but required students to select a polymer or ceramic material. The projects were worth 16% and 18% of the course grade, respectively. The project required students to include: product description including the quantity and role of the focus material (e.g., amount of copper in a phosphor bronze guitar string); material structures (atomic to macro, including microscope photo and phase diagram); material properties (mechanical, thermal, electrical, etc.); processing and production; defects and durability; measurement and analysis; health and safety; environmental sustainability. Students could also add bonus information for extra points, such as economic information (cost), history of the product, etc. Within each of the two projects, sustainability topics (social and environmental) accounted for 20 to 22% of the available points. The detailed instructions for these topics on Project 1 in 2024 are provided in the Appendix.

In 2021 the course paid for a site license to Granta EduPack. This allowed students to access software that included material properties, manufacturing methods, and the Eco Audit. Within the Eco Audit students could see the CO_2 footprint and production energy of a material, including the manufacture, transport, use, and end-of-life phases of a product. In 2022 and beyond, the instructor could not afford the licensing fee. Thus, resources were provided by the instructor via the course management system (examples from Fall 2023 are summarized in Table 3) and students needed to find other information on their own. Integrating lifecycle related social and environmental issues into the context of a product the students self-selected to explore was hoped to be personally meaningful. Most students picked products relevant to their personal interests (e.g., bicycles, bicycle helmets, skateboards, climbing equipment, camping gear, contact lenses).

Table 3. Materials Sources related to sustainability provided to the students

References	Summary	Ref#
Granta2 Materials Charts 2010	Chart 15 approximate material cost Chart 18 Approximate material energy content	[47]
Nuss and Eckelman 2014	Life cycle assessment of metals, using periodic table and impacts such as global warming potential, cumulative energy demand, terrestrial acidification, eutrophication, human toxicity	[54]
Schwartz et al. 2021	LCA of 25 polymers, including 12 metrics such as climate change, human toxicity, eutrophication, water depletion	[55]
ATSDR MRLs 2023	Minimum risk levels for negative human health effects via oral or inhalation routes	[56]
Circular Ecology	Embodied Carbon – The ICE Database	[57]

Students were encouraged to ask for help if they were struggling to find information related to sustainability topics for their material and/or product. This information for most materials is readily available in a wealth of technical papers. For example, a student project in 2022 included an analysis of copper and galvanized steel water pipes and the instructor provided a 2017 paper on the carbon footprint of copper and zinc [58]. Environmental impact data for materials may also be embedded within an analysis of a different product application than the students were studying, but still provide useful information. For example, the embodied CO_2 values for 5 different plastics were reported in a 2015 paper on geosynthetics [59].

UDL Elements

There were two main attributes of the materials projects that embraced the principles of Universal Design for Learning (UDL) / neuroinclusion. First, students were given the option to work alone or with a self-selected group of up to four students. Nearly all of the engineering courses at this institution require at least one group project, so teamwork was not a learning objective for the materials course. Groups were required to compare multiple materials within the same product or different material options for making the same product. As shown in Table 4, about half of the students chose to work alone and half in groups. This was true for both the first and second project. In 2024 working in a group was widely preferred and in 2022 working alone was widely preferred. Most students stayed with the same modality of working alone or with the same peers on both the first and second project, and only a few groups split up after the first project (1 or 2 per term) and few new ones formed. Groups of 2 or 3 students were most common, and 4 was very rare.

Table 4. Number of students each semester who chose to work alone or in a group

Year	Project 1		Project 2	
	N work alone	N work in teams	N work alone	N work in teams
2021	8	16	11	13
2022	17	4	17	4
2023	18	16	20	14
2024	6	15	7	14
TOTAL, %	49%	51%	55%	45%

There are many potential reasons why so many of the students opted to work alone. Working alone gave the student full control of a particular product or material they researched. Many students selected a personal hobby and they may not have found another student interested in that topic. A few students had particular extracurricular activities with scheduling demands that made working in a group difficult (e.g., one traveled frequently as part of the ski team; one worked at a job nearly 40 hours per week). Some students had very high standards and were tired of working in groups with others who don't contribute as much; many of the highest scores were awarded to projects submitted by a student working alone. It is known that some types of neurodivergence may increase challenges with interpersonal interactions (e.g., Autism Spectrum Disorder [60]) and other group activities (e.g., executive function and meeting deadlines for individuals with ADHD [61],[62]). The neurodiversity of students in the course is unknown.

As a second practice aligned with UDL, students could demonstrate that they fulfilled the project learning objectives via one of three options: (1) a standard written report; (2) a website; or (3) a video recording. Table 5 shows the number of students who selected each project format. The most popular option, particularly on the first project, was a standard written report. Students likely felt more comfortable with the written report format and how it would be graded. In 2023 the website option for Project 2 was almost as popular as the written report. Examples of student websites were shared (upon permission from the students in 2021 and 2022) which likely increased student understanding of the expectations for this submission format. There was only a single team of 2 students who completed the video together. This team included a very high performing student who wanted to push himself out of his comfort zone.

Table 5. Number of students who selected each project submission format

Year	Project 1			Project 2		
	Written	Website	Video	Written	Website	Video
2021	24	NA	NA	20	4	0
2022	18	3	0	16	5	0
2023	21	13	0	17	15	2
2024	16	5	0	15	6	0
Total, %	79%	21%	0%	68%	30%	2%

NA = this option not available to students

Assessment

Performance on the two class projects was used as direct evidence of student knowledge of sustainability and technical elements related to materials science. The Appendix shows the content expected to be addressed to earn full credit on the sustainability-related topics, broken into Health and Safety (reflective of social issues) and Environmental Sustainability. Student reports or websites that included all of the content elements in the prompt received full credit. Points were deducted for missing elements. The sustainability-related topics comprised 20-22% of the overall project grade. Similarly detailed requirements were provided for expected content in the technical elements in the report, which included structure, properties, processing, defects, durability, and measurement of properties. The technical topics comprised 56-58% of the overall project score. The overall report had additional graded components (e.g., product description, format, references) that are not considered in this paper.

Table 6 summarizes the number of projects and grades awarded on Project 1 and Project 2 in different years of the course. The points across the sustainability-related topics were summed and are reported as a percentage. The scores on the technical topics were also summed and are reported as a percentage. The ratio of the percentage score on the sustainability topics to the percentage score on the technical topics for each project are reported in Table 6. A ratio score below 100% or 1 represents a project where the student performance on the sustainability topics was weaker than that on the technical topics. Note that projects done by groups of students were logged once which is why the student numbers in Table 5 do not match the number of projects shown in Table 6; for example, the 24 students in 2021 (Table 5) submitted 19 different project reports (Table 6).

Table 6. Grades awarded to sustainability and technical topics on the student projects

Parameter	2024	2023	2022	2021
Project 1 - metal				
Number of projects	*19*	*25*	*18*	*16*
Sustainability score (min – avg – max), %	57-84-100	58 - 80 - 99	0 - 79 - 99	75 - 90 - 100
Technical score (min – avg – max), %	58-88-100	79 - 89 - 100	47 – 87 – 100	71 - 87 - 100
Ratio sustainability / technical score, %	77-96-125	67 - 89 - 118	0 - 90 - 173	83 - 103 - 134
Number of projects s/t score ratio <1	*12*	*17*	*16*	*5*
Project 2 – polymer, ceramic, advanced				
Number of projects	*17*	*26*	*17*	*15*
Sustainability score (min – avg – max), %	41-71-100	55 – 80 – 97.5	60 – 83 – 100	70-89-100
Technical score (min – avg – max), %	71-89-100	55 – 88 – 97.4	79 – 92 – 100	68-89-99
Ratio sustainability / technical score, %	49-82-102	64 – 92 – 125	70 – 90 - 108	79-100-118
Number of projects s/t score ratio <1	*16*	*19*	*15*	*8*

A wide range of student performance is evident in both the sustainability topics and technical topics. At least one submission received a nearly perfect score on the sustainability and technical topics across all years on both projects. The minimum scores were lower on the sustainability topics compared to the technical topics in 2022 (e.g., a Project 1 included no content on sustainability topics and earned 0%), Project 1 in 2023, and Project 2 in 2024. Disappointingly, the student scores did not noticeably improve between Project 1 and Project 2.

Across all years and both projects, 71% of the submissions earned higher scores on technical compared to sustainability topics. In 2022 to 2024 students on average earned higher scores on the technical topics than sustainability topics. There was a slight edge to the sustainability topics in 2021, with 11 of 16 teams earning higher scores on the sustainability issues compared to technical issues on Project 1. That year the students had access to the Granta EduPack software, which readily produced quantitative estimates of energy use and carbon footprint. However, many students reported these numbers without discussing their meaning or implications. In 2022 to 2024 most students wrote good qualitative discussions of an array of human health, social, and environmental factors related to their material and product but often presented little or no quantification of those aspects. Finding this quantitative information may pose challenges, although a number of websites were provided in the assignment (see Appendix). The sustainability related topics were listed last in the project outline and rubric, so if the students were working linearly they may have run out of time to do a thorough job on these issues. Students often procrastinate and so this is one plausible explanation that may contribute to the lower scores on the sustainability topics. This information may also be more difficult to find for particular materials and/or of less interest to the students.

Limitations. Using the scores awarded by the instructor when grading the assignments is subject to error due to different expectations and content topics from year to year. While at a basic level these were remembered to be similar, this might not be the case. Content analysis could be conducted on 5 reports from each year, representing the low, Q1, median, Q3, and highest scores earned on sustainability topics. This would help to verify the quality of sustainability content in the student work and whether it changed between years in the course. Given the different engineering emphasis areas of the students, incoming knowledge and interest in sustainability topics might vary each year; e.g., highest among students in the environmental emphasis.

Future research could explore whether there are particular demographics of students who are more likely to elect to work individually or in groups on the project and write reports or make websites. For example, in Spring 2024 all of the female students worked in groups on the second project. Aligned with UDL, neurodivergent students are of particular interest. ND students could be asked about their preferences for different project attributes, for example. Other dimensions of the course teaching and assessment (grading) practices could also be redesigned to be more neuroinclusive.

It would be interesting to explore students' broader attitudes toward engineering and the important and inextricable social and environmental effects of our work. The extent that students have a dualistic technical/social mindset or an integrated sociotechnical view of engineering perhaps correlates to their engagement with the sustainability topics in the course. Exploring whether student attitudes change across the semester would be interesting, although this is a single course and students would be taking a number of other engineering courses that might overwhelm the impacts of sustainability integration in this course to combat the typical engineering culture of disengagement [63].

Suggestions for Course Improvement

In order to more fully embrace sustainability within the materials science course, it is recommended to add quiz and test questions on sustainability-related topics. In this course we used simulated Fundamentals of Engineering (FE) Exam questions related to materials science on the quizzes and final exam. That did not lend itself to sustainability-related questions. However, this might inadvertently send an implicit message that the technical topics are of greater importance. Questions related to topics in the FE Reference Handbook such as ethics and safety could be included as topics on the final exam to reinforce their importance.

There is a wealth of information about sustainability topics relevant to materials science and engineering. This includes highly scientific journal papers that have conducted life cycle assessment (LCA). These might not be the best resources to share with students, who might get lost in the details. Perhaps the instructor could pre-record a video to walk through an example of a journal paper with a detailed LCA, assign students to read the paper and watch the video, and then discuss in-class. This flipped process would make efficient use of class time and make students more comfortable understanding LCA information on their own. Finding information at an appropriate level for the students was challenging. There is also rapidly evolving and/or contradictory information on human health and safety, environmental impacts, and other social and economic issues. Instructors need to weigh the importance of finding the latest information (e.g., nanoplastics) versus emphasizing a more general understanding and communicating to students the uncertainty of knowledge about many sustainability topics.

The IDE program and University of Colorado Boulder more broadly have not embraced a single model of sustainability education in engineering. Sustainability education efforts are also largely uncoordinated within single departments. Individual faculty seem to simply adopt the sustainability concepts and practices that are of personal interest. This approach is inefficient and may be confusing to students. A coordinated approach could provide significant benefits. The Engineering for One Planet framework appears to be applicable to all engineering disciplines and has a growing body of teaching resources [10], [11]. A curriculum level integration of sustainability topics would also align with promoting a "humanized socio-technical framework", recommendation 3.4 within the *Engineering Mindset* report [64].

Conclusions

This paper described how sustainability topics were integrated into a materials science for engineers course that served students from a variety of engineering majors and concentrations (e.g., integrated design, mechanical, aerospace, electrical, civil, environmental). In addition to using current events to call attention to sustainability issues briefly during lectures, sustainability considerations were a sizeable part of two projects. These projects allowed students to select a material and product of personal interest, and then explore the science, engineering, and sustainability facets. Overall, the instructor's impression is that most students were interested in the sustainability topics. However, most students demonstrated less knowledge of sustainability topics as compared to technical topics in the projects. This likely reflects the greater amount of targeted instruction and teaching of the technical topics via the lecture and textbook, which were reinforced with weekly quizzes, compared to more self-teaching for some of the sustainability information. Most students demonstrated a qualitative ability to identify a few of the environmental impacts, social impacts, and economic implications of materials across their life cycle. This objective embedded an understanding of how raw materials are refined and manufactured, and from there thinking of broader impacts.

Sustainability and LCA is a complicated subject. Environmental engineering offers an entire course on lifecycle assessment, for example. Thus, instructors should weigh the amount of time needed to develop a more quantitative understanding of these elements against the more traditional materials science and engineering topics taught in the course. It is important to reinforce the "triple bottom line", present needs, and future needs aspects of sustainability. One should avoid oversimplifying sustainability to only consider environmental impacts, and the further simplification of environmental issues to the carbon footprint and long-term impacts. Acknowledging the complexity and difficulty of sustainability accounting is important. Through the selection of materials used in the products that we design, engineers can have a significant role in contributing to a more sustainable future.

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Appendix: Project 1 Prompt related to Sustainability Factors

Health and Safety 10 pts

Discuss the human and environmental health and safety related issues of the material on a chemical level

Be qualitative (e.g., causes lung cancer, endocrine disruptor) and quantitative (dose: response; slope factor for carcinogens, threshold of exposure dose without negative effects)

Include the safety data sheet (SDS) for the primary component material(s) in an appendix.
Manufacturers are required to provide for products. Example:
https://www.kloecknermetals.com/products-services/safety-data-sheets/
You should also include SDS for any important chemicals used in the production / processing of your material and/or product.

In particular, look at the human toxicity and other hazards for workers during raw material extraction, material and product production and processing: https://oehha.ca.gov/chemicals
(OEHHA is good for polymers, less helpful for metals and ceramics)
e.g. OSHA: https://www.osha.gov/annotated-pels/table-z-1

Safety to ecosystem: example of where to find information:
https://response.restoration.noaa.gov/environmental-restoration/environmental-assessment-tools/squirt-cards.html
Does the metal cause negative effects to animals, birds, plants, etc.?

Also consider physical hazards (usually in mining, production of your product, but also potentially during product use)

Environmental Sustainability 12 pts

Discuss and quantify (to the extent possible) the environmental impacts across the life cycle of your product.
This includes **primary material production (mining)**, material processing, and product production
This includes air pollution, water pollution, solid waste.
Think about energy use, CO2 / Greenhouse Gases, particulates to air, eutrophication, etc.…
Example: https://circularecology.com/embodied-carbon-footprint-database.html

Another example:
https://www.navfac.navy.mil/content/dam/navfac/Specialty%20Centers/Engineering%20and%20Expeditionary%20Warfare%20Center/Environmental/Restoration/er_pdfs/s/navfacexwc-ev-ug-1302-sitewise3-20130807.pdf

Discuss end-of-life recycling and/or disposal. This includes your product and the metal.
Include the recycling symbol. How much is actually recycled in the US? What happens if it becomes 'trash' in environment? Will it break down? Hazards to wildlife?

Compare across the materials in your group, alternative or additional materials used in your product, and/or other similar metal / polymer / ceramic materials.

Related information: on the ATSDR Substance Priority List https://www.atsdr.cdc.gov/spl/index.html

There are lots of great papers with lifecycle assessment for different materials; the quantification is often meaningful only when compared (such as energy to produce equivalent to driving gasoline car 100 miles; GHG emissions equivalent to average US home, etc)
Ecoinvent - you can get a free guest account and use their database: https://www.ecoinvent.org/
NREL US Life Cycle Inventory Database: https://www.nrel.gov/lci/

Extras (optional: up to 5 pts)

This could be:
Cost – current and historical cost of the metal / alloy
History of how the material and/or product design or manufacturing have evolved over time
Nanomaterial version of the same metal and how properties and applications change
Current research

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