ABSTRACT

This paper outlines an approach to adaptive residential design explored through recent research and an executed prototype, the North House project (2007-2009), undertaken through an interdisciplinary collaboration of researchers and students from the University of Waterloo, Ryerson University and Simon Fraser University in concert with professional and industry partners. This project aimed to develop a framework for the delivery of adaptive detached residential buildings capable of net-zero energy performance in the temperate climate zone, or the near north. Within this project, the term “adaptive” is developed across several tracts of conceptualization and execution including site and climatically derived models for building material composition and envelope ratios, environmentally-responsive kinetic envelope components, intelligent HVAC controls and interactive interface design aimed at producing co-evolutionary behaviors between building systems and inhabitants.

A provisional definition of adaptive architecture is outlined to address this range of considerations that calls into question the stable image of domestic architecture and its relationship to energy and contemporary assumptions regarding sustainable design. This paper also outlines computational approaches to design optimization, distributed building systems integration and the human-controls interfaces applicable to the home’s ecology of physical and information technologies.
1 INTRODUCTION: ARCHITECTURE AS AN ADAPTIVE PLATFORM

The etymology of the term “adapt” is a combination of the Latin ad-, meaning toward, and aptus, meaning fit: toward a fit, for a specific purpose or goal (Gould and Vrba 1982, 5). To discuss an adaptive architecture, then we might first start with some simple questions that are necessary to refine the nature of the problem: adaptive to what? adaptive through what? adaptive with what or by what means? To address the question to what? some obvious starting points include an architecture that could be adaptive to site conditions, adaptive to a specific climate or environmental condition and adaptive to the comfort and/or needs of its inhabitants. One could also consider an architecture that is adaptive to changing program requirements, expansion, manufacturing and construction techniques, energy and resource supply or singular events such as disaster. In most cases, buildings will need to be adaptive to multiple factors, some of which (such as climate or inhabitants) might vary over time, and might also be in conflict or constitute competing demands (such as energy supply and inhabitant lifestyle). To address the question through what? a designer would want to specify how adaptation will occur. This could be through a building’s morphology, its physical infrastructure (that is, structure, envelope, and spatial divisions), communications systems, the agency of its inhabitants or the methods of manufacture and delivery. Finally, to address the question with what, or by what means? a designer might turn to a number of design strategies, techniques and technologies such as flexibility, modularity, redundancy, intelligence, kinetics, material behavior and characteristics or communications technology among others. Doing the algebra of the possible combinations of the aforementioned conditions, we quickly realize the complexity of the question of adaptability, as well as the many permutations of what constitutes an adaptive building.

This paper outlines a recently completed research project that sought to develop a model for adaptive architecture realized as an 800 square foot proof of concept prototype, facilitated through its participation as one of twenty finalists in the U.S. Department of Energy’s 2009 Solar Decathlon competition. A model for the design of an adaptive architecture was mobilized to develop a vision for a contemporary factory-built high-performance home designed specifically for northern climates; one that could annually produce 800 square foot proof of concept prototype, facilitated through its delivery. Finally, to address the question with what, or by what means? a designer might turn to a number of design strategies, techniques and technologies such as flexibility, modularity, redundancy, intelligence, kinetics, material behavior and characteristics or communications technology among others. Doing the algebra of the possible combinations of the aforementioned conditions, we quickly realize the complexity of the question of adaptability, as well as the many permutations of what constitutes an adaptive building.

From the outset, the team agreed that the overarching goals of the project, especially its goal to reduce overall energy and resource demand while in use, would be met by developing an architectural approach that would be simultaneously adaptive to site and locational conditions, environmental resources and extreme climate variability. This approach would be pursued through the adaptive performance of the home via advanced building technologies, new materials, distributed systems and responsive technologies with particular focus on the complex interface with inhabitants. In this way, the North House prototype would not only become a platform through which to experiment with new architectural systems but could also serve as a model for the emergent interaction and feedbacks between these systems. Given the short timeframe between design and the required demonstration of a fully operable and inhabitable prototype, off-the-shelf and customizable technologies were necessarily prioritized. However, it is the conceptual design approach and the ways in which these systems are integrated that we consider being of specific interest to a discussion of adaptive architecture.

This paper is organized according to the three areas of adaptation that the North House addresses—site/situation, climate/environment and human—with each section describing the strategies, simulation techniques, constructed outcomes and performance results of the prototype.

2 SITE ADAPTATION: BUILT FORM AND ENVELOPE MATERIAL RATIOS

Within dominant paradigms of low energy demand design for specific climates, there is a commonly held assumption that buildings for northern climates need to be thick-walled, small-windowed and isolated from the exterior in order to maintain consistent interior comfort conditions. We maintain that this perspective does not acknowledge several important factors. One factor is the broad range of climate variability typical of near-northern climates (that is, the northern portion of the temporal zone). This zone is characterized not only by cold winters (up to -30°C) with low sun angles and short hours of daylight, but also by hot (up to +30°C) and humid summers with high sun angles and long hours of daylight, as well as highly variable shoulder seasons in which both extreme conditions often arise within short timeframes. It is often very difficult to manage these extremes with passive solutions alone. Another factor is the importance of available natural daylight and exterior views on human physical and psychological health, which is increasingly supported by diverse research (Frumkin 2008; Edwards and Torcelli 2002). In near-northern regions where daylight hours are significantly reduced in winter and people spend more time indoors during winter months, these health and psychological benefits are all the more critical. Hence, the team opted for attempting to maximize the amount of glazing on the exterior envelope for the benefits of inhabitant health and
connection to the outdoor environment, proposing the hypothesis that with high enough insulative values and specific exposure ratios, glazed envelope surfaces could become an overall energy source, as opposed to a deficit, via passive performance.

The work of assessing envelope fitness involved evaluating in concert a range of simultaneous optimization regimes, and was predicated on an examination of multiple combinations of opaque and transparent assemblies factoring high thermal resistance values for both. Opaque assemblies with South, East and West exposures would be utilized for energy generation via BAPV (Building Applied Photovoltaic) and BIPV (Building Integrated Photovoltaic) systems. Also, active shading would be combined with transparent areas to optimize passive heat gain so that demand for heating could be achieved passively while defending against extensive heat gain in warmer periods (Lomanowski 2008, 3-5). Within the constraints and context of the Solar Decathlon, configurations prioritized a single volume within the height limitations defined by the competition rules. The general project siting considered was the region north of Toronto, Ontario in terms of historic climatic data and solar exposure resource days. While not absolute, these characteristics are portable to a range of locations within the temperate climate zone.

Built form and glazing ratios were evaluated computationally using a modified ESPr (Environmental Systems Performance research) model with a Sensible Heating Load of 1572 kWh/yr, a Sensible Cooling Load of 1838 kWh/yr, a Total Space Conditioning Load of 3410 kWh/yr predicted on a Total Load per unit area of 55 kWh/m². These studies were also based on the assumption that the glazed area must be insulated to a minimum value of R6 (U-value<0.99W/m²K) and admit solar gain at a minimum Solar Heat Gain Coefficient (SHGC) of 0.4. Though not required for heating or cooling, a Visible Transmittance (VT) of >0.4 was also set as a target for providing high quality day-lighting. These studies delivered
an early schematic model for the prototype. The schematic of the house consisted of a highly insulated opaque assembly (R65–R72) and a 75 per cent glazed vertical envelope that combines high-performance glazing technologies with active exterior shading for variable heating and cooling load management (Lee et al. 2010, 3).

The final configuration of the North House prototype consisted of an 800 square foot volume comprising a highly insulated core service module along the north side of the house, opening up to a large flexible south-facing living space bounded by the high-performance DReSS envelope system (described in the following section) (Figure 2).

3 CLIMATE ADAPTATION: DRESS AND CHAS

In order to manage to the broad spectrum of seasonal climate extremes characteristic of near-northern regions while minimizing energy usage and maintaining interior comfort, the envelope is composed of a system of performative and interdependent layers that serve individual as well as cumulative environmental functions and modify themselves in response to climatic conditions (Thün and Velikov 2012, 267). Variable climate adaptation is achieved through a combination of passive and active building envelope technologies that communicate with each other, and are controlled by an integrated informational system. This system optimizes overall energy usage, prioritizing low-energy physical adjustments of the exterior shading over use of mechanical equipment. The whole building is self-powered through an 8.3 kWp BAPV array mounted on the roof of the building and a 5.3 kWp BIPV rainscreen on the south, east and west façades. The vertically mounted BIPVs capture low-incidence solar energy typical of winter months, early mornings and late afternoons (Figure 3). The entire system was modeled to annually produce as much as twice the amount of electricity used. Additionally, a 4kWp solar thermal evacuated tube collector array is located on the roof for domestic hot water and supplementary space heating and cooling via heat pump. Excess electricity is fed back into the grid, rendering the house a net energy producer and further reducing the overall space-conditioning loads (Figure 6).

3.1 DRESS

The Distributed Responsive System of Skins (DReSS) actively manages passive solar gain through the glazed envelope by combining a dynamically controlled exterior shading with a highly insulated window system and phase change material embedded in the floor (Thün and Velikov 2012, 269-70) (Figure 4). Based on the energy model developed by the team, dynamic shading has the ability to reduce almost 46 per cent of the cooling load for the home while enabling passive heat gain on demand (Figure 5). Phase change material (a salt hydrate solution contained in 15 millimeter thick polypropylene panels and engineered to melt at 76°F and solidify at 72°F) chemically performs as thermal mass, providing thermal energy storage extending periods of passive conditioning diurnally and further reducing the overall space-conditioning loads (Figure 6).

For the exterior dynamic shading, a proprietary system of motorized venetian blind-style exterior shades was selected as it offered the ability for the shades to be rotated almost 180 degrees. This range allowed them to be dynamically positioned relative to any angle of the sun’s rays, optimizing solar control. Another benefit is that this shading system is capable of full retraction, allowing for unobstructed views when shading is not necessary—a characteristic that was desirable for a residence and is not present in many kinetic shading façade systems. A fine-grained, tunable control logic allows the dynamic shades to respond to environmental conditions such as location, direction and intensity of solar irradiation; exterior and interior temperature and humidity; wind velocity; and time of day to manage solar gain. Preset modes can be set and also overridden by the inhabitants (Figure 7). The proprietary motors were customized by the team to enable individual rotational control of an upper clerestory zone of the shade that would allow for daylight to penetrate deep into the space, while the lower portion of the shades were either in solar block or privacy mode. Roof-mounted daylight and wind sensors provided primary data measuring the availability of solar radiation, and the blinds were programmed to retract below 100 lux and at wind speeds of over 12 meters per second.

Given that summer cooling is largely managed by the exterior shades, the glazing system was designed to provide maximum thermal resistance combined with optimized passive solar heat gain during the winter. The design team used THERM software to model over thirty-five combinations of glazing with different types and thicknesses of glass, films, coatings and configurations ranging from double-glazed to quintuple-glazed, and combined in single- or double-skin façade systems with varying cavity offset depths to assess insulated glazing unit (IGU) design. The Lawrence Berkeley National Lab’s WINDOW5 and the University of Waterloo’s VISION4 modeling programs were used to analyze the spectral properties, thermal resistance and
surface temperatures (Lee et al. 2010, 5). Quad-glazed, double skin and Vacuum Insulated Glazing models were each investigated extensively and considered according to their ability to be integrated with frames and operators, product availability, as well as considerations related to constructability.

The chosen IGU was a quad-glazed krypton-filled unit comprised of two 6.5 millimeter sheets of clear, low-iron glass sandwiching two sheets of Heat Mirror 88 (HM-88) mylar films. Low emissivity (low-E) coatings were placed on glazing surfaces 3, 5 and 7 with selective transmittance values engineered to maintain a moderate SHGC across the four-layered assembly (Lee et al. 2010, 5). The overall design of the uninterrupted floor-to-ceiling glazing units minimized the locations of mullions and edge conditions, reducing the ratio of center of glass to frame and resulting in an overall performance of R8 (U-value of 0.71 W/m²K) across the whole assembly. The performance of the IGUs was further enhanced by the design of a custom wood frame curtain wall system and a proprietary low-conductance material for all perimeter spacer locations, reducing thermal bridging at the IGU edge. The optimization of this system was iteratively explored by comparing simulation results of multiple assembly models (Figure 8).

During the test conditions of the Solar Decathlon competition, North House generated more electricity from the photovoltaic array than it consumed. It consistently maintained interior conditions within the comfort zone while exterior temperatures and humidity varied greatly in the October weather (Saeid et al. 2010, 5-6). However, it must also be noted that the unique use requirements of the Solar Decathlon do not map on typical home use patterns, rendering the verification of the simulated performance inconclusive. A comprehensive program of occupancy testing is expected to commence in late 2013.
3.2 CHAS

In order to manage the building’s high degree of adaptability to climate and energy balance, a customized Central Home Automation Server (CHAS) was developed through collaboration with students and faculty from the University of Waterloo and the Simon Fraser University School of Interactive Arts and Technology, along with with industry partner Vertech Solutions. CHAS is a computerized controls architecture, developed primarily from commercially available off-the-shelf products, and designed to manage all of the home’s systems and subsystems while also making high-level decisions that enhance energy performance (Figure 9). Specifically for the North House, Vertech Solutions designed the VerHub™, which uses the mControl™ home automation system as a foundation. This technology had the ability to interface with a wide array of components and also featured the Simple Object Access Protocol (SOAP) interface (Bartram et al. 2011, 55). The controls and logic system was designed to continually optimize available energy flows. For example, CHAS determines the operation of the external shading system as a function of the internal and external air temperatures, the amount of available solar irradiation, exterior wind speeds and the detected position of the sun. Based on sensor readings, the system determines if the house should go into solar heat harvest mode to save on heating energy or solar heat rejection mode to save on cooling energy (Barhydt 2010, 108). Similarly, CHAS controls the HVAC system in conjunction with the operation of the exterior shades to ensure thermal comfort while maximizing energy efficiency.

During most of the year, the house’s heating and cooling needs are met by the combination of the dynamic exterior shades coupled with the passive performance of the building envelope assembly. As this is the most energy-efficient model of thermal management, it is privileged by CHAS, which attempts to manage the interior climate via minute adjustments of the shades and reserves the HVAC system as backup. This model offers significant savings in operational energy as well as capital costs, since, as a result, the majority of the HVAC equipment could be significantly downsized (and had to be custom-designed as no units so small could be found commercially). Collaborating with industry partners, the team also developed a customized solar domestic hot water and HVAC system comprised of a three-tank solar thermal system combined with two variable-capacity heat pumps (Saeid et al. 2010, 4) (Figure 10). It is estimated that this unique system will provide, on average, 65 per cent of the required hot water for space heating, cooling and domestic uses with collected solar thermal energy alone. In total, CHAS interfaces with and coordinates seven systems, including the HVAC, domestic hot water, exterior shades, interior blinds, lighting, bed retraction, energy monitoring and the Adaptive Living Interface System (ALIS) interface.

Continuous real-time data is provided to the CHAS system through embedded interior and exterior sensors, as well as a rooftop weather station. A hysteresis control algorithm allows CHAS to make intelligent decisions based on real-time inputs and previous system states, ensuring smooth transitions between states and avoiding frequent “chattering” between different settings. In the following table that describes the logics for the external shade controls, Ts is the thermostat setpoint, Ti is internal temperature, X is internal temperature hysteresis, Z is solar radiation hysteresis, W is wind speed hysteresis and H is humidity hysteresis (Figure 11). While the hysteresis control algorithm was based on design logics prioritizing energy performance, system logistics were predetermined relative to a range of anticipated scenarios. A future development of the system would include the capacity for CHAS to evaluate various response scenarios relative to both historic performance data and user preferences over time (Thün and Velkov 2012, 108).
276-7). Such an application of machine learning would refine initial
design assumptions in terms of responsive automation interactions
and take advantage of recurring demand requirements and patterns
in establishing evolving operational protocols.

4 HUMAN ADAPTATION: ALIS

An adaptive building is often required to develop “fitness” toward
multiple and sometimes conflicting objectives. The lifestyles of
building inhabitants and their desired uses of the home are a case
in point. Inhabitant desires and behaviors, and their resulting use of
buildings, are often found to be in conflict with energy optimization
regimes for high-performance systems. In the residential sector, dif-
ferences in individual behavior have been shown to produce large
variations in energy consumption—in some cases as much as 300
per cent—even while controlling for differences in housing type,
efficiency, HVAC system composition and family size (Janda 2009,
10; Socolow 1978). Energy and resource consumption in buildings
and associated infrastructure encompasses social, political and
personal dimensions that are as critical to achieving performance
transformations as technical innovations (Cole et al. 2010, 342; Janda
2009, 9; Stern and Aronson 1984, 2-13). A fundamental concern in the
design of North House was that of developing ways in which these
questions could be addressed through design. A primary hypothe-
sis was that one way to achieve this development could be through
the design of information and feedback systems conceived of as
part of the architecture of the home. A key ambition in the human
interface development was to produce a context in which co-evo-

dutionary learning could take place, supporting the adaptation of
inhabitant behaviors toward energy-efficient and informed choices.
The Adaptive Living Interface System (ALIS) is an integrated in-
formation, control and interface system that provides inhabitants
with simple intuitive controls and monitors. It provides meaning-

Overview control architecture of CHAS, ALIS, and their integration with DReSS and mechanical sub-systems

Solar assisted heat pump system: cooling/ dhw mode (left), heating/ dhw mode (right)
ful feedback on the impacts of their behavior, and also provides them with social motivation tools to foster sustainable patterns of living. Led by the faculty and student researchers at Simon Fraser University, the suite of technologies that constitute ALIS includes an extensive monitoring and data-logging system, three different types of feedback mechanisms (integrated within the home and accessible through the Internet and smartphone applications) and a social network connecting the theoretical community of ALIS users (Velikov et al. 2013, 180) (Figure 12). The monitoring system collects data on energy consumption by use, energy production, hot and total water consumption, hot water production as well as interior and exterior environmental conditions. This information is accessible to inhabitants via a web application that allows them to view data in many different combinations, and at different time-scales in breakdowns related to household activities and weather patterns (Velikov et al. 2013, 181; Bartram et al. 2010, 9-10). This system is intended to both educate and support evolving patterns of sustainable human behavior: it allows inhabitants to adapt the home to their needs and preferences, while like many interactive systems, also fosters transformative behavior through information and engagement. It thereby allows the possibility for inhabitants to adapt their own lifestyles and expectations toward more energy- and resource-conserving practices.

Feedback on energy usage is a key aspect of ALIS. Studies have shown that performance feedback can have a positive impact on improving energy use behavior and that inhabitants often express a desire for more advanced building performance data (Woodruff et al. 2008 316-7; Darby 2006, 7). However, the effectiveness of feedback toward transforming inhabitant behavior depends on multiple factors including its context and quality, legibility, frequency of delivery, synergies with other factors, such as goal setting or advice, and the complex motivations and backgrounds of specific inhabitants (Bartram et al. 2011, 55-6; Darby 2006; Chetty et al. 2008, 245-

![Logic diagram for external shade and HVAC state control](image1)

![ALIS components: an integrated suite of building-integrated and mobile interfaces](image2)

8; Woodruff et al. 2008, 315). A variety of accessible setting, query and display modes allow for feedback to be easily comprehended by inhabitants and mapped on to daily patterns, while real-time warnings and alerts influence active modification of behavior by inhabitants. The “Community Network” platform recognizes the potential agency of online communities toward education and motivation for energy- and resource-use reduction (Mankoff et al. 2007), encouraging personal and familial goal setting, friendly competition, community information and resource sharing (Velikov et al. 2013, 186).

The ALIS interface components create an “information ecosystem” that is physically integrated with the architecture of the home, as well as being accessible via portable devices, where it can be ignored (Bartram et al. 2010, 8). Research indicates that for inhabitants to sustain energy-conscious practices, energy feedback infrastructure must integrate with their daily routines and rituals, as consumption patterns can easily revert once feedback...
is removed (Darby 2006). In this vein, the North House also served as a platform for experimentation with ambient and non-numerical informational systems. It addressed the possibility of designing technology and information that inhabits the periphery of human attention and that provides attunement to conditions without requiring attentive focus (Weiser and Brown 1996). The “Ambient Canvas” provides feedback through subtle visual cues on the balance of produced versus consumed energy, and how the inhabitant is progressing toward a self-specified goal. Constructed of LED rope lights and mounted behind the translucent surface of the kitchen backsplash, this surface located in a highly visible position within the home is controlled by resource-use inputs to glow with varying intensity across differentiated zones (Figure 13). This form of information delivery complements the didactic feedback received through the other system interfaces.

While several of the features of ALIS have, since the design of the system in 2008–2009, emerged within mainstream home and energy control products such as the NestTM, we believe that it is the entire system ecology, as well as its close coupling with the architecture of the home, that recommends ALIS as a model for consideration within responsive building design paradigms and the next generation of commercially-available systems.

5 CONCLUSION
As of the summer of 2013, North House has been reconstructed at the rare Charitable Research Reserve in Cambridge, Ontario. In its present location, it can be utilized as a living lab that can undergo long-term post-occupancy testing—a crucial next step in evaluating and refining its interrelated systems and technologies. The design of the project has been physically detailed to enable future research to be undertaken on the system as constructed, while allowing for component modification to occur as new and improved building component technologies become available. Of particular interest in this ongoing and future work is the assessment of the effect on overall performance produced by the combination of the adaptive building controls system (CHAS) with the adaptive human interface (ALIS). Additionally, it is of great interest to the researchers to test any behavioral transformations that are produced by the home and its systems. Designers are able to anticipate construction technology and control system performance through the utilization of simulation software and a range of quantified performance metrics drawn from built precedents in advance of project execution. However, the question of how humans interface with a new class of responsive envelopes and the reciprocal impacts on human behavior remains nearly impossible to evaluate through simulation. Post-occupancy evaluations of such systems will provide valuable insight into their efficacy, and will inform the ways in which such systems can be designed in the future—with a balanced prioritization of potential energy demand impact, and an anticipation of human engagement and adaptation in figuring response.

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