ACADIA // 2016

POSTHUMAN FRONTIERS:
DATA, DESIGNERS, AND COGNITIVE MACHINES

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ACADIA was formed at a meeting 35 years ago on October 17, 1981 at Carnegie Mellon University in Pittsburgh. Since its inception, the conference has served as an incubator for emerging ideas in feedback loops between academia, industry, and professional practice. Over the years, ACADIA’s members, leadership, and attendees have included some of the most inventive and important figures in the fields of architectural education, design, computation, and engineering. While ACADIA is the most selective peer-reviewed conference of its kind in the world, it is also an open setting to discuss and debate experimental ideas no matter who you are or where you come from. The fruits of these debates can be found in influential schools and research centers around the globe; in award-winning software, hardware, products, furniture, and installations; and in much larger constructions that define cityscapes from California to New York, London, Dubai, Beijing, and beyond. Ideas percolate at the ACADIA conference, and are iterated, prototyped, questioned, refined, built, and further interrogated as time passes, and they continue to evolve.

At last year’s event in Cincinnati, we organized a special session called Pioneers of Computational Design moderated by Robert Aish, featuring Don Greenberg, Tom Maver, and one of ACADIA’s founding members, Chuck Eastman. This remarkable session revealed that our founding members’ interests extended beyond “CAD” and included pioneering research in topics including virtual reality, computer graphics, and building information modeling. The session was also a reminder of how far ACADIA has come in 35 years, where computational and technical subjects are no longer partitioned from the complexities of the architecture studio. This year’s conference sessions and publications will no doubt epitomize this transition. Presenters will describe emerging pedagogies and research models from schools, labs, shops, and offices around the globe, where computation and design are now pursued simultaneously, most often entangled with other unexpected disciplinary and non-disciplinary concerns and possibilities.

During a coffee break at one of my first ACADIA conferences, I recall finding myself in a conversation with the late Professor William J. Mitchell (also one of ACADIA’s founding members). He had founded the MIT Media Lab’s Smart Cities Program and his book The Logic of Architecture: Design, Computation, and Cognition, published in 1990, was credited by The New York Times as having “… profoundly changed the way architects approached building design.” Bill had just listened to me present a project and asked me questions that surprised and inspired me: “It is a beautiful project, but what if a city was filled with projects like yours? What kind of world would it be?” While Bill was known as a technologist, he was also deeply interested in broader ideas about the role technology could play to positively shape cities and society. In many ways, his attitude thankfully lives on today. Just look at the range of this year’s ACADIA papers, projects, participants, and speakers. In the words of this year’s Conference Chairs, one of the defining features of this event is to explore the “complex entanglements” and feedback loops between a radically diverse set of design ecologies; what they call, “autonomous and semiautonomous states.” Participants share a fascination with the interplay of these states where computation, artificial intelligence, and human ingenuity can yield radically new and innovative modes of designing, building, thinking, and interacting. In the spirit of William Mitchell, in the midst of our extraordinary experimentation and technological innovation, let’s not forget to ask ourselves and our colleagues: “What kind of world would it be?”
On behalf of the ACADIA Board of Directors and its membership, I want to acknowledge the 2016 University of Michigan Taubman College of Architecture and Urban Planning team for their extraordinary organization, energy, and thoughtfulness. Special thanks to Conference Site Chair Geoffrey Thün, Conference Technical Co-Chairs Kathy Velikov, and Sean Alquist, and others members of the team, including Matias del Campo, Workshop Co-Chairs Wes McGee and Catie Newell, Exhibition Co-Chair Sandra Manninger, staff members Kate Grandfield and Deniz McGee, and many others. As they have now discovered, organizing an ACADIA conference can be a little like using your own backyard to host a wedding, a graduation and a funeral—all in one weekend. Each event requires the hosts to assume different personalities: the strategist, the enforcer, the MC, the inspirational speaker. It requires a thankless series of meetings and tasks that require vision, energy, a sense of humor, diplomacy, and above all patience. That being said, Geoffrey, Kathy, Sean, and the extraordinary team they assembled, have patiently and generously worked with us over two years to not only craft a thought-provoking conference, exhibition, and workshop series, but also produced some of the highest quality publications ACADIA has ever seen. We extend to you, and the entire Taubman College community, our sincerest admiration, respect, and appreciation.

I would also like to acknowledge ACADIA’s many sponsors this year. Year after year, the support of sponsors allows us to host a world-class event with an unsurpassed roster of keynote speakers, awardees, exhibits, publications, workshops, special round-tables, events, and celebrations. Additional sponsorship from Autodesk allowed us to support more ACADIA Conference Student Travel Scholarships than ever before, and a new ACADIA Autodesk Awards Program will honor and financially support emerging paper and project research.

Lastly, I would like to thank the ACADIA Board of Directors and Officers. Through the leadership of this dedicated group of people, ACADIA’s organization, finances, sponsorships, marketing, and other outreach efforts have never been stronger. We look forward to continuing to build upon and evolve these efforts in the coming year as ACADIA prepares to host its follow-up conference at MIT in Boston, Massachusetts in October 2017.
EMERGENT TOOL STREAMS

The conference proceedings extend architectural inquiry to incorporate fields that span material science, robotics, autonomous behavior, interaction, and data-driven approaches. The papers selected for the proceedings describe practices and techniques driven by procedural approaches and externalized knowledge that ultimately take on their own identity, instrumentality, and momentum. Design operates through complex entanglements and feedback with computational as well as physical matter. The processes and products of designers are now intertwined with an emergent tool stream that not only imbues us and our built environments with novel interfaces, senses, and sensibilities, but that also produces spontaneous material and informational excess as byproducts of its autocatalytic processes. Just one example of the manifold correlations demanded by contemporary methods of design—it is no longer a question of how to work with big data, but how to evaluate the quality of data, how to assess the politics of data, and how to consider the impact of design judgment, decision making, and aesthetics within data-driven processes.

POSTHUMAN DESIGN ECOLOGIES

Posthumanism does not entail a condition after the dominance of the human species or without humans, but rather emphasizes an alternative perspective on design that shifts focus away from an anthropocentric position of observation and control. Posthumanist design practices decentralize the role of human judgment and embrace the notion that creative agencies can be conferred to nonhuman entities such as objects, tools, materials, other species, and environmental forces. Externalized knowledge begins to take on identity and instrumentality, and participate in the process of generating novel design ecologies and alternative...
models for architectural design. The panoramic position of the (humanist) designer as sole genius is giving way to a design ecology that operates in autonomous and semiautonomous modes. While bottom-up design techniques have been discussed in architecture extensively, a primary difference in today’s conversation regards the amount of resolution that new technologies yield, the fine grain of the solutions, and the sophistication of their execution. All of these (technological as well as theoretical) aspects allow the integration of a certain level of codified information, and a level of detail that results in an architecture rich in expression and articulation. In a moment when reflective judgment, knowledge, and intent seem less and less understood as the basis of design professions, and when subjectivity and identity are increasingly augmented and fragmented, how can we consider the deep challenges posed to the future of design education, research, and professional practice?

**POSTHUMAN FRONTIERS**

The papers presented at the ACADIA 2016 Conference have been categorized into five sections that are intended to position the dominant conversations emerging from current work in the field.

**Programmable Matter** operates through the commonality between natural systems, architecture, and computational design. The papers describe methods for computation that translate the logic of biological systems into codified material behaviors, which allows formational and performative agency to be shared among designers, materials, computational procedures, and environmental forces.

**Generative Robotics** explores processes of design exploration that are developed through codified actions and procedures as opposed to constraints or predetermined instructions. Robotics are moving beyond instrumental tools to one that are fully immersed within the cyclical processes of design iteration. Robots and humans are becoming collaboratively engaged in the making of material and in the formation and assembly of architectural forms.

**Procedural Design** deploys collaborative and emergent protocols and processes to enable design exploration, ideation, form development, or the construction of physical architectural systems. Procedural designs do not result in singular solutions, but rather fields of possible outcomes emanating from protocols such as game engines, big data scanning, genetic algorithms, and self-assembling agents.

**Posthuman Engagements** explores awareness, interaction, and communication among humans, tools, and intelligent machines. From the use of learning algorithms that aim to achieve life-like behavior in synthetic systems, to gesture-based drawing machines, the papers in this section experiment with material and digital languages that produce new relations and intimacies between humans, environments, and things.

**Material Frontiers** gathers two emerging areas of exploration: computational material agencies that extend beyond instrumentality and performance to engage aesthetics, ontology, and irregular formation, and design work with synthetic biologies, where architectural researchers deploy living matter crossbred with computational, biological, genetic, and electrochemical logics toward new species of architectural and landscape materialization.

The papers gathered in this volume represent some of the most innovative and exciting work currently occurring in the field. This conference helps to document a maturation of computational design into a discipline that embraces instrumental or formal sophistication while also expanding the potential fields of agents, matters, and environments in collaborative and co-evolutionary ways. With the increasingly effortless agility enabled by tools of computational design and digital fabrication, we see the ACADIA community not only address the synthesis of the human and the technological in the process of design, but also consider the participants of a posthuman architecture. We look forward to the conversations at the conference about the potential of such an expanded scope in theory, process, and practice, and anticipate future trajectories that build upon this work from the growing ACADIA community.

Procedural design is often classified as a computational approach relying upon a set of instructions that, when used in a particular sequence, are the generators of form. While within this framework certain methods may be iterative and cyclical, procedural design often denotes the construction, conceptually, of a linear solver. The work documented in this section, though, shows a significant evolution of this approach. Intelligent systems are formed in which computation is given the freedom to absorb, interpret, and respond within the sequential set of procedures, thus shifting from linear logics to networked ones. This is addressed through papers that discuss the language through which such processes are enacted and explore the emergence of a built architecture through dynamic logics of design computation.

Ludwig von Bertalanffy established the sequencing of a feedback system as a part of General Systems Theory. This laid the groundwork for the semantics and structure of procedural design. In essence, it is a methodology that is used to test the relationships of parameters through iteration. Bertalanffy classified the components of a feedback system by count, species, and association. These have been superseded as the metrics of design space, since procedural operations allow for the exploration, testing, and refinement of ideal parametric relationships. In this application, the feedback system is an active agent of design exploration.

Traditionally, procedural design has offered means of testing the relationships of parameters, but the work shown in this section demonstrates an evolution of this approach. Procedural processes become an active agent for resolving the relationships of systems. In Gerber’s “Multi-Agent System for Design” and Savov’s utilization of gameplay, logics of fabrication shift from defining constraints to being exploratory agents for design ideation and the construction of architectural systems. Human inflection becomes an operational procedure in Johnson’s work with SIFT algorithms and Sanchez’s “Combinatorial Design.” Both exploit the iterative facet of the feedback mechanism to scan massive datascapes while interjecting the transformational feature of human intuition.

Emergence is an innate function of a properly constructed procedural design process. Through works such as Andréen’s "Large Swarms of Simple Robots" and Rusenova’s "Aggregate Architectures," it is possible to see a shift from merely seeking emergence to enabling machine intelligence to learn from and respond to specific emergent behaviors. Koschitz, through the visual programming language “Beetle Blocks,” proposes a platform that simplifies the construction of procedural processes and the conceptualization of emergent design. Davis’s incorporation of building evaluation and Smith’s method for building automation subsequently extends, on a grand scale, the scope of procedural design. Data is either a live agent orchestrating building systems or an encapsulation of the live agents—the building occupants—to re-inform successive design explorations.

Collectively, the research in this section brings a valuable ambiguity to the finality of the feedback system. This reverberates into processes and modes of design, where the work provides a clear indication that architectural form is the enmeshment of systems, not just a collection of geometric constructs.

Machine Learning Integration for Adaptive Building Envelopes

An Experimental Framework for Intelligent Adaptive Control

ABSTRACT

This paper describes the development of an Intelligent Adaptive Control (IAC) framework that uses machine learning to integrate responsive passive conditioning at the envelope into a building’s comprehensive conventional environmental control system. Initial results show that by leveraging adaptive computational control to orchestrate the building’s mechanical and passive systems together, there exists a demonstrably greater potential to maximize energy efficiency than can be gained by focusing on either system individually, while the addition of more passive conditioning strategies significantly increases human comfort, health and wellness building-wide.

Implicitly, this project suggests that, given the development and ever increasing adoption of building automation systems, a significant new site for computational design in architecture is expanding within the post-occupancy operation of a building, in contrast to architects’ traditional focus on the building’s initial design. Through the development of an experimental framework that includes physical material testing linked to computational simulation, this project begins to describe a set of tools and procedures by which architects might better conceptualize, visualize, and experiment with the design of adaptive building envelopes. This process allows designers to ultimately engage in the opportunities presented by active systems that govern the daily interactions between a building, its inhabitants, and their environment long after construction is completed. Adaptive material assemblies at the envelope are given special attention since it is here that a building’s performance and urban expression are most closely intertwined.
INTRODUCTION

Parallel advances are occurring in the fields of dynamic building facades and building automation control systems, exposing an increasingly complex terrain of dynamic systems’ theory between exterior and interior built environments. Global trends in computational optimization strategies for automated control systems include the addition of intelligent control schemes, such as adaptive neuro-fuzzy inference systems, and optimization algorithms, such as multi-objective genetic algorithms, simulated annealing, meta-analysis, and others (Shaikh et al. 2014). In addition, efficiencies of conventional HVAC controllers are greatly improving, with emerging studies of applied reinforcement learning techniques indicating 4%-11% energy conservation over conventional control for heat-pumps (Ruelens et al. 2015). At the same time, emphasis on adaptive building envelope performance in response to dynamic environments is gaining heightened interest (Erickson 2013; Kolarevic and Parlac 2015; Zamella and Faraguna 2014). The ever-expanding portfolio of dynamic facade technologies exposes great promise to reduce a building’s reliance on fossil-fuel based mechanical air conditioning in favor of natural, passive mechanisms that consume significantly less energy and simultaneously improve occupant well-being. While each of these fields is receiving significant interest, there is not yet an explicit effort to link the two areas together for reciprocal benefits between proactive automated control systems and responsive envelope actuation functions.²

It is not possible to design in advance a system with a fixed control policy capable of anticipating dynamic outdoor and indoor conditions while also capitalizing on the qualitative and quantitative benefits that are possible in the synergistic interactions of these different socio-environmental control systems. In order to maximize the energy efficiency potential of these technologies, in addition to the qualitative potential for occupant experience and wellbeing, a building’s environmental control operations must be considered holistically within an intelligent and adaptive framework. Such a framework shall be capable of orchestrating all of the building’s systems in concert and adapt to simultaneous changes in internal and external conditions. The Intelligent Adaptive Control (IAC) architecture that we are developing is able to synthesize and adapt an integrated suite of control policies to coordinate building-wide active and passive environmental conditioning systems. IAC learns over time from sensors and history of control actions made during its operation. IAC policies constantly evolve so that its response becomes more finely tuned to the idiosyncrasies of each building’s particular environmental landscape.

² Intelligent Adaptive Control (IAC) experimental framework for building envelope integration.
In this project, our collaborators in Information Science and Electrical and Computer Engineering have identified two relevant control frameworks: Model Predictive Control and an area of machine learning known as Reinforcement Learning. Model Predictive Control (MPC) has become the dominant popular approach to HVAC control (Morari and Lee 1999; Maciejowski 2001; Ernst et al. 2009). Because MPC incorporates an accurate model of its task environment, it can anticipate future events and adjust accordingly based on decision point or fixed-horizon algorithms. MPC controllers require accurate knowledge of the operating environment conditions and become ineffective in unknown and changing operating environments. Reinforcement Learning (RL) is an area of machine learning concerned with how software agents learn to perform a series of sequential actions within an environment in order to maximize some notion of a long-term reward (Sutton and Barto 1998). A reinforcement learner does not rely on an a-priori model of its operating environment like an MPC does; it learns its optimal policy from its history of interaction with the environment. Reinforcement learning has been proposed as one approach to regulate controls within an environment as dynamic and complex as a building interior (Dalamagkidis et al. 2007).

For the conception of linking an intelligent automation system with the building envelope functions, an adaptive controller synthesis paradigm is preferred because the task environment dynamics are more uncertain. For this particular integration, our team has established a direction towards a hybrid approach to the computational control system, blending the benefits of RL with those of MPC (Peng and Morrison 2016). Comprehensively, the IAC framework engages concurrent development of physical dynamic envelope prototypes, simulation of digital design concepts, and analysis of building energy performance.

METHODS

Our experimental framework is an ecosystem consisting of a physical testing apparatus linked to both a digital simulation and analysis environment [Fig. 2]. A range of adaptive facade material assemblies can be inserted within the physical environmental test chamber. Digital configurations of these assemblies are simultaneously developed within a simulation environment for design purposes and in order to apply our experiments to the building scale for energy performance analysis. The bridge between these three environments is the IAC computational control framework. The IAC framework is an autonomous adaptive control architecture based on an adaptive machine-learning methodology. The IAC regulates the electronic controls within the physical testbed as well within the digital simulation. Over time, the data generated within these two experimental arenas train the IAC’s control algorithms toward adaptive performance improvements.

Physical Testbed and Prototypes

The physical environmental test bed is an acrylic chamber designed as a modular kit of parts for testing a range of materials, control mechanisms and data processing models. The chamber is divided into two equal volumes separated by a slot for a removable prototype. Different active facade assembly prototypes can be inserted and tested between chamber A, representing exposure to an external environment, and chamber B, which represents a controlled internal environment [Fig. 3]. This test chamber permits experimental control of environmental conditions (humidity, temperature, light, heat flow) on each side of the testing facade and the monitoring of the response and adaptability of the apparatus to variations in conditions. The testbed is modular by design to enable experimental evaluation of the adequacy of various categories of adaptable materials and data-driven adaptive control policies within the IAC.
Multi-sensory device arrays (thermocouples, photodiode, humidity sensors, infrared camera, etc.) embedded throughout the interior chamber, the facade itself, and the external space produce large-scale data flows used to generate responsive behaviors through adaptive learning. Initial physical prototype baseline studies are being prepared with electroactive photo-chromatic dynamic glazing film technology, which responds to photometric measures in graduated increments of opacity and transparency based on a dimmable halogen lamp array input and photosensor data collection [Fig. 4]. The anticipated result of the combination of advanced facade materials with adaptive control is an autonomously responsive envelope that can maintain internal environmental conditions with appropriate performance levels compared to conventional methods. Specific targets in next-generation building energy management systems indicate the merging of sensor data and predictive statistical models to allow for more proactive modulation as signals are changing (Zavala et al. 2011). Future predictive modeling may also be linked with online sources provisioning communication from urban microclimate data from external sensory networks and utility providers (Pang, Hong, and Piette 2013).

**Digital Simulation Environment**

The work within the design development process of machine learning integration with adaptive building envelope and reciprocal building energy performance is conducted in the Rhino 3D – Grasshopper platform with Ladybug-Honeybee plug-ins and EnergyPlus simulations. In the current work, Python scripts access reinforcement learning algorithms that, along with weather data input and energy simulation output through base building analyses, inform dynamic changes in building envelope properties. Dynamic envelope design concepts developed with the parametric visualization tools [Figs. 5 and 6] can be correlated to dynamic properties for analysis engine input.

The framework developed for this project serves as a design process tool, in addition to informing potential building envelope technologies. There are three primary facets to the simulation process: a) defining the building envelope system and the influence of external environmental stimuli, b) determining the interior building environmental performance through dynamic envelope properties, and c) defining the learning algorithm to actuate change in properties or functionality of the building envelope system. Current building energy simulation models have two drawbacks in these areas—limitation on dynamic envelope analysis and limitation on reinforcement learning algorithm integration (Magoules and Zhao 2016; Sanyal et al. 2014).

The simulation process is more complex than current standards for energy performance models because real-time building performance results are continuously analyzed through algorithmic comparison with concurrent external stimuli to actuate
change in the building envelope properties. The process is dynamic rather than static, and intends for adaptability of an envelope system beyond a two-state control process. Our current analysis framework includes a baseline building model with selective data processing for the surface energy losses and gains at the building envelope for each cardinal orientation [Fig. 7]. The data provides the MPC learning sets, which are utilized for initial building envelope property changes in response to the algorithm actuation. Further development is required to model the dynamic behaviors of envelope response stimulated through the IAC with the EnergyPlus interface for predictive environmental performance results.

**Computational Control Framework**

The multifaceted nature or our testing environment, containing physical as well as virtual components, supports our hybrid approach to the development of the IAC framework. The project methodology allows for two parallel sets of learning data to be developed - one in the test chamber with physical prototypes and sensors, and another in the simulation environment with analysis tools. Our project is also developing a compromise between planning and learning, where planning is represented by the framework of an MPC and learning is represented by a model-free reinforcement learning technique (Morari and Lee 1999; Maciejowski 2001; Afram and Janabi-Sharifi 2014). Both approaches seek to define a series of policies for state-dependent actions to maximize cumulative long term reward.

In planning, it is assumed that a complete model of the task environment is available and the planner induces a policy for choosing the action in each state that achieves optimal performance in terms of total long term reward. The RL approach, on the other hand, does not assume the environment is known ahead of time. Instead, the learning agent has to interact directly with the environment to gather data about the effects of its actions on the world and their reward value, and while doing so searches for an optimal policy for action.

The a-priori model of the task environment is both the strength and weakness of the planning approach. In an environment as complex as a building interior, these conditions are unlikely to be completely known in advance and may change over time.
The learning framework provides a general approach to solving sequential decision-making problems without relying on a pre-existing model of the task environment, but incurs the prohibitively high cost of real-time interaction with the environment that would require multiple parallel processors (Magoules and Zhao 2016). We can potentially get the advantages of both frameworks through a hybrid approach in which we use a suitable platform for offline training of an adaptive learning system through our complementary methodology of physical and simulation environments. In this case, the policy learned in simulation is used to initiate the learner with a reasonable performance that is then transferred to and fine-tuned in real-world interaction. This approach reduces the amount of costly real-world experience required to achieve high performance (Liu and Henze 2006; Cutler et al. 2015).

By constructing a feedback loop between actual and simulated environments, we streamline the development of the learner. At the same time, we iteratively increase the accuracy of our simulation by recalibrating it each cycle based on results recorded from the physical test chamber. The result is a prototyping environment where we can develop a novel environmental control framework that adapts to its ever changing context and continually improves its performance over time. This experimental setup is also designed to anticipate how our IAC might be employed in the field. While in operation as a building control system, a parallel simulation driven by real-time data collected from building sensors would provide an environment where alternative control policies may continuously be explored and evolve.

RESULTS

Initial work on the development of the IAC has focused on its integration with a conventional HVAC control system. Subsequent development will confront the more complex prospect of passive conditioning through an adaptive facade. In simulations of our initial model, the thermostat controller tuned via a reinforcement machine learning algorithm performed approximately 5% more efficiently than a simulated conventional automatic thermostat. We expect that this performance will improve over the course of our work towards single system performance improvements of 8–12%, and our target for accumulated efficiency between a passive facade system and a conventional HVAC system centrally controlled by the IAC technology is 25–35% (Jacobs 2003). The integration of the IAC with adaptive building envelope actuation could provide up to 50% reduction in energy demands.

CONCLUSION

Current work to date has demonstrated performance benefits from the application of an early version of the IAC. The time series of environmental conditions and the state of the facade will be analyzed to create models of system dynamics at multiple time scales. These dynamic models shall serve as the instrument for developing control algorithms to maintain desired chamber internal environment states while optimizing for low energy consumption. This includes using adaptive learning techniques that explore control strategies under different optimizing constraints.

Our efforts have occurred through interdisciplinary collaborations with Information Sciences, Electrical and Computer Engineering, and Material Science Engineering. In order to develop robust IAC policies, further interdisciplinary connections are warranted that will enhance the possibilities for holistic evaluative frameworks in the reinforcement learning algorithms. The primary focus in near-term work required specific attention to linking the RL with the dynamic facade for parametric development of environmental data feedback informing actuation signals. The simplified physical model for the electrochromic dynamic glazing film and photometric analysis will be analyzed with concurrent development of dynamic simulation scripting in the EnergyPlus platform.

This work ultimately pursues the systematic evaluation of a range of adaptive envelope technologies with regard to environmental performance. When complete, the resulting comparative study will undoubtedly have value beyond the bounds of this project and be useful to architectural designers at large. Furthermore, our experimental testbed serves as a generalizable process and kit of parts. It may be adopted and improved upon by future designers for use as tool kit for the study and design of adaptive facades in all of their aspects.

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NOTES


2. The only identifiable emerging market technology in this area is the Provolta Energy OS patent pending machine learning platform by Rengen supported in part by R&D partner Lawrence Berkeley National Laboratory; however, this platform does not explicitly focus on integration with dynamic building envelopes, but rather on improving performance of HVAC control systems through building integration feedback.

REFERENCES


IMAGE CREDITS

Figure 1: Responsive facade modules (Smith, 2016)
Figure 2: IAC Framework Methodology (Smith and Lasch, 2015)
Figure 3: Testbed diagram (Smith and Le, 2015)
Figure 4: Testbed photograph (Smith, 2016)
Figure 5: Adaptive module designs (Smith and Le, 2015)
Figure 6: Adaptive module patterns (Smith and Le, 2015)
Figure 7: Building energy analysis model results (Smith, 2016)
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