The Development and Valuation of Intelligent and Adaptive Building Systems

Kai L. Hansen

IIT College of Architecture, Chicago, Illinois

ABSTRACT: Energy consumption by buildings, especially high-rise buildings, has increased to the point that it has overtaken the industrial and transportation sectors (Perez-Lombard et al., 2008). This unsustainable phenomenon has prompted research into intelligent and adaptive building systems (IABS) for more energy-efficient buildings that current architectural practice and building operations overlook. IABS are bottom-up strategies that provide energy consumption and comfort solutions at any scale of the built environment. In addition to the benefit of reduced energy consumption, occupant physiological and psychological well-being can also be addressed through better control and feedback mechanisms. These improvements can be made through the widespread application of systems that blend many different and readily attainable components. This research seeks to address these issues through the development and study of IABS prototypes, virtual models, and material/component libraries that address the needs of all stakeholders (Table 1). Prototypes that form contextually aware and flexible agent networks will be presented, along with the results from those that have been completed Suggestions for design and interfacing are also discussed. Controlled environments are constructed in and around physical prototypes to carefully observe performance results. Also discussed is how high-rise buildings are ideal candidates for IABS integration.

Table 1: Building stakeholders and relative performance metrics

Stakeholder	Performance Metrics
Occupant	Indoor Air Quality, comfort, health (psychological & physiological)
Building Owner and/or Developer	Return on initial investment, building lifespan, operating costs, occupant satisfaction/rate of occupancy
Building Engineer	Efficient building control and management
Utility Companies	Energy consumption (especially during peak demand)

KEYWORDS: High-Rise, Adaptive, Facade, Building Systems, Intelligent Networks

INTRODUCTION

Architects currently utilize many technologies in practice. Rapid prototyping, BIM, parametric modelling, and information databases are all currently used in the development phase of a building's life cycle. Although these powerful tools have helped with project delivery in many ways, we fail to use them and other applicable technologies in a building's often cyclical maintenance & operations phase, which makes up roughly 85% of a typical 50 year life-cycle (Shabha 2003). Balance can be given to this cycle by identifying ways in which appropriate technologies can be integrated into the built environment (Figure 1). The goal of this research is to seek out technological solutions for the energy and occupant related issues that we currently face.

The degree to which viable IABS are deployed and used is important. Solutions for increasing energy efficiency and comfort within a building exist. However, it is difficult to integrate them into a large number of new and existing structures due to cost and over-customization. Owners and designers have indicated that they desire further progress with advanced facades. Furthermore, they have the ability to reliably predict performance and ensure that availability and cost matches their time and budgetary requirements (Beltran et al., 2003). To change prohibitive trends and convince all stakeholders that IABS can be a viable solution to excessive energy consumption, intelligent building systems should consist of technologies that are readily attainable, affordable, and adaptable thus allowing implementation at a global scale that leads to a tangible effect on energy consumption.

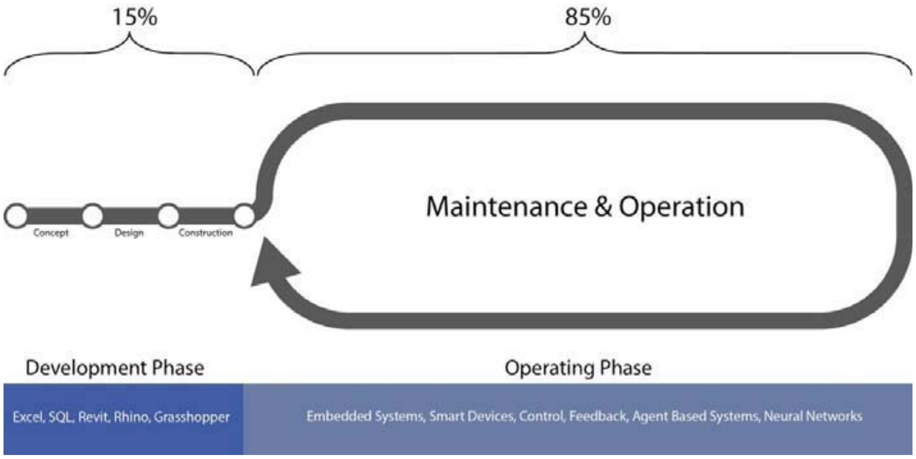

Figure 1: The distribution of technologies throughout the entire life-cycle of a building

Recent research indicates that building occupants value access to daylight and views, as well as the ability to locally control their environments (Beltran et al., 2003). As a bottom up granular system, IABS are able to provide these preferable conditions and create a more productive, as well as psychologically and physiologically healthier environment.

INTRODUCTION OF IABS TECHNOLOGIES

It is necessary to provide a brief introduction on the technologies being utilized in this research before moving forward. Artificial Neural Networks are computational models that are inspired by the structural and/or functional aspects of biological neural networks (e.g. central nervous system), and are adaptive systems that learn to change their structure based on the information that flows through them. Agent based systems are used as computational models for simulating the actions and interactions of autonomous agents to assess their affects on the system as a whole (Niazi and Hussain 2011). They are commonly used to simulate group behavior in financial and sociological studies. A connection exists between these two concepts, in which an interconnected group of agents could be viewed as neurons or groups of neurons. The feedback exchanges fostered by this relationship have the potential to give rise to increasingly intelligent and agile building control networks, providing management capabilities of the built environment at any scale.

Considering the density of the urban environment and the resources required to maintain a comfortable interior condition within a large building, this research makes the reasonable assumption that high-rise buildings are the ideal test vehicles for IABS. The following supposes how an IABS would be integrated within a 16 floor high rise, with a 70’ x 50’ footprint. This example building is arbitrary in nature and without site, program, or specific materials (Figure 2). The subsequent diagrams are meant to illustrate how the IABS network would be integrated with this building. Due to their dynamic nature, occupants have been excluded from these diagrams.

Figure 2: Example High Rise with glass curtain wall, concrete structure, and Agent Computing Mechanism (ACM) distribution

This example illustrates two major and potentially adaptive high-rise components: artificial lighting and curtain wall. Hubs connect to both interior light sensors and controls with other building systems, such as the adaptive facade or HVAC (Figure 3). Each floor is broken up into regions, with a lighting hub in each.

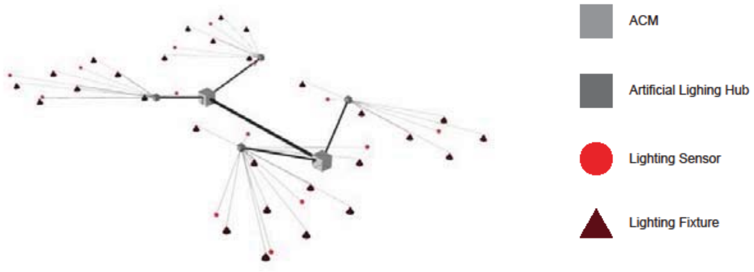

Figure 3: Artificial lighting network and ACM's per floor

Facade modules each represent an adaptive curtain wall panel in this example. There are no specific metrics or adaptive components considered here. However, each module consists of a networked microcontroller, actuator, and sensing components (Figure 4).

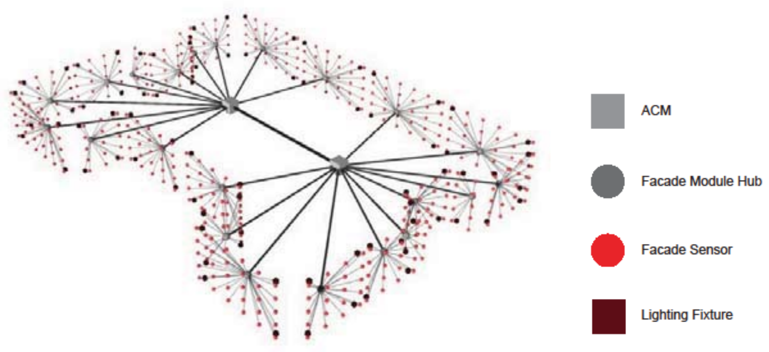

Figure 4: Facade Module Network and ACM's per floor

Agent networks should be considered the foundation layer upon which is laid the Artificial Neural Network. In this example, this is done horizontally floor-to-floor (Figure 5), and vertically from top to bottom (Figure 6). With this arrangement, each individual agent is capable of communicating with any number of others. A goal of this project is to determine if this arrangement is capable of performing better than contemporary systems.

Figure 5: Floor-to-floor agent and neural network integration

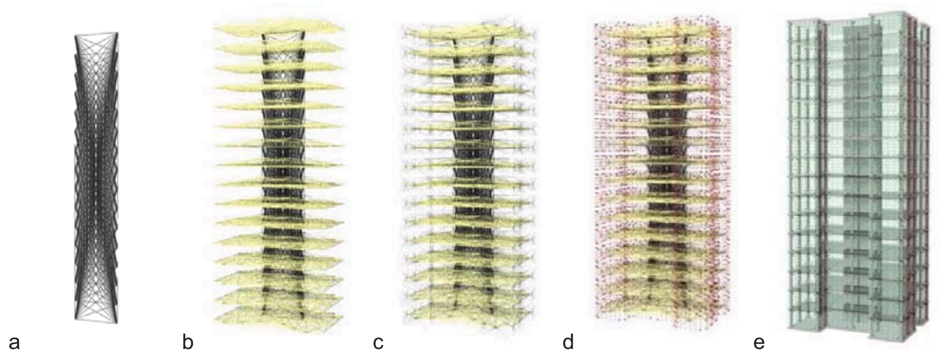

Figure 6: Example high-rise with IABS: a. Interconnected ACM's, b. Floor-to-floor agent neural net, c. Floor-to-floor agent network, d. Sensing and dynamic components, e. Complete IABS enabled building

That agent systems and artificial neural networks can provide superior building automation and management is not a new concept. In fact, numerous research papers have been written on the subject. However, no literature could be found on the development of physical prototypes created to identify component makeups and how they might work. This research attempts to build upon theoretical precedents by developing working IABS prototypes, then examining them qualitatively and quantitatively.

1.0 FACADE AND BUILDING SYSTEM PROTOTYPES

1.1. Facade prototype 1

In the course of this research, two prototypes have been fully developed. The first (Figure 7) served largely as a learning tool, setting the foundation for subsequent versions by necessitating a working knowledge of physical computing and computer programming. Its sole function was to sense the ambient light on one side of the fritted glass module and then actuate a sliding pattern to block or permit light to meet the predetermined requirements. However, the rudimentary nature of the prototype limited its adaptive qualities and the subsequent version would need a more refined mechanical composition.

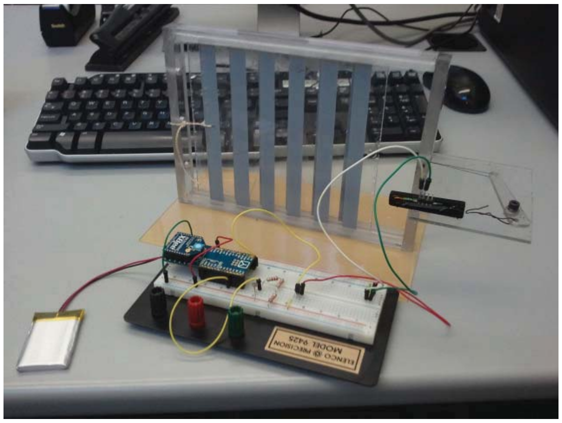

Figure 7: Adaptive Facade Prototype 1

1.2. Micro-enclosure and intelligent building network prototype 1

A second-generation prototype (Figure 8) furthered insight into the same lessons and led to discoveries related to the potential of specific actuators and sensors, device networking, and agent based networks. In an IABS, individual agents are capable of observing behavior, environmental conditions, exchanging data, assuming commands, and acting independently from the rest of the network to provide a more granular approach to the control and monitoring of the many spaces within a building. Observations and commands are transmitted through the wireless or hard-wired building networks where appropriate. Table 2 lists the agents that make up this prototype.

Table 2: Second prototype agent inventory

Agent	Purpose
Agent Computing Mechanism	Acts as a data hub and higher decision making component
Data Base Agent	Stores environmental data and dynamic responses for later access
Cloud Agent	Consists of web based data sources, feedback interfaces, and storage
Micro-Enclosure Agent	Consists of microcontroller, sensors and adaptive components (dynamic frit & vent dampeners) that physically sense and respond to internal and external building environments

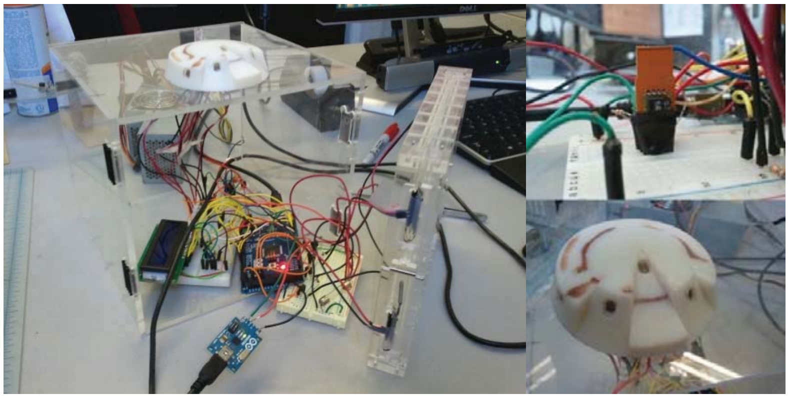

Figure 8: Adaptive Facade Agent with Shape Memory Alloy Frit Actuators; Temperature & Humidity Sensor; Solar Position Array

Every agent in this prototype functioned as hoped, with the exception of the frit and dampener actuators. Although attention was given to how the unidirectional actuators would be counter-balanced to return them to their relaxed state, inconsistent strength through the full stroke limited movement. This translated to a limited stroke and lack of dynamic functionality. Despite this, the prototype yielded a great deal of useful data, and served as a sound proof of concept.

2.0. PROTOTYPES UNDER DEVELOPMENT

With the lessons learned from the initial prototypes, it is necessary to develop a third generation of prototypes that will establish groundwork for choosing effective and sustainable choices in component makeup and functionality for IABS. By developing a series of prototypes, rather than one, the opportunity to draw comparisons between each one becomes available. Moving forward, this paper will focus on five prototypes, and what can be learned from them. Four make up a unique series of prototypes, and will share the same physical construction. However, each will incorporate increasing levels of technological complexity to learn what, if any, ideal makeups exists. An evaluation of performance characteristics will be made, and then compared. The metrics for which include energy consumption, solar control, effective adaptation, maintenance, lifespan, and first/total costs.

Listed from least complex to most, these four prototypes will have the following component makeups:

1. Mock IGU as a control model
2. One non-networked stand-alone microprocessor (Arduino Uno or TI LaunchPad MSP430)
3. One networked Raspberry Pi as the agent control mechanism(ACM), and one microprocessor connected as a slave via Serial Peripheral Interface (SPI)
4. One networked Raspberry Pi as ACM, and two microprocessors. Each

Simple enclosures will be built around each prototype to maintain an agreeable amount of separation between the environment in which the prototypes will be housed and their immediate environment. This ensures that metrics can be accurately measured. Prototypes will be stationed side-by-side along a large south-facing glass curtain wall for testing and observation. To track performance and record data, cameras and appropriate sensors will be placed on and within the enclosure. Energy use/production, temperature, humidity, and light measurements will be monitored and evaluated in each case.

A fifth prototype will consist of an interactive digital model of a high-rise building, working in conjunction with a mobile device application from which the model's components will be controlled and behavioral/environmental data viewed.

2.0.1 Prototype physical makeup

Each facade prototype will consist of the same physical components to eliminate performance data variations. Actuation is performed by black latex balloons inflated with a commercial grade aquarium pump that is activated with a relay switch attached to the microcontroller. Photo-resistors sense the ambient light levels and the balloon inflates in response. In its deflated state, the diameter of the flattened balloon is equal to that of the spacing between glazing panes. Any subsequent increase in volume would result in an outward expansion within the IGU only (Figure 9). Arrayed, equally spaced bulbs would form a loose frit-like pattern. As the balloons expand, they form an increasingly dense pattern, blocking out most solar gain (Figure 10). Each will have a light sensor assigned to it and would be capable of expanding or contracting independent of the others.

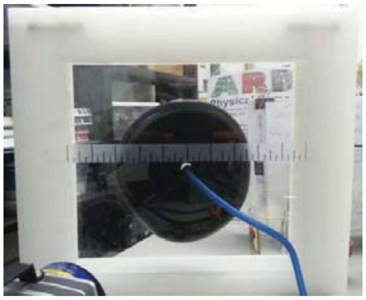

Figure 9: Latex balloon show inflated within the mock IGU

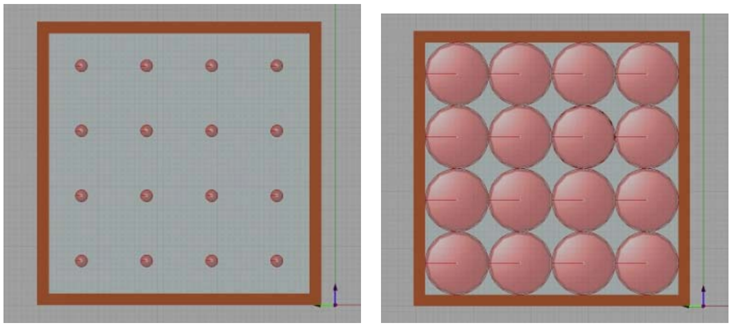

Figure 10: Rubber bulbs shown deflated, then fully inflated

To ensure that the proper amount of air volume is given to the balloon, an analog sensor constantly monitors the air pressure within the balloon. The pneumatic system is capable of recognizing when the balloon needs to be inflated, sealed, or vented to respond to the changing light levels. Electrical consumption, mechanical maintenance, and component life-cycle will also be recorded.

In following tests, special attention should be paid to the color of the balloons used and from where the air to inflate them is sourced. These choices could significantly affect how the prototype performs in terms of heat absorption and redistribution. Here, black balloons have been chosen to provide greater absorption of solar energy, preventing it from reaching the interior. Air will be sourced from outside of the enclosure to reduce heat building up. While in the balloons, the air will be heated. Air is vented outside of the enclosure to reduce heat gains.

2.1 PHYSICAL PROTOTYPES

2.1.1 Prototype 1

The first and simplest system will consist of only the mock I GU and serve as an experimental control. Sensors will be embedded within the enclosure and facade to monitor conditions.

2.1.2 Prototype 2

The second will consist of only one microcontroller, and the I/O devices essential for basic sensing and actuation. The microcontroller of choice is the Texas Instruments LaunchPad MSP430. This microcontroller is the first choice due to its cost ($5). To prove that IABS can be affordable, component costs will be kept to a minimum in each prototype. However, the more developer-friendly Arduino may be substituted if required/desired.

2.1.3 Prototype 3

The third prototype will consist of an agent computing mechanism (ACM), the Raspberry Pi Model B ($35), microcontroller, and peripherals. The Raspberry Pi will communicate with the microcontroller via asynchronous serial communications. This method of interfacing ensures that both can act as independent agents and allows prototype 3 to extract results specific to an agent based system.

2.1.4 Prototype 4

The final prototype has two microprocessors: one to interface with sensors and actuators and the other to act as a physical interface. The interface will be used to manually control and override certain behaviors as well as provide feedback on environmental conditions. The agent computing mechanism will be capable of monitoring and overriding the behavior of either microprocessor. As an agent with more powerful functionality, the ACM will be able to make higher level decisions and communicate them to the microprocessors should their preprogrammed behaviors not suffice. This also means that the ACM can potential lock-out specific control features associated with the interface agent should it be deemed necessary.

Table 3: Third generation prototype series and makeup

Mrk	Microprocessor	Sensors & Actuators	ACM	Network Agents	Agent System	ANN
1	None	None	None	None	No	No
2	One Arduino or TI LaunchPad MSP430	Yes	None	None	No	No
3	One Arduino or TI LaunchPad MSP430	Yes	One Raspberry Pi computer	Database and cloud agents	Yes	No
4	Two Arduinos or TI LaunchPad MSP430's	Yes	One Raspberry Pi computer	Database and cloud agents	Yes	Yes

2.2. Additional agents

Architects have long understood that it is possible to change the way that users interact with the spaces and objects that surround them by integrating logical devices into the built environment, but only recently have such devices become cheap, powerful, and small enough to be economically used in this way (Sterk 2006). This research seeks to add two more agents to this prototype series: human interface and end-user (Diagram 1). Statistics state that almost half of U.S. mobile phone subscribers now own smart phones (The Nielsen Company 2012). Due in part to this trend, there is a vast and readily available network of human interface devices that can be folded into an agent network. Desktop PC's, laptops, and ambient information devices are other examples of suitable interface devices. A dense and familiar network of interface devices delivers the added benefit of improved psychological wellbeing for occupants via the democratization of energy monitoring and limited environmental control (WGDB 2011). Important occupant biometrics (Table 4) can also be monitored from many of these devices, and used to further improve the environmental conditions.

Table 4: Occupant related metrics used to intelligently adjust environmental control

Occupant Metric	Definitions and Examples
Biometrics	Body temperature, heart rate, etc.
Personal Sentiments	Data on personal sentiments regarding the conditions in a building can be mined from social networks, blogs, etc.
Direct Commentary	Provided through explicit communication from occupant to interface

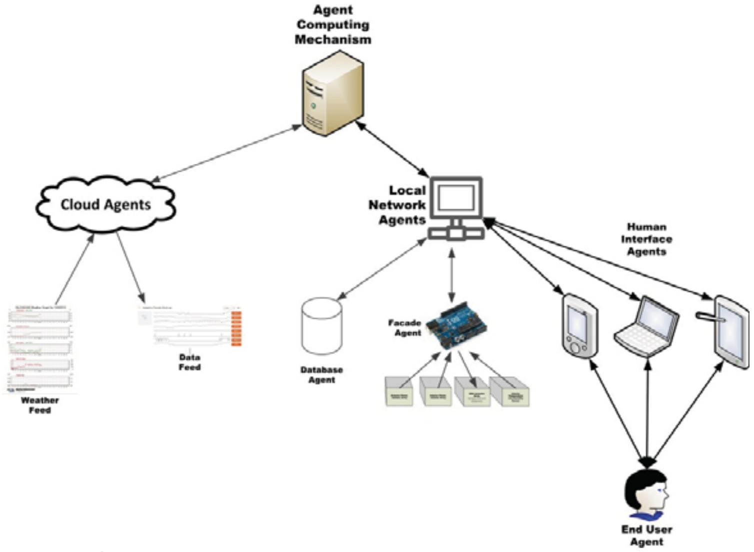

Diagram 1: Representation of functionality and data flow between the primary agents in 3rd generation prototypes

2.3. Virtual high-rise

In addition to the other prototypes already discussed, a virtual model of a prominent downtown Chicago mixed-use high-rise will be produced for the purpose of illustrating the capabilities of IABS. The high-rise to be chosen will be approximately 30 stories tall. This floor count is to ensure that a complete building can be modeled given the project time frame. The building's mixed-use program provides a diverse cross-section of space usage. In addition to the structure, the model will also consist of artificial lighting, HVAC, and adaptive components.

A mobile device application currently in development (Figure 11) will work as an interface for stockholders. With this prototype, model and components can be monitored and/or controlled in ways that are specific to each end-user. The application will run on an iOS 6 platform. Interfaces will differ for each stakeholder, and will allow varying levels of access to data and control. This interface will work as a tool for illustrating IABS capabilities and studying user interaction. User-centered design methodology will be utilized throughout development and testing. The study of subsequent results will be applied to future versions of both interface and IABS systems.

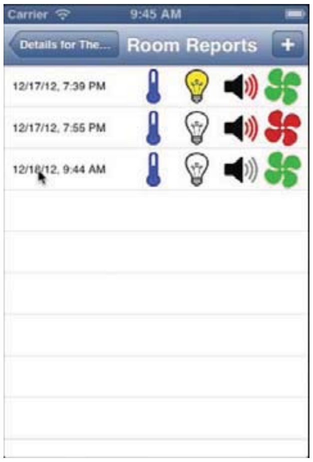

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Figure 11: Mobile device application for environmental feedback and adaptive systems control

3.0. IMPLICATIONS

It should be noted that the proposed system's flexibility allows it to be applied to both new and existing high-rise structures. Since sustainability is a major component of this research, it should be noted that retrofitting existing high-rises could potentially save mor e in resources than starting anew in some cases.

IABS are capable of delivering feedback and control to occupants from any location. It follows that this characteristic can be exploited to function beyond the scope of the building, and into the urban environment as well. If applied at this scale, singular buildings would not just operate independent of others, but also be part of a larger network connected by urban infrastructure. This network would be capable of reallocating a building's resources through an exchange network to support reasonable indoor conditions throughout.

CONCLUSION

Architectural design practices already utilize a vast array of technologies when delivering projects. However, this technological advantage is not seen in the maintenance and operation phase of a buildings life-cycle. Intelligent and adaptive building systems have the potential to fill this gap through the marriage of various established and emergent technologies. Widespread use of these systems is important when trying to make a significant impact on the sustainability of building. They should therefore be as attainable and flexible as possible. Given the relative scale of high-rise buildings, they are a suitable vehicle for determining the technological make-up required to ensure widespread deployment of these systems. To date, this research has produced two prototypes to inform future research, and a 3rd series is in development to satisfy the goals discussed here. This series of prototypes will build upon the previous two by incorporating a more rigid process by which components and materials are chosen and analyzed. It is expected that the addition of the interface and end-user agents to a virtual high-rise model will strengthen for future system developments.

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