

Teaching Civil Engineering through Integrated Projects in GIS

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Abstract

Geographic information systems (GIS) technology is a platform for creating, managing, analyzing, and visualizing spatial data. As GIS technology continues to evolve, its use among engineers is increasing across subdisciplines of civil engineering, particularly in designing and managing of civil infrastructure. A GIS course in the Department of Civil and Environmental Engineering (CEE) at Villanova University was created with an overall objective of teaching civil engineering concepts and software skills through integrated projects in ArcGIS Pro. This project integration includes a collection of smaller, individual projects (IPs) that provide students with the skills necessary to complete an integrated core project (ICP). This semester long ICP is a group project that thematically ties together CEE concepts, guiding students through the sequence of a residential site development project. Part 1 of the ICP requires a comprehensive assessment of the existing site, including topography, slopes, land use, soils, and zoning calculations, which provide real constraints and regulations for the students to adhere to when developing a conceptual site plan layout. Once provided with a final site plan design for Part 2, students apply spatial analysis tools to evaluate drainage patterns and earthwork volumes, extract profiles from existing and proposed surfaces, calculate quantities for a materials cost estimate, and create a web application to manage an asset inventory of the development's storm and sanitary utilities. The first two offerings of this course have used two different ICP sites, both actual development projects designed by a local engineering firm and subsequently built. All projects in this class use real data, with students prompted to solve a problem, analyze a data set, or design a solution from the perspective of the engineer. Thus, the integrated projects link GIS tools and skills to real engineering context, an approach that has proven valuable to student learning. Two semesters of assessment data based on anonymous post-course surveys have shown that students overwhelmingly appreciate the project-based structure of this course. Additionally, survey data has shown that regardless of the ICP site used, students find a core project to be extremely helpful in contributing to their learning and that the core project effectively connected concepts throughout the course. While the perception is that this is a software class, students have agreed this course has helped them learn civil engineering concepts in addition to GIS skills. Thus, the integrated, project-centric approach employed in this course is an effective model that may be translatable to similar, software-focused courses in civil engineering or other technical fields.

Introduction and background

A geographic information system (GIS) is a tool for creating, managing, analyzing, and visualizing spatial data. Because GIS is such a broad term, it can actually be difficult to define in such a way as to capture the various fields in which it can be applied [1], [2]. It is an ever growing and powerful technology, yet there are still limits to its widespread use in education globally [1]. Additionally, GIS instruction is often approached from a "tool-centric view" where the focus of using GIS is on software commands and "button pushing" [2]. Furthermore, GIS can be quite complicated and frustrating for new users. Thus, effective GIS instruction must seek to engage students directly with the technology in an intentional way.

Approaches to GIS instruction vary. Teaching methods commonly applied may include demonstration teaching, interactive learning, and self-paced learning [3], traditional lectures with lab activities [4], or problem-based learning (PBL) with group work (e.g., [4], [5], [6]). Another model applied in an introductory level GIS course was one of concept-based learning where core concepts of spatial information were identified and learning activities designed based on software-independent foundational concepts [2]. In this approach, students are prompted to ask and answer questions about the real world using GIS. Thus, this type of approach attempts to go beyond simply teaching software skills, highlighting critical thinking.

Within the specific context of civil engineering, a web-based GIS learning system has been applied, utilizing a progressive scaffolded approach for students to complete learning modules in geotechnical engineering [7]. This is an effective model to integrate realistic and spatially complex problems and data sets within GIS and expose students to discipline-specific applications. However, from a training perspective, this approach has the shortcoming of placing focus on student use of an instructor-developed tool rather than pushing students to develop skills of their own in a commonly used software package.

While definitions, components, and instructional methods for GIS can vary, its importance and application in subdisciplines of civil engineering have long been recognized [8] and its use for spatial analysis and technical communication continues to grow in the civil engineering industry. Thus, new engineering graduates need to have experience working with GIS technology, but even more so, recognize its fundamental functions and capabilities across a range of applications to translate those skills to solving real problems or analyzing designs. As a result, GIS instruction at the undergraduate level should seek to intersect software training elements with broader discipline-specific learning outcomes.

With a revamped Civil and Environmental Engineering (CEE) curriculum at Villanova University, CEE software electives are being developed and integrated into the undergraduate course offerings. The first of these electives, GIS for Engineers, provided an opportunity for the affiliated faculty to incorporate cutting-edge technology into the classroom in a way that targets skillsets for civil engineers. Therefore, the primary objective in developing this new CEE course was to teach students skills and concepts in GIS, graphical communication, and civil engineering through an integrated approach rooted in real civil engineering projects. This paper details the first two years of this course development effort, providing background on the course and individual project structure, the integrated core project, and the assessment of perceived student learning based on end-of-semester surveys.

Course and individual project structure

GIS for Engineers is a software elective within the Department of Civil and Environmental Engineering (CEE) that was first offered in spring 2021. It is not an introductory level course; its prerequisite course, CEE Fundamentals, is typically taken by CEE undergraduate students in the spring semester of their freshmen year. Fundamentals introduces students to basic GIS concepts like coordinate systems, data types, feature attributes, and creating map layouts [9]. Prior to spring 2022, students in Fundamentals learned GIS using ArcMap; GIS for Engineers utilizes ArcGIS Pro, the newer version of GIS software from the Environmental Systems Research

Institute, Inc. (Esri). Because of this prerequisite structure, students in the GIS course are all at sophomore level or above.

GIS for Engineers utilizes diverse learning activities that follow a tiered instructional hierarchy with progressively less guidance provided for student tasks as knowledge and program skills increase during the semester [10]. Seven types of learning activities are applied in class: overview lectures, instructor-led interactive demonstrations in the program, activities with a small participation grade component (e.g., GIS Data Hunts, field activity with a mobile GIS app), technical memos (used to compile results for submissions), Learn GIS Lessons (self-guided online tutorials offered through Esri), individual projects, and a group-based core project. The foundation of this course is an integrated project structure where seven individual projects (IPs) feed directly into the two-part integrated core project (ICP).

Individual projects are scripted tutorials completed individually by students, intentionally designed to highlight a specific application in civil engineering that requires students to apply various GIS tools to solve a problem or perform analyses relevant to investigating that problem (Table 1). There are four defining characteristics of projects used in the IP sequence:

1. Projects are framed within the context of a real civil engineering project or investigation. Each project places the student in the role of engineer, outlining required tasks and goals of the project that resemble outcomes an actual engineer may pursue using GIS in industry. For example, the prompt for IP-2 on Mapping is as follows:
“As part of a sustainability initiative, the municipal engineer for Chester County, PA is creating an inventory of select county infrastructure and natural resources that are in poor condition. She has hired your civil engineering firm to assist in preparing maps to convey the findings of this project. As an entry-level engineer with GIS experience, you are required to develop a map that effectively shows structurally deficient bridges over streams designated as having impaired aquatic life use. Additionally, the municipal engineer has also requested that a web application be created to share this information with potentially impacted residents living in the county.”
2. Only real data are used. Each project provides students the opportunity to work with actual data, obtained from any number of different sources including state agencies, local municipalities, and engineering consulting firms. Open source data is also leveraged where practical, including shared (open source) content via ArcGIS Online.
3. Some project sites are used for multiple projects. Re-using project sites for different engineering-related tasks allows students to see connections between various analyses as well as highlight aspects of project sequencing. Currently, this course uses five project sites for the IPs, including two sites that are used twice. Additionally, one IP is completed using the ICP site. An example of multiple IPs based at the same location is the Fairfax, VA project site. This site is first used in the Feature Editing Project (IP-4) for establishing road and lot layouts within an undeveloped tract of land, then again in the Construction Calcs Project (IP-6) where proposed site plan features for that same property are provided and subsequently analyzed to find cut/fill volumes and other construction quantities.

Table 1. Individual project details.

Project	Topic	Key GIS Concepts and/or Tools	CEE Application(s)	Project Site
IP-1	Georeferencing	Coordinate systems Georeferencing Feature creation Field calculations	Locate monitoring well locations from old site plan and calculate coordinates	Gas Station in Bear, DE
IP-2	Mapping	Layer symbology Data attributes Map layouts Web applications	Identify structurally deficient bridges along impaired stream reaches	Chester County, PA
IP-3	Spatial Analysis	Extract tools Analysis tools Proximity tools Surface tools Spatial data sets	Assess and quantify existing site conditions (soil types, land use, water features) Identify constrained areas within a site (steep slopes, riparian buffers) Perform zoning calculations	West Goshen, PA
IP-4	Feature Editing	Feature creation Modify tools Data attributes	Propose a site layout including roads, rights-of-way, lots, and setbacks that adheres to local zoning regulations	Fairfax, VA
IP-5	3D Analysis	Surface creation Contour creation Layer symbology Data attributes	Assess levels of groundwater contamination using monitoring well data	Gas Station in Bear, DE
IP-6	Construction Calcs	Surface creation Cut/fill tool Profile extraction Data attributes	Perform earthwork calculations for a proposed site plan Plot proposed roadway profiles with existing site elevations Estimate construction materials quantities for a proposed site plan (earthwork, pavement)	Fairfax, VA
IP-7	3D Visualization	Scenes Feature extrusion Animation	Create an animation to tour a 3D scene of a proposed development	ICP Site

4. Project outcomes align with tasks required for completion of the ICP. Overall integration of projects throughout the course requires that tasks and concepts learned through individual projects connect to at least one part of the core project, with tasks from some IPs being applied in both parts of the ICP. Some core project tasks are identical to those pursued in at least one IP; other ICP tasks push students to build upon previous knowledge to complete a related, but not identical, task from one or more previously completed individual projects.

Core project details

The integrated core project (ICP) is a two part, group project that spans the last two-thirds of the semester and thematically ties the course together. Concepts, skills, and tools that students learn through the IPs are integrated directly into the core project (Figure 1).

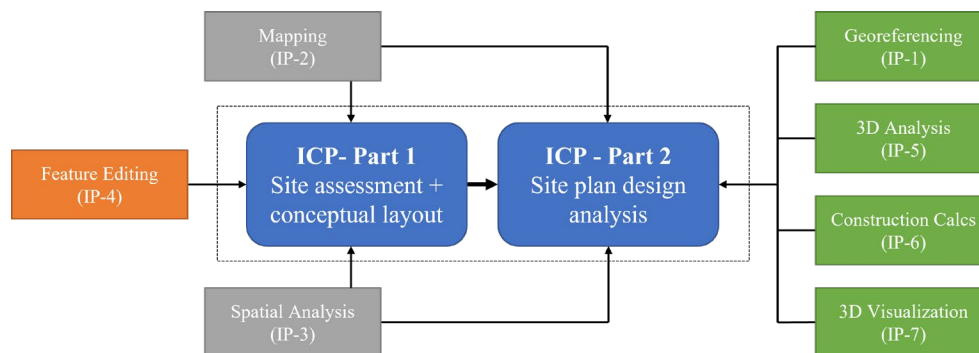


Figure 1. Integrated project structure.

By using actual engineering site plans from a local firm (converted into GIS data layers) and the same project site for each part of the ICP, students are able to see the progression of a real site development project and understand how spatial data analysis can inform and assist in many of the design phases. A different ICP site was used in the first two course offerings. In 2022, a more complex, larger-scale project was used (70 residential lot subdivision on a 120 acre property) than in the 2021 project (23 subdivided lots on a 34 acre property). Regardless of site used, project requirements were nearly identical in each of these years, culminating in the creation and oral presentation of an ArcGIS Story Map that detailed findings of each group's project.

Part 1 of the ICP requires student teams to apply spatial data analysis to investigate a tract of undeveloped land for the purposes of proposing a conceptual site plan layout on that property. Minimal GIS data is initially provided to student teams, restricted to layers representing the property boundary and several existing site features such as building footprints, driveway lines, contour lines, a digital elevation model (DEM), and water features (wetlands, hydric soils, ponds, etc.). The project assignment presents zoning regulations for the municipality as well as certain design requirements that must be met by their proposed site layout following investigation of the existing conditions. Students learn GIS skills needed complete the various tasks associated with this part of the ICP primarily by completing the first four IP's (Table 2) and applying other knowledge of the software learned through additional exercises in earlier classes (i.e., overview lectures, demonstrations, group activities). The final three IPs in the project sequence are not completed until after Part 1 of the ICP, and therefore, are not listed in Table 2.

Table 2. Integrated core project (ICP), Part 1 tasks and links to individual projects (IPs).

Key Project Tasks & Deliverables	IP-1	IP-2	IP-3	IP-4
<i>Quantitative summary of existing conditions:</i> area, elevations, slopes, soils, land cover, water features			X	
<i>Zoning calculations:</i> constrained areas (buffers, steep slopes, etc.), adjusted tract area, minimum required open space			X	
<i>Create conceptual layout:</i> must include roads, parcels, setbacks, house footprints, driveways, and sidewalks			X	X
<i>Quantitative summary of proposed conditions:</i> lot areas, impervious areas, and open space calculations			X	X
<i>Map layout:</i> create PDF map layout that shows proposed site plan		X		
<i>ArcGIS Story Map:</i> use text and maps to summarize existing site, present design, verify zoning regulations are met, explain design decisions		X		

In Part 2 of the ICP, student teams are required to use GIS tools to analyze the actual site plan design for that property. Various elements of the proposed site plan are made available as GIS data layers (e.g., proposed contours and spot elevations, lot lines, right-of-way lines, driveway lines, building polygons, storm/sanitary pipes, storm/sanitary structures, etc.). Student teams work collaboratively to apply skills and tools learned through completing six of the seven IP's, with particular emphasis on tools used in the last three of those projects (Table 3).

Table 3. Integrated core project (ICP), Part 2 tasks and links to individual projects (IPs).

Key Project Tasks & Deliverables	IP-1	IP-2	IP-3	IP-4	IP-5	IP-6	IP-7
<i>Land use and zoning:</i> tabulate lot areas, impervious areas, calculate open space, verify lot setbacks are met			X				
<i>Proposed surface development:</i> create proposed site DEM using contours, spot elevations, and various breaklines					X	X	
<i>Construction:</i> plot road profiles, compute net earthwork volume, map cut and fill depths, create itemized materials cost estimate						X	
<i>Visualization:</i> create animation touring through development in 3D; include trees at locations designated on georeferenced landscaping plan	X						X
<i>Data & asset management:</i> create web application to use as an asset inventory for stormwater and sanitary infrastructure		X					
<i>ArcGIS Story Map:</i> use text and maps to summarize analysis results, verify zoning requirements are met, show animation and web app, recommend sustainability feature(s) to add		X					

The integrated nature between the individual projects and core project is further highlighted by the fact that Part 2 of the ICP requires understanding content and applying skills learned in the first three IPs, which are taught much earlier in the semester. Thus, the integrated project approach demands students to continue to build upon their prior knowledge in applying GIS to solve realistic engineering problems and to aid in design tasks.

Assessment

To evaluate how the integrated project approach impacted learning in this course, students were asked to complete a feedback form following final submission of the ICP (Part 2) at the end of the semester. Participation was optional and all responses anonymous. The distribution of student level for each offering of the course is presented in Table 4. Feedback response rates for all questions were 72% (10/14) and 78% (18/23) in 2021 and 2022, respectively.

Table 4. Course enrollment.

Student level	2021 (and %)	2022 (and %)
Sophomore	14 (100%)	12 (52%)
Junior	0 (0%)	10 (44%)
Senior	0 (0%)	1 (4%)
<i>Total</i>	<i>14</i>	<i>23</i>

Feedback form questions were grouped into three distinct categories: (1) Course Learning Activities, (2), Course Projects, and (3) Course Content and Outcomes. Results from both years are presented below for each of these categories.

Course Learning Activities

Students were asked to rate the various class activities on how effectively each contributed to their learning, using a scale of 1-5 where 1 = not helpful at all and 5 = extremely helpful. As shown in Table 5, individual projects and the core project rated as two of the top three activities in each year, with real-time demonstrations in the program also rated favorably. Students viewed the IPs, which were primarily scripted assignments, as particularly helpful with 100% of students across both years selecting either a 4 or 5 for that type of activity. Consistent with the project-focus of the course, lectures were not viewed as favorably for student learning, nor were activities where students had less instructor guidance (e.g., Learn GIS Lessons). Moreover, in-class activities were not rated as highly, which is likely because those were standalone exercises, lacking the broader application or context that was used effectively in the individual projects.

The lowest rating for any project-based learning activity was the ICP in 2022. While that rating still indicates a generally positive impression of the ICP, the larger, more complex project site used in that second iteration of the course may have contributed to lower ratings. Specifically, some aspects of that site plan were not fully converted to GIS layers correctly, which resulted in several data discrepancies between GIS and the provided site plan PDF file that frustrated a handful of students. Additionally, the ICP is a group project so there is always the possibility that some students' views of the project as an educational opportunity are skewed by negative group interactions. The end-of-semester survey is optional and anonymous, but peer evaluations revealed that one of the project groups in 2022 had difficulty allocating work equitably.

Therefore, it is feasible that some of the less-positive feedback about the core project overall came from one or more members of that group. In future iterations of this course, group dynamics and work allocation are being critically reviewed to maximize the benefit of the project for every student, including the use of weighted grades that more directly account for individual contributions and correctness/quality of work produced.

Table 5. Feedback form results on course learning activities. Project-based activities are bolded and italicized in the table.

Learning Activity	2021		2022	
	Avg. Score	% Rating 4 or 5	Avg. Score	% Rating 4 or 5
Lectures/notes	3.4	50%	3.8	61%
In-class demonstrations	4.2	80%	4.7	94%
In-class activities (participation grade only)	3.7	60%	3.9	67%
<i>Individual projects (IPs)</i>	4.9	100%	4.9	100%
Submittal memo templates	4.1	80%	3.7	56%
Learn GIS lessons	3.5	40%	3.8	67%
<i>Core Project (ICP)</i>	4.7	90%	4.1	78%

Course Projects

Students were asked to share their level of agreement on seven question prompts in an effort to elicit specific feedback related to the projects utilized in this course. Question prompts addressed IPs and the ICP, as well as the connections between projects and the civil engineering field. These results, presented as averages in Table 6, are based on a Likert scale of agreement ranging from 1 = Strongly disagree to 5 = Strongly agree.

Table 6. Feedback form results on course projects: average scores.

Question	2021	2022	Overall
1. I enjoyed the project-based focus in this course.	4.8	4.9	4.9
2. Projects were set up in a way that emphasized applications within the civil engineering field.	4.9	4.7	4.8
3. Using the same site and/or data for multiple projects helped me see connections between different phases of the engineering design process.	4.8	4.8	4.8
4. The IPs prepared me well to complete tasks for Part 1 of the ICP.	4.7	4.6	4.6
5. The individual projects prepared me well to complete tasks for Part 2 of the ICP.	4.6	4.4	4.5
6. I was able to apply my GIS skills to complete ICP tasks that did not exactly match tasks from previous individual projects.	4.7	4.4	4.5
7. The ICP effectively connected concepts throughout the course.	4.5	4.7	4.6

Average scores were all well above 4 out of 5 across these seven questions. Furthermore, a closer look at the total distribution of student scores for these project-related questions (both years) reveals that very few students chose a score of 3 or less for questions in this part of the feedback form, and no student chose a score of 1 (Figure 2).

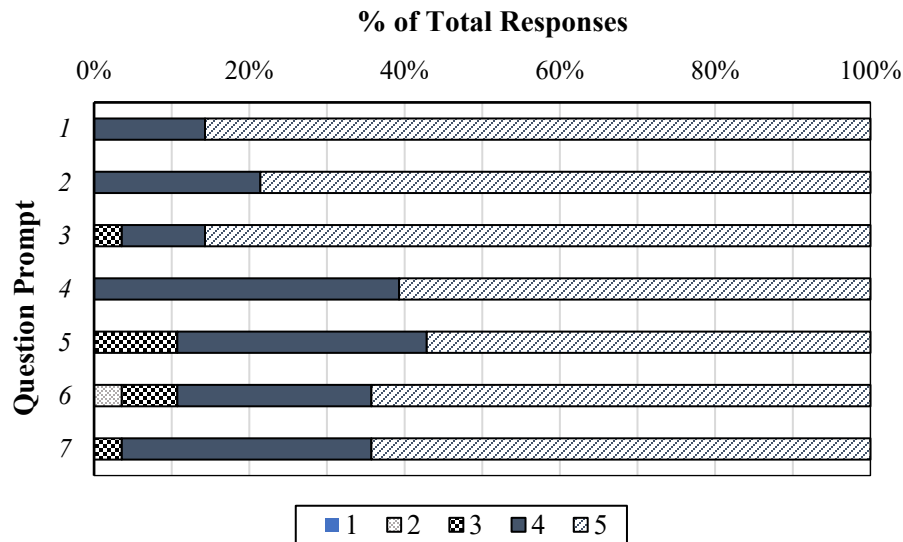


Figure 2. Feedback form results on course projects: distribution of student ratings for questions in Table 6. Combined results from 2021 and 2022 course offerings are shown.

Overall, feedback on course projects was overwhelmingly positive, not just in that the students enjoyed the project-based focus of course (Question 1), but also in that they connected the application of the projects to the civil engineering field (Question 2) and/or overall design process (Question 3). Thus, making connections between software tools and concepts and engineering applications is foundational to an integrated project approach of teaching GIS. Student feedback indicates the effectiveness of this interconnected approach, highlighted by the role the ICP played in connecting course concepts throughout (Question 7).

Course Content and Outcomes

The overall effectiveness of the integrated project approach was assessed through three questions specifically targeted at course outcomes (Table 7), using the same Likert scale as applied for course projects.

Table 7. Feedback form results on course content and outcomes.

Question	Year	2021		2022	
		Avg. Score	% Rating 4 or 5	Avg. Score	% Rating 4 or 5
This course helped me learn concepts and skills in GIS.		4.8	100%	4.8	100%
This course helped me learn concepts and skills in graphical communication.		4.7	100%	4.7	89%
This course helped me learn civil engineering concepts.		4.7	100%	4.7	94%

Students across both years strongly agreed that this course helped them learn concepts and skills in GIS, graphical communication, and civil engineering. In fact, nearly every student that responded to this survey over the two course offerings agreed (score of 4 or 5) that this project-centric course attained its core outcomes. Thus, the integrated approach seems to be quite effective in helping students learn software skills as well as civil engineering, which was the primary goal in developing this course.

Conclusions and recommendations

A new course was developed to successfully teach civil engineering concepts and GIS through a project-based approach that utilizes individual projects that integrate into a two-part, core project. The sequence of seven individual projects (IPs) leverages real data and targets civil engineering applications in a way that connects students to the civil engineering design process as they continue to build skills in GIS through the semester. These IPs prepare students for similar tasks required to complete the core project, first performing a site assessment to prepare a conceptual site plan layout (Part 1), then analyzing a full site plan design using spatial and 3D analysis tools and asset management concepts (Part 2).

Student feedback has been very positive through the first two offerings of this course, thus highlighting the effectiveness of the project structure and supporting the central goal of the course that GIS, graphical communication, and civil engineering concepts can all be learned through an integrated project approach. In addition to these positive results on perceived student learning, the influence of this project-based course has been observed through senior capstone design projects involving students in the first two cohorts of GIS for Engineers. Multiple teams in spring 2023 utilized GIS to perform tasks across various stages in their respective projects, including map creation, site assessment, design, and 3D visualization. Former students applying GIS in their capstone projects, when there is no requirement to do so, is an encouraging outcome that speaks to the true benefit of this course model.

Assessment of student learning in this course will continue, emphasizing the impact of course projects and connection between software skills and engineering concepts. Additionally, course revisions are continually being considered whether exploring new project sites (IPs and ICPs) or working with other faculty to better integrate concepts with other CEE courses at Villanova such as CEE Fundamentals, Project Development, or Capstone Design.

The integrated approach presented here should be translatable to other software packages (e.g., AutoCAD, Civil3D) or disciplines, whether sub-disciplines of civil engineering (e.g., structural, transportation, water resources) or in other fields. In adapting this approach for a different course, it would be important to maintain the defining basis of the integrated project approach: guided individual projects using real data to explore meaningful applications that clearly connect to an overarching core project. The specifics would obviously vary with software package and discipline, but intentional integration to connect the software to discipline-specific learning outcomes is the key element.

Learning software skills are valuable (and marketable) for students, which on some level can be at least partly obtained by the traditional approach of learning by clicking through a program.

While that is certainly a part of this course, the use of integrated projects to learn GIS while reinforcing core civil engineering concepts has shown to be an impactful model, providing students context and connections to enhance their learning in multiple areas beyond the software.

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