A Prototype Hut for the Post-Digital Age

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Abstract. The paper presents how the latest advances in autonomous building management and electrically activated materials affect the design, production, and operation of residential buildings. The innovative features of an elementary prototype house, which is at the final stage of construction in Trento, N. Italy, are discussed with a view to expose the opportunities and the problems that these new technological developments pose to design research.

Keywords. Electrically activated materials; model-based control; design; implementation; operation.

INTRODUCTION

In his influential work Essai sur l’ Architecture, Marc-Antoine Laugier describes an elementary edifice involving four living, still growing and rooted in place tree-trunks, with lintels composed of sawn logs and branches providing an elementary pitched roof (Herrmann, 1962). Laugier’s description was not depicting an actual house to live in, but a conceptual prototype of an elementary “living hut”. This conceptual prototype as it was carried forward to the modern times served to promote rationalism and simplicity in architecture. Today, for the first time, it is possible to conceive buildings whose aesthetic presence and performance can be sensibly readjusted in real time, based on the natural conditions and the preferences of the inhabitants. Hence, the possibility of a “living hut” becomes attainable. This possibility is being currently explored by researchers in complete absence of an architectural theory, adapted to the new circumstances, or a vocabulary for describing the produced effects and their consequences.
This paper examines how the advances in building management engineering and electrically activated materials, affect the design, implementation, and operation of residential buildings. The innovative features of an elementary prototype house, which is at the final stage of construction in Trento, N. Italy, are exposed. The features of the prototype, rest on the capacity to monitor and modify the state of key architectural elements of the house in real time. A network of sensors and actuators embedded within the physical architecture and driven by a model-based, distributed control, allows the automated, precise adjustment of these elements, which become responsive. This capacity revolutionizes architecture, where operable building components normally require actuation by users.

After a brief overview of background work, this presentation is divided into three parts, namely, design, implementation and operation. The first part is exposing how the performance and the technical characteristics of the innovations used in this project affected the design process. The second presents the process of implementation of the house systems. The third discusses the opportunities and problems that the new technological developments impose in changing the experience of the built environment. The presentation concludes with a summary of the contributions of this research.

BACKGROUND
Technological potential runs always ahead of its integration into physical architecture. Firstly because architects need to experience an innovation before extrapolate new uses for it. Secondly because compared to the range of the technological aids available the attitude of the construction and manufacturing sector tends to be conservative. And thirdly, because clients and users demand robustness and do not forgive if anything goes wrong, even if it is their imprudence that causes a device to malfunction or brake. Hence, there is normally a time-gap between technological innovation and the exploitation of its full potential into the built environment. This time-gap is usually occupied by prototypes, experimental structures, which are not considered actual buildings. The production of prototypes involves physical experimentation but also speculation and brainstorming, in which a whole new ecosystem of ideas is generated, making the eventual physical integration of a particular technology to become thinkable.

Earlier research in Computer Aided Design (CAD) focused on digital methods and tools of design production and fabrication (Lee 1999), leading architectural design towards previously un-thinkable modes of physical manifestation, but also often towards excessive levels of geometrical complexity (Allada 2001). The involvement of computation in these constructions is limited to digital generation and production of form, leaving aside how the various kinds of computational power, which can be delivered into the inhabited space, may affect the aesthetic, structural, and functional attributes of buildings. Today, prototypes of smart buildings begin to re-position the attributes of built environments in the late digital age, calling for an integrated, holistic approach of the involvement of computation in design. New design paradigms, encapsulate the lively interest of researchers in environmentally and socially responsible practices and account for the advances in programmable materials, autonomous computing, distributed sensing, and feedback infrastructure design. Like Laugier's "living hut", smart buildings have no need to adhere to geometrical complexity to claim architectural originality. The challenge is to improve experience, performance and the quality of the inhabited space, while promoting sustainable operation. In the connected sustainable home these objectives are achieved in three ways: a) by developing a simple physical architecture out of natural and programmable materials, b) by enabling autonomous management of energy resources that is robust to uncertainty and user comfort levels and c) by facilitating intuitive and practical interactions between buildings and their occupants. The prototype blends elegantly these features, into modular, transportable structure making a unique test-bed for exploring
the future and the management of media ecosystems at a residential scale.

Two relevant articles on building optimization methods and performance-driven design tools are Luebkeman and Shea (2005) and Shea, Aish and Gourtovaia (2005). Luebkeman and Shea (2005) show how navigating the performance space of a design solution promotes design thinking and present the relation between variations and performance. In Shea, Aish and Gourtovaia (2005) performance-driven generative methods are used to produce design concepts and solutions based on modeling of conditions and performance criteria.

Given that the electrochemical properties of programmable materials, like electrochromic glass, are not broadly known, a number of papers describing the state of the art in this particular research domain are referenced. Gugliermetti and Bisegna (2003) present a study on energy management with electrochromic technology. Hauser et al. (2003) present a technical comparison of data determining the physical features of electrochromic glass. Selkowitz et. al (2003) offer an overview on automated lighting and energy control systems.

The plan executive for the connected sustainable home Probabilistic Sulu (p-Sulu), is built upon the Iterative Risk Allocation (IRA) algorithm (Ono and Williams 2008) and a deterministic plan executive (Ono 2012). A novel technique, based on iterative risk allocation research extends IRA to deal with time-evolved goals while ensuring that the risk of failing to meet them is always kept within specified bounds (Grabill 2012).

Finally, Kotsopoulos et al. (2012a) present an innovative building approach for the envelope of the prototype as a modular, transportable structure of sustainable components. A shape grammar producing a language of possible patterns for the electrochromic façade of the prototype is presented in Kotsopoulos et al. (2012b).

**THE CONNECTED SUSTAINABLE HOME PROTOTYPE**

Connected sustainability aspires to a vision of autonomous building management, at a community and urban level. It is based on a concept of smart homes that co-operate to achieve sustainability in the spirit of the early farm communities. Distributed control systems, operating at each home, will be connected into a network constantly exchanging information to balance energy load and to assure efficient management of the available resources. A variety of renewable energy production and storage devices will be used, while symmetric connections will allow for energy sharing using dynamic pricing.

The connected sustainable home (Figure 2) supports precise adjustment of the building’s physical presence and operation, in sensitive response to evolving conditions and requirements. This becomes possible through the integration of five diverse systems: i) a high thermal mass envelope, ii) a high thermal mass base with heating and cooling capability, iii) a programmable south facing curtain-wall, iv) a renewable energy production system, and v) a high level control system, controlling all the above.
**Design**

The prototype connected sustainable home was conceived as a detached residential unit consisting of a loft space with an open-view glass wall facing south. Although there is a provision for the basic house utilities (living, sleeping, and eating) and a patio area adjacent to the south façade, the interior of the prototype was not deployed as an agglomeration of rooms, but as a free space, open in layout, and differentiated functionally by the built-in specialized furniture and equipment. The interior was left flexible to be reconfigured in alternate ways, as needed. For example, it becomes simple to convert the living room into a temporary bedroom for a visitor, or into a work space, through light screens, which will operate as room dividers that can be moved.

The overall design of the house is one whose final configuration was driven by the methods of environmental management. It should be emphasized that the interior of the house would have been uninhabitable (and therefore, non-architecture) without the contributions of environment-management technologies. The section and the plan of the house were adapted to the environmental systems. And since more than one system was deployed, the architecture of the envelope had to be adapted to accommodate the different systems. The material distribution of the house, gives tectonic expression to the various systems of environmental management. The prototype demonstrates the relevance of the overall design intend and of the architectural details to the functional and environmental systems. For example, the main reconfigurable, programmable component of the dynamic façade, oriented towards south, is placed back-to-back with a high thermal mass component that is oriented towards north.

Early typological studies were produced to map schematic building layouts and their ability to accommodate various energy production possibilities. Combinations of energy production systems such as solar panels, wind turbines etc., and building lay-
outs such as the single flank arrangement, or the enclosed atrium arrangement, were examined to see how particular geometries affect the performance of the energy systems (Figure 2). The selected layout for the prototype was the single flank, simple “bar” arrangement. Solar and wind powered schemes were developed in parallel, also integrating reconfigurable windows and high thermal mass elements, but when the compilation of weather data for the city of Trento, Italy, indicated that harvesting the wind would not yield adequate energy results the wind-powered scheme was aborted and a system of solar, micro combined heat and power (CHP) generator was developed instead.

Central to the design was the integration of a model-based, distributed control system. The algorithm of the system Probabilistic Sulu (p-Sulu), balances performance versus risk for continuous, stochastic systems. In the case of the prototype, performance is equivalent to energy efficiency and risk is equal to deviation from a user desired range of comfort. The controller was designed to allow the residents to specify desired ranges of room temperature as well as their time schedule and to execute plans with time-evolved goals. While guaranteeing that the goals are achieved, the controller minimizes the use of energy consumption from heating, cooling, lighting etc. The control system is fully integrated with the physical architecture through a network of sensors and actuators allowing the automated, precise adjustment of key architectural elements. Hence, the same tectonic elements can appear and be used variously, at different times, in response to the exterior conditions and the interior activities.

The prediction of the yearly house performance became increasingly important during the design process. Variables for humidity, illuminance, temperature and thermal comfort were identified and weather information was compiled, including statistical data, and data produced via simulation. The simplicity of the geometry permitted better control over the input and output data in calculations. A custom simulator computed the performance of the envelope while taking into account the changing

Figure 5
The consideration of the daylight, the orientation and the performance of the building materials informed the design.

Figure 6
The south, dynamic, façade was designed as an alternative to a traditional system of blinds, or shutters exploring a novel and unconventional fenestration practice. On the north, a high thermal mass component was designed to achieve high thermal resistance and low conductivity, to sustain heat during the winter and prevent from excessive heat during the summer.
states of the materials and the local weather conditions. The threefold design-simulation-evaluation was based on the parametric platform grasshopper3d. The consideration of the daylight, orientation and performance of the materials informed the design (Figure 5). Consecutive iterations explored the features of a well proportioned scheme involving passive and active systems aiming at protecting the house from the exterior environment and at preserving the in-house conditions with minimum energy cost. The south façade was envisioned as an alternative to a traditional system of blinds, or shutters, exploring the design of dynamic windows—an unconventional fenestration practice. The façade was designed as a matrix of independently operable windows. An overlay of two electronically switchable materials allows each window-pane to obtain variable degrees of opacity and chromatism. A result caused by these features is that various configurations for the south elevation became possible. On the north, a high thermal mass component was designed to achieve high thermal resistance and low conductivity, to sustain heat during the winter and prevent excessive heat during the summer (Figure 6).

**Implementation**

Typically, buildings combine conservative modes of environmental management that conserve thermal energy, selective modes of environmental management that selectively admit favorable exterior conditions to the interior, and regenerative systems that use electrical power to restore favorable conditions of lighting, heating or cooling. The connected sustainable home combines responsive, conservative, selective and productive modes of environmental management to minimize the use of regenerative systems.

The conservative component of the house is made out of wood, a renewable resource produced in Trentino, adding value to the local forest and boosting the economy. The building system of the house allows constructing dwellings in a controlled manner, in the factory fast and safe, like cars. These are constructed in modules, with all their technological systems in place, and then are transported for assembly. Each house module was developed as a structurally independent, self-standing box, open from south, west and east, and closed from north, top and bottom. Cross-laminated panels (X-Lam) panels of three different thicknesses 174 mm, 135 mm and 105 mm were used in the load-bearing parts of the floor, the north wall and the roof respectively. The panels were connected with metal angles, ringed annular-shacked nails and self-drilling screws. The thermal conservation and insulation features of the envelope were ensured by a multilayered system of natural materials. The interior side of walls was covered with a double layer of fiber gypsum panels, improving the acoustic insulation. An air gap between the fiber gypsum and the X-Lam panels improves insulation, and provides space for cables and air pipes. A double layer of fiber wood panels of different density was used for thermal and acoustic insulation. A breathable barrier film was applied next to protect from the external air and humidity, while it is permeable from the inside out. The complete north wall is 72 cm in thickness securing high-level heat transmission resistance. The exterior skin of the wall is covered with ventilated double
board warping and larch trapezoidal cladding. The roof has the same insulation package with the wall, while the roof cover was made of larch wood, similar to the external skin of the house.

The selective system of the house involves the south façade. A structural grid, made of galvanized steel, holds the Fiberglass window frames of the façade and completes the structural system of the prototype (Figure 7, center). Each windowpane is an overlay of two digitally controlled materials: the first, polymer dispersed liquid crystal (PDLC) layer adjusts visibility and secures privacy; the second, electrochromic layer, adjusts sunlight penetration and secures performance (Figure 7, right).

The energy production system servicing the prototype integrates different energy sources and conversion technologies (Figure 8). The system involves thermal energy storage, energy cogeneration from a pellet boiler and energy management for electricity, heat, cool and hot sanitary water delivered to the building. This distributed energy system is realized into five main components, two roof based and three allocated on a separate “energy box”: (1) a low temperature solar thermal system, (2) a photovoltaic system, (3) a solid thermal storage system (for summer cooling and middle seasons heating/cooling), (4) a liquid thermal storage (hot sanitary water), and (5) a pellet cogeneration boiler (for electrical power and thermal energy, complimentary with solar energy availability).

The solar driven, thermal energy storage system, developed by FBK-REET Laboratories, in Italy, is based on a double adsorption/desorption cycle, coupled with an evaporative cycle for the generation of the cooling effect. The pellet boiler is provided of thermal energy stored in microporous solid thermal storage material. The stored energy is converted into cooling or heating power. The storage material is regenerated by solar thermal collectors providing heating and cooling by adsorption cycle integrated with an evaporative system. The existing prototype provides a cooling capacity of 25-30 kWhth and a retrofittable cooling power of 2-5 kWth. The cold temperature is between 12÷16°C.

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Sampling rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor temperature / humidity</td>
<td>On the order of 15 min - 1 hr</td>
</tr>
<tr>
<td>Outdoor temperature</td>
<td>On the order of 1 hr</td>
</tr>
<tr>
<td>Motion</td>
<td>High; ˘1 min / On motion trigger</td>
</tr>
<tr>
<td>Airflow</td>
<td>High; ˘1 min</td>
</tr>
<tr>
<td>Illumination</td>
<td>High; ˘1 min</td>
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The COP is 0.7. The energy system is in open configuration with the indoor environment. To integrate the operation of all the house systems it is necessary to monitor the activities of the occupants and the states of the envelope, the energy production and the HVAC systems. A wireless network of sensors is integrated into the physical architecture for this purpose (Table 1). Sensors include standard electrical and HVAC measurement devices for monitoring equipment state, as well as motion sensors. As a whole, the sensor system collects data enabling the control to become increasingly responsive.

**Operation**

It is possible to infer that the free flowing interior, open plan space, the indoor and outdoor open areas and the wide curtain wall, all presuppose considerable expense of thermal power and air control for the environmental management of the prototype. In reality, the interior atmosphere of the prototype is optimally serviced by its multiple systems. The use of innovative environmental management and energy production methods is accompanied with delivery of new qualities and capabilities to the inhabited space. The responsive system proactively adjusts the interior environment of the house, to the weather conditions at minimum energy cost. The key to this new mode of environmental management is fine-tuning of the house systems.

The house systems operate in a concerted manner to attain complementary objectives. For example, the electrochromic properties of the south façade permit the regulation of the incoming natural light and heat by enabling the programming of the chromatism and transmittance value of each windowpane. The windowpanes are managed to exploit the thermal capacity of the building envelope. During the hot summer days, to protect the interior from direct sun exposure, the control sets the electrochromic material to its minimum solar transmittance. During the cold winter days, to expose the interior to the winter sun, the control sets the electrochromic material to its maximum solar transmittance, thus making the storage of solar heat possible. It is likely that, at any moment, there will be many possible façade configurations that will meet the requirements for energy-efficient behavior of the building envelope. This provides freedom to respond, in sensitive and delightful ways, to the needs of the inhabitants for various combinations of privacy, visibility, and views to the exterior, and for the control to incorporate these responses into its repertoire as necessary.

Further, each windowpane of the south façade can be opened and closed by precise amounts, through a system of electronic actuators, so that the pattern of permeability of the façade to air flow can be automatically and sensitively adjusted. Cross ventilation becomes possible when windows facing north and windows facing south are open simultaneously. The remaining feature of the façade concerns the regulation of visibility. Windows allow a gaze to pass through, thus negotiating different boundaries of inside and outside for different needs of privacy and display (Figure 9). They welcome the new morning, by signifying the waking up of the inhabitants and communicating their availability to the neighbors. Knowing that the residents prefer to
sleep until eleven o’clock on Sunday morning, the autonomous control system may adjust the windows to allow sunlight and fresh air to wake them up late in the morning.

DISCUSSION

This paper presented how the advances in building management engineering and electrically activated materials affect the design, implementation, and operation of residential buildings. The innovative features of an elementary prototype house, which is at the final stage of construction in Trento, N. Italy, were discussed. The features of the prototype, rest on the capacity to monitor and modify the state of key architectural elements, which become responsive. This capacity revolutionizes architecture, where operable building components normally require actuation by users.

Computed aided design, has often been identified with new expressive possibilities bursting through the conventionally conceived architectural forms. The involvement of computation in these constructions was limited to digital generation and production of form, leaving aside how the various kinds of computational power, which can be delivered into the inhabited space, may affect the aesthetic, structural, and functional attributes of buildings. The prototype connected sustainable home attempts to bridge innovation of structural form with that of creating a responsive human environment.

The design of the envelope both in detail and in mass, keeps pace with the transformation of the interior economy of the house environment. These impositions were turned into architectural purposes. Simulations played important role in the design, not only by providing quantitative data, which were used for material and geometry selection and distribution, but also by offering a platform for testing. Simulations obtained the importance of quick sketches that informed the design by checking if a conceptual idea was feasible before implementing it, and by providing a preliminary knowledge base related to the natural conditions and the architectural geometry. The implementation of the prototype introduces a consistent building philosophy, optimizes energy performance, automates climate control, and encourages ecologically responsible behavior. It is modular at every scale, allowing efficient assembly, disassembly, and transportability. The selection and distribution of materials is thorough, since it was the result of exhaustive analysis and evaluation. An optimal combination of conservative, selective, productive and responsive modes of management was applied. The problem of achieving robustness was important as optimization almost always pushes a system to its constraint boundaries. The autonomous control of the house solves this problem by taking a risk-sensitive optimization approach that optimizes performance within acceptable risk bounds. Improving the operation of the house involved devising an intuitive and efficient network of interactions between systems and inhabitants. The goal was to design an expressive building membrane that not only functions like an energy-efficient, climate moderator, but also can take active roles in shaping the behaviors of the residents. The intuitive communication with the house systems allows the inhabitants to specify efficiency goals, and the systems to communicate the plans for achieving the specified goals. Ultimate vision was to provide a responsive home environment that “gains knowledge” on usage patterns without requiring explicit manual input by the users. Until this vision can be realized, the objective is to permit users to command continuous, stochastic systems, in a manner that is both intuitive and safe.

The reprogramming of architectural elements opens broad avenues to renew design, while acknowledging not only the quest for functionality and performance, but also the social and aesthetic implications of architecture. For example, the programmable windows of the south façade, re-establish the attributes of traditional windows, in the late digital age. The alternating states of the programmable facade, range from moderation of view and air, to privacy control, personalized daylight, and ultimately to personal communication. Except from
its function as interior climate regulator, the facade becomes a responsive mediator between the private and the public domain. It is likely that in the future, the extensive use of interactive building components, will give rise to new conceptions of space, and eventually to “new architectures”, where inhabitants will become engaged in novel aesthetic social and intellectual experiences.

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REFERENCES


