HUMAN-BUILDING COLLABORATION

A Pedagogical Framework for Smart Building Design

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Abstract. We introduce Human-Building Collaboration (HBC), a pedagogical framework for the design of next-generation smart buildings in architecture. Using the framework’s philosophy, model, and tools we show designers how to enhance smart building performance by increasing and diversifying the ways humans have to share their intelligence with that of the building. We apply this framework through design exercises and present the result of two projects: (1) a tangible wall interface for lighting co-optimization and (2) a shape display facade interface for rainwater purification and reuse. Preliminary findings demonstrate that the framework helped designers proposing new means for humans to collaborate with smart buildings.

Keywords. Smart Buildings; Artificial Intelligence; Tangible Interfaces; Human-Building Interaction; User Experience Design.

1. Introduction

In 2016, an AI computer program, AlphaGo, beat a top-ranking professional player in the ancient game of GO (Silver et al. 2017). An achievement that demonstrates how artificial intelligence is getting closer and closer to reach our human intelligence. The excitement for this great feat, however, has been so large that AI researchers and enthusiasts have missed an important fact. While Lee Se-dol, the player, needed only his brain and a cup of coffee to perform the task, AlphaGo required 1,202 CPUs and 176 GPUs, consuming more than 350 kilowatts of energy. Yes, the human lost. The machine won at a well defined closed type of complex problem and in order to do so, it consumed 3000 times more energy than its opponent.

We do not have to look into complex problem-solving, such as playing GO, to understand AI’s intensive energetic needs. Let us consider a simpler task, like recognizing an object in a room. For example, recognizing a cat. A task that does not require a top-rank professional and that any three-year-old child could perform easily in a fraction of a second. This task took Google’s most advanced lab and 16,000 computer processors to perform (Le et al. 2012). We call this the cat recognition problem, demonstrating a broader context of efficiency and effectiveness of AI: in the current approach, the smarter the system the more energy and material resources it will require.
We claim that this intensive energetic requirement could become an obstacle to AI being integrated into our broader built environment, precisely because of its high energy cost. Today, smart buildings are integrating AI capabilities with the purpose of optimizing energy consumption and increase the sustainability of the built environment (Lorenzo-Eiroa and Sprecher 2013; Sinopoli 2009). State-of-art propositions track occupancy and environmental conditions and then respond by adjusting their internal lighting and mechanical systems and/or actuating their facades (Kolarevic and Parlac 2015; Klooster 2009). Yet, similar to what is happening with AlphaGO, the practitioners and researchers on the smart building industry are missing a key fact: the smarter the building that they develop, the more energy and material resources it will require.

We propose an alternative framework towards next-generation smart building design. We call this framework Human-Building Collaboration (HBC). We claim that if we had to design a truly intelligent built environment, the notion of smart buildings needs to be expanded in order to include an effective way for AI to collaborate with humans (Licklider 1960). We can no longer afford to separate processing intelligence from energy intelligence. Smart buildings cannot pretend to be intelligent if they require much energy to reduce the energy of their regular use and operation. For us, the cat recognition problem, as a collaborative framework for building intelligence, is a shift from being one of autonomous intelligence to be one of collaborative intelligence (Daugherty and Wilson 2018). The question should not be limited to how can the smart building recognize the cat but instead how can a three-year-old transmit the location of the cat in an effective way to the building. It is our working assumption that intelligence should not be limited to individual processing intelligence but instead on active, bi-directional communication intelligence. That is what we mean by collaboration, human and building working together to obtain an intelligent result.

Our strategy to formulate the HBC framework is two-fold. First, we focus on the interaction between the human and the building. We are neither focusing on the AI nor the human intelligence but on the interface between the two. i.e., the means for human and building to communicate with one another. We want to expand and diversify the ways humans have to interact with these increasingly more intelligent and informed building systems. In this context, we align our work with human-building interaction (HBI) (Nembrini and Lalanne 2017), a research domain within human-computer interaction (HCI). While HBI investigates how to integrate HCI technologies into buildings, our model addresses smart building design from a pedagogical perspective. This difference with HBI constitutes our second strategy. The objective of our framework is to provide guidelines for practitioners, students, and researchers engaging in the actual design and development of smart buildings. Instead of proposing a specific technological solution, we introduce a framework that is meant to be taught, learned, and practiced in design.

In this paper, we introduce the foundations for HBC, including a philosophy, a model, and a set of tools. The philosophy corresponds to a new way of thinking about interaction in the context of a collaboration between humans and smart buildings. The model turns this philosophy into a set of design guidelines, through
a diagram describing the relational interactions and opportunities for collaboration between human and building. The tools apply the model through materials, examples, and techniques to be used in hands-on design practice.

Finally, we show a preliminary application of this framework through the design work of students at the Center for Architecture Science and Ecology (CASE). We found that the framework helped these students design smart building solutions with diverse interactions and collaboration modes. We conclude by elaborating on these findings and describing next steps. Future work involves specifying HBC functionality types, integrating new AI software techniques and implementations, and extending HCI towards new architectural methods.

2. How the (Smart) Building Sees Us

In 2004, Dan O’ Sullivan and Tom Igoe, HCI professors, used an illustration of “how the computer sees us” to assess the interaction of their current digital technologies (O’ Sullivan and Igoe 2004). In the illustration, the human is represented as a hand with one finger, two ears, and one eye (Fig.1, Left). This depiction of the human is relevant because it exposed the limited means we had to interact with the computer at that time.

This illustration shows how the computer saw us in 2004. Today, 14 years later, HCI applications have somewhat progressed. We now have multi-touch screens and voice user interfaces (VUI). Therefore, today we have two fingers and a mouth. This updated depiction, however, is only valid for computers embedded in devices, such as personal computers, smartphones, wearables, tablets, and the IoTs. These are objects located inside our spaces. HCI has not yet been integrated within our spaces, as part of walls, floors, ceilings, doors, windows, and facades.

We want to propose a new illustration of “how the (smart) building sees us.” In this depiction, the building is smart when it integrates computers, sensors, and effectors responding to environmental changes and user needs. In the illustration, we represent the human as a blob with two extensions (or arms) and one eye. This blob can move in a two-dimensional plane and can produce and feel temperature (Fig.1, Right). This illustration exposes the limited ways that humans have to
communicate and collaborate with smart buildings today.

In most smart building applications, not even interaction is considered, and the building systems or facades respond automatically to environmental changes by adjusting lighting and heating conditions (Sinopoli, 2016). In other cases, the building tracks position and number of people and optimize lighting and heating in response to occupancy (Kolarevic and Parlac 2015; Klooster 2009). In exceptional cases, facades or walls respond to the human movement in space and arm movements or gestures in real-time (Fox 2016; Krietemeyer et al. 2015).

For O’ Sullivan and Igoe, “the human being as seen through the computer’s input devices is a sad creature” (O’ Sullivan and Igoe 2004). We claim the same for the current state of human-building interaction: the human being as seen through the smart building’s input devices is still a sad creature. Humans do not have hands, fingers, feet, bodies. In sum, in current smart building solutions, humans have limited means to act on the building and sense a response coming from the building. We argue that this limitation constitutes an obstacle for human-buildings collaboration. We need to reframe interaction in this context, from a simple action-response relationship to a communicative process allowing the human and the building to work together: increasing and diversifying the ways humans have to share their intelligence with that of the building.

3. The Model

The model turns the philosophy into a set of design guidelines, through a diagram (Fig.2) describing the relational interactions and opportunities for collaboration between human factors (senses and actions) and building factors (detectors and responses). Using these factors and their relationships, the designer can explore the multiple and rich ways in which humans can interact, communicate, and thus collaborate with smart buildings. For example, a designer can choose touch for human action, and then sound for the building response to that action.

In the diagram, we illustrate a person inside a room. Next to the person, we describe the human actions and senses. In the top of the diagram, we note the building detectors and responses. The interaction takes place through a loop that we represent with one arrow connecting human actions to building detectors, and with a second arrow connecting building responses to human senses.

This is how the interaction between human and building unfolds: The human acts directly on the building by walking around, speaking, gesturing, or touching the building directly. All these actions are basically movements, i.e. the coordinated motion of body parts (limbs, hands, fingers, head, face, mouth, tongue, eyes). Even speaking could be described as the coordinated movement of mouth and tongue while breathing (Rosenberg 2015). The building detects these actions using sensors embedded in any of its material elements, namely points, lines, surfaces, and volumes. These elements can take the form of corners (points), railings (lines), walls (surfaces), and rooms (volumes). Then, the building, using embedded computers with AI capabilities, process this data and responds by adjusting and actuating any of its material elements. The building could open the facade, turn on the lights, increase the heat of an HVAC system, modify the surface...
of a wall to display information. Finally, in the model, the loop is completed by the human feeling this response using the body senses.

This model not only shows all these factors and their relationships but also organizes them as a continuous loop of chronological and sequential interactions. Most of the current propositions have focused on one unique moment of interaction, and have emphasized the building side of the loop—the building sensing and then responding. Our model shows the flow of interactions between both sides of the loop: a person acts, the building detects and responds, and then the person senses and acts again, as the loop starts over. This interaction flow becomes the means for communication and collaboration between two intelligent systems, the human and the building. The human can act on the building to provide solutions that could be complemented by the smart building system. For example, the human can touch the wall to tell the building where and how to increase the light of a room.

Finally, the model is a diagram to be used in design. We are demonstrating the whole range of human and building factors and their relationships in order to show all the options that designers can use for their designs. The model explains how humans could use the full range of their body capabilities for both, acting and sensing. Also, it shows how buildings could use any of their material elements, for both detecting and responding. Most of the current propositions have incorporated a limited set of human senses, mostly sight. They have also relied on an interaction mediated by smart devices (smartphones, wearables, touchscreens, IoTs). Through this model, we are proposing an unmediated way of achieving intelligent outcomes. Instead of using devices as a means of collaboration, the model shows how the actual buildings’ elements can become the interface between the human and the machine.
4. Tools

While the model provides the guidelines to direct the design process, the tools translate the model into materials, practical examples, and techniques to be applied in hands-on design practice. These tools include an electronic toolkit and a set of representational techniques. Using these tools, designers can learn electronics, prototype working demos, research supporting technologies for their designs, and represent their designs as systems and sequential moments of interaction and collaboration.

The Toolkit corresponds to a set of electronic components and supporting technical exercises. The primary objective of this toolkit is to provide a palette of materials to be used by designers developing smart buildings. Using this toolkit, designers can comprehend the basics of analog and digital electronics and can prototype and explore initial HBC propositions.

We selected sensors and effectors according to the HBC model, with sensors that could detect a wide range of human actions; and effectors that could be sensed by humans using all their senses. These sensors and effectors are connected and controlled using microcontrollers (Arduino) programmed using the personal computer. The sensors include capacitance (touch), knock, switch, pressure, sonar (distance), accelerometer (movement). The effectors include vibration motor, buzzer (speaker), DC and servo motors, and LED strips. This toolkit also includes a set of active materials that can be used as inputs or outputs. The input materials include graphite-based (resistive) materials, steel grids, magnets, and organic (capacitive) materials. The output materials include photochromic and thermochromic paint, fiber-optics, and transducers.

Finally, the toolkit introduces technical examples from next-generation interfaces, namely tangible interfaces, ambient media, and shape displays (Ishii 2008). These applications go beyond the current Graphic User Interface (GUI) paradigm, showing research and solutions in the field of material, physical, and spatial HCI. In our toolkit, we use these HCI applications as technical references and investigate how to expand them into architectural HBC solutions.

Figure 3. Information Architecture Diagram (Left) and Communication Map (Right).
The Representational Techniques constitute the medium for designers to represent, think, and develop their HBC designs visually. We adapted techniques from computer science and user-experience design (UX) and combined them with architectural 2D and 3D modeling and rendering. Our representational techniques include information architecture (IA) diagrams, communication maps, and experience-based storyboards.

The information architecture diagrams (Fig.3, Left) are network-graphs showing the different computational components, their relationship, and the flow of digital information. This visualization tool helps designers address complex computational systems, by focusing on the interactive components (inputs and outputs) and the role they play within the whole infrastructure. On the other hand, the communication maps (Fig.3, Right) are table-charts that describe the rules for interaction, connecting inputs and outputs. Using this tool, designers specify a *language*, i.e. a set of rules for explicit communication between the human and the building. This language helps designers map out the different human actions and how they trigger particular building responses, and vice-versa.

![Figure 4. Experience-based Storyboards.](image)

Finally, the experience-based storyboards (Fig.4) are 3D visualizations expressing the sequential experiential moments of a user interacting with a smart system. Each moment, or frame, can illustrate how the human collaborates with the building by acting on the building and sensing its response. Since the collaboration takes place in time and space, this visualization aids designers to explore how the sequence of human actions and building responses relate and unfold from moment to moment (Rosenberg 2015).

5. Design Application

We have conducted preliminary design exercises to put our framework into practice. Students were introduced to the model, background, and tools through a design process in an architectural studio environment at CASE. As in any design studio, we also facilitated their process and helped them explore specific HBC opportunities. We present the result of two projects, were students investigated different collaboration modes through tangible and spatial ways for people and building to interact with one another.

The First Project explores a cooperative way to optimize interior lighting. In this case, the collaboration is initiated by the human. The user tells the building *where* and *how* to adjust the light of the space. The AI senses interior and exterior light and combines natural and artificial light to reach the user goal. For the
mechanical output, the students used an adaptive facade system already developed at CASE (Krietemeyer et al. 2015).

This interface is comprised of a set of magnetic tokens attached to the building’s surfaces or walls (Fig.5). The tokens are magnetic yet passive devices that do not need power, all sensors and computing capabilities are embedded in the building’s surfaces (walls). There are multiple tokens in the space, which are tracked by the building in real-time. The users can place, move, and rotate these tokens to delimit specific areas for which they define their desired lighting conditions. By moving the tokens from left to right, the user can define the temperature of the light. By rotating the tokens the user can define the intensity of the light. While the user places and moves the tokens, the building computes interior and exterior light and adapts facade and lighting in response.

In this project, the human intelligence is about deciding lighting location (where) and lighting qualities (how). The artificial intelligence is about optimizing interior and exterior light, providing the required qualities for the specified locations. By optimizing energy, the building does not provide a predictable lighting result but suggests an approximation. The user can modify the tokens until a satisfactory result is produced. The building learns from the user actions, the user learns from the building responses. The lighting solution is co-created between the human and the building.

Figure 5. Tangible Walls for Lighting Co-optimization.

The Second Project explores a cooperative way to capture, purify, and reuse rainwater. In this case, the collaboration is initiated by the building. The building filters rainwater using green algae and then displays information inviting people to release this water for irrigation (Fig.6).

This interface is composed of a shape display facade connecting the roof of the building to a garden on the street level. On the roof, a pool collects rainwater and uses algae as a renewable purification method. Between roof and garden, the facade, made of transparent pipes, brings the water to the street level while displaying patterns and messages using digitally-controlled air bubbles. Through these messages, the smart building informs people about the state of purification and invites them to participate when the water is ready to use.

The facade then becomes a tangible interface that people can touch directly to activate the irrigation system. Using the water as a capacitive sensor, these pipes can sense human touch and can open and close to release filtered water in response. The channels between the tiles in the pavement system connect the water coming from the pipes to specific areas and plants in the garden.
In this project, the artificial intelligence is about cleaning the water and then communicating when the water is ready to use. The human intelligence is about deciding when and where to irrigate the garden. The user chooses a specific area for irrigation by touching the pipes that would direct the flow towards that selected area. After the user releases the pipes, the building suggests other areas for irrigation by opening untouched pipes. The user can accept or reject. A playful communication emerges between the user and the building. Ultimately, human and building have cleaned the water and irrigated the garden, together.

6. Conclusions

This paper introduced a new pedagogical framework for smart building design. The objective is to contribute to smart buildings development by expanding and diversifying the way humans and buildings have to interact and collaborate with one another. We have presented the framework’s philosophy, model, and tools, and we have tested this framework through preliminary design exercises.

We have found that the framework helped students to envision and prototype smart building systems with interfaces that incorporate new means for human-building collaboration. They developed building systems that detect various types of human actions (walk, move, tap) and that respond through multiple sensory channels (see, hear, touch). These interfaces were embedded within the actual buildings' material elements, including walls, floors, facades, and ceilings/roofs. They applied these diverse interaction modes to foster collaborative intelligence, in which building and human worked together to (1) optimize lighting and (2) purify and reuse rainwater. Therefore, we conclude that through these projects, we are demonstrating how our framework can begin contributing to the development of next-generation smart buildings.

Regarding next steps, we have observed how these design applications defined different functionalities for human-building collaboration. For example, the functionality of the first project was optimizing environmental conditions and the second resource reuse. More functionalities could be explored and generalized...
to help guide the HBC design process. Future research will also incorporate AI software into our pedagogical framework. Particularly, we will integrate machine learning algorithms as a means for the building to gain intelligence, as well as to grow and evolve the collaboration between the building and the human over time. Finally, some additional work will explore the boundaries between HCI and Architecture. Through HBC, we will explore and propose the appropriate scale, materiality, functionality, and interaction modalities for a spatial and material HCI integrated into architecture. Our goal is to identify modes of thought and practice that enable effective collaborative intelligence within our built environment.

Acknowledgments
This research was supported by Rensselaer Polytechnic Institute (RPI) and the Center for Architecture Science and Ecology (CASE). We acknowledge and thank the work of our students. The first project was developed by Daniel Polgreen, Mikaela Naval, and William Zaleskiewicz. The second project was developed by David Kitchen, Richard Markgraf, and Qinglan Luo.

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