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Data Science in the Civil Engineering Curriculum

Dr. Ashraf Badir, Florida Gulf Coast University

Dr. Badir is a Professor in the Bioengineering, Civil Engineering, and Environmental Engineering Department at the U.A. Whitaker College of Engineering in Florida Gulf Coast University. He earned his B.Sc. (1982) in Civil Engineering and M.Sc. (1985) in Structural Engineering. He also holds a M.Sc. (1989) and a Ph.D. (1992) in Aerospace Engineering from Georgia Institute of Technology. Dr. Badir is a licensed Professional Engineer in Florida, and a civil engineering program evaluator for ABET.

Dr. Seneshaw Tsegaye, Florida Gulf Coast University

Dr. Seneshaw Tsegaye is an Associate Professor in the Department of Bioengineering, Civil Engineering, and Environmental Engineering at Florida Gulf Coast University. He is the Backe Chair of Research for Sustainable Water and Renewable Energy. He has 10 years of experience in the fields of integrated urban water management, water-energy-food nexus, infiltration-based best management practices, flood modeling, and decision support systems for transitioning to vegetation-based stormwater systems. Dr. Tsegaye's latest research project is focused on the application of Virtual Reality for flood resiliency and engineering education. With many years of teaching and research experience in both developed and developing nations, Dr. Tsegaye has strong relationships for international collaboration.

Dr. Long Duy Nguyen, P.E., Florida Gulf Coast University

Dr. Long Nguyen is an Associate Professor in the Department of Environmental and Civil Engineering at Florida Gulf Coast University (FGCU). Before joining FGCU, he was the deputy director of Tuan Le Construction and a lecturer at Ho Chi Minh City Universi

Data Science in the Civil Engineering Curriculum

Abstract

Data science is an emerging field that encompasses several STEM domains and offers exciting career prospects in a wide range of engineering applications. Given the rapid adoption of data analytics in engineering and the societal importance of many of its applications, there is an urgent need to train the next generation of civil engineers in data science. Several studies have emphasized that the use of data science in the present civil engineering undergraduate curricula is mostly restricted to simple introductory subjects, usually with the use of Microsoft Excel. The curriculum does not encourage students to fully benefit from big data since data science is not extensively used. Additionally, there is a lack of clear guidance on how to strengthen the synergy between common civil engineering courses and data science.

In this paper, the authors report on a recently introduced course entitled “Data Science and Engineering Systems Analysis,” at Florida Gulf Coast University (FGCU), incorporating the integration of R programming into data analytics, and systems thinking for the analysis and design of civil engineering applications. The course aims at empowering students with the necessary tools to apply statistics in a civil engineering context, and perform data transformation, data wrangling, visualization, and modeling using *R for data science.* Students learn how to gather and analyze data as part of the engineering design process, apply systems thinking to an engineering or societal phenomenon, collaborate with peers to find solutions, and effectively present solutions to an audience. Through a careful examination of the course's key features, its applications, and its synergy with the existing curriculum, this paper provides guidance for data science curriculum development, implementation, and evaluation in civil engineering.

Introduction

The need to manage, analyze, and extract knowledge from data is becoming a necessity for every sector of society including industry, government, and academia. Engineers routinely encounter massive amounts of data, and new techniques and tools are emerging to create knowledge out of these data [1]. The compounded accessibility of data has considerably altered the civil engineering and the construction profession, and data analysis skill is recognized as a crucial experience desired in engineering graduates [2-4]. Data science in civil engineering has a very wide scope. Data science employs a variety of scientific and mathematical tools, processes, and methods to collect data which is then analyzed using programming languages such as R, Python, C, Java, and others. R is widely used in data science because it is open source, performs complex statistical calculations, has static graphics that produce high-quality data visualizations, and fosters a community of its own [5]. It is an upcoming field with huge potential and demand in the marketplace. It has the potential to transform the construction industry with the help of its vast variety of tools and techniques. A recent paper [2] addresses the strategic importance of data science in civil engineering with the aim of encouraging interest in the next generation. Civil engineers can exploit data science to make use of huge amounts of data acquired through advanced technical computing systems [6], which cannot be achieved by spreadsheets. Civil engineering students, however, often lack programming skills and the motivation to acquire competences in data analysis [7-9]. Current approaches in the undergraduate formation of civil engineering are thus failing to prepare students to enter a job market that is increasingly demanding competencies in data analysis. Understanding data science instruction in multiple STEM domains is necessary for jobs across many disciplines [10]. A recent National Academy of Sciences report advocates that to train students for the explosion of data-driven work "academic institutions should encourage the development of a basic understanding of data science in all undergraduates" [10, 11].

This paper presents a recently introduced course at FGCU entitled "Data Science and Engineering Systems Analysis (DSESA)," which incorporates R programming into data analytics and systems thinking for civil engineering applications. This work aims at reporting three main issues, namely (1) the unique components of the current integrated DSESA Course, (2) an account of selected civil engineering projects using *R for data science*, and (3) a strategy to enhance synergy between data science and other engineering courses within the curriculum. It is anticipated that a thorough examination of the course's features, and course synergy-enhancing factors would help to develop a guideline for data science curriculum development, implementation, and evaluation in civil engineering.

Data Science Course in an Undergraduate Civil Engineering Curriculum

The DSESA course offered at FGCU introduces data science skills targeting applications in civil engineering and environmental engineering. The students participating in this course are juniors in civil and environmental engineering majors. The course detailed herein was first introduced in Fall 2020 in a virtual instruction. The course was substantially redeveloped and delivered in-person in Spring 2021 with an enrollment of 9 students. The enrollments in Fall 2021 and 2022 were 32 and 27 students, respectively. The course meets twice a week, for a total of four contact hours, with 3-credit hours. The course instructions closely follow the Excellence in Civil Engineering Education (ExCEEd) Teaching Model [12]. Since the course is taught in the lecture/lab format, there is ample time and opportunity for active, hands-on learning during the class period. All instructors require attendance, take roll, and for students who have an excessive number of unexcused absences, there is a grade reduction outlined in the syllabus.

Figure 1 shows the DSESA course within the undergraduate Civil Engineering curriculum. A more readable Civil Engineering Curriculum Flowchart shown in Figure 1 is available in Appendix 1. The direct prerequisites for the course are Statistical Methods or Statistics with Calculus, Computational Tools for Engineers (Excel and MATLAB), and Engineering Mechanics or Fundamentals of Environmental Engineering, all with a minimum grade of C. Statistical Methods and Computational Tools for Engineers provide students essential knowledge and skills to succeed in the DSESA class. In Computational Tools for Engineers, students learn Excel spreadsheets and basic programming skills with MATLAB. Engineering Mechanics or Introduction to Fundamental Engineering as prerequisites ensure students truly enter into their majors to better tailor the DSESA course in specific application domains (Figure 1). As "distant" prerequisite, Introduction to the Engineering Profession discusses and fosters students research in topics related to the Grand Challenges in Engineering identified by the National Academy of Engineering (NAE). This is beneficial for students to find relevant project topics for the DSESA course as discussed later in this paper.

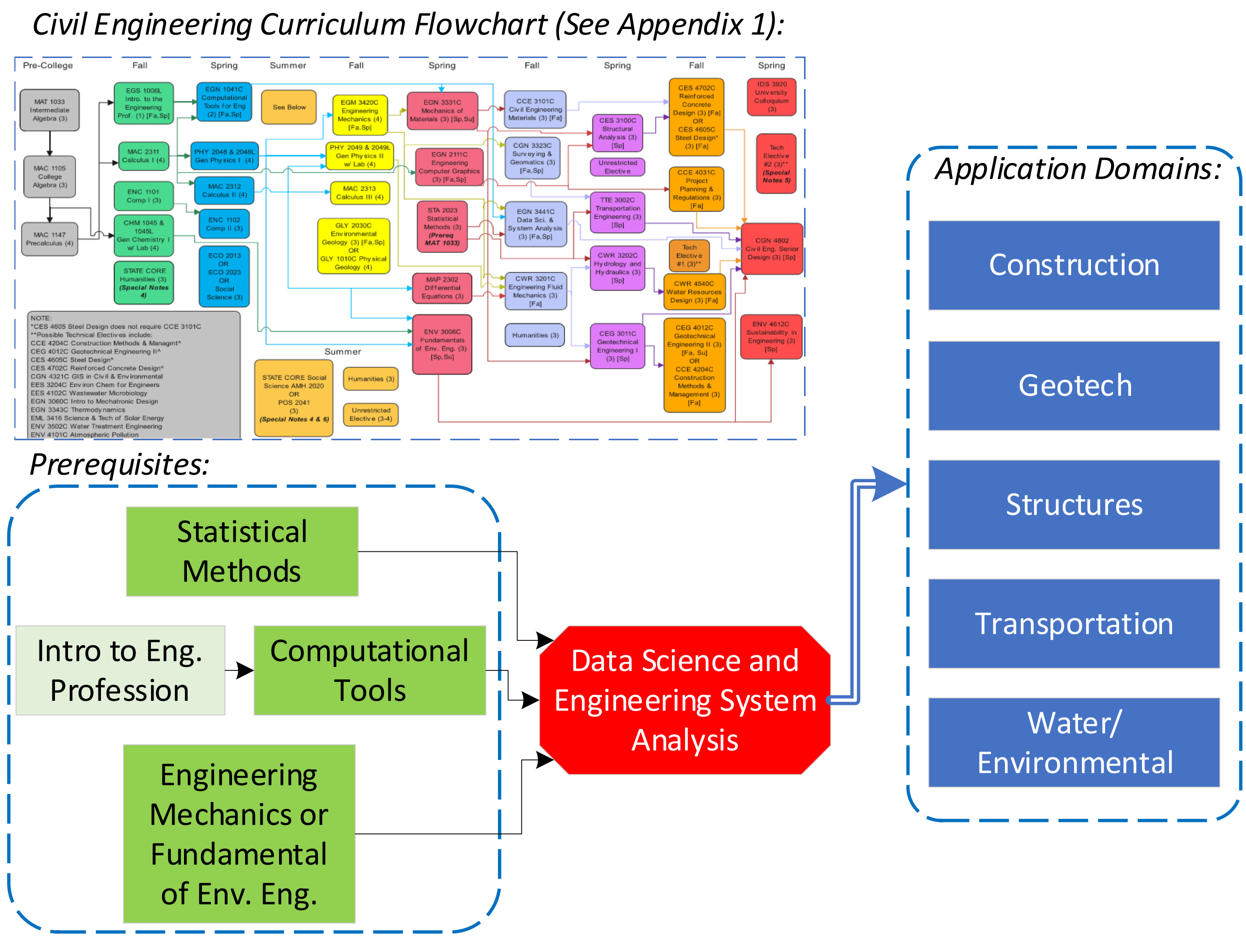

Figure 1. DSESA course within Undergraduate Civil Engineering Curriculum

Data Science Topics Covered, Delivery and Assessment

The newly introduced course aims for the students, after completing the course to be able to (1) apply statistics in an engineering context, (2) perform data transformation, visualization, and modelling using appropriate tools, (3) collect and analyze data as part of the engineering design process, (4) conduct systems thinking on an engineering or societal phenomenon, (5) collaborate on solutions to engineering or societal challenges, and (6) effectively present solutions to peers and instructors. By the end of the semester, students will have achieved outcomes related to the ABET outcomes 1 through 7. The required textbook "*R for Data Science: Import, Tidy, Transform, Visualize, and Model Data*" [13] is freely available online. As a recommended book, "*Engineering Systems: Meeting Human Needs in A Complex Technological World*" [14] is electrically available at the institution library.

The DSESA course was taught by engineering faculty members from the Civil Engineering Program and Construction Management Department. As an added resource, a Learning Assistant (LA) was available to help students with problem-solving and coding in class, held online office hours, and conducted exam review sessions open to all students. The LA Program started at FGCU in the fall of 2016 following the Generalized Program Elements (GPEs) of the Learning Assistant

Model [15]. Most LAs work in introductory STEM classes such as math; however, the program has grown significantly with LAs working in other areas, such as business, history, composition, language, and now engineering. The LA was utilized in Data Science in the Fall 2021 and 2022 but not during the Spring 2021 semester. LAs are undergraduate students who have been or are undergoing training in pedagogy and, through the guidance of faculty, facilitate student learning by encouraging active engagement in and out of the classroom. LAs are not Teaching Assistants (TAs) who are involved in grading; the focus of the LA is on assisting students throughout the learning process, as a peer mentor who has recently taken the course, which enables them to provide guidance and insight from the student perspective.

The major assessments were homework, exams, and a group project. A single data set that was local, freely available and discipline-specific was used for all six homework assignments in data science. Table 1 presents these formative assessments with topics introduced using same data set. Using the same data throughout the course helps students understand more about the data at hand with more Data Science tools introduced. This also helps students see the advantages and limitations of spreadsheets such as Excel and how Data Science with open-source programming such as R and Python can fill the gap. The exams are summative assessments where students applied their data science skills taught in class, and practiced through in-class activities and homework assignments to discipline-specific data. Using discipline-specific data makes the exam questions more relatable and understandable and hence more directly assess students' data science skills.

Table 1. Homework assignments with data science topics assessed

Homework Number	Number of Questions	Data Science Topic Assessed
1	10	Data visualization
2	10	Data transformation
3	10	Exploratory data analysis
4	10	Data wrangling and programing basics
5	10	Data modeling
6	5	Hypothesis testing

The course also includes a semester-long project to perform data analytics with data of each team's choice in order to gain insights on an engineering or related system of interest to the team. The topic selected is open-ended although its connection to an engineering system is preferred. Students may choose a topic that they are interested in and genuinely curious about. They may think of some questions that they have not known the answers yet and then look for data that might help them answer those questions.

Students work in teams of four people. Once the groups are set up, they prepare a team contract and submit it to the Learning Management System (LMS). Table 2 summarizes the project deliverables and the submission type (Team vs Individual). For Team submission, only one student of the team submits on behalf of the whole team. In addition, each individual will be responsible for *Peer Review of Team Member Contribution* and *Peer Evaluation of Project Presentations* at the end of the semester.

Table 2. Project Deliverables

Deliverable	Submission	Description
Team contract	Team	Lay out the expectations of what it means to be an effective team member, general scheduling and logistical information, and consequences of not meeting deadlines, expectations, etc.
Project topic	Individual	Briefly describe your project topic and data following the Introduction and Data description sections described in the Semester Project Description.
Project Proposal	Team	Select the final project topic based on project topics submitted previously by team members. The proposal focuses on the Introduction, Theoretical Background and Data Description sections.
Project Data Analytics	Team	Update the project proposal and draft the next two sections Data Wrangling and Transformation and Data Analytics and Results. *Submit both R Markdown and PDF files.*
Final Project Report	Team	Complete all required sections of the project report. See the project report rubric on the LMS for additional information. *Submit both R Markdown and PDF files.*
Project Presentation	Team	See the project presentation rubric on the LMS for information.

The Project Data Analytics and Final Project Report deliverables must be compiled in a R Markdown file. Students are required to submit the final project report that consists of: *introduction*, *theoretical background*, *data description*, *data wrangling and transformation*, *data analytics and results*, *discussion*, *conclusions,* and *references*. These sections as presented to students are available in Appendix 2 at the end of the paper.

Table 3 features project topics generated by students in the three semesters. The Civil Engineering related application domains show in the last column for demonstration purposes. The topics are rather varied in accordance with students' interests.

Table 3. Featured semester-long projects and application domains

Topic	Scope	Application Domain
National Bridge Inventory (NBI) Rating Scale	Explore the NBI data with the particular focus on the reliability and condition of Florida's infrastructure and bridges due to excessive use.	Structures
Biogas Digester and the Correlated Gaseous Effluents	Whether Biogas is an adequate and reliable source of sustainable fuel	Water/ Environmental
Sinkholes in FL	Whether a trend between soil type and size of the structure will be key factors for what cause sinkholes in FL.	Geotech

New York City (NYC) Bridge Quality Analysis	Establish variables which explain why NYC bridges receive certain American Association of State Highway and Transportation Officials (AASHTO) inspection evaluations	Structures
Effects of Covid-19 on Transportation Industry	Examine the impact of freight transportation on both the economy and the lives of people	Transportation
Analysis of Climate Change in Alabama and Utah	Information on ecosystem vulnerability with regards to changes in weather over an extended period of time	Water/ Environmental
CO_2 Emissions	Study carbon dioxide emissions from coal combustion among countries around the world	Water/ Environmental
Coal Production in the United States	Examine how the trend of coal production has changed in the US over the last 20 years	Water/ Environmental
Residential Homes Sold in the last 5 years	Provide trend analysis to help overwhelmed buyers from the abundant number of choices and decide between states	Construction
Bridges in Florida	Understand the conditions of the bridges and their surrounding area	Structures
Traffic Analysis	Analyze and describe changes in traffic in Southwest Florida in the following areas: Population, Safety, Routing and Time.	Transportation
Aviation Accidents	Determine the possible or most likely reasons for continuously occurring aviation accidents	Transportation
Traffic Safety in Florida	Examine whether Florida a safe state for non-motorist and what factors are related to fatal and severe accidents	Transportation

Through the various types of assessments (homework assignments, project deliverables and exams), the course objectives and ABET student outcomes can be assessed at the end of the semester. Table 4 shows the mapping of the assessments employed to the course learning objectives and ABET seven student outcomes. The assessments provided a good coverage of the course objectives and ABET student outcomes, especially student outcomes 1, 6, and 7.

Table 4. Mapping the assessments to course objectives and ABET student outcomes

Assessments	**Course Objectives***						**ABET Student Outcomes****						
	1	**2**	**3**	**4**	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Homework:													
1 - Visualization		x										x	
2 - Transformation		x										x	
3 – Data Analysis	x		x									x	
4 - Wrangling			x	x								x	
5 - Modeling	x	x	x									x	
6 - Testing	x		x									x	
Semester Project:													
Team Contract					x					x	x		
Topic				x				x					
Proposal				x	x		x				x		x
Data Analytics	x	x		x	x		x			x	x	x	x
Final Report					x	x		x			x	x	
Final Presentation					x	x		x	x		x		
Exam:													
Exam 1		x										x	
Exam 2	x	x										x	
Exam 3				x									

**Course objectives:*

1. *Apply statistics in an engineering context*
2. *Perform data transformation, visualization, and modelling using appropriate tools*
3. *Collect and analyze data as part of the engineering design process*
4. *Conduct systems thinking on an engineering or societal phenomenon*
5. *Collaborate on solutions to engineering or societal challenges*
6. *Effectively present solutions to an audience*

*******ABET Student Outcomes*

1. *an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics;*
2. *an ability to apply engineering design 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;*
3. *an ability to communicate effectively with a range of audiences;*
4. *an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts;*
5. *an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives;*

6 *an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions;*

7. *an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.*

Student Feedback and Lessons Learned

Every semester, the university administers the Student Perception of Instruction (SPoI) Survey to assess instructor performance, course content and the delivery method. The SPoI for the DSESA course has been revised with new, pertinent questions to investigate how the course is perceived by the students. Although 50% of students strongly agreed or agreed that they comprehended the materials from the DSESA course, they struggled to put it into practice when attempting to solve difficulties. 75% of the respondents agreed or strongly agreed that it would be difficult to apply the same concepts to a different situation. 80% of respondents agreed or strongly agreed that it was necessary to divide the problems into smaller ones in order to address them. 50% of the respondents agreed or strongly agreed that using "R for Data Science" to comprehend reasoning can be useful in their daily lives. However, students' perceptions revealed that only 29% of students enjoyed solving problems with R. One of the causes is that students struggle with basic programming skills and spend a lot of time learning and using basic syntaxes. Also, more work could be placed into demonstrating the value and relevance of the DSESA course in solving engineering-related problems. The prerequisite courses and the student's prior knowledge have not been extensively looked at in this study. This warrants further study to investigate student prior knowledge and how the prerequisite courses help build fundamental coding skills, the synergies within senior courses and its applicability to real-world problems, and how DSESA enhances learning outcomes.

Conclusions

Data science is an emerging field that encompasses several STEM domains and offers exciting career prospects in a wide range of engineering applications. This paper presents the unique components of a recently integrated Data Science and Engineering Systems Analysis course for Civil Engineering junior students, including a description of its assignments and associated semester project. In addition, the paper provides a course map outlining how the existing Undergraduate Civil Engineering Curriculum can be improved to include Data Science courses and application domains. Statistical Methods and Computational Tools and Engineering Mechanics courses serve as prerequisites and are expected to provide students with essential knowledge and skills to succeed in the Data Science class. It is the hope of the authors that the presented course would be beneficial to other programs envisioning introducing Data Science into their curriculum. It is anticipated that a thorough examination of the course's features, and course synergy-enhancing factors would help to develop a guideline for data science curriculum development, implementation, and evaluation in civil and environmental engineering. Future research on the impact of data science on ABET student outcomes, graduation rates, and employability is warranted.

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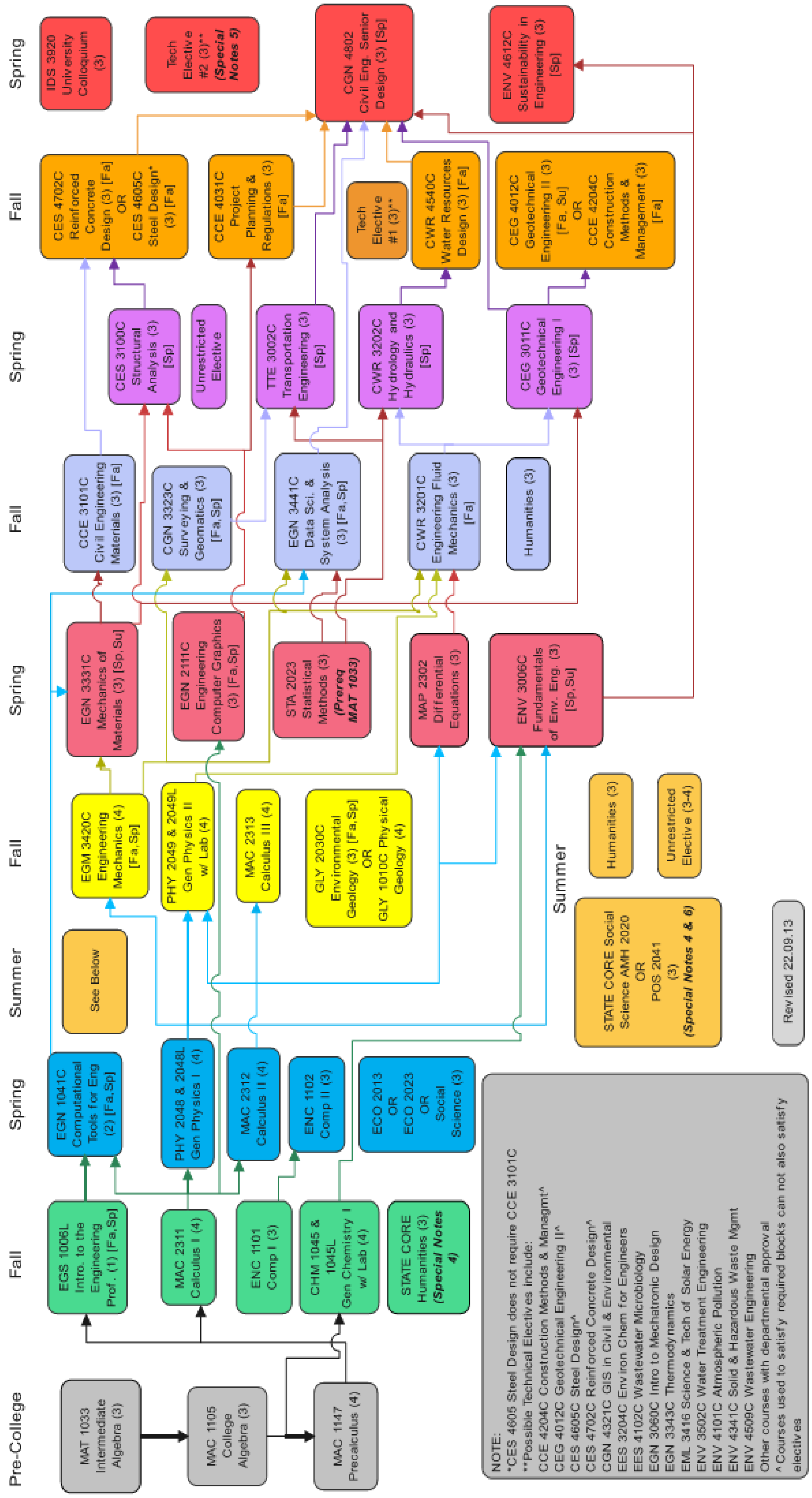
Appendix 1. Partial Civil Engineering Curriculum Flowchart



Appendix 2. Sections of the semester-long project report as described to students

Section [limit]	**Expectation**
Introduction [suggested: 1/3 page]	Explain why you chose this topic and the main goal or question you are interested in studying. Provide context for readers who are not familiar with the topic. Provide direction and briefly outline the report. Briefly provide evidence of societal impact and relationship to engineering systems where appropriate ("big picture").
Theoretical background [suggested: 2/3 to 1 page].	Include historical background and current status of the topic. Elaborate your main goal/question stated in the Introduction into sub-questions and/or hypotheses. Provide at least ten references with in-text citations. At least five references are from peer-reviewed sources.
Data description [suggested: 1/2 to 1 page]	Describe the data sources: who was responsible for collecting the data? How was it collected? Provide some basic information about the dataset: types of variables, number of records, etc. Describe any issues/problems with the data, either known or that you discover. The data can be pulled from multiple sources; it does not need to be a single dataset. Be sure to get data from the original source. For example, if you wish to work with data collected and distributed by the U.S. Environmental Protection Agency, that is where you should go to access the data, not a third party that has posted the data. Do not use datasets that have been processed and cannot be traced to the source. For example, datasets from Kaggle are not good choices unless you can find the original source of the data. The following are examples of data sources among many others: • The U.S. Government's Open Data: https://www.data.gov/ • Data USA: https://datausa.io/. You may find many types of data, including at the local level such as Lee County https://datausa.io/profile/geo/lee-county-fl • World Health Data Platform: https://www.who.int/data • World Bank Open Data: https://data.worldbank.org/ • International Energy Agency Data and Statistics: https://www.iea.org/data-and-statistics • Florida Department of Environmental Protection Data and Maps: https://floridadep.gov/fgs/data-maps • Florida Department of Transportation Data Portal: https://www.fdot.gov/agencyresources/mapsanddata.shtm • County GIS Open Data: https://leegisopendata2-leegis.opendata.arcgis.com/ • Elsevier's Data in Brief: https://www.journals.elsevier.com/data-in-brief • Zillow Housing Data: https://www.zillow.com/research/data/

Appendix 2. *(Continued)*

Section [limit]	Expectation
Data wrangling and transformation [suggested: 1/2 page]	Describe the process of getting the data into a form in which you could work with it in R. Describe any patterns you discover in missing values.
Data analytics and results [suggested: 4-8 pages, 6-12 graphs or tables plus commentary, a plot with multiple facets counts as one graph]	You have a lot of freedom to choose what to do, as long as you restrict yourselves to tools used for data science [13] and engineering systems analysis [14] discussed in this class. Your analysis must be clearly documented and reproducible. To help you get started with this section, you may watch the YouTube video created by Robinson [16] that explores a dataset in R live, without looking at the data in advance. Use subheadings as appropriate. See Schneider [17] for examples of thoughtful and informative subheadings. Describe whether the results answer your questions and/or confirm your hypotheses. Correctly label and caption tables, graphs and figures so readers understand full content of these illustrations without referring to text. Equations provided where appropriate, are correctly labeled, and all variables are clearly explained. All equations, figures, and tables are accompanied by textual description/interpretation and referenced within written work in appropriate location. Take extra care to clean up your graphs. Add the echo = False parameter to your code chunks to prevent printing of the R codes in your final project report.
Discussion [suggested: 1/2 to 1 page, excluding any figures]	Discuss the implications of your results with regard to (contribution to the understanding of) the engineering or related system of interest. Provide the system boundary and limitations of your findings. Ideally, provide a conceptual diagram to describe the system and system boundary and include endogenous variables (variables that are parts of your study) and exogenous variables (variables that are not parts of your study but affect the system). Refer to Figures 5.1 through 5.8 of engineering systems analysis [14] as examples of possible diagrams that describe the relationships among the components of your team's semester project.
Conclusions [suggested: 1/2 page].	Provide a short nontechnical summary of the most revealing findings of your analysis written for a nontechnical audience. The conclusion should concisely summarize key points without providing new information.