# Integrating Responsive and Kinetic Systems in the Design Studio: A Pedagogical Framework

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*Responsive architecture is one of the growing areas of computational design that is not getting adequate attention in CAAD curricula. A pedagogical approach to designing responsive systems requires more than the typical knowledge, tools or skill sets in architectural design studios. This paper presents a framework for integrating responsive and kinetic systems in the architectural design studio. The framework builds on findings of two design studios conducted at The American University in Cairo, Egypt. In both studios, students were asked to design elements of responsive architecture that work towards the development of their projects. The paper demonstrates the process and outcomes of both studios. It then demonstrates how concepts of integrated project delivery are incorporated to propose a framework that engages students in designing, fabricating and operating responsive systems in different phases of the design process. A discussion follows regarding dynamics of design studio in light of the proposed framework.*

**Keywords:** *Responsive architecture, Kinetic systems, Digital fabrication, CAAD education, Integrated project delivery*

## INTRODUCTION

CAAD education has traditionally focused on delivering skills related to specific software tools. With today's abundance of computational methods and systems, this approach has proven to be flawed in terms of its learning outcomes. One of the growing areas of computational design, which has not adequately received sufficient attention in CAAD curricula, is responsive and kinetic architecture. Compared to other constituents of an architectural project, a pedagogical approach to designing systems such as responsive structures or kinetic façade systems requires much more than the typical knowledge and skill set. It extends to include a variety of components such as digital fabrication and making, physical computing, parametric modeling and generative design, kinematics and motion, and material exploration, to name only a few.

In this paper, we propose a pedagogical framework that integrates responsive and kinetic systems in the design studio. Some of the key questions addressed through this proposed framework include: How can the skills and tacit knowledge required for designing responsive systems be delivered to students of architecture? How can the process of designing these systems be integrated in the design studio? How does this process change the dynamics and logistics of the architectural design studio in general? And how can it augment - rather than impede - fundamentals of the design studio, such as design thinking and integrity, in addition to drawing skills and representation?

We first present a review of pedagogical approaches to incorporating kinetic and responsive systems in architectural design. Then we describe the process and outcomes of two architectural design studios that incorporated the design of responsive systems. In both studios, groups of students at the American University in Cairo (AUC) worked on designing responsive elements for their projects, including components of an exposition center, such as a hotel tower, an office building, a conference center and exhibition halls. The goal was to identify an element that responds to exterior aspects, such as environmental conditions, or interior aspects, such as behavioral patterns within architectural spaces.

We show the process and outcomes of both design studios, as the process was intentionally slightly different in sequence. In the first studio, students start by developing their group and individual projects throughout design development, then work on designing their responsive system. In the second studio, they design their responsive system upfront and then work on design development. In both cases, they are asked to show how their systems reflected on the overall architectural or urban design development and detailing. The paper discusses results of both studios, implications for CAAD education, and proposes a framework for integrating responsive systems in the architectural design studio.

## APPROACH

Attempts to integrate the design of kinetic structures in education go back as early as 1970, but more involving product than process (Zuk and Clark, 1970). More recent pedagogical attempts include the work of Fox and Hu (2005), which focused on a bottom-up approach of designing mechanical structures then adding sensors and actuators to produce full scale responsive environments. Other efforts, such as El-Zanfaly (2011), provide basic guidelines for designing kinetic structures based on shape and motion grammars. Efforts that followed include intensive workshops or brief course modules. This paper aims at a more comprehensive integration of designing responsive systems as a pedagogical approach in architectural design studio.

We propose a framework for designing responsive systems in the design studio that incorporates learning by doing (Ozkar, 2007) and making in design (Blikstein, 2013). We hypothesize that integrating the learning of these systems in studio enhances student perception of spatial quality, mechanism and structural integrity, behavior and time, in addition to attention to scale, detail and connections, therefore informing the design process at both the architectural and urban design level.

We introduce below the process of two design studios in two consecutive semesters at the Department of Construction and Architectural Engineering at the American University in Cairo (AUC). This digital design studio (Architectural Design Studio V) aimed at integrating parametric and generative design in architectural projects, within the wider framework of integrated practice and project delivery, building information modeling, and advanced building technology. Within the studio, students designed, fabricated and operated elements of responsive and kinetic architecture that addressed a specific need in their projects. To do so, the students first developed parametric models of their proposals and then linked them to sensor networks feeding continuous real time input data. This data represented conditions from the surrounding exterior and interior environment. Sensor-planning-action mechanisms were proposed to develop the responsive systems. This was done using Grasshopper and Firefly plug-in, and a physical computing environment using the Arduino microcontroller.

The first studio was mainly divided into three phases: (1) master plan and preliminary form generation, (2) design development of individual buildings, and (3) design, fabrication and operation of a responsive/kinetic component. Students worked on an exposition center in the heart of Cairo, consisting of a 500-room hotel, a 20-storey office building tower, conference center, shopping center, and an exhibition area. In phase (1) of the course, each group was required to develop a master plan for an exposition center based on parametric design strategies. Individually, students then worked on one building type within the master plan, and were encouraged to use simulation and analysis tools, producing design development drawings by the end of phase (2). In phase (3), which is the main focus of this paper, each group was asked to work on a level of detailed design that involved developing working prototypes of kinetic and responsive systems or structures in their designed buildings. They were free to design elements that represented shading devices, façade paneling systems, window apertures, canopies, lighting features, etc. The students were asked to reflect on how this phase affected their design thinking process at different levels and scales of their projects.

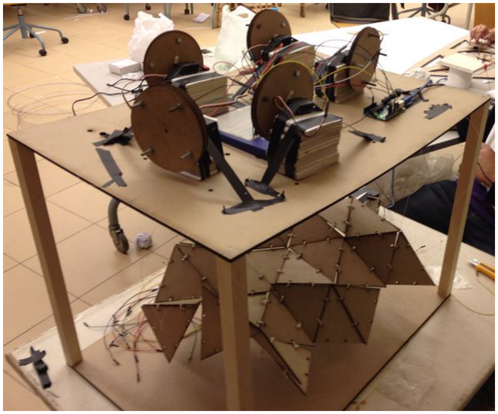
In the second studio, the sequence of phases was slightly modified, with the assumption that switching phases (2) and (3) would add to the richness of the design development process. The phases for this studio were as follows: (1) preliminary form generation, (2) design, fabrication and operation of a responsive/kinetic component, and (3) design development and detailing. The students were exposed in parallel to design computing literature and readings in areas of parametric design, scripting, responsive architecture, emerging practice, building information modeling, and integrated project delivery. They were asked to work in groups to design a 300-350 room hotel tower in downtown Cairo. While working on one building in this studio rather than developing a master plan, each group was asked to develop specialties among its group members while developing their designs; for example, a project architect, a BIM manager, a façade designer, a fabrication specialist, and a sustainability analyst. The goal was to delve into as much detailing and development as possible for the building components and process. In phase (3) of the project, the students worked on developing and detailing their buildings, and were encouraged to build on their findings in phase (2) to inform their design development effort, and develop models involving evaluation methods and using simulation and analysis tools regarding a topic of their choice.

## STUDIO OUTCOMES AND OBSERVATIONS

We describe below the main outcomes and general observations in both studios. Out of three group projects per studio, we chose two per each for observations and discussion.

### *Studio I (Fall 2014)*

Students varied in their approaches regarding the location and function of their selected responsive element. Some students developed alternatives for building elements such as apertures and louvers, and others developed alternatives for outdoor shading elements and structures. Group 1A chose to develop an outdoor roof structure as their responsive element. Conceptually, this structure was based on kinetic movement, where human behavior and density underneath the outdoor structure would generate electricity based on piezoelectric materials within the environment, in addition to volumetrically altering the space underneath, therefore allowing for larger spaces and more ventilation in high traffic areas and durations. In this sensing-planning-action mechanism, the environment would sense the thermal behavior and movement of users in space, and accordingly plan for necessary changes in height in the roof structure, in addition to generating electricity. For the exercise prototype (Figure 1), the students developed a scaled model of their roof structure.



The students used simple laser-cut triangular MDF connected parts to represent the roof structure, and pullies to simulate the motion of the roof parts, moving up and down to change the volume of space underneath. An Arduino microcontroller was connected to the model, and 6 servo motors were used to pull and push wire threads connected to the pullies to simulate the desired motion. The students used their cell phones to simulate the sensing component of the model using a light source, where the intensity of light controlled the volumetric change underneath the roof.

Group 1B chose to develop a building facade screen consisting of kinetic window apertures that respond to environmental conditions. Conceptually, the element was based on response to exterior conditions such as solar heat gain and daylighting, where the responsive aperture within a double-skin screen would open and close to allow for different daylighting and heat gain scenarios according to different times of the day. For the exercise prototype (Figure 2), the students developed a full-scale model of a 60cmX60cm screen using MDF boards. The screen was divided into four identical panels, each hosting a central core with motion rails working in 2 perpendicular directions to guide the kinetic movement of the modular screen units that shape the overall screen pattern. An Arduino microcontroller was connected to the model, and 4 servo motors were connected to each of the motion rails to achieve the desired opening and closing movement of the screen units. The students simulated the sensing activity using their cell phones, where the intensity of light controlled the angle of motion of the motors and consequently aperture sizes.

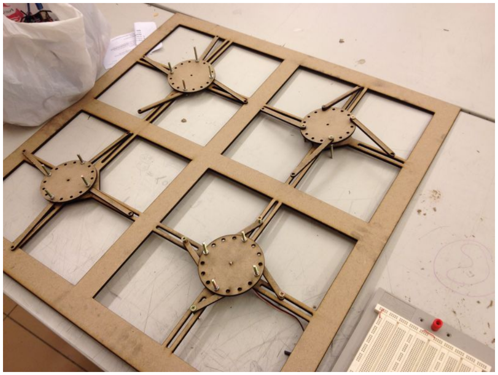


Figure 1
Responsive prototype of Group 1A: Kinetic Roof Structure

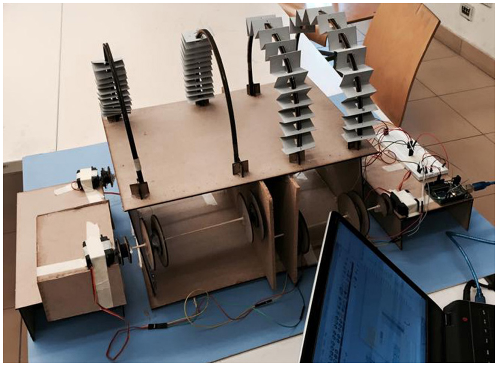
Figure 2
Responsive prototype of Group 1B: Window Aperture

### *Studio II (Spring 2015)*

Instead of introducing the responsive exercise at the last stage of design, this studio aimed at integrating it as part of the design process, with the goal of informing stages of design development. Students also varied in their approaches and their choices of responsive elements, where some selected elements related to the building facade skin, and others selected elements related to outdoor kinetic structures. Group 2A developed an outdoor responsive structure attached to their hotel building, as a shaded pathway taking users from the surrounding landscape to the building entrance. Conceptually, the structure would provide continuous shading and semi-shading for users along the path leading to the entrance of the hotel, by both responding to user movement and daily sun movement patterns. For the exercise prototype (Figure 3), the students developed a scaled model of a segment of the shading pathway using MDF and cardboard.

Figure 3
Responsive prototype of Group 2A: Outdoor kinetic shading pathway

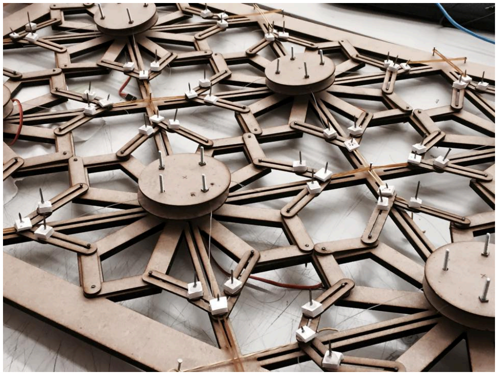
Figure 4
Responsive prototype of Group 2B: Dynamic Building Facade Screen



The model consisted of pieces of cardboard running across wooden rods representing guide rails for the shading path. The students used a number of pullies connected with threads to simulate the movement of the shading elements along the rails. An Arduino microcontroller was used and connected to Grasshopper, and 4 servo motors were used to control the motion around the pullies and consequently the shading patterns along the pathway.

Group 2B chose to develop a building facade screen consisting of a kinetic skin system. The system is composed of 1mX1m units that respond to heat gain analysis. Using a pre-programmed system that pulls weather and heat gain analysis data, the building facade should automatically respond to external conditions, while still allowing for user intervention upon desire. Each modular unit consists of muscle wires comprising electrostrictive materials that contract or expand based on the electric power they receive. These contractions and expansions produce variations in the overall shape of the building screen, producing varying patterns in the interior of the hotel building.

For the exercise prototype (Figure 4), the students developed a full-scale model of a sample 90cmX60cm screen using MDF. The screen was divided into six identical panels, each hosting a number of motion rails to guide the kinetic movement of the modular screen units that shape the overall building pattern. An Arduino microcontroller was connected to the model, and 6 servo motors were connected to each of the units to achieve the desired opening and closing movement and patterns. The students simulated the sensing activity using their cell phones, where the intensity of light controlled the angle of motion of the motors and consequently aperture sizes.



Some of the basic findings and observations upon conducting the two previous studios are: (1) the significance of the order of introducing responsive systems within an architectural project, and (2) the student team dynamics and collaborative process, and (3) the skill set and knowledge required to integrate responsive systems in a project. Typically in the Fall studio, the students could not capitalize on their responsive elements in developing their designs, as they were introduced in the final phase of the project. In the Spring studio however, there was a significant progress in the detailing and development that students expressed in their designs. Getting the students to design, fabricate and operate their responsive elements early in the process allowed for development at a number of levels, including structural detailing, environmental analysis, parametric modeling, and facade design.

As the students were asked to assume different roles in the Spring semester within their teams, this allowed for a further level of detailing. *Project architects* were expected to set the general strategy for the building form and function, *sustainability analysts* were expected to work on a detailed daylighting and heat gain analysis of the responsive system, *facade designers* on the overall building facade pattern design, *fabrication specialists* on the construction and operation detailing of the responsive and kinetic system, and *BIM managers* on software coordination within the team and programming the sensing-planning-action mechanisms for the system. Students varied in their approaches to applying these roles. Some teams worked within a discrete role-per-student model, while others distributed the tasks and roles among all team members. In both cases, this allowed for a thorough level of detailing of the projects, as well as a high level of awareness of integrated design and project delivery.

## FRAMEWORK FOR INTEGRATING RESPONSIVE SYSTEMS IN THE DESIGN STUDIO

Based on the previous findings, we propose a pedagogical framework for integrating responsive systems in the architectural design studio (Figure 5). This framework involves two main components: (1) the phases of design in which responsive systems are to be integrated, and (2) the different tasks, roles and skill sets required from students in order to design and develop those systems. The framework promotes phases of design as devised by the American Institute of Architects' Integrated Project Delivery (IPD) Guide in 2007 [1], where the phasing of design is slightly different than that in traditional project delivery based on some of the fundamental principles of integrated design and project delivery. These principles include collaborative innovation and decision making, early involvement of key participants, early goal definition, intensified planning, and the use of appropriate cutting edge technologies. For this framework, we highlighted the following IPD phases as most relevant in the design of responsive systems and applicable in an educational studio setting: conceptualization (expanded programming), criteria design (expanded schematic design), detailed design (expanded design development), and implementation documents (construction documents).

We identified tasks, roles and skill sets that are most relevant to the design of responsive systems, such as BIM management, facade design, fabrication and detailing, and cost and sustainability analysis. By BIM management, we refer to all the required skill sets related to modeling, selection of appropriate tools, interoperability, in addition to dealing with the physical computing programming environment and sensing-planning-action mechanisms. By facade design, we refer to all tasks and skill sets related to building facade pattern design, and form generation and massing strategies. By fabrication and detailing, we refer to all tasks and skill sets related to the hardware components of the responsive system, fabrication, assembly and operation of its components, as well as construction detailing and documentation. By sustainability analysis, we refer to all tasks and skill sets related to environmental analysis of the operational use of the responsive system, especially daylighting analysis, solar heat gain and visual accessibility. By cost analysis, we refer to all skill sets related to checking and optimizing the cost of the responsive system, both in its prototype and actual construction phases.

Within this framework, students of architecture should be encouraged to work in teams (possibly interdisciplinary teams as well if applicable with more complex systems) in order to acquire collectively the necessary skill sets. Concepts of BIM management, interoperability, integrated design and project deliv-

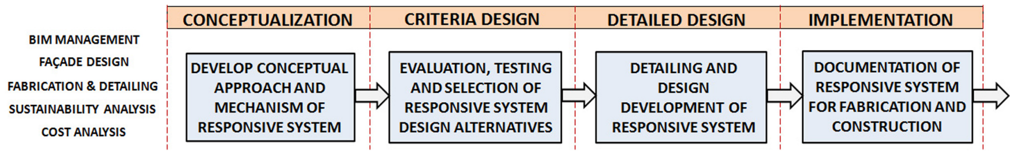



Figure 5
Framework for integrating responsive systems in the architectural design studio

ery, thermal comfort, daylighting, energy analysis, facade design and retrofit, cost analysis, digital fabrication, parametric modeling, and physical computing all contribute towards the success of designing, fabricating and operating such responsive systems. These concepts and their related literature should be highly integrated within this studio as well as in relevant prerequisite courses where appropriate. Below is a brief overview of the expected activities and workflow in the design studio for each of the aforementioned phases: conceptualization, criteria design, detailed design, and implementation documents.

### *Conceptualization*

The main purpose of this phase is to allow the students to develop a conceptual approach and mechanism narrative for the required responsive system, while understanding and analyzing its value and significance to the architectural project. Following the principles of IPD, students should integrate concepts of BIM, cost, sustainability, facade design and fabrication collectively at this early stage in design. Below is an outline of some of the activities required at this phase:

**BIM management.** At this early stage of design, the activities related to BIM management include defining the general modeling strategy for the responsive system components, identifying the required software and programming interfaces, modeling the different alternatives, and planning the responsive system scenario in the software development environment.

**Facade design.** At this stage, the activities related to facade design include devising the general strategy for facade treatments, analyzing and generating patterns for building skin, developing alternatives for responsive mechanisms, and studying impact on building exterior form and interior functional spaces.

**Fabrication and detailing.** At this stage, the activities related to fabrication and detailing include extracting modeling data of responsive system components and their alternatives for prototyping and fabrication, building preliminary physical models for evaluation and testing, and testing basic sensor-planning-action mechanisms based on the narratives.

**Sustainability analysis.** At this stage, the activities related to sustainability include specifying performance goals, target values and sustainability criteria for responsive system, analyzing building massing and orientations, and developing narrative for daylighting, and solar radiation, in addition to any specific environmental considerations such as acoustics, visual access, etc.

**Cost analysis.** At this stage, the activities related to cost analysis include identifying a preliminary budget for responsive system elements in the project, and extracting modeling data of responsive components and their alternatives to generate cost estimates for prototypes and projected total costs upon construction, based on material selection, scale, systems and technologies implemented.

### *Criteria Design*

The main purpose of this phase is to allow the students to test, evaluate and select an appropriate responsive system for development and implementation based on a number of set criteria. Below is an outline of some of the activities required at this phase:

**BIM management.** At this stage, the activities related to BIM management include coordinating the testing and evaluation of all design alternatives and selecting best fit based on the criteria set in the conceptualization phase, in addition to programming the required interface of the responsive system, and linking parametric model data to the physical computing interface.

**Facade design.** At this stage, the activities related to facade design include evaluating and adjusting the proposed facade designs and generated patterns according to building function and desired exterior form until an optimum facade design is selected. This evaluation should take into account user behavior and interaction with responsive system within building spaces, as well as exterior environmental factors.

**Fabrication and detailing.** At this stage, the activities related to fabrication and detailing include digitally fabricating the selected responsive system prototype, connecting physical components such as sensors, motors and micro-controllers to the programming environment and building model data, and studying the materials, size and implemented technologies of the system upon actual construction.

**Sustainability analysis.** At this stage, the activities related to sustainability include evaluating all responsive system alternatives against desired daylighting and solar radiation target values, selecting best fit options and conducting the necessary optimization procedures.

**Cost analysis.** At this stage, the activities related to cost analysis include evaluating all responsive system alternatives against the budget identified in the conceptualization phase, selecting best value alternatives, adjusting system components, and updating prototype estimate and projected total cost upon construction.

### *Detailed Design*

The main purpose of this phase is to allow the students to develop, detail and further refine their selected responsive system. Below is an outline of some of the activities required at this phase:

**BIM management.** At this stage, the activities related to BIM management include linking the developed building model data (and environmental simulation data) to the physical computing interface of the responsive system, executing the scenario of use and operation of the responsive system under the set requirements and constraints, and conducting continuous refining and testing of the system based on updated building model data and input variables to ensure correct and complete operation of system.

**Facade design.** At this stage, the activities related to facade design include finalizing both the overall facade pattern scheme and details of the building envelope design by means of studying partial wall sections and 3D models, and updating the scheme based on refinement of fabrication details and operation of responsive system, in addition to devising a detailed scheme of materials, textures and colors.

**Fabrication and detailing.** At this stage, the activities related to fabrication and detailing include finalizing the responsive system prototype regarding materials, connections, assembly, and operation of sensors, micro-controllers and actuators. This phase requires attention to the mechanics and assembly logistics of the system, especially with regards to forces, weights, torque values, kinetic behavior of materials and the different applied mechanisms, as this can only be visualized and assessed upon physical testing (or otherwise in complex simulation software), and may require testing with actual users in case of full-scale models.

**Sustainability analysis.** At this stage, the activities related to sustainability include continuous simulation and optimization operations of the selected responsive system with respect to daylighting, solar radiation and any other desired environmental factors. Results of these operations should be coordinated between building model data and physical computing interface to allow for accurate refining of the selected system.

**Cost analysis.** At this stage, the activities related to cost analysis include continuously updating the building model with cost data such that the development and detailing effort of the prototype and final constructed project is always informed by the cost factor. At this point, major decisions regarding cost cuts should be enforced, such as reducing panel sizes and thicknesses, modifying material selections, and optimizing the use of physical computing components by devising for example mechanical schemes that use fewer actuators while preserving the required performance.

### *Implementation Documents*

The main purpose of this phase is to allow the students to properly document their responsive system design for construction. Below is an outline of some of the activities required at this phase:

**BIM management.** At this stage, the activities related to BIM management include extracting all relevant data for full documentation and construction of the responsive system and its components and detailed drawings.

**Facade design.** At this stage, the activities related to facade design include documenting and producing technical drawings for the building facade skin, including elevations, wall sections, 3D details, and blow-up details.

**Fabrication and detailing.** At this stage, the activities related to fabrication and detailing include carrying the responsive system from the prototype phase to actual construction phase, where a thorough study of mechanisms, systems, materials, panels, glazing, and technologies is conducted.

**Sustainability analysis.** At this stage, the activities related to sustainability include extracting simulation and optimization data for documentation and producing technical drawings, and carrying out further analysis for actual construction based on data for materials and systems.

**Cost analysis.** At this stage, the activities related to cost analysis include updating cost data and extracting it for documentation of quantities and pricing, and conducting further refinement for actual construction based on updates from sustainability and construction data.

## DISCUSSION

The benefits of addressing responsive systems within the integrated design and project delivery realm rather than a discrete phase of design were seen as twofold: (1) facilitating the process of designing, building and operating responsive systems, and (2) augmenting the basic principles and dynamics of the architectural design studio. First, the skills, tasks, and tacit knowledge required for designing, building and operating responsive systems could be delivered to students of architecture in a way that fosters collaboration and allows for group thinking and learning. As students assume specific roles in the process or are conscious of the types of activities required to comprehensively fulfill the design and operation of a given responsive system, the tacit knowledge required is infiltrated indirectly into the general design process. Observations from the Spring semester case study showed that the explicit roles related to sustainability, fabrication, facade design and BIM management and their integrated roles among the teams forced the students to develop their responsive system designs in a much more elaborate and all-encompassing process. The students realized that even if they did not work in a model where their role was discretely defined as a specialist in any of the assigned domains, they were still able to capture what was required of them as an integrated team in order to produce and deliver their designs.

At the same time, it was important not to compromise the dynamics of the design studio nor impede fundamental skills typically acquired in a design studio setting. The proposed phasing of the integrated design process addresses specifically this issue. Students are still exposed to a thorough development, detailing and documentation process following their conceptualization process and their extensive non-conventional iterations with digital fabrication, physical computing and programming. The added value, however, is that the students perform these documentation procedures and go through intensive technical drawing exercises while being informed by a rich cycle of iterations, digital and physical prototyping, testing and operation. Another added value is the rationale that is carried along each of the design phases at different levels, where students can feel more comfortable about their designs, having tested them virtually and physically. Throughout the proposed phases, students can justify their design decisions in different domains, including constructability, cost and value engineering, sustainability and environmental control, and operation and management.

Looking at the large picture, engaging students in a model far from a conventional educational setting, but rather a simplified model of architectural teams in practice like the one proposed in this paper, would further their understanding of teamwork and interdisciplinary collaboration in the AEC industry. We hope to further develop this work by testing this pedagogical framework in the coming semesters and build on the feedback of students and of practicing professionals. Including participants from other disciplines such as structural and MEP engineers in an interdisciplinary course would also enrich our understanding of this framework and help develop it to a wider scope of implementation.

## CONCLUSION

This paper proposed a pedagogical framework for integrating responsive systems in the architectural design studio. Based on the findings of two design studios at The American University in Cairo, the proposed framework engages students in a design process that utilizes the concepts of integrated project delivery in its phases and activities. The framework builds on introducing students to a number of necessary skill sets, activities and concepts in order to design, fabricate and operate responsive systems, such as BIM management, facade design, fabrication and detailing, cost analysis, and sustainability analysis. The paper demonstrates how these activities can be integrated in different phases of the design, ranging from conceptualization to implementation documents.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