Adopting Parametric Construction Analysis in Integrated Design Teams

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Abstract

This paper reports on an industry-academia collaboration for integrating construction and engineering analyses into a graduate-level architecture design studio, including the developed workflow and curriculum, and lessons learned from the students' and instructors' experiences. The studio program pursues two learning goals namely implementing multi-variate analyses to develop a sustainable design concept as well as practicing collaboration and communication inside an interdisciplinary team. The results of this paper are mostly useful for students and new professionals in the AEC field who want to take most advantage of the emerging data-driven built environments and adopt a new mindset that supports the integration of construction information into the design process. Specifically, the outcomes of the design studio effort are summarized in the following three categories: (1) the development of a generalized and standard workflow for implementing parametric, computational, and performance-based design and construction approach that assists project teams to create design concepts, evaluate their design performance, and visualize the results, (2) the establishment of a framework for evaluating the quality of design process and collaboration in an integrated design team, and (3) the creation of visual programming methods and tools and design/construction software applications for systematic design programs' analysis and data visualization/interpretation for knowledge-based decision making (this work is in progress).

Keywords

Parametric design and construction • Computational design and construction • BIM • Performance-based design • Team collaboration and communication • Interdisciplinary team • Design studio

42.1 Introduction

The emergence of data-driven built environments has affected the Architectural, Engineering, and Construction (AEC) industry significantly over the last decade. It has helped the industry to improve its current practices, increase productivity, and reduce risks associated with design and construction. It has also required practitioners from all disciplines to reconsider

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their workflows, to practice communication and collaboration more effectively, and to adopt new technologies. As a result, experts from both academia and industry aimed to find new solutions for their traditional problems (e.g. fragmented design and construction processes) through applying the new approach of design and construction. For this purpose, professionals need to gain the related technical skills such as computational and parametric methods for performance-based design development and analysis as well as organizational skills including effective communication and working inside integrated multi-disciplinary teams.

42.1.1 Motivations for Integrated Design Studio Program

The fast-growing demand for gaining the mentioned technical and organizational skills in the AEC industry is the basic motivation for creating integrated design studio programs in the academia. An integrated design studio has students from multiple disciplines working together on a shared design project. The main purpose of such program is to develop a practical curriculum for training a new generation of professionals who have adequate understanding of other disciplines in the built environments (e.g. architecture, construction management, and related engineering fields) and have ability to collaborate and communicate with project team members to achieve best possible solutions.

In addition, the integrated studio program contributes to the aim of reducing the current fragmentation between design and construction processes. Traditionally, construction teams have a limited understanding of design intent and design teams have also a limited understanding of cost estimation and constructability considerations at the early stages of design. The result of such limitations is increase in RFIs and change orders as well as cost overruns during the construction phase and discrepancy between designed and actual building's performance during the occupancy phase [1]. More integrated project delivery systems such as Design-Build (DB) and Integrated Project Delivery (IPD) addressed this issue by providing project teams a method for better collaboration. However, finding the professionals prepared for collaborative design and decision-making is still a challenge. In this case, the integrated studio program is considered as a long-term solution that prepares such professionals.

Finally, the integrated studio program is a potential opportunity for industry and academia collaboration. This is specifically critical for implementing scientific and data-driven practices in the industry that leads to more knowledge-based decision making and fill the existing gap between construction and non-farm/manufacturing industries in terms of labor productivity [2]. Proper utilization of building data collection, analysis and visualization helps project teams to revise their purely experience-based design and construction methods. In this regard, the academia plays a key role by transferring computational and analysis methods from other science disciplines into the built environments for developing new methods and the integrated studio program serves as a research and development (R&D) environment for testing new methods and technologies.

42.1.2 Definition of Parametric Design Approach

The core of the integrated design studio program is learning about the parametric, computational, and performance-based design approach. Existing literatures have different definitions for the terms "parametric design", "computational design", and "performance-based design" [1, 3, 4]. In the context of the developed studio curriculum, parametric design is defined as determination of specific design-related parameters for creation of different design alternatives by changing in the parameters' values. Additionally, the computational design refers to applying computer-aided methods and applications to generate design intent, automate the process of design generation/alteration, and make different analyses for the generated design. Last, the performance-based design is defined as identification and consideration of building's performance-related criteria at the conceptual design stage in order to develop a design intent that meets the project team's established performance requirements.

Accordingly, the parametric, computational, and performance-based design approach consists of determining desired building's performance, identifying relevant design parameters to generate design intents/alternatives, and using computational methods to analyze/revise design intents till achieving the desired performance. Also, the explained design approach guides project teams to gather all the data required for leveraging data-driven methods and technologies not only during the design phase but also at the construction and operation phases.

42.1.3 Selected Building Design Project's Background

This paper reports on an integrated studio program developed by a team of faculties and TAs at the University of Washington department of Architecture and Department of Construction Management with architects and researchers from Perkins+Will, an Architecture firm. The coursework was structured around a graduate design studio co-led by a faculty member in Architecture and a practicing architect. Two course-linkages were created comprised of construction management students and structural engineering students led by faculty in the Construction Management Department and the Architecture Department respectively. These course linkages were intended to foster collaboration and to provide technical feedback in the area of costing, economic value analysis; and structural systems selection and design. This team (called instructor team) defined the studio project as developing design proforma for a high-performance multi-story mixed-use building that meets the city's sustainability program (Seattle's Living Building Pilot Program). For this studio, the instructor team selected a real project at the downtown Seattle (which is in design phase) as a case study. Students had access to the project location and were provided a preliminary design package including zoning information, relevant codes and standards, and early design studies.

The instructor team is currently working on improving the studio program based on the gained experiences and completing the computational tools visualization platform for the next round of the studio class.

42.2 Methodology

42.2.1 Structure of the Integrated Design Team

In this studio, the team formation was based on the idea of Integrated Design Process (IDP) which is defined as "an approach to building design that seeks to achieve high performance on a wide variety of well-defined environmental and social goals while staying within budgetary and scheduling constraints. It relies upon a multi-disciplinary and collaborative team whose members make decisions together based on a shared vision and a holistic understanding of the project" [5].

Accordingly, the students worked inside multi-disciplinary teams consisting of two-three architecture students as designers, one construction management student as construction management (economy and constructability) consultant, and one civil engineering student as structural consultant. Each discipline was led by a faculty and each consultant group had its own internal weekly meeting session during which students shared their work progress with their peers and discussed their technical issues with each other and with invited experts from industry. Also, students shared their experiences with working inside an integrated team and learn about the effective ways of collaboration and communication with other groups. Core to the structure of the graduate design studio was the *Design Space Construction* framework [6], a process tool aimed at supporting problem formulation, alternative generation, impact analysis, and value assessment.

During the studio program, students had several training sessions including tools and software tutorial sessions. A custom suite of visual programming-based analytical tools aimed at supporting multi-variate criteria analysis was developed specifically to support the design studio project. The design studio syllabus and schedule structured installation and use of the intended computational tools, design critic meetings with professionals from architecture, engineering, and real estate fields for having studio teams presenting their design concepts and receiving feedbacks, and three technical design workshops for water efficiency, energy efficiency, and façade development.

42.2.2 Standard Workflow for the Integrated Studio Program

In general, the integrated studio programs are created based on a main task and objective, a step-by-step process (for achieving the objective) that specifies the required sub-tasks, and tools/methods needed for accomplishing those sub-tasks. Currently, there are several integrated design studio programs in U.S. universities. For instance, researchers at the Georgia Tech University developed a curriculum for design space exploration and analysis [7] and researchers at the University of Southern California and Stanford university developed a methodology for design optioneering and optimization [8].

The University of Washington instructor team determined two learning goals for the integrated design studio program namely 1. apply the parametric, computational, and performance-based design and construction approach for creating a high-performance building's design concept that reflects all three aspects of sustainability (ecology, economy, and experience), and 2. practice collaboration and communication with the built environment's disciplines inside the integrated design team. To achieve these goals, the instructor team developed a standard workflow that is summarized in Fig. 42.1.

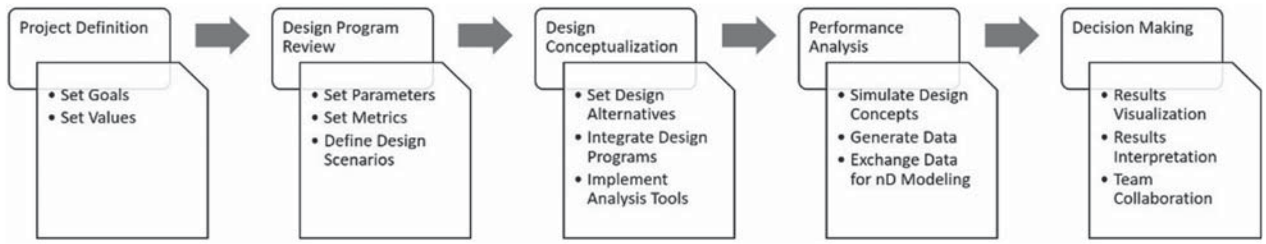

Fig. 42.1 Standard workflow for the integrated studio program

The standard workflow starts with project definition. In this step, the student team should set their goals for the project (e.g. designing an energy-efficient, profitable, or ecological building). Also, the student team should determine its weighted values which reflects the priorities and importance of different characteristics of design program (in practice, it is provided by owners and main stakeholders). The values will be later used for making decisions between generated design alternatives.

The next step is design program review, during which the student team sets design parameters that significantly impact the building performance (e.g. wall/window ratio in the enclosure, building envelope shape/orientation, and structural system). Also, the student team identifies all important metrics for performance analysis (e.g. energy efficiency, initial cost, and embodied carbon), and defines design scenarios for the project (in this studio it was defined as maxing out economy, ecology, and experience scenarios)

The third step is design conceptualization that includes creating design concepts' alternatives, integrating design programs based on the trade-offs between design scenarios in order to create one preferred alternative or a set of revised alternatives, and customizing design analysis methods/tools based on the determined design parameters and metrics.

In the next step, performance analysis, the student team simulates design concepts in the provided computational tools for architectural performance analysis such as energy, water, and daylight efficiency. The analyses results are generated/stored, and subsequently the consultants' required data is transferred into BIM-oriented platforms for construction performance analysis including design alternatives' economic, structural, and constructability analysis.

The last step is decision making. The student team imports all required information into a design dashboard that effectively visualizes design intents. The dashboard facilitates the data interpretations and serves as a platform that team members use for collaboration and knowledge-based decision making.

42.2.3 Project Evaluation Framework

In addition to the proper implementation of the explained technical workflow, the success of an integrated design studio will depend on the collaborative design development and communication of performance-based spatial, material, and formal solutions and synergies that evolve from the performance metrics. As a result, the instructor team developed an evaluation framework based on the idea of experiential learning in which students learn through experience and reflect on their work results. This framework evaluates studio teams' dynamics and performance using two groups of criteria.

First, it measures the quality of outcome-based criteria such as technical data generated, use of intended technologies, and created visuals (e.g. floorplans, rendered images, and axonometric diagrams). In terms of data generated as the results of architectural and construction analyses, the instructor team determined a list of metrics that students had to use for analysis and report. Figure 42.2 shows these metrics categorized in ten main groups.

Second, the framework evaluates process-based criteria including team collaborations, internal/external team communications, and design progress documentations. In particular, the design students had weekly desk critics to share their ideas, design approaches and any work created and to receive feedbacks from the instructors. Also, the construction management consultants documented their progress through submitting weekly work plans (WWP) and using plus/delta technique for reflecting on their team's performance in terms of technical, collaboration and communication effectiveness. Specifically, the technical factor evaluated weekly goals and questions students defined for balancing tradeoffs between design intent, constructability, and budget constraints. Also, the collaboration factor measures students' performance in the multi-disciplinary team-based decision-making process and communication factor evaluates the use of group discussions and visualization techniques to support communication across disciplines.

Categories	Building Morphology	Program Distribution	Energy Efficiency	Water Efficiency	Experience
Metrics	GSF [ft^2] Height [ft] Floors [#] Enclosure Surface-Area [ft^2] Roof Area [ft^2] WWR [%]	Retail [ft^2] Office [ft^2] Residential [ft^2] Other [ft^2]	Heating/Cooling-EUI [kBTU-ft^2/yr] Total Building EUI [kBTU-ft^2/yr] Total Energy Use [kBTU/yr] EUI Target [kBTU-ft^2/yr]	Rainwater on Site [GaL/yr] Potable Water-Demand [GaL/yr] Graywater-Produced [GaL/yr] Graywater Reuse [GaL/yr]	Average Lux [lux] Lux that meet target-illuminance UDI [%]
Categories	**Living Building Pilot**	**Affordable Housing**	**Economics**	**Structure**	**Business Cases**
Metrics	Zero Energy Petal [Y/N] Zero Water Petal [Y/N] Materials Petal [Y/N]	Affordable Housing Units [#] Fee Paid [$] Construction Cost [$, $/$ft^2$] Potential Loss [$] Value of Bonus FAR [$] Total Value Added [$]	Total Construction Cost [$, $/$ft^2$] Enclosure Cost [$] Renewables Cost [$] Gross Revenue [$, $/$ft^2$] Residual Value [$, $/$ft^2$] Payback Period [yrs]	SF of Concrete [%] SF of Steel [%] SF of Wood [%] Embodied Carbon-Estimate [kg/ft^2]	Developed Business Cases for the Innovative Design Programs

Fig. 42.2 Pre-determined metrics for the outcome-based evaluation

42.3 Provided Tools and Methods

The instructor team provided different tools to implement the sub-tasks determined in the standard workflow. However, students encountered some challenges in interoperability between tools. In addition, some of the subtasks (such as structural and economic analysis) were accomplished manually and students could not take advantage of a fully model-based analysis using the existing tools. Therefore, the instructor team started creating new tools and a data flow map between these tools. Some parts (including structural/constructability analysis and design dashboard) are currently being prepared or optimized. Figure 42.3 indicates the suggested mapping diagram.

The process starts from creating a 3D model inside Rhino software. At the conceptual design phase, the model contains most important architectural and possibly structural elements. The created model is then used for architectural analysis and it is also transferred into Autodesk Revit for construction analysis. The construction management consultants use the Revit model for economic analysis, import the model into other tools (e.g. Navisworks) for constructability analysis, and share it with structural consultants for structural analysis. Once analyses are done, all the results are organized and stored in an Excel file. Also, another Excel sheet is created that contains project metadata including design concepts' morphology and weighted values. Finally, these two Excel files are imported into Microsoft Power BI as the visualization tool to create the design dashboard.

42.3.1 Architectural Analysis

The studio teams used a Grasshopper script (developed by Perkins+Will) to run multi-variate architectural analyses including parameters of geometry, as energy, and daylight performance. The provided tools and methods have been developed over two years of curriculum refinement at UW [9]. Students could change their intended design parameters

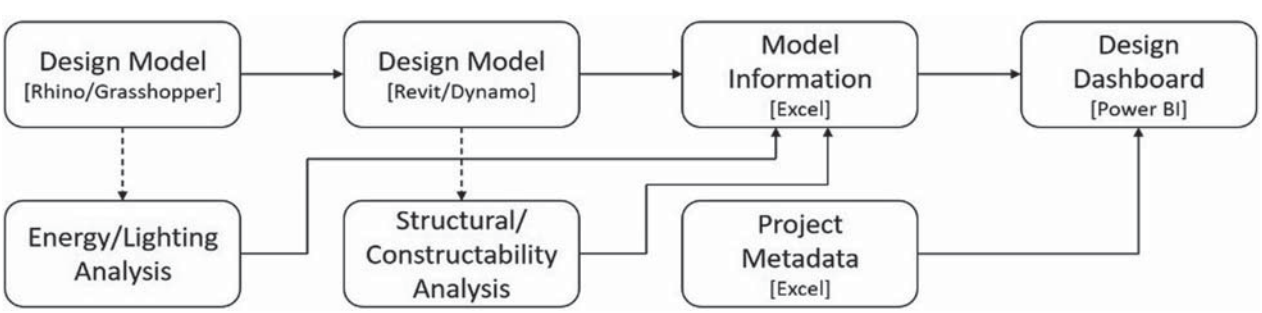

Fig. 42.3 Mapping between authoring, analysis, and visualization tools

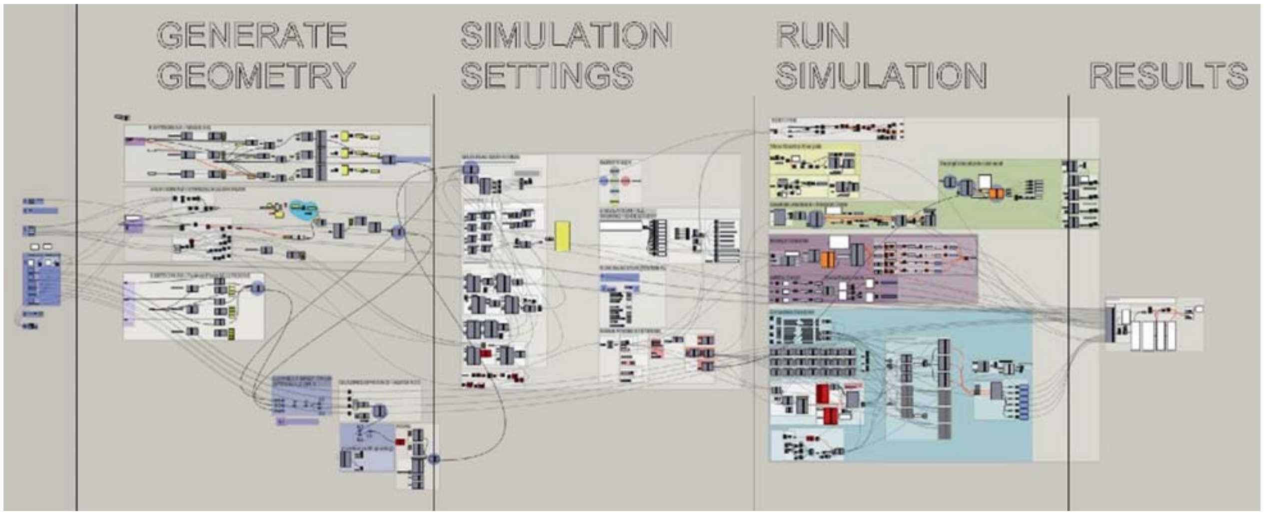

Fig. 42.4 Rhino/Grasshopper script for automating architectural analysis

inside the script and run the program for multiple alternatives to realize how those parameters impact the performance of their design concepts. Figure 42.4 shows the categorizations of nodes/code blocks in the developed script.

Once the analysis is complete, an Excel sheet was generated automatically that showed the results (including but not limited to calculated areas for floors, roof, and walls, window/wall ratio (WWR), zone peaks for heating/cooling, Energy Use Index (EUI), and lux) for the input design alternatives.

42.3.2 Construction Analysis

The main responsibility of the construction management (CM) consultants was to provide feedback on economic analysis. For this purpose, the CM consultants developed a business case for each design alternative, which included cost estimation and real estate analysis using the provided metrics. CM Consultants employed two methods for cost estimation including conceptual estimating (using RSMeans square foot cost book) at the early stages and then more parametric estimating (based on building systems) as design matured. Also, regarding the real estate analysis, students developed a project proforma consisting of effective gross income (EGI) based on design program distribution (commercial, residential, retail, etc.), total annual revenue, total project residual value, and payback period. During the team meetings, CM consultants were asked to share not only the results but the process/methods of economic analysis with other students, discuss the cost impacts of various design ideas, and provide recommendations based on the cost/benefit tradeoffs.

Based on the studio experience, the instructor team decided to create a computational script to automate the process of economic analysis. Figure 42.5 shows the primary functions of the developed script which are creating and exporting quantity takeoff (QTO) of the building elements that are identified as most important cost drivers, and creating user-defined visuals (sheet of floorplans, elevations, sections, and 3D views) for the purpose of visualization.

42.3.3 Data Visualization

As a brief definition, "visualization represents a product in a form that is meaningful to a divers group of stakeholders. Visualization creates understanding of what the product looks like and how it will function" [10].

Data visualization is an important part of the workflow because it is the preliminary tool for collaboration and communication inside an integrated team. Moreover, it is critical to find an optimized point between standardization of visualization (e.g. using pre-established template for all teams) for the ease of comparison and innovation of creating the visuals that best communicate the design intent.

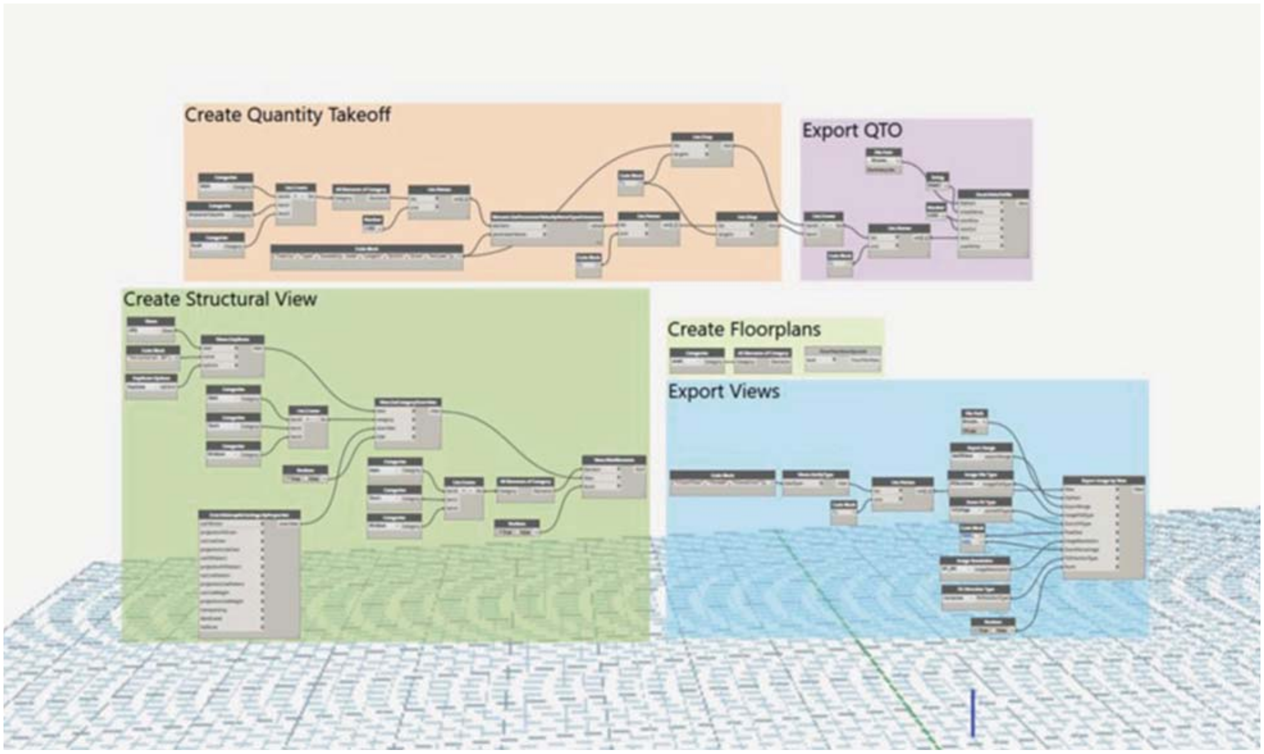

Fig. 42.5 Revit/Dynamo script for automating economic analysis

During the studio program, students used various methods to visualize their design intent and results of analyses. A lesson the instructor team learned was that creating a design dashboard helps students to prepare the required visualization items in a more consistent manner. Therefore, a last step is added to the developed workflow, during which studio teams visualize their work output by importing architectural and construction analyses' data as well as other useful information (e.g. 2D/3D views, analysis images, etc.) into a dashboard. For this purpose, the instructor team is currently developing a design dashboard template using the Microsoft Power BI.

42.4 Conclusion

This paper shares the experience of an integrated design studio program in terms of forming an integrated multi-disciplinary team, implementing a standard framework for parametric, computational, and performance-based design, developing a framework for evaluating the design decisions based on multi-variate empirical performance metrics, and adopting new computational tools for design development, analysis, and visualization.

The integrated studio program is a fast-growing pedagogical practice in the academia as it responses to the current demand for integration between design and construction processes and enables project teams to benefit from the emerging data-driven built environment and also provides an opportunity for industry-academia collaboration.

In this studio, the instructor team aimed to make a balance between the three teaching scopes of computational methods namely BIM tools, and Visual Programming Language (VPL) tools (Grasshopper and Dynamo), discipline-specific knowledge and practices, and integrated team collaboration and communication. As a result, although students took advantage of computational methods for design generation and analysis they still had the freedom to explore design concepts from different perspectives and create design alternatives beyond the use of parameters and metrics. Additionally, students practiced their domain-specific methods using the provided assignments and in parallel learned to manage collaboration with other disciplines through early definition of roles and responsibilities, clear and timely communication of their data requirements, and implementation of divergent/convergent thinking during the process of idea generation, discussion and decision making.

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