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Machi Zawidzki

Discrete Optimization in Architecture

Building Envelope

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In memoriam Prof. Witold Kosiński

Preface

This book concerns itself with the building envelope (BE), which besides the size and proportions of a building is the most apparent aesthetic quality in architecture. The book is divided into three parts. Part I briefly introduces the concept of an Intelligent Building Envelope, while Part II presents the dynamic cellular automaton-based shading system (CASS) for BEs. The book also addresses the optimization of CASS with graph-theoretic and heuristic algorithms. The optimization criteria include the "grayness" monotonicity, and pattern distribution error, which respectively represent the level of control over the cellular automaton (CA) pattern, and the uniformity of the CA pattern over an entire array of cells. The robustness of CASS and various types of prototypes are also discussed. Part III presents an algorithm for creating selective static solar shading for free-form apertures of a free-form building.

This book presents results of the research titled: "*Effective computational methods for grid and raster-based modeling of practical problems in architectural and urban design*" conducted from December 2013 to November 2015 under the Singapore University of Technology & Design and Massachusetts Institute of Technology Postdoctoral Program.

Warsaw, Poland
July 2016

Machi Zawidzki

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Acronyms

AD	Average Density
BA	Backtracking Algorithm
BC	Boundary Conditions
BE	Building Envelope
BIM	Building Information Modeling
CA	Cellular Automaton
CA_{SH}	General two-color one-dimension radius-2 cellular automaton rule {3818817080,2,2} (so called "shading cellular automaton")
CASS	Cellular Automaton-based Shading System
CF	Cost Function
CU	(Cellular Automaton) Control Unit (of the original CA-based Shading System prototype)
DR	Dihedral Rotation
DXF	Drawing eXchange Format
EA	Evolutionary Algorithm
ECA	Elementary Cellular Automaton
EN	Even Number
ES	Evolution Strategy
FFS	Free-Form Surface
FOR	Final Opacity Rate
FPGA	Field Programmable Gate Arrays
GDE	Grayness monotonicity and pattern Distribution Error
GF	Grayness Function
GFE	Grayness Function Error
GIS	Geographic Information System
GOL	Game of Life
G_S	*Grayness* at the Stable State
HE	History of Evolution
HP	High Sun Position
IA	Initial Angle

IBE	Intelligent Building Envelope
IC	Initial Conditions
IGS	Icosahedral Geodesic Sphere
LC	Liquid Crystal
LED	Light-Emitting Diode
LP	Low Sun Position
MAD	Median Absolute Deviation
NCCA	Number Conserving Cellular Automaton
OBR	Order-based Representation
OPX	One-Point Crossover
PCB	Printed Circuit Board
PFM	Polarized Film Module
PFSS	Polarized Film Shading System
PFSS-D	Directly controlled Polarized Film Shading System
RP	Randomly distributed (“noisy”) Patterns
RS	Random Search
RTG	Regular Triangular Grid with Voids
SIC	Sequence of Initial Conditions
SOCA	Second-order Cellular Automaton
SP	Shading Panel (of the original CA-based Shading System prototype)
SQ	Square
sSIC	Straightforward Sequence of Initial Conditions
ST	Semi-totalistic (Cellular Automaton rule)
SZ	Shade-Z
T	Totalistic (Cellular Automaton rule)
TCA	Triangular Cellular Automaton
TM	Test Mesh
TR	Transition Rule
UX	Uniform Crossover
XO	Crossover

Part I
What is Building Envelope?

This part outlines the functions of a Building Envelope, particularly in the context of *daylighting*.

Chapter 1
The Skin of a Building

Abstract This chapter describes the main functions of Building Envelopes, particularly in the context of *daylighting* (including the role of the outside view, smart windows, etc.). The functions of Building Envelope are compared with organic skin. Finally, an example of a relatively successful integration of adaptivity and aesthetics in the building of the Arab World Institute is presented.

Keywords Daylighting · Intelligent building · Visual comfort · Well-being · Window

1.1 Introduction

In architectural design, together with the size and shape of a building, its envelope (BE) is the most apparent manifestation of creativity. However, according to Ref. [34], architectural decisions too often are based on aesthetics only, which has the evident disadvantage of limiting the potential of performance improvement. BE is an interface between the interior and exterior, and serves a number of essential functions, e.g.:

- To protect from external factors, especially to provide security and to alleviate the external pollution and noise.
- To protect from climatic factors, e.g.: the temperature and humidity outside the comfort range, glare, etc.
- To provide and control natural light.
- To control, i.e., to allow or block the visual connection with the environment.

Moreover, modern BE is usually a part of building's energy conservation strategy. It is realized by reduction of the artificial lighting demand and collection of solar energy or protection from its excess. According to Ref. [1], rising energy prices and the need for reduction of the greenhouse gas emissions necessitate the development of intelligent buildings (IB) that operate on an energy-efficient and user friendly basis. According to Ref. [8], the role of IB is to provide a productive and a cost-effective environment for the users. This objective can be achieved by multi-criterial optimization of the

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following elements of a building: Structure, Systems, Services, and Management. Reference [1] indicates the optimization of the trade-off between energy consumption and comfort of the occupants, as the most challenging. The climatic requirements for the interior conditions are slightly different for individual occupants. On the other hand, the exterior climatic conditions vary considerably in the annual cycle and circadian cycle. Thus, the building envelope (BE) of an intelligent building (IB) should intelligently: respond to the changes in variable outdoor environment and adapt to usually also variable requirements of the occupants.

1.2 The Role of *Daylighting*

> *"No space, architecturally, is a space unless it has natural light."*
> – Louis Kahn

Daylighting implemented to building design is beneficial in several ways, e.g.:

- Economically and ecologically – D. can considerably conserve the energy and reduce the greenhouse gas emission [3, 5].
- Physiologically – D. effectively stimulates the human circadian and visual systems.
- Well-being: D. provides high illuminance and allows for excellent color rendering and discrimination. It enables an occupant to see well both: the space and a task. It also allows an occupant to experience certain environmental stimulation [6]. Moreover, work by daylight is believed to cause less stress and discomfort.
- Societal – occupants with higher social status in organizations are usually allocated closer to windows or in rooms with more windows [6].

For the survey of literature on the benefits of daylight provided through windows, see [7]. The shading effects study presented in [20] show that in a hot and humid climate such as Hong Kong, daylighting always results in energy savings. The direct solar gain can substantially reduce the heating demands in Nordic climates. However, it can also be the source of undesired glare [5]. It is noteworthy, that according to Ref. [23], the toleration for glare from a daylight source is much higher than from its artificial equivalents. Moreover, as documented in Ref. [10], persons at workstations receiving large portions of natural light reported substantially fewer eyestrain incidents. Furthermore, according to Ref. [27], high luminance contrasts were more tolerated when the window occupied a large portion of the visual field. The difference in thermal comfort and visual comfort is substantial. Post-occupancy evaluation studies show that

- The satisfaction of occupants regarding the room temperature is strongly correlated with the possibility of altering their working environments. It can be provided by: operable windows, room temperature controls, etc.

- This satisfaction also correlates with the sensation of real alterations of working climatic conditions, e.g.: perceivable increase or decrease of temperature [16].
- Conversely, according to Ref. [24] the satisfaction of the occupants poorly correlates with the factual room temperature and the temperature sensation.
- Available manually controlled shading devices are usually permanently set and rarely adjusted.
- If a photo-controlled shading device is to be accepted, it also requires a manual override option available to the occupants [14].
- Personal preferences of illuminance level, and the degree of discomfort caused by glare vary.
- The desired quantity of additional artificial light depends on the type of task and interestingly – on the distance from window.

The above observations confirm with the classic findings of modern psychology. Namely, the perceived control can moderate stress reactions [33]. For example, people with given opportunity to turn-off an aversive noise (without using it) did not report the negative after-effects on task performance, experienced by people without this opportunity [15]. For the literature survey on the human comfort factors in the indoor environment see [13].

Daylight provides dynamically changing patterns which stimulate human eye. However, the range of daylight illuminance is very wide: from 0 to 25 000 lx and above. This is far beyond common visual requirements, i.e.: 10–1000 lx, which correspond to the lowest level of color discrimination, and the bright appearance, respectively [11]. Figure 1.1 visualizes these relationships.

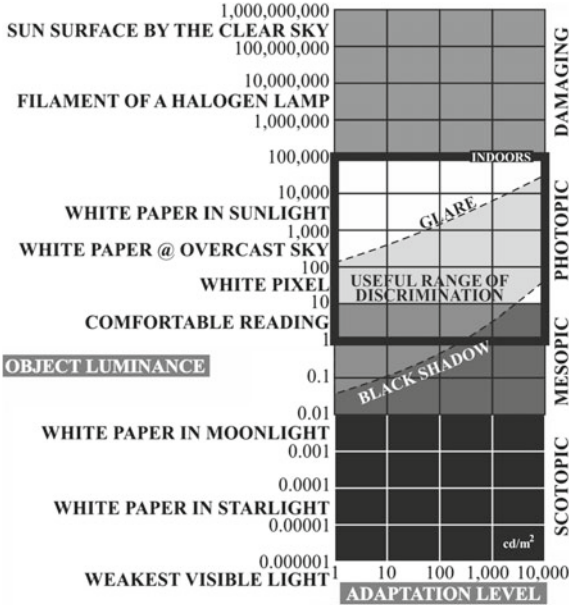
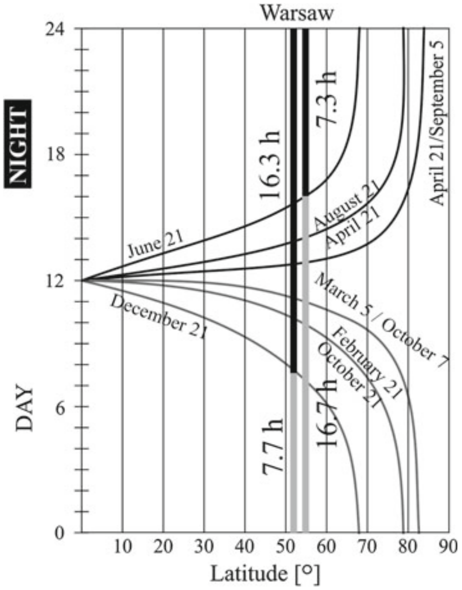


Fig. 1.1 Visual adaptation and luminance levels occurring in nature. The useful range of discrimination depends on the initial level of luminance

Fig. 1.2 For high-latitude locations, the difference between lengths of day and night varies substantially throughout a year



The annual variations of direct sunlight availability is illustrated in Fig. 1.2.

Several systems for daylight control are commercially available. Light entering the building interior through a window can be controlled by the following devices: light-guiding shelves, sun-directing glass, louvers, (anidolic) blinds, prismatic and laser-cut panels, etc. Daylight can also be collected, usually from roofs, and distributed inside buildings by so-called, light tubes. The survey of such systems can be found in [18].

None of these systems can be considered universal. The decision on selection of a daylight control device should be based on the local climatic characteristics, i.e., the building site latitude and predominant sky type. According to Ref. [2], in order to create a high-quality environment, it is necessary to carefully integrate daylight-control systems with the rest of the building design as early as possible.

Since the external illuminance level on does not only depend on the light coming directly from the sun disk and sky, but also depends on the component reflected from the ground and obstructions above the horizon — the control and modeling of daylight in urban areas are particularly challenging [29].

1.2.1 The Outside View

In most cultures, window serves not merely as an aperture in BE admitting natural light, but also provides visual contact with exterior. Studies indicate that views incorporating sky and horizon are the most appealing to human eye, especially after dark.

Interestingly, the night urban scenery with city skyline seems to be equally, or even more pleasing than natural scenes [22]. Visual landscape is important not only due to its aesthetic quality, but since it influences emotional state of an occupant, it also affects one's psychological *well-being*. Thus, according to Ref. [31], the outside view should be given explicit attention in planning and design decisions. Positive effect of natural scenery on restorative process of surgical patients have been demonstrated in [32], and therapeutic advantages of urban scenery over natural views for chronically under-stimulated patients have been suggested in [30].

Considering all the arguments listed above, the control of incoming daylight through natural aperture of a building, i.e., window is the most reasonable approach for the concept of intelligent building envelope (IBE).

1.2.2 Smart Windows

A window with optical properties which can be dynamically controlled seems as a straightforward solution for IBE. Although the technologies of: *electrochromism*, liquid crystal switching and *electrophoretic* switching have been discovered in the 1970s and in the next decade they have become available to the market, according to Ref. [4] the progress has been slow. However, after several decades, dynamically tintable, so-called smart windows (SW) have become commercially available. Reference [19] provides the requirements of SW necessary for effective control of the building energy: operating temperatures at: colored and bleached states, switching voltage, solar reflection and transmission, memory and cycling lifetime. Reference [4] examines and compares the following technologies for dynamic daylight and solar energy control in buildings: electrochromism, gasochromism, electrophoresis, and liquid crystal and suspended-particle devices. According to the survey conducted among window manufacturers and professional architects accredited by Leadership in Energy and Environmental Design, the most desired properties of SW are:

- High UV blocking;
- Low thermal emissivity (low-e);
- Integration with other coating types;
- Consistent appearance at all tint levels and window sizes;
- Fast switching speed;
- Glare reduction;
- Full control of the transition from transparent to opaque states.

Nevertheless, due to relatively low durability and cost-effectiveness, the use of SWs in architecture is rather sparse. However, according to Ref. [26], the interest among architects in this technology is gradually growing due to

- Increase of the consumer interest in quality-of-life enabling technologies;
- Generally increasing awareness regarding energy efficiency;
- Positive impact of daylighting;

- Introduction of large SW to the market;
- Steady growth of demand for doors and windows.

Nevertheless, although many SWs seem promising, so far none of them is fully satisfying, as analyzed in [4]. In conclusion, the requirements for BE are not only difficult to meet, but often contradictory. Furthermore, dynamically changing building facade altering its appearance according to occupant's whim or adapting to external conditions is one of the perpetual dreams in architectural design.

1.3 Comparison with Skin

"Skin of a building" is a concept in engineering and architecture which reflects the functional complexity of this interface between interior and exterior of a building. Table 1.1 compares the skin of the mammals or other animals [9, 21, 25, 28] with BE.

Table 1.1 The functions of BE and biological skin compared

Function	Skin	Building envelope
Protection	S. is an anatomical barrier from pathogens and damage between the internal and external environment in bodily defense [21, 25]	Outer shell to protect the indoor environment
Sensation	S. contains a variety of nerve endings that react to heat and cold, touch, pressure, vibration, and tissue injury	Users' sensory contact with the outside (mostly visual, also audial)
Heat regulation	S. contains a blood supply far greater than its requirements which allows precise control of energy loss by radiation, convection and conduction. Dilated blood vessels increase perfusion and heat loss, while constricted vessels greatly reduce cutaneous blood flow and conserve heat	Temperature control (insulation, solar gain, heat transfer, thermal mass, etc.)
Evaporation control	S. provides a relatively dry and semi-impermeable barrier to fluid loss [21]	Moisture control (e.g. air conditioning)
Storage and synthesis	S. acts as a storage center for lipids and water	Heat storage (e.g., thermal mass, Trombe wall [28])
Absorption	Oxygen, nitrogen and carbon dioxide can diffuse into the epidermis in small amounts, some animals use s. for their sole respiration organ [9]	Ventilation (indoor air quality, hygiene and public health)
Water resistance	S. acts as a water resistant barrier so that essential nutrients are not washed out of the body	Water barrier (water condensation)
Pigmentation	Camouflage, mimicry, UV protection, communication, sexual reproduction, warning etc.	Appearance (aesthetics, communication)
Structure	Other animal coverings such the arthropod exoskeleton or the seashell have different developmental origin, structure and chemical composition	Structural integrity (shell)

Table 1.1 shows that the physical properties and functions of BE are indeed analogous to those of the skin. Both are multi-layered complex composites made to face the constantly changing environmental conditions. Even today, it seems that the organic skin outperforms the manmade building façades.

1.4 The Arab World Institute

The Arab World Institute (AWI) in Paris, France, is probably the most recognized commission of adaptive BE. It has a form of an array of 24 × 10 metallic screen compounds as shown in Fig. 1.3. The screens unfold with moving geometric motifs to control incoming natural light and to express certain aesthetic qualities of the Arab architecture.

The compounds of the south façade are independently controlled and all of them comprised of several diaphragms. This highly complicated mechanical system is an impressive architectural feature, however, prone to failure. Soon after completion in 1987, several malfunction have already been reported. Moreover, the transmission dynamics, which is approximately 1:4, is rather limited [12]. Nevertheless, despite its present function as a mere decoration, it can be considered as a classic and one of the most successful embodiments of the intelligent building envelope idea. At least conceptually, in AWI the aesthetics and adaptivity are fully integrated.

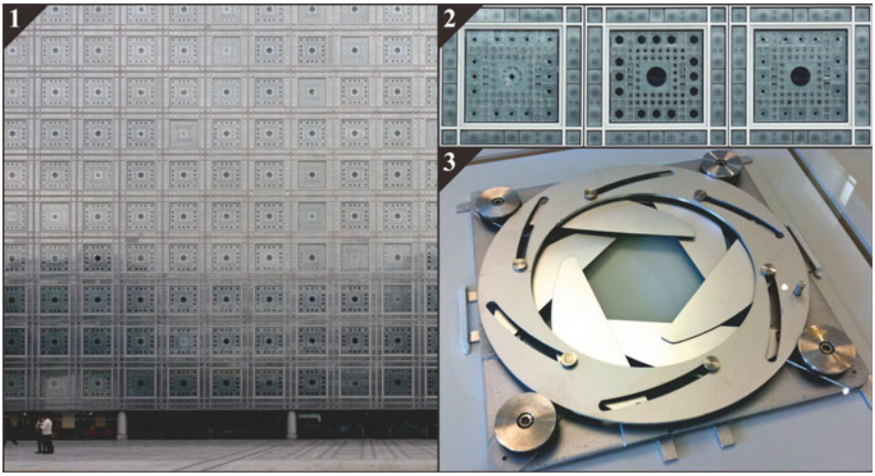


Fig. 1.3 Arab World Institute: (*1*) A part of the south façade; photograph © Lisa Wong. Its shading system is comprised of 240 mechanical compounds arranged in an array of 24 columns and 10 rows. (*2*) Three compounds in various opening configurations; photograph © Darrell Godliman. (*3*) Detail of the diaphragm; photograph © Petitechinoise