Developing a Collaborative Undergraduate STEM Program in Resilient and Sustainable Infrastructure

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Abstract

After a natural disaster, multiple disciplines need to come together to rebuild the damaged infrastructure using new paradigms. For instance, urgent restoration of services demand to abridge the projects' schedule and provide innovative solutions, thus making collaboration and integration essential for the project's success. Commonly, the academic preparation of scholars on infrastructure-related disciplines takes place in isolated professional domains, rarely tackling interdisciplinary problems and/or learn from the systematic research of previous experiences. In Puerto Rico, the aftermath of Hurricanes Irma and Maria has heightened awareness regarding the education on infrastructure-related disciplines to provide transdisciplinary solutions to pertinent complex challenges. This taxing context compels the academia to train a new cadre of professionals properly prepared in those STEM disciplines. Further, current public awareness of the vulnerability of the existing infrastructure creates an opportunity to recruit and prepare students to become those much-needed professionals. The present work offers the conceptual framework of a collaborative effort among Architecture, Engineering, and Construction (AEC) to develop an interdisciplinary program in resilient and sustainable infrastructure. The framework includes the development of transformational pedagogic interventions and changes that will challenge the disciplinary splits among AEC. The framework targets values and skills for inter and transdisciplinary problem solving, as well as helps smooth the transition from academic education to professional practice. To implement the initiative, the project created a collaborative platform among three campuses of the University of Puerto Rico System. Each of these campuses offers a different educational component relevant to the enriching educational initiative. We expect this approach to create a new breed of professionals ready to face the challenges posed for the development of robust infrastructure. The strategy fosters readiness in environmental design in engineering and construction through evidence-based design and inter/transdisciplinary problem solving. Thus, this research contributes to the body of knowledge by presenting a collaborative effort to train future professionals to design and build a robust infrastructure that can overcome the impact of major natural catastrophes.

Introduction

Hurricane Maria made landfall on September 20, 2017 in Puerto Rico as a category 4 hurricane, the fifth strongest hurricane to ever hit the United States. Hurricane Maria plowed through the island from southeast to northwest damaging the infrastructure and causing devastation and death. The widespread outages of power and telecommunication service left the island practically uncommunicated [1].

The current devastation caused by the hurricane and the subsequent (and ongoing) recovery efforts heightened awareness about designing and building infrastructure able to withstand the impact of natural events. It became evident that, in order to be able to design and build said infrastructure, we need to train future professionals in infrastructure related disciplines to work together to provide interdisciplinary solutions to these complex infrastructure challenges.

Currently, the Architecture/ Engineering/ Construction (AEC) curriculum has students developing in silos, without the required interaction and learning experience of work with other infrastructure-related disciplines. This interaction would have enhanced these professionals' ability to collaborate [2]. After a natural disaster, multiple disciplines need to work together to compress the projects' schedule and provide innovative solutions, resulting in collaboration and integration essential for the project's success [1]. A salient example of this shift in the industry towards interdisciplinary collaboration in design and engineering practice comes from the experience in the aftermath of Hurricane Katrina devastation of New Orleans. There, integrated design solutions were used because "leaders quickly realized that a more integrated approach to building resilience into the Louisiana coastline made more sense than many individual efforts." [3].

To achieve integrated design solutions, interdisciplinary knowledge is required. The interdisciplinary and integrative capabilities of the profession are two of the aspects stressed by the "A Vision for the Future of US. Engineers" document of the American Engineering Society [4]. Interdisciplinary education means on one hand to have together students of more than one discipline, but also to develop syllabi and curricula beyond the discipline's boundaries. Integrated design solutions also require communication and collaboration of people coming from different professional backgrounds, and not always sharing similar goals and/or worldviews [5][6]. These skills are stated in the Criterion 7 of the Student Performance Criteria of the National Architectural Accrediting Board (NAAB). This reads that in architects' education it is required for students to develop "collaborative skills ability to recognize the diverse talent found in interdisciplinary design project teams in professional practice and work in collaboration with other students as members of a design team." These skills are also present in the accreditation criteria by ABET (Accreditation Board for Engineering and Technology). However, as mentioned before, the current education curricula seldom expose students to collaborative experiences.

These integrated solutions will improve critical infrastructure such as the electrical and water systems. For example, the impact of Hurricane Maria in Puerto Rico's electrical infrastructure led to a slow and painful rebuilding process of the power system that has not finished. This sluggish process has had many problems as in the case of the numerous power outages due to the unstable energy generation and supply system. More contemporary approaches to interdisciplinary solutions and power generation and distribution (i.e. distributed generation, intelligent microgrids, storage and solar generation systems) will likely increase the resilience of Puerto Rico's power system in the face of natural disasters. These systems are characterized by generating electricity at the same point of consumption, making it unnecessary to have large electric transmission lines and allowing independent operation in times of crisis [1].

A Collaborative Intercampus Platform

Our project consists on the implementation of strategies that will change and challenge the traditional separate academic preparation between the academic units involving Architecture and Engineering. In addition, we will also minimize the differences between the educational and the professional worlds by creating experiences with government agencies and laboratories that will be included as part of the academic preparation. The involved team is developing a targeted curriculum to achieve these goals.

To implement this initiative, the three university campuses established a collaborative intercampus cooperation platform. This agreement will allow faculty from the campuses to develop an integrated curriculum that will enhance the educational experience. Each of these campuses offers a different educational component relevant to the interaction required to train students to provide integrated design solutions. One campus offers a bachelor's degree on Environmental Design. Another one offers degrees in Civil, Electrical, and Materials Science and Engineering, among others. The third campus (the smallest of the three) offers, among others, two-year degrees on Construction and Architectural Drafting. The present project provides a shared curriculum across the three campuses that increases collaboration among campuses. The program allows a seamless transition path among students pursuing the two-year degree that would like to transfer to any of the four-year programs offered by the other two. The team is developing a shared curriculum that will allow, in the long term, the development of a degree in Resilient Infrastructure and Sustainable Engineering. This would allow including other engineering disciplines such as Mechanical Engineering as well as fields like Urban Planning among others. The inherent inclusiveness of the project rests on the Hispanic Serving Institution nature of the university where this study takes place. The University of Puerto Rico is a system that serves over 60,000 students, of which 99% are Hispanic, with Spanish as their primary language.

The project has two main expected outcomes: 1) Capacity Building through Critical Transitions and 2) Capacity Building through Cross Sector Partnerships. Capacity Building will be reached through the development of a sequence of courses and experiential learning experiences that will lead to a minor degree. Regarding Cross Sector Partnerships, they will be reached by means of an Advisory Board composed by government agency representatives and faculty, and through the development of a plan for hands-on experiences for participating students of the program.

Communication as well as collaboration are critical in the design and construction of infrastructure. Collaboration is fostered by through courses that will require students to interact in teams. The course contents require developing both intra and interdisciplinary actions that require collaborative problem-solving skills. Because of the geographical location of all campuses, both collocated and remote interactions among partaking students are needed. A pedagogic tool, which the team believes could be of great assistance is Project Based Learning (PBL). This approach allows students to learn through experience. As part of the collaboration framework, PBL activities and teaching methodologies focus on collaborative problem-solving, learning while solving and communications.

Conceptual Framework

To prepare students to achieve integrated design solutions to conceive and build resilient and sustainable infrastructure, substantial changes in the way in which we deliver professional knowledge in AEC need to be made. To address this situation, the team developed an interdisciplinary Resilient Infrastructure and Sustainability Education – Undergraduate Program (RISE-UP). The program emphasis hinges on both the development of interdisciplinary research skills (experiential learning) and case study research and turns them into hands-on solutions for real problems/projects, starting with the ones generated by the impact of Hurricanes Irma and Maria (figure 1). The timely collection of evidence of the infrastructure damages caused by the 2017 hurricanes in Puerto Rico facilitates the development of evidence-based solutions in the curriculum. An advisory board comprised of experts from pertinent US federal agencies and state professional engineering and architecture board, along with an internal and an external project evaluator will assess the project.

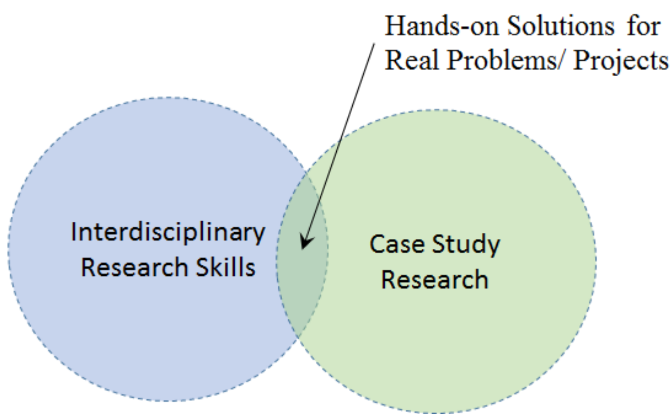

Figure 1: RISE-UP infrastructure design and construction solutions

Methodology

The research design for this study follows a quasi-experimental approach. According to Johnson and Christensen [7], "a quasi-experimental design is an experimental design that does not provide full control of potential confounding variables. In most instances, the primary reason why full control is not achieved is because participants cannot be randomly assigned to groups" (p. 328). In this study, the participants that are already enrolled in one of the participating academic programs, apply to join RISE-UP and the best are selected. Therefore, randomness is not possible. The study uses a mixed methods approach, which includes hard data and observations, to achieve and in-depth understanding of the factors that may contribute program's success. To develop an interdisciplinary program in resilient and sustainable infrastructure, the researchers used a two-prong approach: case study research and interdisciplinary curriculum development.

a. Case Study Research

As Breslin and Buchanan point out, in design “case studies have a rich history for exploring the space between the world of theory and the experience of practice” [8]. In order to support our project-based learning strategy, we advocate for the use of evidence as a tool to inform both learning and decision-making. The evidence to be used will be provided by previous cases related to the impact of natural events to the infrastructure in Puerto Rico, using the case-based learning method. We use the definition stated by [9] in which a case study is “an intense study of a single unit with the purpose of a larger class of (similar) units”, and with the pedagogical purposes cases have been used in academia following the methods originally pioneered by Christopher Langdell in which cases are used as instances to understand situations that later on students can use to understand and solve novel situations [10].

Following the conceptual diagram presented in figure 2, students will turn variables coming from the environment under study, into content that can be retrieved then after from the database in terms of design variables and actions that can be then after applied to their decision-making processes pertaining specific situations posed to them on the advanced courses of RISE-UP.

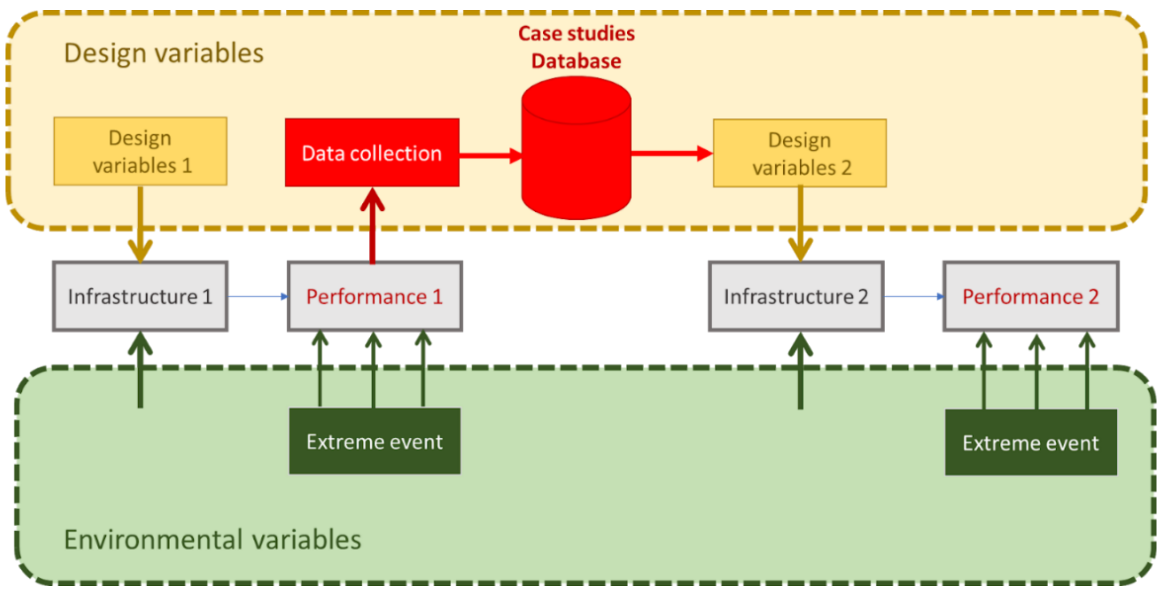

Figure 2: Case study database model

Once the system is up and running, the cases produced throughout the RISE-UP first level courses will use a model of data collection presently in development that will, in a comprehensive way, collect data related to what is called conceptually an IBIS (issue-based information system) [11]. We will document characteristics of the problematic situation (i.e., location, type of infrastructure, issue to be addressed), documents either exchanged and or produced (i.e. photos, diagrams, plans, contracts, bids), information about the stakeholders (i.e. role, expertise), and actions performed by them. Through the preliminary courses, in the field students will collect information regarding performance aspects of buildings connected to design issues. Then, they will feed the information into an *ad hoc* repository. A major framing element of the content in the database will be:

a. the performance of the infrastructure under high environmental stress conditions, and
b. how this performance can be either replicated for successful cases or improved for those that fail upon extreme events.

All case studies will be selected based according those two criteria. The system will ultimately become a source of indexed narratives of precedents that students can use as 'lessons-learnt" from which they can derive experiences, avoidance of pitfalls and successful actions that they might implement in their required and future projects in RISE-UP. Therefore, and for the ending learning cycle of RISE-UP, students in the design level courses will be then asked to use this rich information to take data-informed decisions regarding the development of new infrastructure. Once they are implemented, they will also become valuable resources for the cases' database. Students are expected to bridge the gap between a problem/situation posed to them in the final course of the sequence, and to use the precedents stored in the case-study database as tools to frame and aid the solving of the problematic situation.

In due time, the results of the student work will also become part of the database as exemplars of application that will also add to the knowledge repository and will be publicly available for use of researchers, faculty and students at other universities. Therefore, the long-term goal will be not only to provide this tool to students and faculty of the program, but also to provide access to other stakeholders, and ultimately share this knowledge and the knowhow behind the system with other institutions interested in creating similar knowledge repositories.

b. Interdisciplinary Curriculum Development

To design and build infrastructure requires communication and collaboration of people from different professional backgrounds, and not always sharing similar goals and/or viewpoints [5][6]. Accordingly, this collaborative effort between faculty in architecture, engineering, and construction provides a shared curriculum for students pursuing associate and bachelor degrees in the above-mentioned professions. In the RISE-UP curricular sequence in figure 3, all courses share a common goal of creating synergetic interactions among these four domains:

- Integrated Project Delivery: "a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction" [12].
- User-centered design: a process focused on the intended users to offer tailor-made solutions that better meet their needs [13]

- Problem-solving: students will work with faculty and stakeholders to explore and offer solutions to complex infrastructure problems
- Sustainability and resiliency: students will work with faculty and stakeholders to develop design solutions that are both resilient and sustainable.

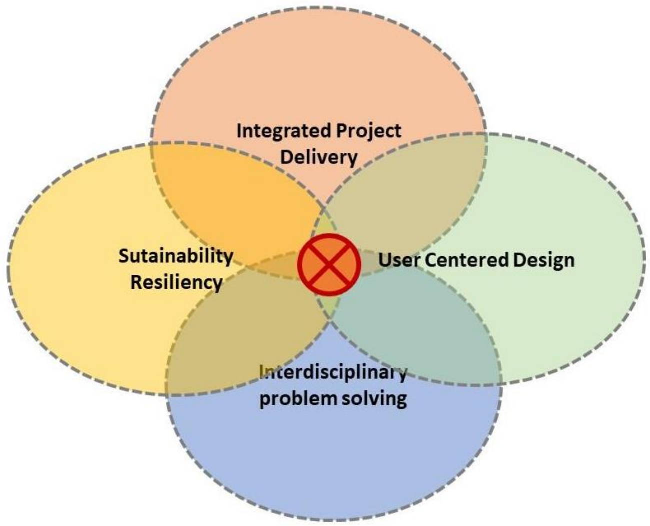

Figure 3: Four domains

The RISE-UP curricular sequence integrates instructional scaffolding, consisting of 5 different levels (figure 4). The idea of scaffolding in learning was originally developed by Vygotsky, and it is connected with the zone of proximal development, which he defines as "the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem-solving under adult guidance, or in collaboration with more capable peers" [14]. “Similar to the scaffolding used in construction to support workers as they work on a specific task, instructional scaffolds are temporary support structures faculty put in place to assist students in accomplishing new tasks and concepts they could not typically achieve on their own. Once students are able to complete or master the task, the scaffolding is gradually removed or fades away the responsibility of learning shifts from the instructor to the student” [15].

The sequence of courses shown in figure 4 will count towards a proposed new minor in “Integrated Practice in Architecture and Civil Engineering”. In level 1, students complete a “Fundamentals in Resilient and Sustainable Design and Construction” course. In this course, students learn the implications of natural disasters on the design and construction processes, including the human factors, for solving problems of the design team. Students also learn the relevant dimensions for resilient and sustainable design and construction solutions, from the perspective of integrated practice and the integrated production of projects.

In the level 2 “RISE-UP Seminar Series”, student will look in depth at problems caused by a natural disaster, such as floods, and structural damage that occurred in hurricane Maria. Information technology seminars will allow students to build the necessary technical skills needed to develop design solutions in the advanced courses of the curricular sequence.

In level 3, students complete a “Resilient and Sustainable Design and Construction Course”. This one includes the study of sustainable development and the application of sustainability and resiliency to architecture/ engineering design and construction. It includes a discussion of the architecture/ engineering and ethical principles needed to support sustainable and resilient design and construction. It encompasses a discussion of the architecture/ engineering and ethical principles needed to support sustainable and resilient design and construction processes (i.e., the impacts the process to deliver and assess sustainable and resilient construction, the construction system for resource optimization, the reduction on environmental impact, and the use of the integrated building design to achieve sustainability and resiliency). It features a discussion of the architecture/ engineering and ethical principles needed to support sustainable and resilient design and construction processes (i.e. the impacts the process to deliver and assess sustainable and resilient construction, the construction system for resource optimization, the reduction on environmental impact, and the use of the integrated building design to achieve sustainability and resiliency)”. In order to gain real world experience and bring it back to the classroom for the final course, in level 4, i.e., “Experiential Learning”, students will complete internships and research with faculty, government agencies and industry partners. Level 5 consists of a capstone course, “Design-Build Project Delivery” in which students apply concepts learned throughout RISE-UP courses and in their experiential learning experience. Learning though all levels in the RISE-UP curricular sequence will be assessed by means of the use of the Depth of Knowledge (DOK) framework developed by Norman Webb [16].

Level	RISE-UP Courses	Credits
1	Fundamentals of Integrated Practice for Resilient and Sustainable Infrastructure	3
2	RISE-UP Seminar Series	3
3	Experiential Learning (Internship/ Undergraduate Research)	3
4	Resilient and Sustainable Design and Construction	3
5	Design- Build Project Delivery	3
	Total Credits	15

Figure 4: RISE-UP Curricular Sequence

Experiential Learning

Integrated in the curricular development, the project encompasses targeted undergraduate research and internship opportunities. The broader impact of intervening in college education by providing students with a research component proved an effective retention tool for underrepresented minorities [17]. In particular, the said target could represent necessitated solutions to environmental problems in particularly affected regions [18], even as a component of other lecture-based instruction [19].

After a natural disaster (flooding, landslide, hurricane, etc.), the devastation calls for, first and foremost, innovative solutions to accelerate the recovery with minimal resources and under geographical constraints. In this stringent context, of interest are the student population that underwent the event onset and its aftermath. They are particularly knowledgeable of the distress and the first response to alleviate it in their own communities. Environmental design and engineering students apply their training to problem-solve critical situations, such as damaged houses and roads.

To reduce the vulnerability of the infrastructure, experiential learning is mandatory while seeking for resiliency in logistics associated with infrastructure from construction to electrical power and communications. Thus, the experiential learning component of the present project as related to environmental design, civil, electrical and materials engineering, construction, and complementary areas represents a critical component. The effect of undergraduates involved in advancing research in a Hispanic institution was evinced in the literature [20]. In this enriching environment, college students became main authors and co-authors of numerous peer-reviewed publications [21]-[22]. By involving undergraduates through critical thinking in a highly focused problem-solving project, this project seeks to develop a cadre of not only creative scholars but also socially- and environmentally-conscious ones [23].

Professional development assessment cannot be implemented for partaking undergraduates until postgraduation, which falls beyond the scope of this work. However, a seminal work by Hunter et al. states that undergraduate research is "a powerful affective, behavioral, and personal discovery experience" that contributes not only to career direction but also to upcoming professional development [24]. Thus, a successful integration of undergraduate research into the planned curricular development and execution will be evaluated and the ensuing results would become an indicator of potential success in the professional career of the participants

Conclusions

The devastation caused by Hurricane María in the Caribbean and the challenges in the ongoing recuperation efforts increased awareness regarding the need to educate future architecture, engineering, and construction professionals to design and build infrastructure that can withstand the impact of natural events and can regain functionally expeditiously if damages occur. In particular, the damage to the informal housing construction sector, healthcare facilities, and widespread outages of power and telecommunication services evidenced the need to intervene in infrastructure related disciplines to provide interdisciplinary solutions to complex infrastructure challenges. The case study research model this project pursues stresses on evidence-based design built on the development of a comprehensive database of case studies. This database is both built through the research component of this project and used for the design component of the integrated coursework. The case study database will be shared with other institutions as well as

AEC professionals with the long-term goal of building a variety of case studies from various natural disasters. This open access database will allow faculty and students to increase their knowledge on complex infrastructural problems and will also serve as repository of cases for problem-solving scenarios. The case study database will be shared with other institutions as well as AEC professionals with the long-term goal of building a variety of case studies from various natural disasters. This open access database will allow faculty and students to increase their knowledge on complex infrastructural problems and also serve as repository of cases for problem-solving scenarios.

Acknowledgement

This material is based upon work supported by the National Science Foundation under grants No. HSI #1832468 and 1832427 (HSI program). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

The authors would like to acknowledge the contributions of the following project team members: Dr. Drianfel Vásquez, Dr. Luis Suárez, Dr. Ricardo López, Prof. Ismael Pagán; Dr. Milagritos González (Assessment), Dr. Walter Díaz (External Evaluator); and the undergraduate and graduate students involved in the project.

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