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Ajla Akšamija, University of Utah, ajla.aksamija@utah.edu

INNOVATIONS IN ARCHITECTURE: RESEARCH, DESIGN AND TECHNOLOGY

Abstract

Architectural designers are currently faced with many challenges—technological changes, environmental and economic impacts, necessity to innovate and raise the bar in building performance, and the paradigm shift in architecture with the wider adoption of advanced computational design and fabrication techniques. This paper focuses on innovations in architecture, relationships between scientific research and design, and advanced building technologies. Several research projects are presented, including use of virtual and augmented reality for design, smart facade systems for generating heating/cooling and electricity, and regenerated buildings with improved performance.

Keywords: innovations, architecture, research, design, emerging technologies

ИНОВАЦИЈЕ У АРХИТЕКТУРИ: ИСТРАЖИВАЊЕ, ПРОЈЕКТОВАЊЕ И ТЕХНОЛОГИЈА

Апстракт:

Архитектонски дизајнери су тренутно суочени са многим изазовима—технолошким промјенама, еколошким и економским утицајима, потребом да се иновира и подигну границе у перформансама зграда, и промјена парадигме у архитектури са ширим усвајањем напредног дигиталног дизајна и конструкције. Овај рад се фокусира на иновацијama у архитектури, односе између научних истраживања, пројектовања и напредне грађевинске технологије. Представљено је неколико истраживачких пројеката, укључујући кориштење виртуелне и проширене стварности за дизајн, паметне фасадне системе за генерисање гријања/хлађења и електричне енергије и обнова зграда за побољшане њихове перформансе.

Кључне ријечи: иновације, архитектура, истраживање, пројектовање, нове технологије

1. INTRODUCTION

1.1. INNOVATION IN ARCHITECTURE: WHAT AND HOW

The general definition of innovation is that it is the process of introducing changes to methods, services, or products. These changes must be useful and meaningful, adding value to the established norms and contributing to our knowledge. Innovation and technological changes are complementary in nature since innovation relies heavily on scientific research and technological developments. Although the concept of innovation within the context of architectural design is not new, the deliberate use of the word "innovation" in architecture has become widely popular during the last decade [1]. A singular cause for this phenomenon remains elusive. However, a confluence of factors likely contributed, including advancements in building technologies and systems, and the wider adoption of advanced computational design techniques. Additionally, the paradigm shift in design, collaboration, and construction facilitated by Building Information Modeling (BIM) has demonstrably influenced the embrace of innovation.

The core tenet of architectural innovation within the contemporary context lies in the transformation of ideas into tangible or intangible outcomes. These outcomes can manifest as physical structures (buildings), or as the design process itself, an intangible service. Regardless of the form, innovation necessitates the application of novel ideas to generate value and positive outcomes. Figure 1 serves as a visual representation of the interplay between the aspects subject to change (product, service, and process) and the degree of innovation achieved (incremental, radical, or transformational). In the context of architectural design, the "product" encompasses the building itself, the physical space it creates, and the materials or objects used in its construction. The "service" refers to the way users interact with the building and its occupants. Finally, the "process" signifies the design methodology employed to conceive and construct the building, space, or system. All three categories present opportunities for innovative interventions, ranging from incremental improvements to paradigm-shifting advancements. Incremental innovation may affect a singular architectural project or a building typology, while transformational innovation influences the entire profession.

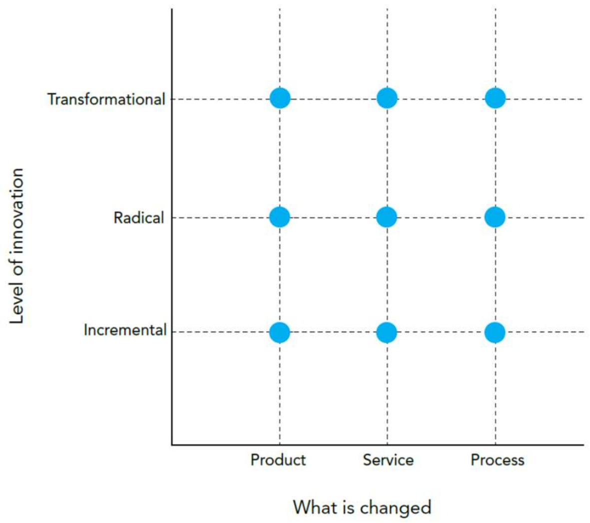

Figure 1. Types and levels of innovation (Source: Author [1]).

Further investigation into the drivers and value propositions for innovation within architectural design is crucial. Innovation serves as a catalyst for organizational progress, impacting efficiency, quality of work, and the improvements of design processes. Architectural innovation necessitates the implementation of novel design strategies and project delivery methods. These innovations, encompassing new design tools, materials, building technologies, and construction techniques, contribute to the creation of buildings that are more responsive to their environment and the needs of their occupants. An integrated model for innovation in architecture is shown in Figure 2, which demonstrates how these different factors influence innovation.

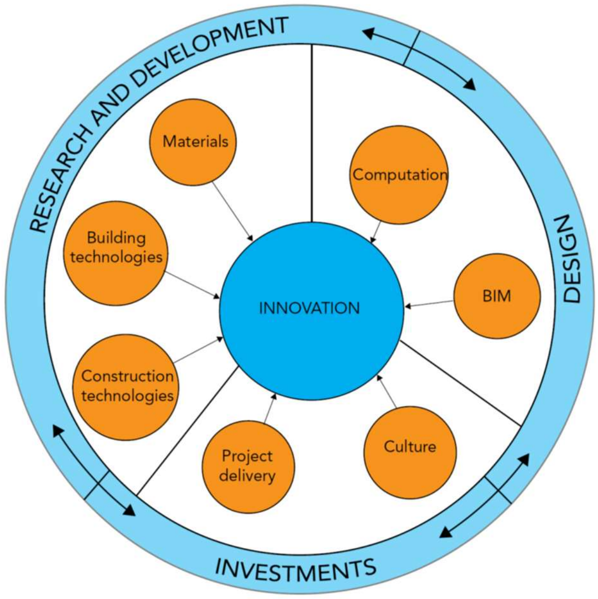

Figure 2. Model for integrating innovation in architecture (Source: Author [1]).

1.2. RELATIONSHIPS BETWEEN RESEARCH AND INNOVATION

The role of research in innovative practices is paramount. Research, within this context, is defined as systematic investigation and creation of new knowledge and applications, utilizing rigorous research methods [2]. Integrating research within the design process is essential for developing new knowledge, solving design and technical problems, overcoming different types of challenges present in the contemporary profession, and improving the design process and architectural work. Research results can be implemented on specific architectural projects but should also be disseminated to the wider design community to improve the knowledge base and architectural profession.

Research and development can bring immense value to any organization for which innovation is important [3]. However, considering the lack of universal models for integrating research with practice, the realities of client requirements, schedules, and budgets, as well as risks and liability—research within the architectural profession is challenging. Organizing and maintaining research departments within architectural design practices can be costly, time-consuming, and risky. Therefore, taking a careful and systematic approach to establishing research departments and defining operational models and relationships between research, design practice, and business performance are essential. It is necessary to balance and determine different priorities, including short-term goals and long-term strategic focus, alignment with firm's motives and values, developing internal capabilities, or collaborating and partnering with external research partners. These following aspects should be considered in integrating research with design practice:

- How to establish the research arm of the firm and its structure and organization.
- What are the connections and relationships between the firm's core values, practice and research?
- What are the long-term strategies and objectives of research vs. short-term actions?
- How to fund research activities and how to mitigate risk and liability issues.
- How to translate results of research efforts into practice.

Figure 3 shows the impacts of research and innovation on revenue, as a direct measure, and value as a measure of all indirect benefits. Investments in research and development require initial capital, but results impact the activities and practices of the firm, influencing design services and methods. Cutting-edge firms and leaders in innovation create a niche market, thus increasing the revenue for their services due to increased market demand. On the other hand, late adopters of innovation do not possess value differentiation. Continuous investment in and implementation of innovative strategies maintains higher revenues for firms whose core values focus on research and development and improvement of design services and methods, as seen in Figure 4.

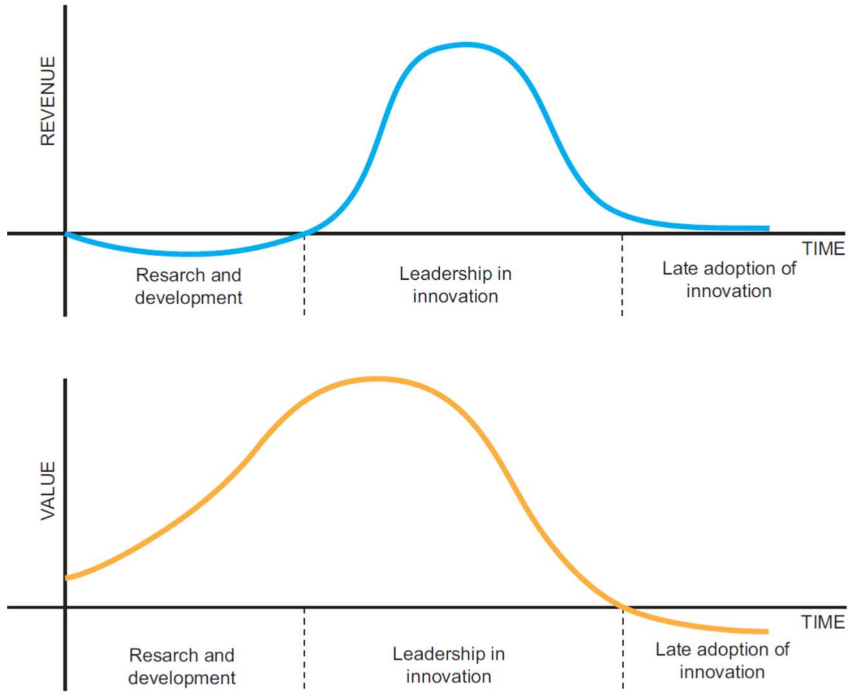

Figure 3. Impacts of investments in research on revenue and value over time (Source: Author [1]).

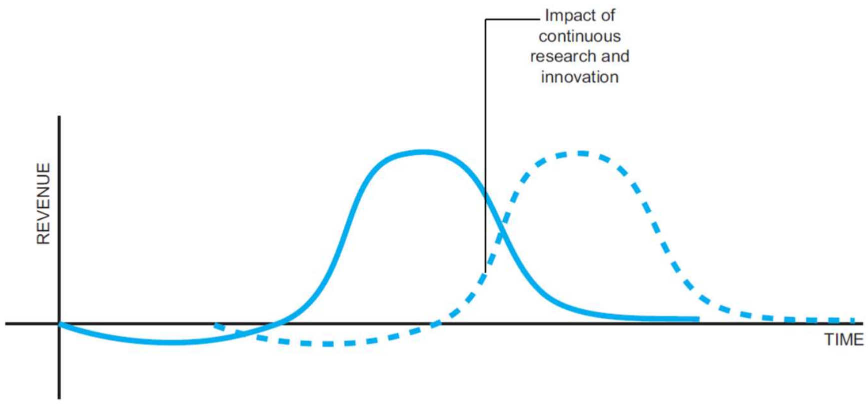

Figure 4. Impact of continuous research and innovation on revenue over time (Source: Author [1]).

2. CASE STUDY 1: AUGMENTED AND VIRTUAL REALITY IN ARCHITECTURAL DESIGN

Augmented reality (AR) and virtual reality (VR) are computer-generated, simulated representations of real or imagined environments, where users can interact with simulated representations using various digital technologies. The similarities between AR and VR technologies are that they rely on digital representations of real or imagined scenes, objects, and environments and utilize advanced 3D modeling and visualization strategies. However, the major differences relate to the level of interaction, where AR can only be “viewed”, and VR can be “experienced”. AR superimposes computer-generated visuals into a real-world environment and utilizes mobile devices, tablets, and computer displays to augment the physical environment with digital projections. On the other hand, VR offers a fully immersive digital environment and uses 3D computer-generated visuals to produce representations of the real world or imagined environments.

AR and VR applications are a promising new direction for architectural design, since improved understanding of architectural design and communication procedures are the primary benefits of these novel technologies [4]. These tools offer exploration of designed environments that is not possible with the traditional forms of representation, since they allow users to immerse themselves, visualize, and explore spaces during different design stages and before construction. However, studies focusing on the integration of these advanced digital technologies in the architectural educational curriculum are limited. Therefore, the primary research objectives of this study were to investigate implementation of AR/VR tools in architectural education and to determine whether these novel digital technologies are beneficial for the educational experience of students [2].

A combination of qualitative, quantitative, and experimental research methods was used, including interviews, qualitative and quantitative surveys, modeling, and experiments. The experiments were conducted during the different stages of the design process and involved three different groups of users. The first experiment analyzed the effectiveness of AR/VR tools (personal assessment by the designer) during the conceptual design, schematic design, and design development. The second experiment investigated the effectiveness of these tools in collaboration and communication between the designer and the "client" during the conceptual design, schematic design, and design development (communication procedures), considering that in the context of architectural education, faculty members are acting as clients. The third experiment involved graduate architecture students, and evaluations were conducted in a group setting (student effectiveness), during the design development phase. These evaluations only included VR applications, since research results indicated that AR tools are most suitable for the early stages of the design process.

Ten different evaluations were conducted to investigate the difference between AR and VR tools, their effects on design and communication protocols during different stages of the design process, and the perspectives of various participants. Each step involved evaluation of the AR or VR building model, shown in Figure 5, which lasted approximately 30 minutes for every participant. These evaluations were followed by a survey (qualitative and quantitative) and interviews (for open-ended questions). In the case of AR, the digital model was visualized within the physical environment by superimposing a 3D digital model in the real environment, and the walk-throughs were conducted by simply rotating a mobile device to visualize different aspects of the model. In the case of VR, each study participant was fully immersed within the VR environment, where they had an opportunity to "experience" the VR model, as seen in Figure 6. This immersive experience included visualization of the VR model (the scale, building geometry, surrounding buildings, building structure, etc.), as well as a walk-through within the site and the building.

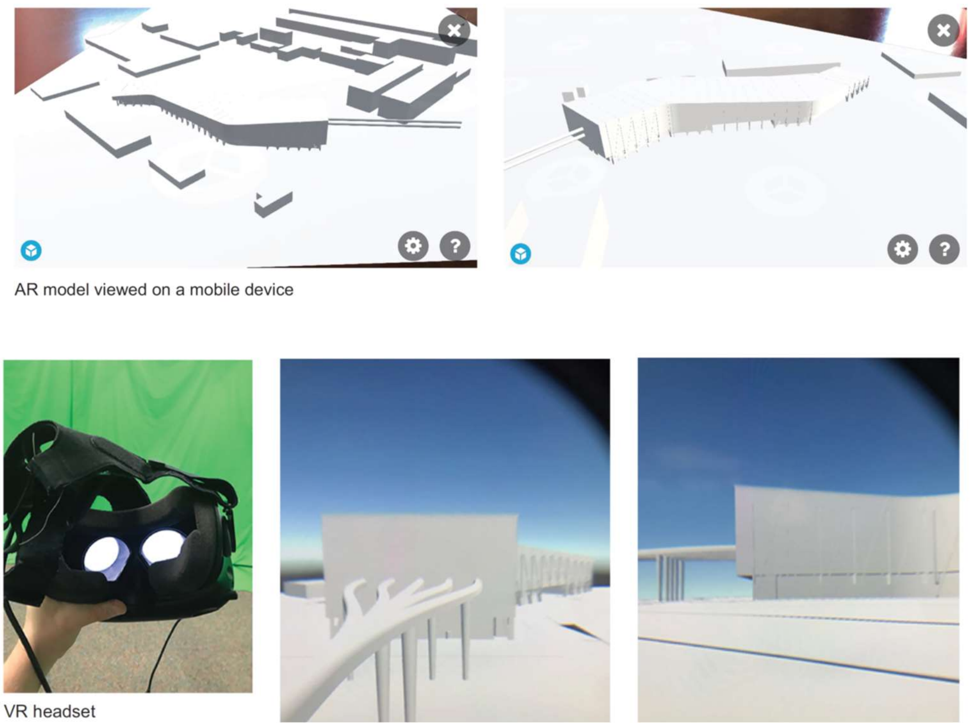

Figure 5. Visualization of the AR and VR model (Source: Author [2]).

Experimental setting for VR experiments

VR experiments

Figure 6. Experimental set-up for VR experiments (Source: Author [2]).

The results of the interactive evaluation showed that AR was beneficial for visualizing the overall site and scale of the building and its relationships to the surrounding context. However, it had limited use for resolving design problems. The results indicated that the AR is useful for understanding the overall building massing and relaying large-scale design ideas to the client. The application of this technology in the early stages of the design process is similar to utilizing physical models, which are very typical in architectural education. The main benefit of AR is that digital models can be created automatically from BIM software and displayed in AR environments, thus saving time and resources compared to building physical models.

The immersive nature of the VR and the ability to experience the building helped to provide an insight as to what would it be like to explore this architectural design in person. From the designer's perspective, the primary benefit of using VR at this stage was the ability to explore and visualize the design, but it was not greatly helpful for making design decisions. The results of the interactive evaluation and communication procedures between the designer and client indicated that the primary benefits of using VR in the conceptual design stage are the ability to explore and visualize the scale of the building, its relationship to the site, the overall form, and movement through the building. The last aspect—the ability to experience the building from the perspective of a building occupant and circulate through the digital model as if moving through the real building—is the most important one, because no other visualization technique offers this capability. The client was more satisfied with the design, workflow, and navigation than the designer, while the designer gave higher ratings for visualization and success, as seen in Figure 7. The results for schematic design evaluations indicated that the designer was more satisfied with the VR model and its effect on design decisions than with the VR model for the conceptual design. The VR model was more developed and included the overall structure, interior partitions, building envelope treatment, and circulation elements (stairs and elevators). Therefore, the immersive experience was more beneficial since it was easier to notice design problems that would be difficult to notice in typical architectural drawings. The final evaluations conducted during the design development implemented the most detailed VR model. The design issues raised during earlier stages were resolved, and the model was updated to reflect these changes. The immersive experience was the most convincing at this stage because it was possible to fully explore all aspects of the VR model (integration of the building with the site and surrounding context, structural systems, building envelope design, circulation, etc.). Figure 7 shows evaluations results for different stages of the design process.

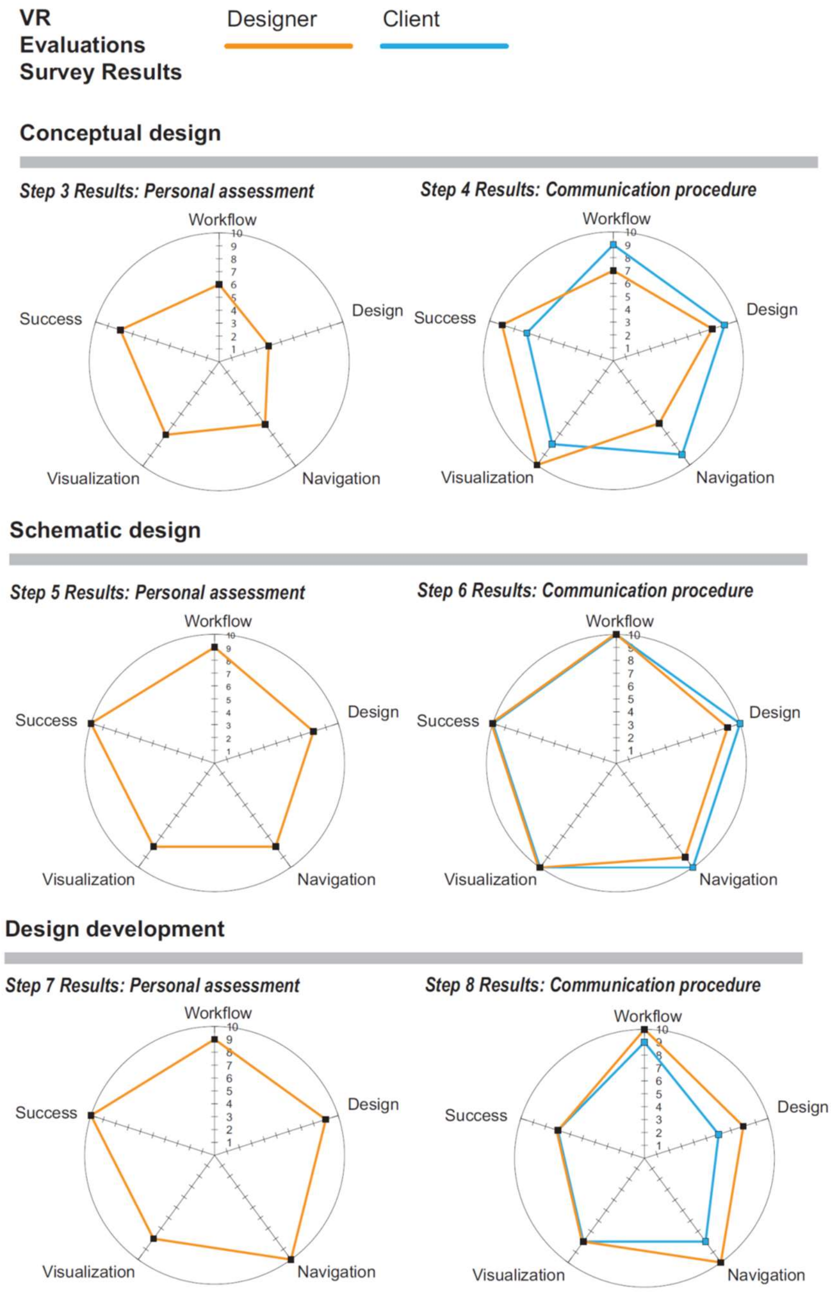

Figure 7. Results of VR evaluations (Source: Author [2]).

The results of the study indicated that AR and VR tools are beneficial for the architectural design process and can advance architectural education. These benefits include improved collaboration, improved communication, investigation of design mock-ups, and possibility to conduct visual, immersive reviews. Specific results of various evaluations indicated that VR and AR tools are useful for visualizing building form, scale, and design elements, as well as understanding movement and circulation through the building. No other design representation method offers such an immersive experience and visualization of design elements nor an ability to move through a digital representation of a building. Therefore, these technologies can greatly benefit spatial cognition, design communication, and visualization of architectural projects.

3. CASE STUDY 2: SMART FACADE SYSTEMS FOR ENERGY GENERATION

Smart facade systems can be defined as building enclosures that react to the exterior environment, adapt to environmental changes, regulate their performance and functioning (by self-regulation or by users), integrate smart materials and components, and, in some instances, provide renewable energy for building's operation. Smart facade systems are an important aspect of advanced building technologies that can revolutionize our buildings and significantly improve their performance. This research focused on the development, design, evaluations, and applications of new, intelligent facade systems, which integrate thermoelectric materials [5]-[8]. Thermoelectric materials are smart materials that can produce a temperature gradient when electricity is applied, exploiting the Peltier effect, or generate a voltage when exposed to a temperature gradient, utilizing the Seebeck effect. These types of materials can be used for heating, cooling, or power generation.

Quantitative and experimental research methods, including modeling, simulations, prototyping, testing, and experiments were employed in this research. Initially, two prototypes were designed and constructed. These prototypes were first tested in ambient room conditions to measure the heating and cooling outputs of thermoelectric materials. Then, an experimental study was utilized to physically evaluate heating and cooling outputs of the constructed smart facade prototypes, where a controlled thermal chamber was used to represent different exterior temperatures, and interior temperature was kept constant. Thermal imaging was used to measure the heating and cooling outputs under varying voltage and power supply, as seen in Figure 8. The results were promising and indicated that facade-integrated thermoelectric materials would provide sufficient heating and cooling. The coefficient of performance (COP) was numerically calculated based on the experimental results and compared to conventional HVAC systems [5].

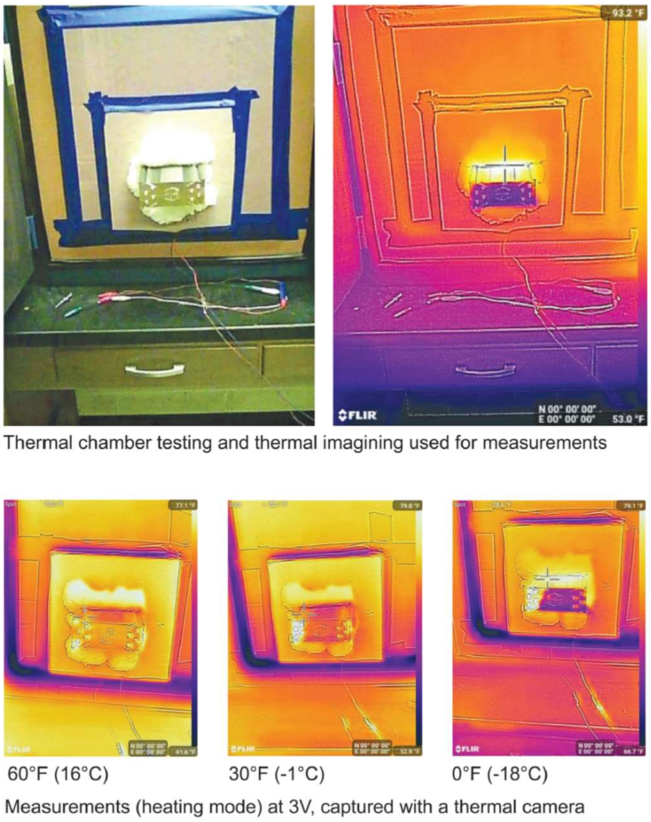

Figure 8. Experimental set-up (thermal chamber) for measuring heating and cooling potential of smart facade systems (Source: Author [2]).

The next step of the research focused on the design, modeling, and physical prototyping of real facade systems that would integrate thermoelectric materials. Figure 9 shows various facade systems and designs.

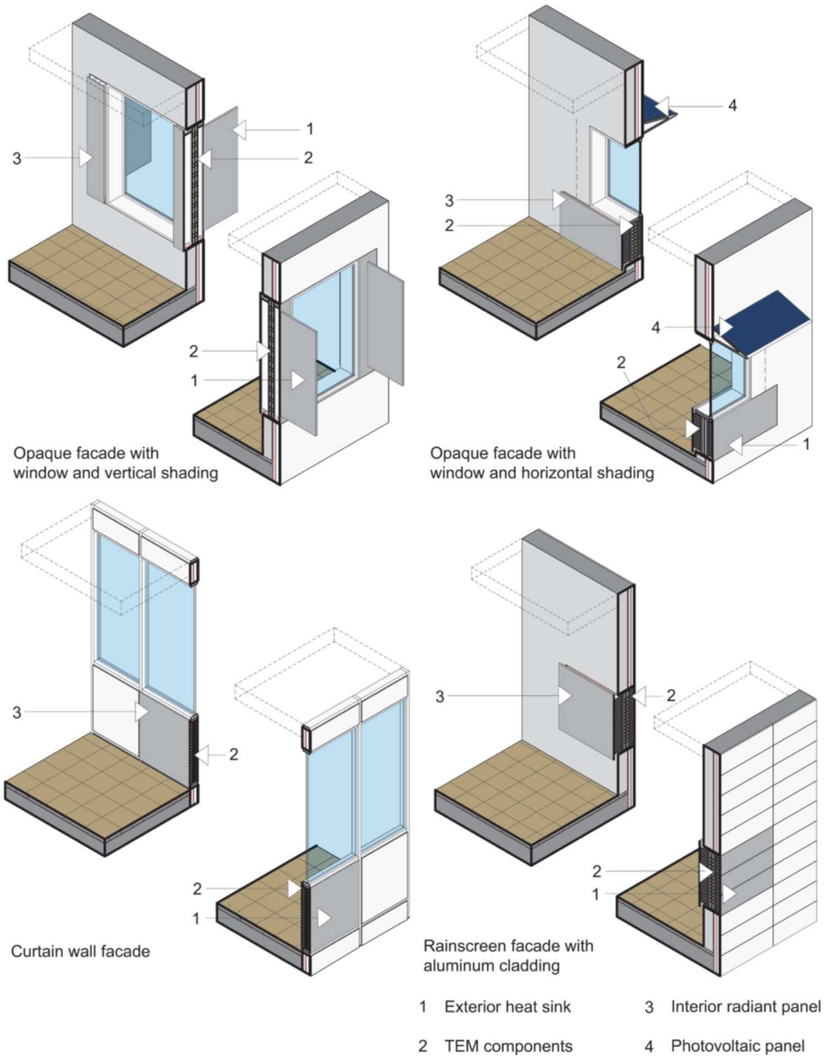

Figure 9. Different smart facade systems that integrate thermoelectric materials for heating, cooling, and power generation (Source: Author [2]).

Table 1. Climate zones used in the energy modeling study of smart facade systems.

Climate zone	**City**	**Zone**	**Region**
1A	Miami, FL	Very hot	Moist
2A	Houston, TX	Hot	Moist
2B	Phoenix, AZ	Hot	Dry
3A	Memphis, TN	Warm	Moist
3B	El Paso, TX	Warm	Dry
3C	San Francisco, CA	Warm	Marine
4A	Baltimore, MD	Mixed	Moist
4B	Albuquerque, NM	Mixed	Dry
4C	Salem, OR	Mixed	Marine
5A	Chicago, IL	Cool	Moist
5B	Boise, ID	Cool	Dry
6A	Burlington, VT	Cold	Moist
6B	Helena, MT	Cold	Dry
7	Duluth, MN	Very cold	N/A
8	Fairbanks, AK	Subarctic	N/A

The last part of the study investigated the heating and cooling potentials of these novel systems for conditioning commercial office spaces. Computational Fluid Dynamic (CFD) simulations were conducted under various exterior environmental conditions to determine interior temperature distribution and the necessary wall coverage with thermoelectric components. Energy modeling was conducted for a single office space, as well as a whole large-scale commercial building, to determine energy saving potentials. Simulations were conducted for fifteen different climate zones in the United States, as seen in Table 1. Figure 10 shows energy modeling results for various climates, indicating energy savings associated with these innovative facade systems compared to conventional HVAC systems.

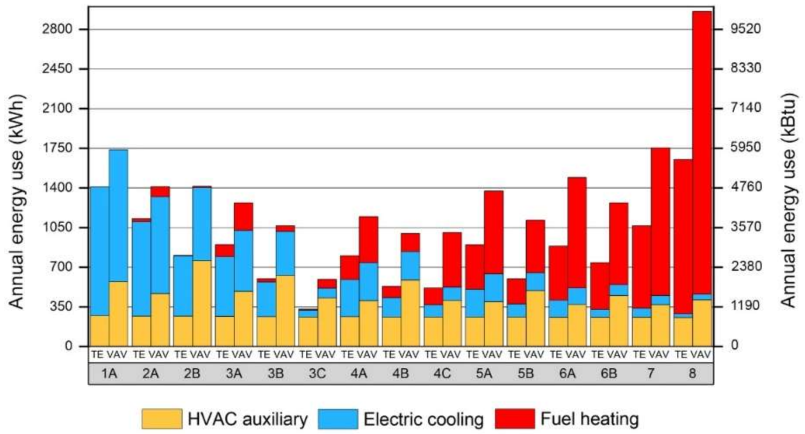

Figure 10. Annual energy use comparison of smart facades with thermoelectric material vs. conventional VAV system for various climate zones (Source: Author [8]).

The results of this research indicated that thermoelectric materials are promising smart components that can be used in facade assemblies for heating and cooling purposes, controlling buildings' interior environments. This is an independent system that does not require moving parts or harmful substances and solely relies on the temperature difference between the interior and exterior environments to operate. Maintenance of these advanced systems would be easier than the conventional HVAC systems because they can be treated as individual components. Furthermore, they can be used as a personalized system which occupants of each space within the same building can use based on personal thermal comfort preferences.

4. CASE STUDY 3: REGENERATIVE DESIGN OF EXISTING LABORATORY BUILDINGS

Existing buildings are the largest contributors to global energy use and greenhouse gas emissions [9]. Recent research shows that energy use in existing buildings can be significantly reduced through proper retrofitting strategies [10], and that retrofitting is one of the main approaches in realistically reducing a significant percentage in carbon emissions [11]. A specific building typology, scientific research laboratory buildings, pose specific challenges for energy-efficient retrofits. The most pronounced challenge is their disproportionate demand and utilization of energy since these buildings typically consume significantly more energy per area than other building types, such as office or residential buildings. This high energy demand is associated with increased ventilation requirements, equipment loads and plug loads. Another challenge is that not all research laboratory buildings have similar mechanical and operational needs, and retrofitting comes down to a case-by-case approach [12].

This case study investigated design strategies for achieving a high-performance retrofit of an existing higher-education laboratory building, located in a cold climate [12]. The primary objective was to evaluate current state and potential retrofit strategies to improve building performance of this building. Research methods included analysis of archival data and empirical data, and computational software modeling and simulations. Using original construction drawings and current state photographs, a full BIM model was developed for analysis and energy simulations. Also, actual energy consumption data was collected for a period of three years. Building's formal and spatial qualities were analyzed and the building's response to environmental conditions was evaluated using performance simulations. Next, thermal and moisture resistance performance of a typical facade system was evaluated. Lastly, a whole-building energy simulation was conducted to evaluate current building performance, and simulation results were compared to the actual energy consumption data. Results were then used to inform proposed retrofit solutions, spatially and formally. Energy simulations of retrofit design were then conducted and evaluated to assess improvement in building performance. Lastly, potential renewable sources of energy were evaluated to reduce the environmental impact of the building and produce on-site renewable energy.

The site plan of the investigated building is shown in Figure 11. The original building was built in 1947, and the addition was built in 1964. Both buildings have their elongated east facades facing the main street. The original building is a two-story, flat-roofed, brick faced building with a central, limestone architrave entrance and tall, metal framed windows. The addition building is a four-story, flat-roofed, also brick faced building characterized by ribbon storefront glazing along the main level and the top story. Levels 2 and 3 do not have any windows, and the only daylight comes from the windows located at the far ends of interior corridors. The addition building also includes a single-story central volume that serves as the main entrance and provides a connection to the original building. The fan shaped volume also includes a lecture hall.

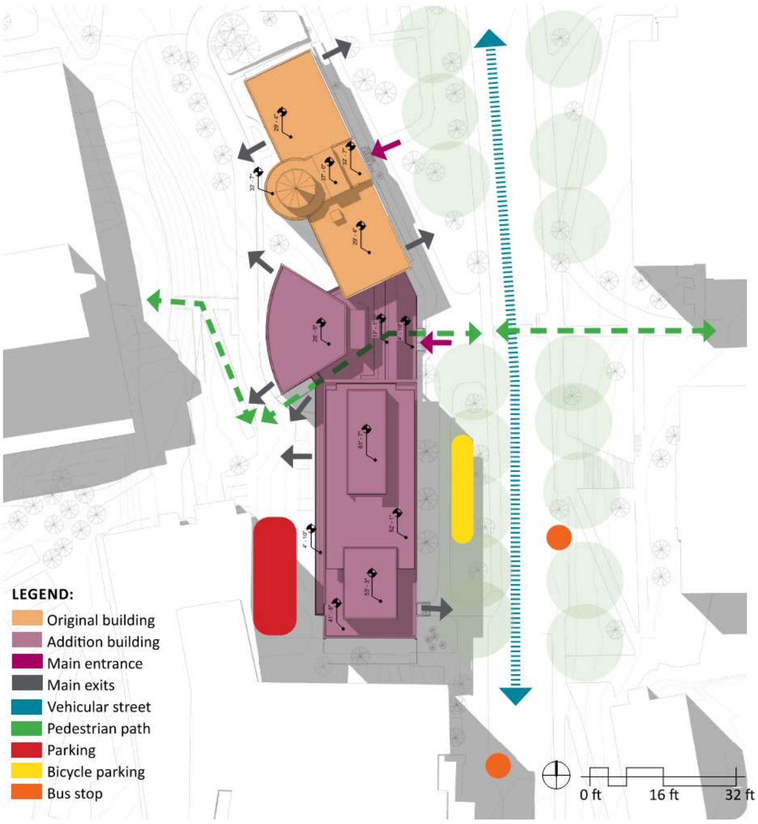

Figure 11. Site plan of the analyzed building (Source: Author [12]).

The building program is composed of primarily research laboratories and administrative spaces, which branch off the central corridor to the east and the west of each floor level, without a particular pattern at both the original and the addition buildings, as seen in Figure 12. Laboratories and office spaces are segregated into separate spaces without visual transparencies between these functions, and the general size of these types of spaces is irregular. Current practice encourages larger laboratories that implement visual transparencies to encourage collaboration, flexibility to allow for adaptions to space function in the future, and decentralization and clustering of energy systems by program function to balance energy needs. These aspects were considered in proposed retrofit design strategies, which influenced the proposed reconfiguration of floor plans and interventions at the building facades. This resulted in an addition of significant building area and volume, which were later included and accounted for in whole-building energy simulations. Figure 13 shows retrofit design strategies.

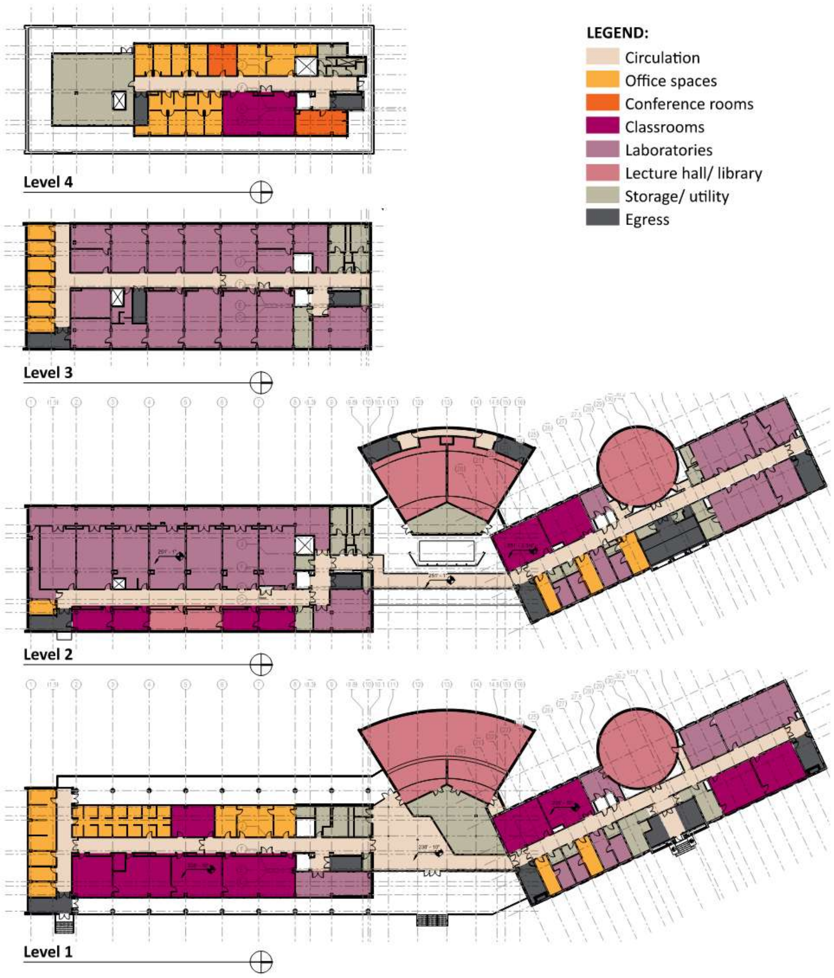

Figure 12. Original spatial organization of the analyzed building (Source: Author [12]).

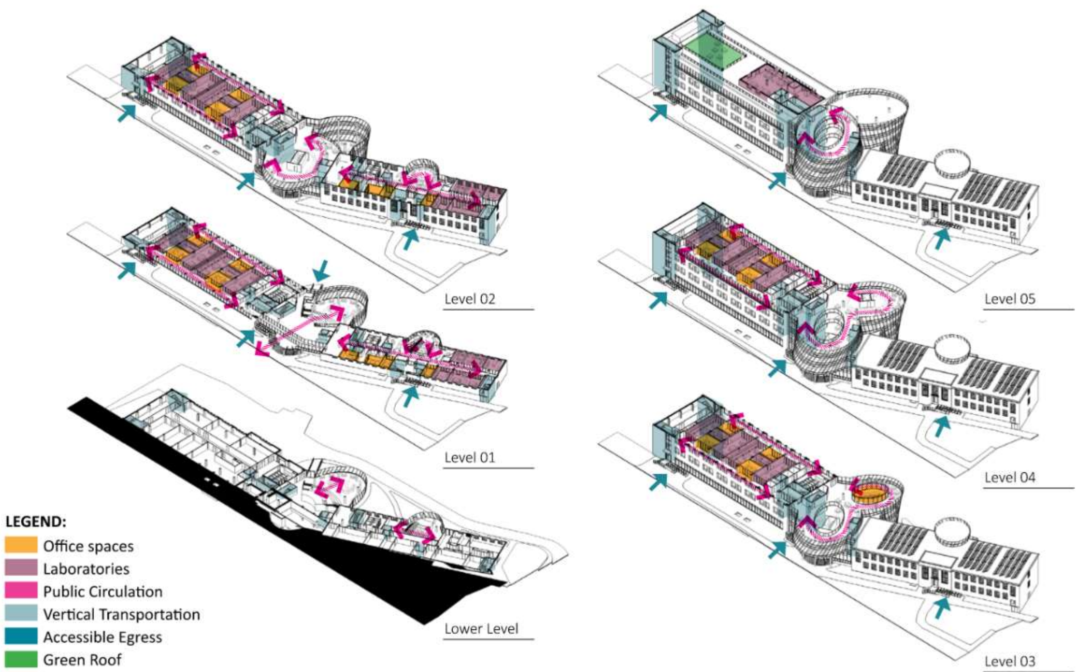

Figure 13. Retrofit design strategies for the analyzed building (Source: Author [12]).

Whole-building energy modeling was conducted, and Figure 14 indicates results for the current building, retrofit design and comparison to actual energy consumption data. The building's actual annual electricity and steam consumption data was collected and averaged over three years (2017, 2018 and 2019).

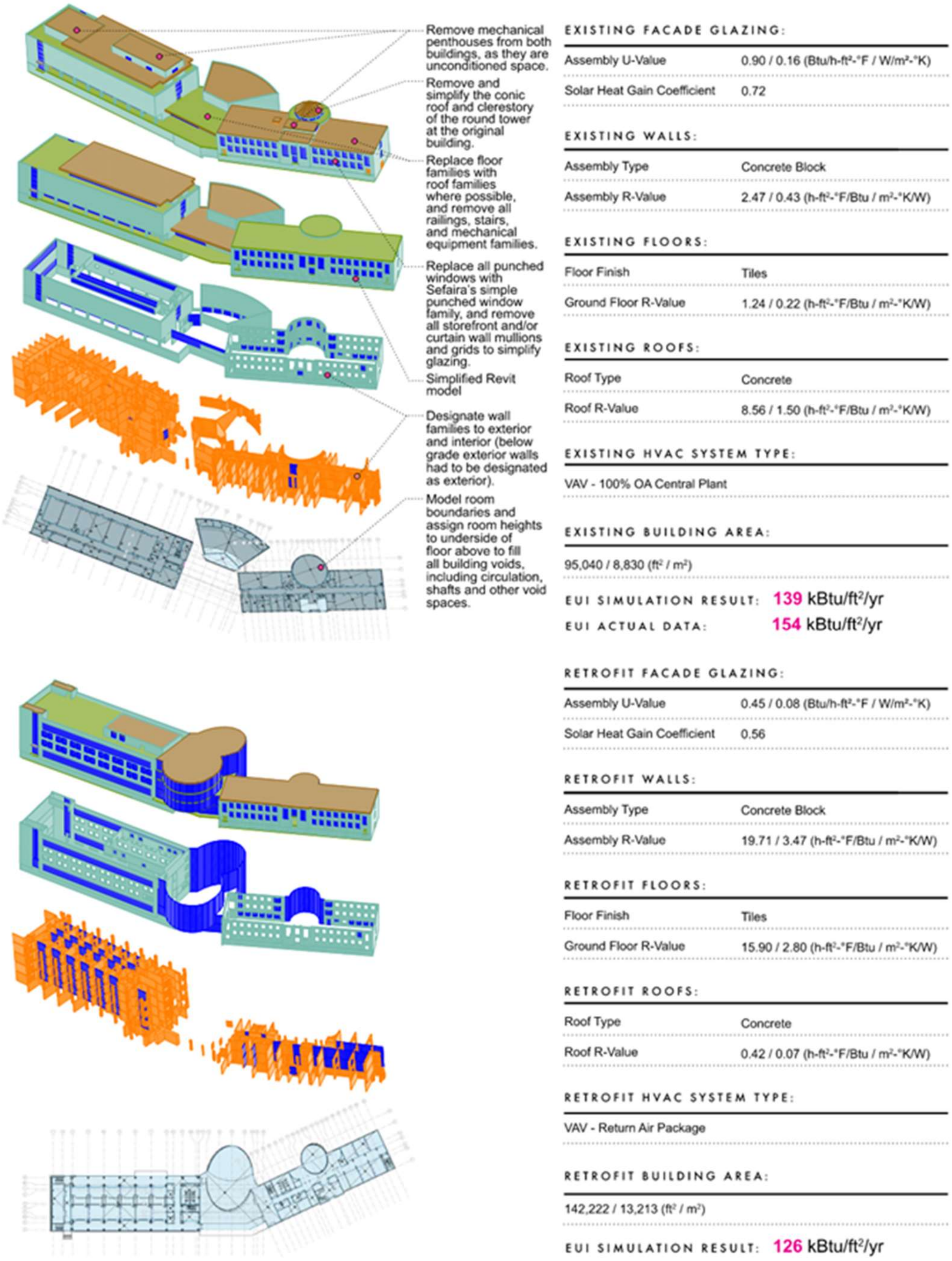

Figure 14. Energy consumption of the current building (modeled and actual) vs. retrofit design (Source: Author [12]).

Typical original window details of the original building and addition building indicated a rather simple technology, utilizing painted aluminum, non-thermally broken frame profiles, aluminum spacers, and single layer, clear glazing of slightly different thicknesses, respectively. Similarly, typical solid, exterior wall sections at both buildings indicated few layers and no insulation in their brick veneer and concrete masonry unit (CMU) frame assemblies. Figure 15 illustrates the typical solid and glazed facade systems at the addition building, as well as retrofit strategies. Solar wall cladding system was considered, since it acts both as an additive air insulation layer and as a heat harvesting, passive, double skin facade system that could be applied to existing facades. Choice to integrate this technology was a result of the existing condition, where the embodied energy of the existing concrete and brick layers dictated that these layers remain as part of the assembly, and that the complete lack of insulation dictated that additional facade layers were necessary and would have to be applied either on the exterior, or on the interior of the existing facade. Thus, a choice was made to treat the existing facade layers as structure, and to insulate and reclad on the exterior.

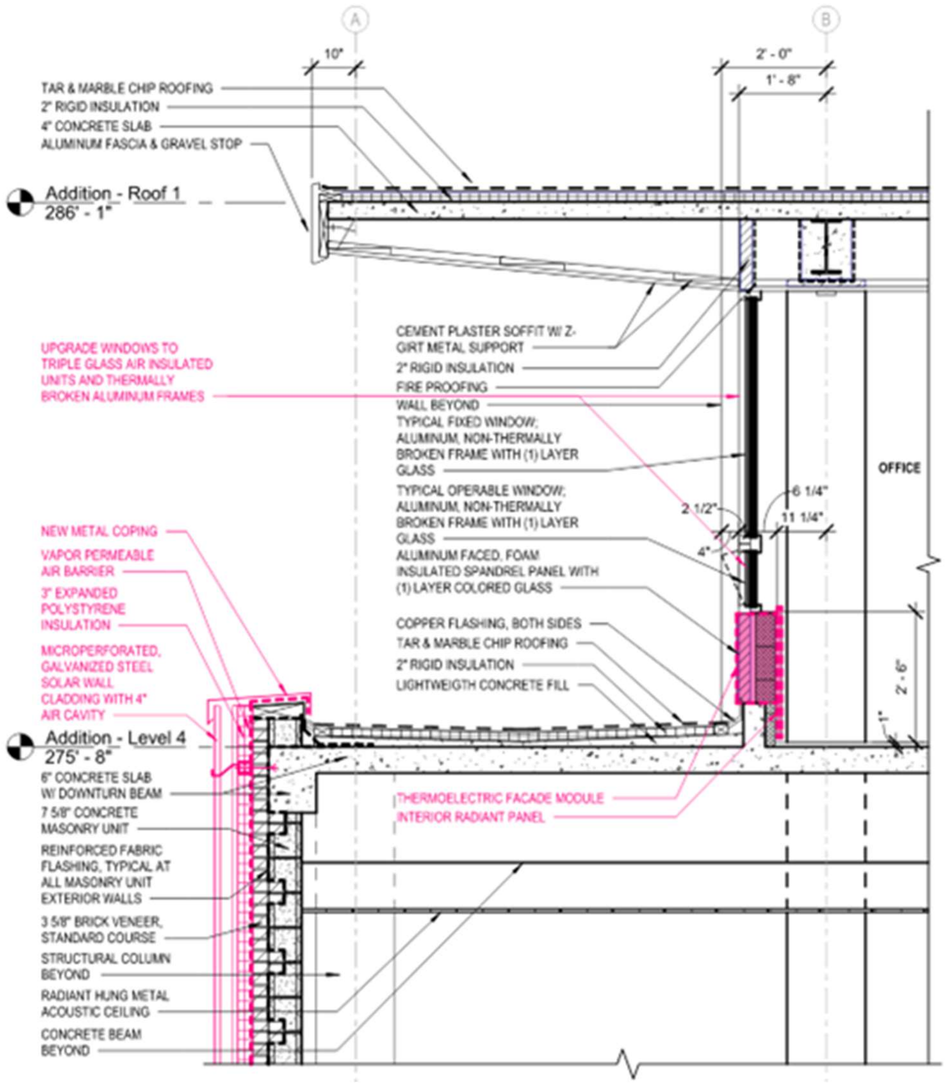

Figure 15. Typical exterior wall for the addition building, indicating existing facade components (in black) and retrofit design strategies (in color) (Source: Author [12]).

Final research results showed that the existing building drastically underperforms in all evaluated criteria. Building enclosure at both buildings, whether solid or glazed, severely underperformed in terms of thermal performance and moisture resistance due to minimum thermal resistance and lack of any insulation. Such underperformance in a predominantly cold climate poses significant challenges for a potential retrofit process, as the building skin would have to be either built up on the exterior or interior sides of the enclosure. Moreover, the interior program and spatial organization was segmented and scattered, without any visual transparencies or inviting program for the public and users to socialize, and several floors of occupied science laboratories and offices did not have any windows. Additionally, egress and accessibility were insufficient. Such state would also pose significant challenges for potential retrofit process, as the interior spaces would require a deeply invested intervention and reconfiguration, which may result in needing to provide additional building area to accommodate additional public, interdisciplinary, and casual program in addition to likely having to significantly enlarge and equip existing laboratories to current standards.

Primary passive retrofit strategies included improvements in building enclosure, specifically adding insulation and water drainage to the exterior walls and insulation and thermally broken components to window systems. Thermal performance of the proposed solid facade system, a solar wall and double skin facade, showed significant improvements. Thermal performance of the proposed glazed facade systems (triple, air insulated glazing units with a thermally broken frame) also showed significant improvements. Integrated retrofit design strategies, shown in Figure 16, resulted in an overall 13% reduction in energy consumption, despite a 67% increase in retrofit building area (an addition of a large 5-story atrium between the two existing buildings).

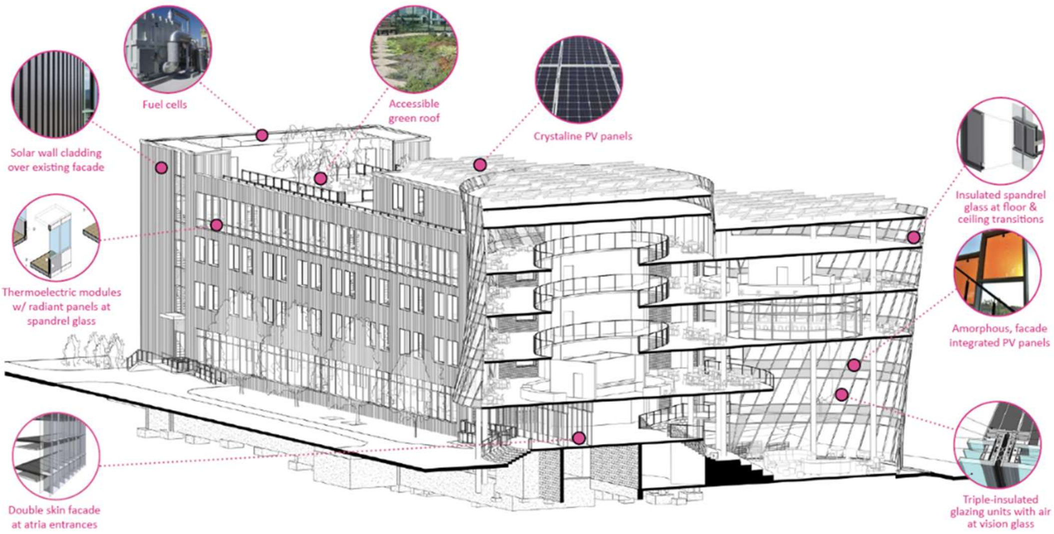

Figure 16. Integrated regenerative retrofit design, illustrating combined passive and active strategies (Source: Author [12]).

Overall results, for a building typology that heavily relies on energy intensive mechanical systems, show that the sequential process of analysis methods and simulations used in this case study helped to inform retrofit decisions as a reiterative process. It helped quantitatively maximize on passive strategies to lower the overall energy consumption before considering active systems. Regenerative design of existing buildings, aimed to improve their performance and reduce energy consumption, requires integration of building performance analysis procedures during the design process.

5. CONCLUSION

This paper discussed innovations in architecture, particularly focusing on design methods, integration of research, and advanced building technologies. It also presented three distinct case studies: research on advanced digital technologies (AR and VR), development of smart facade systems and regenerative design of existing buildings. Research is an integral part of innovation, and as such, it is necessary to discover new knowledge, improve our understanding of the architectural design process and its results, find new methods for design, collaboration, and construction, investigate the impacts of architecture on the environment and people, and ultimately improve the built environment. Historically, most architectural research came from academic and research institutions, rather than architectural practice. But this is changing, and many architectural firms are realizing the need to invest in research and the necessity of conducting research. This is due to many challenges that the contemporary architectural profession is facing, such as climate change, urbanization, depletion of natural resources and environmental concerns, societal transformations, and the changing economy. On the other hand, technological advancements, new materials and building technologies, developments in architectural digital technologies, and new fabrication methods are creating a paradigm shift in architecture and requiring architects to understand how emerging technologies are influencing their work. Therefore, research is essential to understand the effects of these changes and to improve the teaching, learning, and practice of architecture.

LITERATURE

[1] A. Aksamija, Integrating Innovation in Architecture: Design, Methods and Technology for Progressive Practice and Research. Chichester, UK: John Wiley & Sons, 2016.

[2] A. Aksamija, Research Methods for the Architectural Profession. New York, NY: Routledge, 2021.

[3] T. Hult, R. Hurley, and G. Knight, "Innovativeness: its antecedents and impact on business performance", *Industrial Marketing Management*, vol. 33, no. 5, pp. 429–438, 2004.

[4] M. de Freitas, and R. Ruschel, "What is happening to Virtual and Augmented Reality applied to architecture?" in *Proc. of the 18th International Conf. on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, Hong Kong, China, 2013, pp. 407–416.

[5] A. Aksamija, Z. Aksamija, Z., C. Counihan, D. Brown, and M. Upadhyaya, "Experimental study of operating conditions and integration of thermoelectric materials in facade systems," *Frontiers in Energy Research*: *Special Issue on New Materials and Design of the Building Enclosure*, vol. 7, 2019, Art. no. 6.

[6] A. Aksamija, A., Z. Aksamija, G. Vignaeu, M. Upadhyaya, and M. Farid Mohajer, M., "Thermoelectric facades: simulation of heating, cooling and energy generation potential for novel intelligent facade systems," in *Proc. of the Facade World Congress 2020*, Aug 5-27. [Online]. Available: https://www.facadetectonics.org/papers/thermoelectric-facades

[7] A. Aksamija, M. Farid Mohajer, and Z. Aksamija, "Novel active facade systems and their energy performance in commercial buildings: impact of thermoelectric materials on heating and cooling in different climates," in *Proc. of the Facade World Congress 2022*, Los Angeles, CA, 2022, Oct 12-13. Available: https://www.facadetectonics.org/papers/novel-active-facade-systems-and-energy-performance-of-commercial-buildings

[8] A., Aksamija, and M. Farid Mohajer, "Thermoelectric facades: modelling procedure and comparative analysis of energy performance in various climate conditions", in *Proc. of the Architectural Research Centers Consortium/European Association for Architectural Research (ARCC/EAAE) 2022 International Conference*, Miami, FL, 2022 Mar. 2-5, pp. 407-414.

[9] United Nations Environment Programme, "2022 Global status report for buildings and construction: towards a zero-emission, efficient and resilient buildings and construction sector," 2022, [Online]. Available: https://globalabc.org/sites/default/files/inline-files/2022%20Global%20Status%20Report%20for%20Buildings%20and%20Construction.pdf

[10] A. Aksamija, "Impact of retrofitting energy-efficient design strategies on energy use of existing commercial buildings: comparative study of low-impact and deep retrofit strategies," *Journal of Green Building*, vol. 12, no. 4, pp. 70–88, 2017.

[11] Z. Ma, P. Cooper, D. Daly, and L. Ledo, "Existing building retrofits: methodology and state-of-the-art," *Energy and Buildings*, vol. 55, pp. 889-902, 2012.

[12] S. Milosevic, and A. Aksamija, "High-performance retrofit strategies for existing science and laboratory buildings within academic institutions: considerations and design strategies," *Perkins&Will Research Journal*, vol. 14, no. 1, pp. 35-59, 2022.