Window Panes Become Smart

How responsive materials and intelligent control will revolutionize the architecture of buildings

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Abstract— **The use of electronically activated, variable transmission materials, and artificial intelligence control methods in buildings can enhance environmentally and socially sustainable behaviors. It is presented a smart façade, allowing automated control of temperature, daylight, view and privacy in the interior of a prototype house. The programmable materials of the façade allow the precise adjustment of solar transmittance and visibility, while an intelligent controller optimizes the house performance based on the conditions. Using constraint violations as a measure of success, the intelligent controller outperforms the deterministic control models.**

Keywords— ***Responsive materials; intelligent control; smart windows.***

I. INTRODUCTION

This paper acknowledges the potential of programmable materials and artificial intelligence (AI) methods to building control, in enhancing the quality of environmentally and socially sustainable living environments. Responsive, interactive skins can bridge the gap between the traditional modes of building and the recent developments in material science, artificial intelligence, and human-computer interaction. The merits from the adoption of technological innovation in buildings can be multifaceted. The ability to monitor and modify the attributes of architectural components can have far reaching implications in energy efficiency and in the ways we practice design. This paper addresses the designing of 'smart windows', where the traditional form and functionality of windows are revisited with a view to integrate the current advances in electrically activated materials research and control systems engineering.

A window is a transparent or translucent opening in a wall, or a door that allows the passage of light and, if not closed, air and sound. Windows are usually glazed or covered in some transparent or translucent material like float glass. They are held in place by frames, which prevent them from collapsing and they can be un-operable or operable. Operable windows may be actuated by the users, to allow ventilation, or they may remain closed, to exclude inclement weather. Windows play important role in the adjustment of the interior lighting and thermal conditions in buildings, and in the relationship between interior and exterior. They also obtain significant social, aesthetic and cultural associations. Primitive windows were simple holes on the wall. Gradually, windows were covered with animal hide, cloth, or wood, and shutters that could be opened or closed were soon added. Over time, materials such as small pieces of mullioned glass, paper, flattened pieces of translucent animal horn, or plates of thinly sliced marble have been used in window panes. Ordinary glass windows became common in homes in the early 17th century, while modern-style floor-to-ceiling windows became possible only after the industrial glass making process was perfected.

Today, responsive materials and intelligent control methods, promise to add new dynamics to windows, including the real time, adaptation of their aesthetic presence and their performance, based on given conditions. Smart windows aim to take active role in the dynamic optimization of building performance with low operational cost. For example, by actively controlling the state of electrochromic glass panes, the solar transmittance of windows becomes a programmable feature, by which it is possible to regulate the interior illuminance and temperature [1], [2]. The transitions of smart windows, optimally operated, can contribute to the reduction of energy consumption by heating and cooling [3]. Further, polymer dispersed liquid crystal films (PDLC) and suspended particle displays, can eliminate the need for traditional blinds and shutter systems and revolutionize building aesthetics. Optical dimming and density variation can replace mechanical actuation with solid-state shading, glare and view-control. Windows equipped with such capacities, can provide new ways to think about the management of energy, of daylight and of privacy, and can drastically transform the way we perceive and inhabit the built environment [4].

An example of the advantages in optimizing these technologies at residential scale is presented next. It is examined a building element of a prototype house –a façade involving a matrix of smart windows – and the adjustment of the lighting and thermal conditions at the house interior. The façade operates as a dynamic filter between exterior and interior. It filters solar radiation and heat by allowing the modification of the chromatism and light transmittance of each individual window. Varying the number and the distribution of the active windows on the façade permits the regulation of the incoming sunlight and heat, and affects the aesthetic presence and performance of the house. The apparatus of the example, yields optimum façade configurations through the efficient management of the electrochemical properties of the windows by an intelligent control system.

Figure 1. South elevation of the prototype house in Rovereto, Italy.

II. BACKGROUND

The connected sustainable home concept – a prototype of which is under construction in Rovereto, Italy (Figure 1) – is an exemplary building structure resulting from the integration of innovative physical and computing architecture. This prototype house constitutes a responsive environment, aiming at remaining well tuned to the comfort levels of the inhabitants, improving quality of life, and supporting socially sustainable living.

One of the most notable features of the house is its south façade. The windows of the façade incorporate electrochromic technology, which permits the regulation of the illuminance and temperature at the house interior through the modification of the chromatism of each individual windowpane. The smart windows are optimally managed by an intelligent control system, aiming to reduce the use of Heating, Ventilation and Air Conditioning system (HVAC) and artificial lighting, and to keep the overall energy consumption of the house minimal overtime. The intelligent control system of the house exploits the passive thermal capacity of the building envelope. During the hot summer days, keeping the interior temperature lower than the exterior becomes a high priority. To protect the interior from direct sun exposure, the control system sets the electrochromic material of the windows to its minimum solar transmittance. Conversely, during the cold winter days, taking advantage of the sun heat becomes a high priority. To expose the interior to the winter sun, the control system sets the electrochromic material to its maximum solar transmittance, thus permitting the storage of natural heat in the home’s building structure. Hence, sunlight, heat and shade are used to maintain comfortable interior conditions with minimum use of artificial heating, cooling and lighting.

The key to this approach is the fine management of the passive and active systems of the house. Natural conditions vary and so do the activities of the inhabitants. Programmable materials enabled by the intelligent control, contribute in securing proper living conditions, while keeping energy cost minimal. The residents are prompted to specify the preferred indoor temperature, humidity and illumination, or they can allow the system to take charge, yielding suitable conditions based on the weather. The intelligent control maintains the stability of the indoor environment, whenever the building is occupied. Of course, uncertainty in weather and occupancy patterns poses a risk of failure. The control system limits this risk by explicitly addressing uncertain factors.

After an overview of related background work, this presentation is divided into two main parts, namely, *responsive materials* and *intelligent control*. The first is exposing the performance and the technical characteristics of the responsive materials used in this project. The second is presenting the intelligent control system. More specifically, the setting of a performed simulation test is outlined and the comparison of the proposed controller with two other baseline models is discussed. This presentation concludes with a discussion summarizing the objectives and the contributions of this research.

III. RELATED WORK

Given that electrochromic technology is not broadly used, a number of papers describing the state of the art in this particular research domain are referenced. For example, [1] describes a study in which the effects of electrochromic technology are monitored in a cube 3.0 m x 3.0 m x 3.0 m; [2] presents a technical comparison of data determining the physical features of electrochromic glass; [3] offers an overview on automated lighting and energy control systems; finally, [4] reviews the historical basis of building compliance methods determining minimum energy efficiency and comfort standards, and proposes a new basis for more efficient metrics.

The application of AI methods to building control has been pursued by computational sustainability research. For example, [5] employs the stochastic model-predictive control (SMPC) approach to significantly reduce the energy consumption of a building with stochastic occupancy model. Further, [6] models end user energy consumption in residential and commercial buildings. Another relevant work is [7], which uses a robust plan executive for autonomous underwater vehicles. The proposed plan executive, p-Sulu, is built upon the Iterative Risk Allocation algorithm [8] and a deterministic plan executive, Sulu [9].

IV. RESPONSIVE MATERIALS

The smart façade of the prototype house is a matrix of programmable windows that are individually addressable. It was designed to achieve three performative objectives: (1) regulate the percentage of sun-heat that penetrates the house; (2) regulate the interior illuminance; and (3) regulate the airflow. Each window pane is an overlay of two electronically switchable materials. The first layer, the electrochromic glass, is applied on the external glazing to provide the desirable degree of sunlight penetration securing daylight and thermal performance. The second layer, the polymer dispersed liquid crystal film (PDLC), is applied on the internal glazing to provide the desirable degree of visibility, securing privacy (Figure 2).

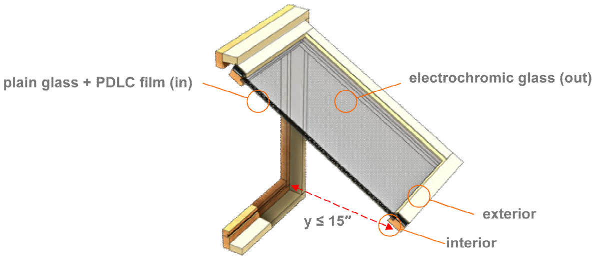


Figure 2. Axonometric section of the window. Each window pane is an overlay of two materials: electrochromic glass and PDLC film.

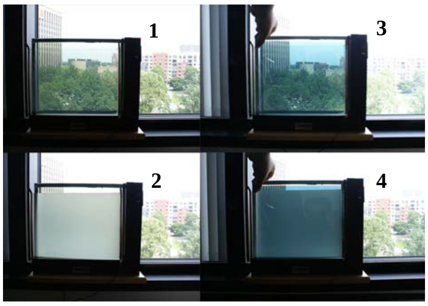


Figure 3. The overlay of materials: (1) the electrochromic and the PDLC layers are inactive; (2) the electrochromic layer is innactive and the PDLC layer is active; (3) the electrochromic layer is active and the PDLC layer is innactive; (4) the electrochromic and the PDLC layers are active.

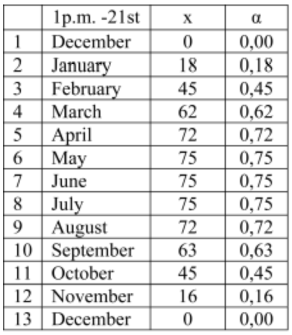
Smart windows operate in selective mode, admitting natural light, heat, and air, or excluding any of the above as needed. At the global level, the windows are directed by the central control system, without having any interference among them. At the local level, each window is driven by its own low level intelligence, software and custom electronics that enable the activation of its switchable materials. Each window pane is equipped with a photocell to calculate the amount of light that it is exposed to, while an IR sensor detects the presence of the residents. The windows provide this sensory feedback to the central control that compiles the information to activate any number of windows is required. Since the switchable materials have varying response times and exhibit different optical, thermal and power consumption characteristics, their activation processing is preplanned. The slow dimming response of 8 minutes, of the electrochromic glass, is suitable for controlling sunlight and heat, while the instant transition of the PDLC film is useful for controlling shade and privacy. The PDLC film can be switched to entirely block the view, or it can adjust the degree of its opacity based on the detection of specific patterns of user activity. For example, the PDLC film can be programmed to output a varying opacity, corresponding to the gesture of holding the hand in front of the photocell for a range of time durations.

The management of the façade is driven by the autonomous control system of the house. The electrochromic technology operates as an alternative to a traditional screening system [10]. Façade patterns can be enabled to adjust the transmittance value of window panes. The values of transmittance (τ) vary from 60-75%, for idle glass, to 3-8% for active obscured glass [2]. Extensive analysis and evaluation of simulation data allowed to discover how the activation of the electrochromic glass affects the levels of thermal comfort and interior daylight illuminance, on the specific building, at the specified site, throughout the year. The simulation software used in this analysis was Relux Professional by Relux Informatik AG. The climatic data used in the simulations was provided by the database of the software, which also integrates the lighting standards determined by Italian law. Relux Vision (a plug-in of Relux Professional) was used in the ray-tracing simulation. Typical outputs of each simulation test included: a) the min/max and average values of illuminance and b) the lighting uniformity values and average daylight factor.

Illuminance in daylight conditions is subject to constant change of intensity and distribution. Interior daylight is affected by the movement of the sun and of the clouds in the sky. The parameters determining the optimum daylight vary based on the daytime and month of the year. The existing simulation models for buildings provide a poor account of daylight modification [3]. These models identify and approximate uncomplicated settings, which do not reproduce the natural sunlight conditions. For our purpose, two models – established by the *Commission Internationale de l'Eclairage* (CIE) – were used in the analysis and evaluation of natural light. The first, is the Standard Overcast Sky model, which provides an account of the sunlight emitted through cloudy sky. The second is the Standard Clear Sky model, which computes sunlight under the assumption that the sun is the single lighting source, without calculating the diffused and reflected light by the sky. Although the two models offer an accurate account of the interior sunlight distribution in two distinct settings, they provide only a partial understanding of the phenomenon of daylight change. Because, they exclude the assessment of transitory conditions, such as the momentary passage of clouds across the sun [11].

Despite these limitations, the aim of calculating the optimum façade settings is within reach. Exhaustive simulation tests were performed and data corresponding to the daylight conditions for each day of the year, was collected, classified and used for the integration of an optimization algorithm into the control system. After setting a desired value of interior daylight illuminance in lux the simulation tests helped to identify the required numbers of active windows to reach this value for every day of the year. A predictive model associating coverage ratio and illuminance, in any specified time interval was extracted and integrated into the control system. Based on this model the number of active windows ensuring the illuminance threshold in overcast sky throughout the year, ranges from 50 to 75, in a total of 100.

The produced database was used as a foundation for optimizing sunlight and heat. The combination of this information with real time feedback from sensors enables the reprogramming of the façade, even in conditions that cannot be predicted by the static simulation model. The overall system achieves two complementary objectives: a) determines the optimum number of active electrochromic glass units to reach the desired interior temperature and illuminance level, and b) confines the current façade patterns to this threshold.



	1p.m. -21st	x	α
1	December	0	0,00
2	January	18	0,18
3	February	45	0,45
4	March	62	0,62
5	April	72	0,72
6	May	75	0,75
7	June	75	0,75
8	July	75	0,75
9	August	72	0,72
10	September	63	0,63
11	October	45	0,45
12	November	16	0,16
13	December	0	0,00

Table 1. Maximum numbers of active windows throughout the year at 1 p.m. in *Standard Overcast Sky* after simulation with Relux.

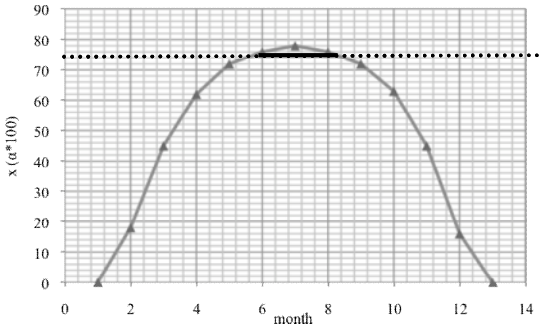


Figure 4. A model gives the maximum number of active windows yielding the threshold value during the whole year in Overcast Sky. In doted line is the 75 % limit.

The interior daylight simulations confirmed that the façade could switch from one pattern to another while maintaining the same activation ratio, in order to possibly satisfy other factors of performance. A generative grammar producing any class of patterns was then specified so that any desired level of interior daylight conditions could be reached. In [12] the simulation process of the electrochromic windows is described in detail and the generative grammar capturing the language of the optimum façade configurations for the prototype is presented.

V. INTELLIGENT CONTROL

The next sections describe the computational apparatus managing the states of the responsive materials and the temperature at the house interior. The windows are controlled in a concerted manner by the central control without having autonomous intelligence capability. The controller is implemented in C++. Uncertainty in outdoor temperature is taken into account. The hardware hosting the controller is a standard computer with 8GB of RAM and Intel Core i7 processor. A Mini-ITX system secures low energy profile. The controller also manages illumination and humidity. These extensions, which are included in the prototype, are not presented here. First, the three main control requirements enabling this overall achievement are outlined, and then, the proposed solution is exposed.

A. *Goal-directed planning with continuous effect*

The controller should allow residents to specify desired ranges of room temperature (i.e., state constraints in a continuous domain) as well as their schedule (i.e., temporal constraints). Concisely, the control must be able to execute plans with time-evolved goals, which are specified as a sequence of state and temporal constraints. Then, it must optimally adjust the operation of windows and the HVAC system, so that the specified constraints are satisfied.

B. *Optimal Planning*

While guaranteeing that the time evolved goals are achieved, the controller should also minimize the use of non-renewable energy consumption.

C. *Robust planning with risk bounds*

Optimal plan execution is susceptible to risk when uncertainty is introduced. The house, involves a risk of failure to maintain the room temperature within a specified range due to unexpected climate changes. In the winter, when the residents are absent, the energy consumption can be minimized by turning off the heating. But, this involves a risk that the pipes may freeze. Such risks must be limited to acceptable levels specified by the residents. The plan executive guarantees that the system is able to operate within these bounds. Such constraints are called chance constraints.

D. *Proposed Solution: p-Sulu*

The proposed solution [13] to overcome these challenges is a newly developed robust plan executive called p-Sulu. Previous research [14] presents the risk-sensitive finite-horizon planner, called p-Sulu planner, which has the three capabilities. However, p-Sulu planner is an off-line planner, meaning that it pre-plans the control sequence for the entire plan duration. The off-line planner could not possibly control the Sustainable Connected Home due to two technical challenges. First, the house must be operated continuously with no interruptions, while p-Sulu planner can plan only for a finite time duration. Second, building control requires frequent re-planning every few seconds, while p-Sulu planner's solution time is typically on the order of minutes. For example, a simple path planning problem with only 10 time steps takes about 30 seconds to solve [14]. Moreover, the computation time of p-Sulu planner varies widely from problem to problem.

To overcome the first challenge a receding horizon control approach was adopted. At each planning cycle, a planning problem is solved with a finite duration, which is called a horizon. In the next planning cycle, the planning problem is solved again over a horizon with the same duration starting from the current time (hence, the horizon is “receding”), by considering the latest observation of uncertain parameters. This re-planning process is repeated with a fixed time interval. The second challenge was faced by building upon an anytime algorithm for chance-constrained programming, called Iterative Risk Allocation (IRA) [8]. IRA was originally developed for path planning problems without time-evolved goals [8]. The proposed approach extends IRA to deal with time-evolved goals.

p-Sulu RH takes as an input a plan representation called a *chance-constrained qualitative state plan (CCQSP)*, which encodes both time-evolved goals and chance constraints [14]. The goal is to find a control sequence, which is an assignment to real-valued control variables, as well as a schedule, which is an assignment of discrete execution time to events.

An advantage of p-Sulu over existing deterministic plan executives is that it can explicitly consider a stochastic plan model, which specifies probabilistic state transitions in a continuous domain in the following form:

$$x_{t+1} = A_t xt + B_t u_t + w_t$$

where x_t is a continuous state vector at time t, u_t is a continuous control vector at t, and w_t is a disturbance whose probability distribution is known.

A chance-*constrained qualitative state plan* (*CCQSP*) is a four-tuple $P = \langle \mathcal{E}, \mathcal{A}, \mathcal{T}, \mathcal{C} \rangle$ where $\mathcal{E}$ is a set of discrete events, $\mathcal{A}$ is a set of *episodes*, $\mathcal{T}$ is a set of *temporal constraints*, and $\mathcal{C}$ is a set of *chance constraints*.

An example of a resident schedule for a day is presented in Figure 5 as a *chance constrained qualitative state plan* or *CCQSP*, while the state space of the same graph appears in Figure 6.

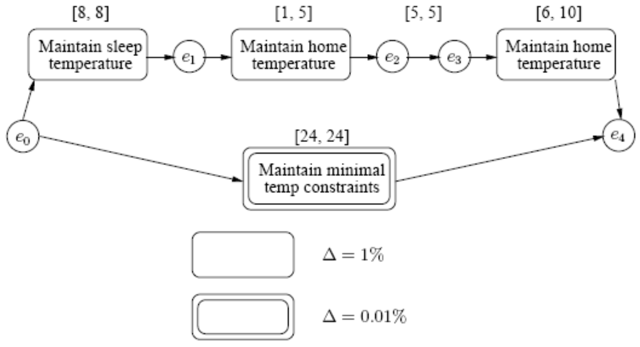


Figure 5. An acylic directed graph depicting the resident's schedule in the sample planning problem for the Connected Sustaianble Home

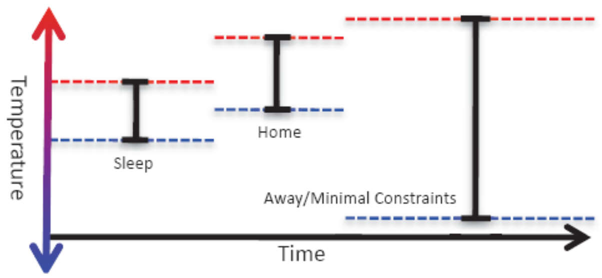


Figure 6. The state space of the previous graph based on the 3 specified ranges Home, Asleep, and Away.

The schedule is described first in plain English, as follows:

"Maintain a comfortable sleeping temperature until I wake up. Then, maintain room temperature until I go to work. I may work at home, but I have to do 5 hours of work at the office sometime between 9 am and 6 pm. No temperature constraints while I am away. When I get home, maintain room temperature until I go to sleep. The probability of failure of these episodes must be less than 1%. The entire time, make sure the house doesn't get so cold that the pipes freeze. Limit the probability of such a failure to 0.01%."

At any time, the schedule confines a temperature range to maintain over some duration. In the experiments, it was assumed that a resident can specify one of 3 ranges: Home, Asleep, and Away. In actuality, one is able to select any number of temperature ranges. It was assumed that the temperature must remain between 20° and 25° C while the resident was at Home, between 18° and 22° C while Asleep, and between 4° and 35° C while Away, to ensure that the pipes would not freeze. Home and Asleep episodes, were associated to a single chance constraint class, with risk bound 10 %. This is the risk the resident is willing to take that the temperature may become uncomfortable. Away episodes were associated to a single chance constraint class with risk bound 0.01 %. This is the acceptable risk by the resident that the pipes may freeze.

The above schedule was tested on a simulation setting [15]. Two baseline models were compared with the proposed controller p-Sulu: (a) a PID was used to illustrate the energy savings of a model-predictive controller compared to a traditional heating controller, and (b) Sulu, the deterministic predecessor to p-Sulu, was used to illustrate the robustness of p-Sulu. The initiating stage of the PID controller was 21° C. The planning was based on the resident schedule graph spanning a week. Then, uncertainty w_t is introduced and the plan is executed in a stochastic simulation. Each controller was evaluated on the basis of energy savings and percentage of executions that fail because of constraint violations.

The next figures illustrate the results of a stochastic simulation over two different days in the year, January 1 (Figure 7) and July 1 (Figure 8). It should be noticed that the deterministic predecessor Sulu of the newly proposed controller plans right up to the edge of the constraints, often violating constraints when uncertainty is introduced, while p-Sulu leaves a margin of the stochastic simulation.

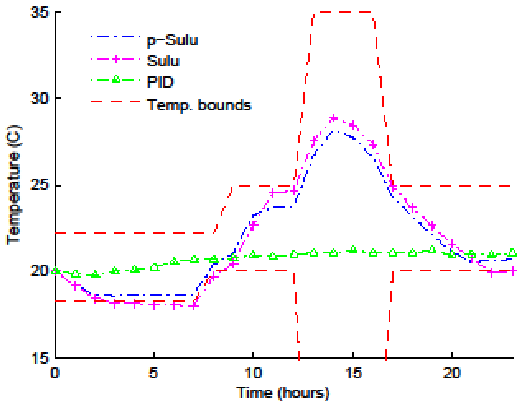


Figure 7. Results for PID, Sulu, and p-Sulu controllers on January 1. p-Sulu controller appears in blue line.

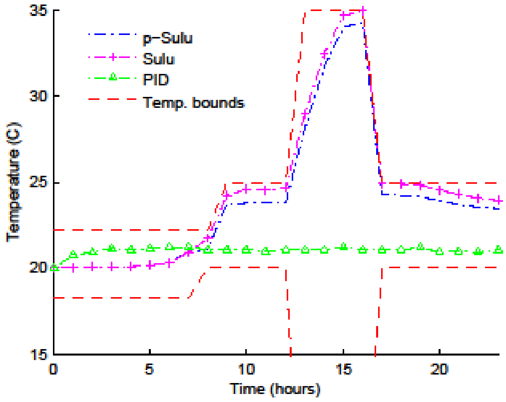
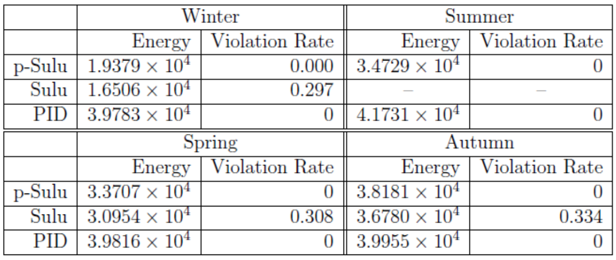


Figure 8. Results for PID, Sulu, and p-Sulu controllers on July 1. p-Sulu controller appears in blue line.



	Winter		Summer	
	Energy	Violation Rate	Energy	Violation Rate
p-Sulu	1.9379×10^4	0.000	3.4729×10^4	0
Sulu	1.6506×10^4	0.297	–	–
PID	3.9783×10^4	0	4.1731×10^4	0
	Spring		**Autumn**	
	Energy	Violation Rate	Energy	Violation Rate
p-Sulu	3.3707×10^4	0	3.8181×10^4	0
Sulu	3.0954×10^4	0.308	3.6780×10^4	0.334
PID	3.9816×10^4	0	3.9955×10^4	0

Table 2. Comparison of energy use and failure rate of the PID, Sulu, and p-Sulu controllers over a week-long schedule in all four seasons. Failure rate is measured as the percentage of time steps with constraint violations.

Table 2 presents the results on the weeklong scenario, averaged over 100 Monte Carlo trials each. Notice that the failure rate of p-Sulu is actually significantly lower than the risk bound. Out of the 200 trials of Sulu in the winter 159 failed to complete due to infeasibility. Of the 41 trials that completed, every single one had constraint violations on at least 31 of the 168 time steps of the plan. All trials of Sulu in the summer failed due to infeasibility.

Furthermore, the results illustrate that although the PID controller did not violate temperature constraints, the Sulu and p-Sulu performed drastically better in energy consumption. While p-Sulu sacrificed some energy savings compared to Sulu, these loses were met with drastic improvements in robustness.

As a measure of comfort, one may compare the trials that completed and consider the fraction of time steps on which a constraint was violated. Table 2 shows that out of the 168 time steps, Sulu violated constraints on 29.7% of time steps in the winter, 30.8% in the spring, and 33.4% in the autumn. Only a single trial of p-Sulu violated a single constraint in winter. All other seasons, all trials satisfied all temperature constraints. Using constraint violations as a measure of success, the approach of p-Sulu outperforms the deterministic approach of Sulu on every trial. Averaged across all trials, p-Sulu exhibits a difference of 30.88% in improvement in comfort over Sulu.

These results illustrate how critical risk-sensitive control is in guaranteeing resident comfort and encouraging the adoption of the technology. A control system that produces uncomfortable conditions 30% of the time would quickly be abandoned by the users.

VI. DISCUSSION

Programmable materials and AI methods to building control can be used to enhance sustainable living in buildings. This paper addresses the designing of smart windows at residential scale. The aim and functionality of windows are revisited with a view to integrate innovative building materials and control solutions.

The features of a programmable façade for a prototype house were discussed. These features, rest on the capacity to monitor and modify the state of each individual window in real time. Each windowpane is an overlay of two electronically switchable, variable transmission materials. The first, electrochromic layer, provides the desirable degree of sunlight penetration, securing sunlight and thermal performance. The second, polymer dispersed liquid crystal (PDLC) layer, provides the desirable degree of visibility, securing privacy. At the global level, the windows are directed by a central control system, without having interference among them. At the local level, each window is using low-level intelligence, software and custom electronics that enable the activation of its switchable materials.

An autonomous control system aiming at optimizing the long-term energy performance of the house enables the management of the programmable materials of the façade. The control compiles data related to the seasonal levels of light and heat, and real time feedback from sensors, to reprogram the state of the façade, in order to take advantage of the sun and to minimize energy use. Hence, the façade functions as a responsive component, admitting natural light, heat, and air, as needed. And further, the adjustments of the façade transform how the house is perceived from the public street.

Windows are typically operable building components that are crucial to the good thermal performance of buildings. Windows had evolved from holes covered with cloth, mullioned glass, or paper, to modern-style floor-to-ceiling curtain walls, sealed with industrial glass. Today, responsive materials and AI control methods promise to add new dynamics to the functionality and the aesthetics of windows.

The "smart window" offers a new basis to rethink the role of windows in buildings. It combines environmentally responsible design with inventive technology, and it points to new ways of improving the interaction among people. The reprogramming of a smart window enables autonomous, responsive and interactive behaviors, while taking into account not only functionality, but also social and cultural aspects. Smart windows re-establish some familiar attributes of traditional windows in the digital age.

For example, modern-style floor-to-ceiling glass curtain walls backed with constant artificial lighting, heating, ventilating and air-conditioning, were aiming to secure air-and-sound sealed interior environments. These conventions of performance no longer apply, since the use of artificial cooling and heating is energy intensive. At the social level, modern curtain walls were restraining human behavior by confining people strictly "inside" or "outside" of a building.

The flexible modes of use of the dynamic façade range from moderation of view and air for each window, to privacy control, personalized daylight or shade, and ultimately personal communication and self-expression. Except from its function as interior climate regulator, the façade operates as a responsive mediator between private and public domain.

It is likely that in the future, interactive building components, will give rise to new conceptions of space, and eventually to "new architectures", where people will become engaged with their environments in novel emotional, social and intellectual modes.

ACKNOWLEDGMENT

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Figure 9. Visualization of electrochromic patterns on the south façade of the prototype house, as percieved from the exterior and the interior.

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