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Integrating Climate Change Into Engineering Education

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Abstract

Climate change is one of the major societal challenges of this century and students that graduate from engineering programs must be equipped and prepared to address this challenge. Addressing it will require broad societal changes with impacts that will reverberate through all engineering disciplines. Therefore, it is imperative that climate change and its associated impacts are integrated into engineering curriculum so that the future workforce will be ready.

In civil engineering, the impacts will present challenges to the design and maintenance of critical infrastructure systems that support daily life. The key question then becomes "how do we prepare students for careers that will be dominated by climate change and the associated societal changes that it will generate?" Adjusting the curriculum to include climate change requires careful consideration of the impacts that it would have on the students and therefore the impacts it would have on society.

For the desired impact, the undergraduate and graduate level will need different considerations based on the fact that the two students are in different stages of their careers. At the undergraduate level students are preparing for entry-level engineering jobs which will then lead to more senior engineering jobs through experience gains as they advance in their careers. Also at the undergraduate level, curriculum is aligned to ABET student outcomes With one of the key criteria being the preparation of students to become lifelong learners. With this in mind, climate change considerations can be integrated into the existing undergraduate curriculum in civil engineering such that the students that graduate are aware of the impacts that uncertainty in climate change will be having on critical infrastructure systems. At The Graduate level, students are trying to advance their careers through gains and experience in particular disciplines. It is at the graduate level that new courses added to the curriculum can better prepare students to able to analyze and advocate for solutions that combat uncertainty associated with climate change and its impacts effectively. For graduate students to be fully prepared to address climate change, they need to be equipped with skills in two main areas: (1) risk and resilience and (2) game theory. Skills in risk and resilience are necessary to be able to properly analyze and decide on solutions that minimize the risk that climate change will have on critical infrastructure systems. Skills in game theory are necessary to be able to navigate the complexity that climate change represents which creates a highly uncertain and entirely dependent upon the choices that are made today and into the future. The introduction of course modules was focused on climate change into a selection of the courses in the undergraduate curriculum of civil engineering fostering the growth of the mindset of students to be able to take on the daunting challenge of climate change. The introduction of new courses in risk and resilience and Game Theory at the graduate level is producing engineers with the capabilities to address the challenges of climate change in new ways.

Introduction

Climate change is one of the greatest societal challenges of the 21st Century, the impacts of which extend throughout the critical infrastructure systems that society depends on for daily life. It is the responsibility of engineers to design, maintain, and protect critical infrastructure systems such that the quality-of-life of at-risk communities can be preserved. With this in mind, the future engineers that are being produced through universities and colleges must be prepared for challenges that are unlike what has been historically encountered. Particularly in civil engineering, designs have been based on historical climate data on the assumption of climate stationarity, but recent history has challenged that assumption with rising seas and more frequent extreme weather events. Therefore, it is imperative that engineering education adapts in order to provide the engineers that society needs with the knowledge, skills, and abilities to address the challenge of climate change.

This paper explores the need for climate change considerations in civil engineering curriculum at both the graduate and undergraduate levels. The first section focuses on a review of relevant literature on how climate change has been integrated into engineering education. The second section focuses on the methodology consisting of three parts: (1) identification of the key knowledge, skills, and abilities for climate change in engineering, (2) design of new curriculum that integrates climate change, and (3) assessment of the newly designed curriculum. The third section presents the results of the assessment of the new curriculum and a discussion of the implications of the results for further improvement of the curriculum. Lastly, the fourth section presents the conclusions of the paper and identifies future works that will be generated as a result of this research effort.

Literature Review of Climate Change Integrated into Engineering Education

The literature focused on climate change in engineering education is growing rapidly as the impacts of climate change are becoming more prevalent and severe thus promoting further development. The literature can be divided into three parts: (1) importance of climate change in engineering education, (2) pedagogical approaches, (3) challenges and successes.

Importance of Climate Change in Engineering Education

Engineers have an important role to play in the response to climate change due to the risks to infrastructure systems. Martin et al. [1] notes that engineers have two major challenges in relation to climate change and engineering education must be revised to address these challenges: (1) transition to carbon neutral and (2) minimization of the impacts of climate change. The authors further state that engineers will need to possess new skills in order to be able to: (1) link climate and sustainability to design, (2) develop multi-disciplinary solutions, (3) understand ethics and justice implications, and (4) collaborate with diverse communities.

Milovanovic et al. [2] present compelling evidence that undergraduate engineering students in the United States have misconceptions about climate change science and college courses involving sustainable development did not correct the misconceptions. Even more troubling is that Shealy et al. [3] found that half of high school students, that were interested in civil engineering, did not believe in human-caused climate change. This highlights the need for more exposure to climate change throughout the engineering curriculum to not only clarify any misconceptions, but also to instill a change in the belief of the existence of human-caused climate change.

Boucher et al. [4] argues that current definitions of mitigation, adaptation, and climate engineering lead to confusion and propose a new categorization with five classes:

1. Anthropogenic emissions reductions (AER): Reducing greenhouse gas emissions from human activities.
2. Domestic greenhouse gas removal (D-GGR): Removing CO2 and other greenhouse gases from the atmosphere within a specific territory.
3. Trans-territorial greenhouse gas removal (TGGR): Removing CO2 and other greenhouse gases from the atmosphere on a global scale.
4. Targeted climate modification (TCM): Modifying the Earth's climate system to counter the effects of climate change.
5. Climate change adaptation measures (CCAM): Adapting to the impacts of climate change.

Irwin et al. [5] argues that understanding climate change is crucial for education to remain relevant in the modern world. The traditional industrial model of education is no longer sufficient in the face of climate change. A new eco-centric orientation is emerging, and education must adapt to address the issues of climate change.

<u>Pedagogical Approaches</u>

Monroe et al. [6] present a systematic review of climate change education strategies that identified four key strategies for effective climate change education:

1. **Focusing on personally relevant and meaningful information:** Students are more likely to be engaged if they can see how climate change affects their own lives and communities.
2. **Using active and engaging teaching methods:** A variety of teaching methods, such as role-playing, simulations, and field trips, can help students understand climate change concepts in a more meaningful way.
3. **Engaging in deliberative discussions:** Discussions that allow students to share their thoughts and perspectives on climate change can help them develop critical thinking skills and a deeper understanding of the issue.

4. **Interacting with scientists:** Opportunities to interact with scientists and experts can help students learn from firsthand experiences and gain a better understanding of climate science.

Tang [7] proposes a new model of Climate Change Education (CCE) that focuses on bridging the gap between students' attitudes and behaviors towards climate action. This model consists of three domains: knowledge, practical CCE, and community CCE. The knowledge aspect aims to provide students with a solid understanding of climate change concepts and address misconceptions. Practical CCE equips students with skills to assess their carbon footprint and make lifestyle changes to reduce their emissions. Community CCE encourages students to engage in community-based climate action initiatives, reinforcing the attitude and behavioral changes learned in the other two domains.

Hess and Collins [8] analyzes the general education curricula of top US universities and liberal arts colleges to assess the prevalence of climate change education. It finds that only 17% of students are likely to take at least one climate change course through their core curriculum. The probability is higher at research universities, in core programs with more science and social science courses, and at public universities in Democrat-controlled states. The paper suggests strategies to increase the likelihood of climate change education in core curricula, such as creating new climate change courses, integrating climate change into existing courses, and providing faculty development opportunities.

Molthan-Hill et al. [9] highlights the importance of climate change education (CCE) in addressing the global climate crisis. It emphasizes the need for universities to integrate CCE into all disciplines, not just climate science, to achieve the required decarbonization on a large scale. The chapter also discusses the importance of integrating climate change adaptation education into university curricula to prepare students for the impacts of climate change. Finally, the chapter examines how CCE can be embedded into various disciplines, such as agriculture, biology, business, and psychology, and concludes with strategies for scaling up CCE on an institutional, national, and international level.

Linow [10] argues that mechanical engineering education needs to be updated to include climate change concepts. It suggests that thermodynamics and fluid dynamics courses can be adapted to incorporate climate change topics without overburdening the curriculum. The paper aims to discuss the possibility of including basic understanding, relevant mitigation approaches, and evaluation tools into these courses. It will share experiences from a pilot program that has been implemented to test this approach.

Axelithioti et al. [11] highlights the importance of engineering education in addressing climate change. It explores the extent to which three engineering departments (mechanical, civil, and electrical) incorporate climate change mitigation and adaptation (MACC) content in their curricula. The study found that MACC content is largely absent from module descriptions and learning objectives, indicating a disconnect between engineering education and the climate crisis. The authors propose a novel approach to integrate MACC into module outlines, paving the way for future integration of climate change into engineering curricula. This research emphasizes the urgent need for climate-conscious engineering education.

Challenges and Successes

Leal-Filho et al. [12] suggests that universities take the following actions to address climate change education:

- **Cross-cutting Emphasis:** Ensure climate change is integrated across various courses and disciplines.
- **Curriculum Assessment:** Identify strengths and weaknesses in existing curricula to guide improvements.
- **Staff Training:** Provide training programs to enhance the expertise of teaching staff.
- **Interdisciplinary Collaboration:** Foster collaboration among different disciplines and stakeholders.
- **Institutional Support:** Create a supportive environment for climate change education initiatives.

Fahey [13] discusses the challenges faced by higher education institutions in preparing future leaders to address complex global issues like climate change. It highlights the importance of multi-disciplinary thinking and the use of objectives-based and action research models in curriculum reform. The study emphasizes the need for continuous evaluation and revision of curricula to ensure that they are aligned with institutional goals and external directives. By focusing on these aspects, higher education institutions can equip their graduates with the skills and knowledge necessary to navigate a complex and uncertain future.

Anderson [14] argues that the education sector has a significant opportunity to combat climate change. It defines Climate Change Education for Sustainable Development (CCESD) as a comprehensive and multidisciplinary approach that includes relevant content knowledge, institutional factors, and skills development. The article presents evidence-based findings on factors influencing behavior change and highlights the importance of focusing on local, tangible, and actionable aspects of sustainable development. It also identifies areas for future research to guide effective climate change education policy and practice.

Rousell and Cutter-Mackenzie-Knowles [15] found that while there is a growing body of research on climate change education for children and young people, much of it focuses on didactic approaches that have limited effectiveness in changing attitudes and behavior. The authors argue for the need for more participatory, interdisciplinary, creative, and affect-driven approaches that directly involve young people in responding to the challenges of climate change.

Methodology

The methodology described in this paper consists of three major steps: (1) identification of the key knowledge, skills, and abilities for climate change in engineering, (2) design of new curriculum that integrates climate change, and (3) assessment of the newly designed curriculum. The first two steps focus on how to adapt engineering education for climate change and the third step focuses on an assessment of the effectiveness of the proposed curriculum elements of this research work.

Identification of the key knowledge, skills, and abilities for climate change in engineering

In order to identify the knowledge skills and abilities that students will need to have to address the challenges that climate change will present to their future careers, it is first necessary to conduct a full analysis of the impacts that climate change will have across the many sub-disciplines within engineering and the critical infrastructure systems associated with those sub-disciplines. Civil Engineering can be divided into five main sub-disciplines: (1) Water Resources Engineering, (2) Transportation Engineering, (3) Structural Engineering, (4) Environmental Engineering, and (5) Geotechnical Engineering. Table 1 below presents the critical infrastructure sectors and each sub-discipline of civil engineering that is involved with each sector.

Table 1: Mapping of Civil Engineering Sub-Disciplines to Critical Infrastructure Sectors

Critical Infrastructure Sector	Critical Infrastructure Systems	Civil Engineering Sub-Disciplines	Climate Change Impacts
Energy	Power Plants, Transmission Lines, Energy Distribution Networks, Oil and Gas Pipelines	Structural, geotechnical, environmental	Extreme weather events, infrastructure damage, power outages
Transportation	Roads and Highways, Bridges and Tunnels, Railways, Airports	Transportation, structural, geotechnical	Extreme weather events, infrastructure damage, disruptions
Telecommunications	Telecommunications Networks, Data Centers, Internet Backbone	Structural, geotechnical	Extreme weather events, infrastructure damage, disruptions
Water	Water Treatment Plants, Water Distribution Networks, Wastewater Treatment Plants, Sewage Systems	Water resources, environmental, geotechnical	Extreme weather events (e.g., droughts, floods), water quality issues, infrastructure damage
Agriculture	Irrigation systems, Drainage systems, Water treatment plants	Water resources , environmental	Extreme weather events, soil erosion, crop failures

Banking and Finance	Telecommunications Networks, Data Centers	Structural, geotechnical	Extreme weather events, infrastructure damage, disruptions
Healthcare	Medical supply chains, data centers, emergency response infrastructure	Structural, geotechnical, environmental	Extreme weather events, infrastructure damage, disruptions, healthcare access
Emergency Services	Emergency response infrastructure, Roads and highways	Structural, geotechnical, transportation	Extreme weather events, infrastructure damage, disruptions, emergency response

Examination of the climate change impacts reveals three key themes: (1) Sea level rise, (2) extreme weather, and (3) damage and disruption. The first two themes focus on what can happen in the future where the third focuses on not only the impact to the critical infrastructure systems but the disruption that the damage to those systems would create on communities. Table 2 below presents the knowledge, skills, and abilities associated with each of these climate change impacts.

Table 2: Knowledge, Skills, and Abilities for Climate Change Impacts

Issue	Knowledge	Skills	Abilities
Sea Level Rise	Coastal engineering, oceanography, hydrology, climate science	Risk assessment, modeling, adaptation planning, infrastructure design	Problem-solving, critical thinking, communication, collaboration
Extreme Weather Events	Meteorology, hydrology, structural engineering, geotechnical engineering	Risk assessment, disaster management, emergency planning, infrastructure resilience	Adaptability, leadership, decision-making, teamwork
Damage and Disruptions to Critical Infrastructure Systems	Civil engineering (various sub-disciplines), materials science, economics	Infrastructure design, maintenance, risk assessment, disaster response	Problem-solving, critical thinking, project management, leadership
Overlapping Areas	Climate science, environmental science, public policy	Policy analysis, stakeholder engagement, communication	Interpersonal skills, negotiation, advocacy

The identified skills can be separated into two main categories: (1) risk assessment and (2) planning and response. The skill of risk assessment is multi-faceted and would enable students to be able to: assess vulnerability, analyze uncertainty, and develop adaptation strategies.

Vulnerability assessment could be further broken down into the identification of hazards and the quantification of potential impacts. The identification of the relevant hazards for a selected area is crucial for decision makers to develop adaptation strategies that are the best response. Quantification of potential impacts covers the consideration of the broad range of impacts including economics, sociology, and environmental science. Analysis of uncertainty is crucial in the context of climate change due to the wide differences in the projections from climate models and their associated error estimations. Wrapping up risk assessment, is the ability to develop adaptation strategies which is the key elements for translating theory into practical applications to support decision making and the protection of critical infrastructures systems.

The skill of planning and response builds upon risk assessment and is focused mainly on decision support and highlighting resilient strategies. The three key elements of planning and response are: (1) scenario planning, (2) adaptation planning, and (3) mitigation planning. Scenario planning is useful for disaster preparation and response in that plans are developed for the hypothetical scenarios of what could happen such that the impacts of an extreme event are minimized to the best extent possible. Adaptation planning differs from scenario planning in that it focuses on how a community would adapt to a changing climate especially when considering sea level rise that can lead to permanent displacement of individuals or businesses. Mitigation planning focuses on minimization of the carbon footprint of communities such that the overall global greenhouse gas emissions are decreased as a means to avoid worsening the climate crisis.

Design of new curriculum that integrates climate change

While the above analysis is generally focused on what students will need to know for the future, it is necessary to further breakdown the knowledge, skills, and abilities by academic level as there is a vast difference between undergraduate and graduate students. Undergraduate students, upon graduation, are looking at entry-level positions that require foundational knowledge of civil engineering and give hands-on experience with career progression occurring naturally as the students gain more experience. Graduate students are looking at more specialized roles that require advanced knowledge such as in research and development or even leadership roles. This drastic difference means that, for the preparation of the students to address the issues of climate change, undergraduate students and graduate students will need to be treated differently based purely upon the positions and roles that are expected upon their graduation.

Undergraduate Level

Engineering education for civil engineering undergraduate students Is focused on building foundations and Core Concepts that span multiple subdisciplines of civil engineering. The goal of undergraduate studies is to prepare students for entry-level positions or entry into graduate school where students would gain more specialized knowledge in a particular sub-discipline of civil engineering. In addition to the specialized knowledge, graduate students are gaming more advanced skills in research methods, data analysis, and problem solving. A key difference between undergraduate and graduate students is that graduate degrees open doors to more specialized and advanced positions that may include research roles or Consulting.

As part of ABET criteria, civil engineering undergraduate students are expected to have exposure to multiple sub-disciplines of civil engineering as well as foundational engineering, math, and science courses. The introduction of a new climate change focused course would be relegated to an elective thus severely limiting its impact on the students, therefore the introduction of course modules to existing undergraduate courses would have a much larger impact. Additionally, the course modules could be introduced to the sub-discipline courses of civil engineering and be very focused on the specific climate change impacts within that sub-discipline thus better preparing students for their future careers if they choose to work in that sub-discipline.

Graduate Level

Given that graduate studies are more focused than undergraduate, the introduction of new climate change courses would generate the largest impact on the students and help them develop key skills to address the challenges that climate change will present. It was revealed in the earlier section that the skills of risk assessment and planning are crucial for students, therefore, new courses in climate change should focus on the development of these two skills. Reliability, sustainability, and resilience are all topics that align well within the theme of risk assessment.

Decision making and planning are ideal skills for graduate students in civil engineering to gain, but the uncertainty of climate change presents significant challenges to decision making that require additional consideration. Game theory presents an intriguing avenue to address uncertainty that aligns well with the fact that while the future climate of the planet is uncertain, it will be a result of the decisions that society makes. While the countries of the world collectively decide the future climate of the planet, it is up to city planners and engineers to protect the welfare and security of communities despite whatever may occur as a result of climate change. This interdependency of decision making is where game theory is most applicable and presents the most advantages.

Assessment of the newly designed curriculum

The assessment of the efficacy of the proposed graduate courses and undergraduate course modules is focused on the development of the knowledge, skills, and abilities of the students. The chosen mechanism for the assessment were two surveys, one for graduate students and another for undergraduate students, that included three main sections: (1) assessment of student knowledge and abilities before the course or course module, (2) assessment of student knowledge and abilities after the course or course module, and (3) assessment of the improvement of skills due to the course or course module.

The assessment of student knowledge and abilities before or after the course or course module consisted of five questions that were repeated for before and after in order to generate results for direct comparison. Each question was answered using a likert scale ranging from 1 to 5 with 1 being "No Understanding" and 5 being "Very Strong Understanding":

1. Risk assessment related to climate change
2. Reliability and resilience of critical infrastructure
3. Apply simple probabilistic tools in updating the probability of events & associated risk based on newly observed data from recent extreme events
4. Preparedness measures for climate change impacts
5. Impacts of climate change on various sectors (e.g., civil engineering infrastructure, agriculture, energy, health)

The assessment of the improvement of students skills consisted of five questions. Each question was answered using a likert scale ranging from 1 to 5 with 1 being "No Improvement" and 5 being "Very Strong Improvement":

1. Analyzing climate change data
2. Develop alternate ways to make optimal design decisions in the face of uncertainty
3. Evaluating climate change risks and vulnerabilities
4. Developing climate change adaptation strategies
5. Communicating climate change information effectively

Results

With regards to climate change, two courses and two course modules are currently introduced at UDC: (1) Game Theory Applications in Engineering and Advanced Risk Reliability & Vulnerability Analysis for graduate students and (2) Introduction to Risk & Resiliency in Engineering and Transportation Engineering for undergraduate students. The results are presented below for each group.

<u>Undergraduate Level</u>

At the undergraduate level in the pre-course module assessment, at least 60% of students answered that they had strong to very strong understanding (scale 4 or more) for all topics of climate change. In the post-course modules assessment, 100% of students answered that they had strong to very strong understanding (scale of 4 or more) for all topics of climate change with the exception of "Apply simple probabilistic tools in updating the probability of events & associated risk based on newly observed data from recent extreme events" which was at 75% of students answering strong to very strong understanding (scale of 4 or more). These responses reveal that the current generation of undergraduate students have already been exposed to the topics of climate change, but these course modules were effective elevating their level of understanding across all topics covered.

In reference to the growth of skills, at least 50% of students answered that they saw strong to very strong improvement (scale 4 or more) in their skills related to climate change with most students answering that they saw at least moderate improvement across all skills. The exceptions were that one student answered little to no improvement (scale 2 or less) for the skills "Analyzing climate change data", "Develop alternate ways to make optimal design decisions in the face of uncertainty", and "Evaluating climate change risks and vulnerabilities." These responses reveal that the climate change focused course modules were effective in elevating the skills of undergraduate students with regard to climate change.

<u>Graduate Level</u>

At the graduate level in the pre-course assessment, at least 50% of students answered that they had little to no understanding (scale 2 or less) for any of the climate change topics. In the post-course assessment, at least 75% of students answered that they had moderate to strong understanding (scale 4 or more) for any of the climate change topics and no students answered that they had little to no understanding (scale 2 or less) for most of the topics with "Preparedness measures for climate change impacts" being the sole exception with one student answering that they had little understanding. These responses reveal that the current state of undergraduate engineering education is only preparing half of the students for the implications of climate change and these two courses were effective for helping graduate students to bridge that knowledge gap.

In reference to the growth of skills, at least 75% of students answered that they saw strong to very strong improvement (scale 4 or more) in their skills related to climate change with most students answering at least moderate improvement (scale 3) for all skills except two where one student answered little improvement, "Apply advanced optimization techniques to evaluate the probability of failure and hence the reliability of a system" and "Perform risk and reliability analysis of a built engineering system such as a natural or engineered earthen slope considering variability in soil properties and rainfall events." These responses reveal that both courses have been effective in elevating the skills of graduate students and are thus achieving the goal of producing engineers that are ready for the challenges that climate change will present.

Conclusions

This research work explored the literature of climate change in engineering education, identified key knowledge, skills, and abilities for climate change in engineering education, and proposed the introduction of new courses and course modules that were targeted towards developing the identified skills of risk assessment and planning. The results of surveys support that both undergraduate and graduate students gained awareness of climate change impacts and improved their skills even though two different delivery methods were used. The incorporation of climate change modules in existing undergraduate courses addresses one of the concerns that was identified in the literature that students have only a 17% chance of taking a course related to climate change. Through the introduction of course modules 100% of the students that pass through the Civil Engineering program are exposed to climate change and its impacts and the results support that this structure is effective and has achieved the desired results of better preparing students to be able to address the future challenges that climate change will present.

Future Work

The results presented in this research effort represent a mid-course assessment and thus the results may improve beyond those at present. As part of the course design, practical application projects are included that will expose students to real-life problems that incorporate the uncertainties surrounding climate change. These projects will provide a direct assessment of the knowledge, skills, and abilities of the students that will provide a more robust insight into the efficacy of the proposed methodology for integrating climate change in engineering education.

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