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COGITATIVE BUILDINGS: CONCEPTS, TECHNOLOGIES, IMPLEMENTATIONS

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EDITORS: Rezgui Y, Zarli A, Hopfe C J

Ardeshir Mahdavi, Univ. Prof. Dr.
Department of Building Physics and Building Ecology, Vienna University of Technology
amahdavi@tuwien.ac.at

SUMMARY: *This paper is concerned with the necessary conditions for the emergence of cogitative buildings. A cogitative building is defined here as one that possesses a multi-faceted representation of its context (site, micro-climate), its physical constituents (elements, components, systems), and its processes (occupancy presence and actions, indoor climate controls). Moreover, a cogitative building can dynamically update this representation and use it for virtual experiments toward regulation of its systems and states. The paper presents a summary of the required key technologies and the related state of their development, together with general reflections on problems and prospects of cogitative buildings.*

KEYWORDS: *cogitative buildings, self-updating representations, building automation, simulation-based control*

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1. INTRODUCTION

Projection of anthropomorphic attributes such as intelligence and sentience unto inanimate objects has a long tradition in myths, literature, and popular culture. The underlying motivations may be explained, in part, by psychologically based conjectures. Similar attempts toward development of sentient constructs in the engineering field need, however, a more utilitarian explanation. One such motivational contributor may have been the challenge of system complexity. The understanding and control of the behavior of complex human-made artifacts may benefit from observing and emulating behavioral and control patterns in naturally complex biological and sentient beings. Consequently, engineering systems embellished with features and capabilities that support intelligent behavior in living systems, may also display advantages in terms of optimal operation under dynamically changing boundary conditions (Bertalanffy 1976, Brillouin 1956, Wiener 1965). Accordingly, efforts to supplement buildings with intelligence, sentience, and self-awareness have often stated, as their goal, realization of buildings that can optimally meet user requirements while operating efficiently (Mahdavi 2004a). From this vantage point is, thus, endowing buildings with human-like attributes of intelligence and sentience not an ends in itself, but rather a means of improving buildings' performance.

In this context, two questions arise. First, what does it mean (or what does it take) to make a building intelligent, or sentient, or self-aware, or cogitative (capable of thinking)? Second, if successfully realized, does a cogitative building perform actually and measurably better than a conventional one?

The author does not intend to provide a definitive answer to these complex questions. Nor will he make an attempt to exhaustively treat the considerable body of literature on research and development in this field. Rather, a specific and selective view of the concept of cogitation in the context of building design and operation is presented and consequently examined in view of its technical feasibility and promise. This specific view is primarily informed by the previous research performed by the author and his research team, explaining the present paper's high frequency of self-quotations.

Section 2 of the paper provides the author's working definition of a cogitative building, focusing on the notion of self-representation. Section 3 enumerates the essential requirements that the representational core of a cogitative building must meet. Section 4 describes a central utility (application potential) of a cogitative building's dynamically updated digital building representation, namely the realization a novel kind of proactive simulation-based systems control technology. Section 5 summarizes the stat of existing and required technologies that are required for the functionalities associated with the operation of a cogitative building. Section 6 addresses ongoing research addresses technological advances toward generating and maintaining self-updating building representations for cogitative buildings. Specifically, provision of updated information concerning buildings' context, internal processes, and interior elements) are discussed. Section 7 illustrates a recent prototypical implementation of cogitative building technologies involving an actual test bed. Finally, section 8 provides concluding remarks and general reflection regarding the promise and challenges of cogitative buildings.

2. DEFINITION

Recent advances information and sensor technologies have given rise to frequency and consistency of efforts to augment conventional buildings via implementation of pervasive sensing infrastructures and intelligent control devices and methods. This, however, has not resulted in a consensus as to the exact nature of those intrinsic features that make a building intelligent, or – as suggested in a number of the author's previous publications – self-aware, or sentient (Mahdavi 2004a, 2001a).

The gist of these suggestions may be summarized as follows. A critical (not necessarily sufficient) condition for a cogitative system is the presence of a representational faculty. According to this view, a system capable of cogitation must have at its disposal a dynamic, self-updating, and self-organizing representation of not only its environment, but also its own situation in the environment (self-representation). It must thus possess the capability to autonomously reflect on its primary mapping processes (representation of the environment) via a kind of meta-mapping aptitude, involving the consideration (awareness) of its own presence in the context of its surrounding world (Bateson 1972, Mahdavi 1998). Put simply, a cogitative system has a model of itself, a model of the environment, and a model of itself in the environment. Moreover, it can use the latter model to autonomously perform virtual experiments (i.e. consider the implications of its own interactions with a dynamically changing environment) and use the results of such virtual experiments to determine the course of its actions.

3. ELEMENTS

Following the above minimum definition of a cogitative building, a number of requirements emerge. Such a building must have a dynamic (real-time) and self-organizing (self-updating) representation that includes at least three kinds of entities associated with a building, namely:

i) Physical components and systems;

ii) Context (surroundings, micro-climate), and

iii) Internal processes (occupancy, indoor climate).

A simple way of thinking about this complex representation is to consider a virtual (digital) model of a building that "runs" parallel to the actual building. This model encompasses real-time information about the properties and states of salient building components and systems, about the immediate surrounding environment of the building, and about its internal processes.

4. APPLICATION

The presence of a comprehensive dynamic representation provides, as such, a number of benefits. It can act as an interface, allowing users to conveniently obtain information about their building and to communicate operational requests (i.e. desirable states of control devices and/or room conditions) to the building's environmental systems control unit. To the building managers and operators, it can provide, in addition, a reliable and highly structured source of information toward supporting operational decision making in facility management, logistics, service, diagnostics, monitoring, and surveillance (Brunner & Mahdavi 2006).

However, these kinds of functionalities alone would not make a building cogitative. Rather, the critical faculty of a cogitative building is grounded in its autonomous use of the previously mentioned model toward auto-regulatory operations. A case in point is the operation of buildings' environmental systems for indoor climate control (heating, cooling, ventilation, lighting). A cogitative building can use a dynamically updated digital building representation toward implementation of a novel kind of model-based systems control technology that has been previously termed as simulation-based (or simulation-assisted), and proactive (Mahdavi 2001b, Mahdavi 2008, Mahdavi et al. 2005). The idea is that, in this case, a system bases its decisions regarding its future states on virtual experiments with its own digital representation. Thereby, the implication of alternative (candidate) future states of the systems are virtually tested and compared before one of them is realized. A simple instance of this approach may be summarized as follows (see Figure 1):

At time t_i the actual state of the virtual model is used to create candidate options for the state of the building in a future time point t_{i+1}. These candidate options may include different positions of the buildings environmental systems and devices for heating, cooling, ventilation, and lighting controls. The options are then "virtually enacted" using predictive tools such as explicit numeric simulation algorithms or statistically based regression models and neural networks. Thereby, the computation of future system states makes use of the building model and the predicted boundary conditions (weather, occupancy) to derive the values of various building performance indicators (energy use, thermal and visual comfort) for a future time step t_{i+1}. The prediction results are subsequently compared and evaluated based on objective functions set by building users and operators. The option with the most desirable performance is selected and either realized by direct manipulation of the relevant control devices, or communicated as recommendation to the users and occupants.

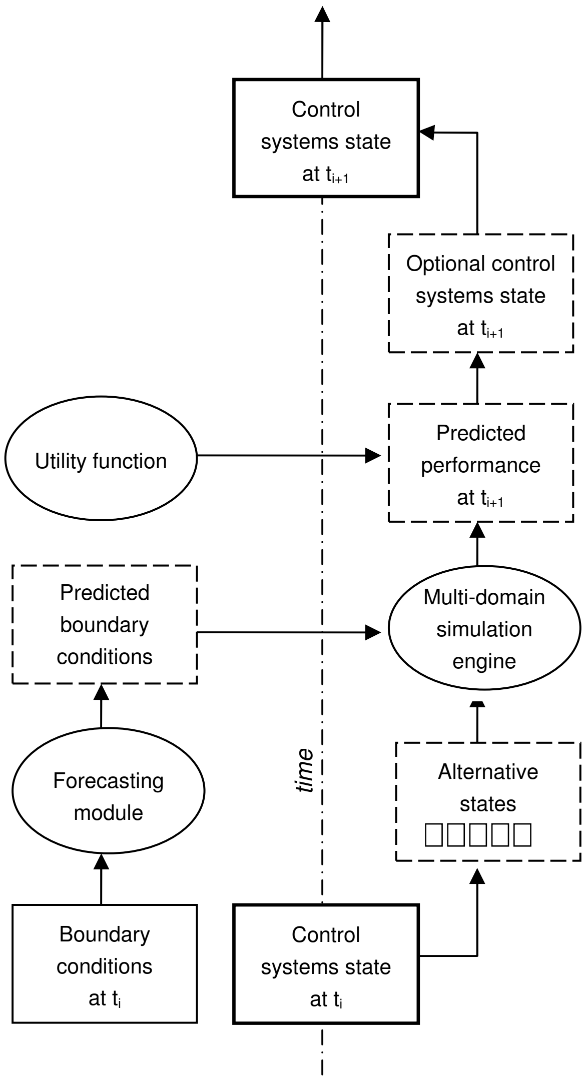

FIG. 1: The schematic illustration of a simulation-assisted building systems control strategy

5. TECHNOLOGY

Some features and ingredients of a cogitative buildings, as postulated in the previous sections, are already realized or under development. Others still await technical solutions versatile and scalable enough for wide use in practice. A number of related observations are expressed below, following the representational requirements of the three entity types discussed in section 3:

i) The long tradition in building product modeling research has resulted in detailed schemes and templates for the description of static building components and systems (IAI 2008, Mahdavi et al. 2002). Thereby, one of the main motivations has been to facilitate hi-fidelity information exchange between agents involved in the building delivery process (architects, engineers, construction specialists, manufacturers, facility managers, users). The representational stance of building product models has been mostly static. In contrast, building control processes require representational systems that can capture procedural sequences of events, decisions, and actions. As opposed to abundant literature in building product modeling, there is a lack of an explicit ontology for the representation of building control processes. Specifically, there is still a lack of consistent representations that would unify building product, behavior, and control process information. However, progress in this area is occurring and existing problems are probably neither fundamental nor insurmountable (Mahdavi 2004b, Brunner & Mahdavi 2006).

ii) The sensory devices necessary for provision of information concerning external (e.g. weather) conditions represent fairly standard technology. Advances are required to broaden the range of monitored conditions (to cover, for example, sky dome's luminance distribution and cloud cover). Robust and low-cost designs would encourage a more pervasive application of such technologies (Mahdavi et al. 2006).

iii) In the past, the "sensory deprivation" of buildings has been recognized as a potential area of deficiency. New buildings are thus increasingly equipped with comprehensive sensory networks to monitor occupancy, indoor climate conditions, and, to a certain degree, states of technical devices for systems control. The main challenges in this area are twofold. On the one hand, further developments are needed to fulfill the aforementioned criteria of representational self-organization. This means that, in order to keep the digital model of the buildings' physical constituents up to date, the sensory systems must detect and report changes in the location and position of building elements as well as interior objects (furniture, partition elements) and people (İçoğlu & Mahdavi 2005). On the other hand, the large amount of real-time monitored data must be structured and stored in an efficient and effective manner to support operational processes in building management domain.

A few recent efforts by the author's research team in the above mentioned technological development areas are briefly discussed in the following section.

6. RECENT ADVANCES

To address some of the research and development needs mentioned above, ongoing research addresses technological advances toward generating and maintaining self-updating building representations for cogitative buildings. Specifically, provision of updated information about external (sky) conditions, internal conditions (including people's presence and actions), and position of objects (interior elements) are discussed below.

6.1 External environment

Basic local meteorological data (air temperature and relative humidity, wind speed and direction, horizontal and vertical global irradiance and illuminance) can be dynamically monitored using standard sensing equipment. However, more detailed (high-resolution) monitoring of sky radiance and luminance distribution (including cloud distribution detection) still require complex and high-cost sensing technologies. Past research efforts (Roy et al. 1998, Mahdavi et al. 2006) have demonstrated that sky luminance mapping with digital photography can provide an alternative to high-end research-level sky scanners. This approach requires, however, careful calibration, as the camera is not a photometric device.

In a recent research effort (Mahdavi 2008), we further explored the use of a digital camera with a fish-eye converter toward provision of sky luminance maps of various real occurring skies (Figure 2). Toward this end, we developed an original calibration method that involves simultaneous generation of digital images of the sky hemisphere and measurement of global external horizontal illuminance. For each of the regularly taken sky dome images, the initial estimate of the illuminance resulting from all sky patches on a horizontal surface can be compared to the measured global illuminance. The digitally de-rived luminance values of the sky patches can be corrected to account for the difference between measured and digitally estimated horizontal illuminance levels.

Thereby, the difference between measured and calculated global illuminance can be assigned to a sky area associated with the sun position (Mahdavi et al. 2006).

To empirically test the performance of calibrated digital sky luminance distribution mapping, we used a sky monitoring device equipped with twelve illuminance sensors that measure the horizontal illuminance resulting from twelve different sky sectors (Figure 2). We then compared the illuminance predictions resulting from calibrated sky luminance maps to those resulting from respective photometric measurements. The results (see Figure 3) suggest that calibrated digital photography can provide a feasible technical solution toward provision of reliable high-resolution real-time sky maps (luminance distribution patterns) as part of the context model within the representational core of a cogitative building. Such context models can support, inter alia, the implementation of proactive control methods for the operation of buildings' lighting and shading systems.

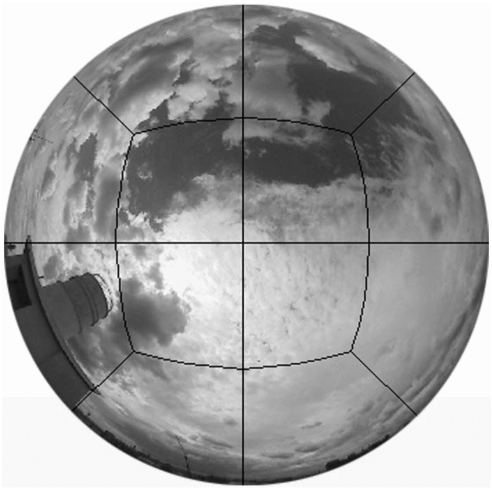

FIG. 2: Fisheye digital image of sky dome (together with the projection of twelve sky sectors as "seen" by illuminance sensors)

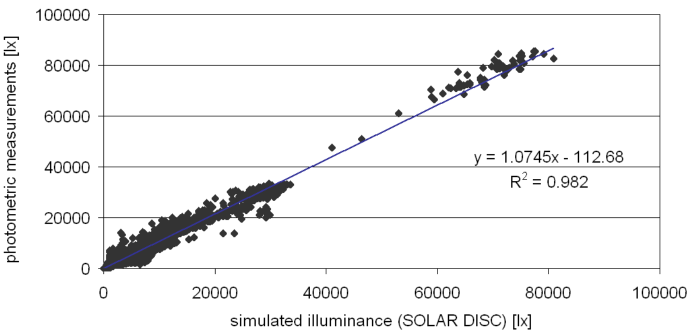

FIG. 3: Comparison of measured external illuminance levels with corresponding camera-based values

6.2 Dynamics of spatial models

To generate and maintain a self-updating model of the physical elements of a spatial unit in a building (e.g. the enclosure elements of and furniture elements in a room) is not a trivial task. Various location sensing technologies and methods have been proposed to autonomously track changes in the location of objects and artifacts in facilities. Such information could be used to continuously update product models of facilities. In previous research (İçoğlu & Mahdavi 2007), we first experimented with network cameras (some equipped with pan-tilt units to broaden the coverage area). Thereby, the location-sensing functionality was based on recognition of visual markers (tags) attached to objects (walls and windows, furniture elements, etc.).

To test the system, we selected a typical office environment (Figure 4) that involved 25 objects relevant for the demonstrative operational application (lighting control system). For each object, a tag was generated.

Consequently, the tags were printed and attached on the corresponding objects. The implemented location sensing system achieved in our test a 100% identification performance, extracting all tag codes and recognizing all objects. A graphical representation of the test-bed, as generated and displayed by the system, is illustrated in Figure 5. The object location results can be seen together with the sensed occupancies. To evaluate the accuracy of location results, "position error" is defined as the distance between the ground-truth position (actual position information) and the sensed position of the tag. "Orientation error" is defined as the angle between the tag's true surface normal and the sensed surface normal. Generally, the test implied for the system an average position error of 0.18 m and an orientation error of 4.2 degrees on aggregate. The position error percentage had a mean value of 7.3% (İçoğlu & Mahdavi 2007).

The above implementation was, as mentioned before, based on network cameras. To achieve the required level of scene coverage, most of such cameras in a facility need to be augmented with pan-tilt units. To explore an alternative that would not involve moving parts yet would offer wide scene coverage, we have also considered the potential of digital cameras with fisheye lenses as the primary visual sensing device (Mahdavi et al. 2007). Toward this end, we have performed an initial test, whereby, other than the cameras, all other components of the previous implementation (tags, detection algorithms, test space) are unchanged. The test involved the following steps: *i)* we equipped an ordinary digital camera with a fisheye lens; *ii)* we mounted this camera in the center of the test space. Altogether 17 tags were used to mark various room surfaces and furniture elements; *iii)* four fisheye images of the test space were generated by the camera from four different vantage points close to the center of the room (see Figure 6 as an example); *iv)* these four images were dissected into nine partially overlapping segments (see, for example, Figure 7); *v)* the resulting image segments were analyzed using the previously mentioned image processing method (İçoğlu & Mahdavi 2007). Figure 8 shows the relationship between the actual and computed tag-camera distances. This initial test resulted in a rather modest tag detection performance (67 %) and distance estimation accuracy (6 ± 10%). However, further calibration of the camera and assorted software improvements are likely to improve the performance of the system in the near future.

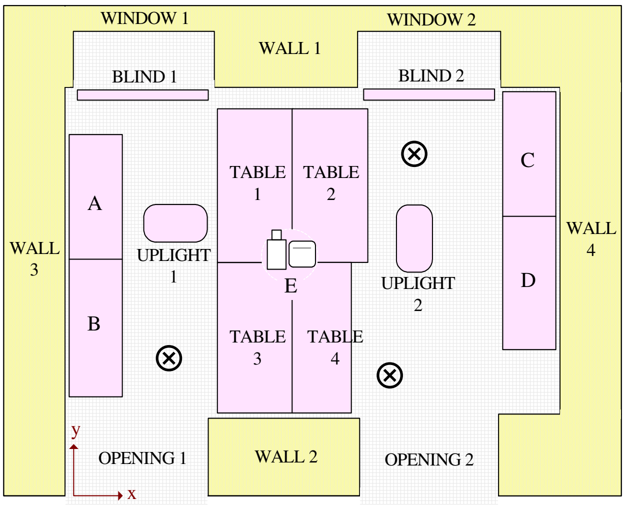

FIG. 4: Plan of the test-bed ("A" to "D" refer to Cabinets; "E" refers to Camera)

FIG. 5: Graphical representation of the test-bed generated by the user interface server. The objects are drawn with the extracted locations

FIG. 6: Sample fisheye image of the test space

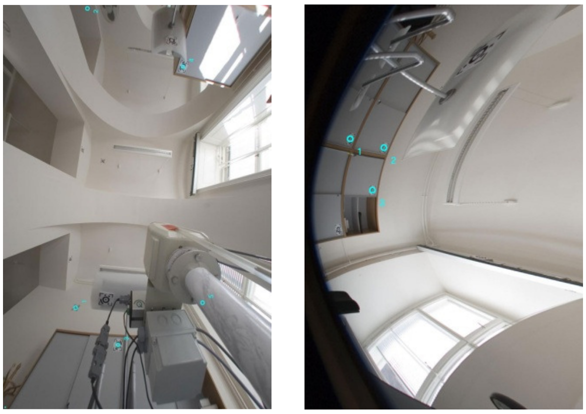

FIG.7: Examples of image segments extracted from the fisheye picture using equi-rectangular transformation

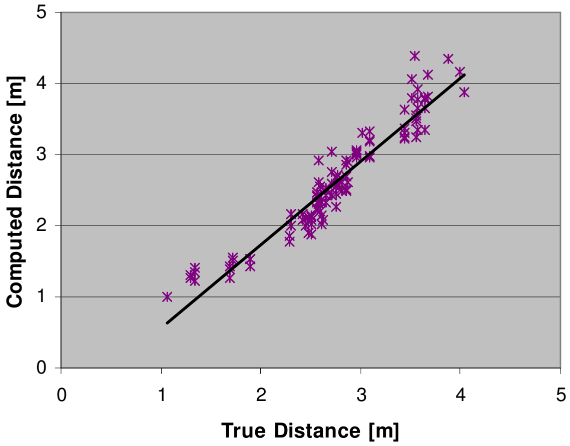

FIG. 8: Actual versus computed tag-camera distances

6.3 People and their actions

People's presence and their interactions with the buildings' environmental systems (for heating, cooling, ventilation, lighting) have a major effect on buildings' performance (Mahdavi 2007). Such interactions can be hardly predicted accurately predicted at the level of an individual person. For example, Figure 9 shows the considerable diversity of the observed mean occupancy (in percentage of the working hours) over the course of a reference day (representing observations over a period of 12 months) in seven staff offices in a building in Vienna, Austria. However, general control-related behavioral trends and patterns for groups of building occupants can be extracted from long-term observational data. Moreover, as our recent research in various office buildings in Austria has demonstrated, such patterns show in many instances significant relationships to measureable indoor and outdoor environmental parameters (Mahdavi 2007). Figure 10 illustrates, as an example, a model derived based on data collected in two office buildings for the prediction of the occupants' use of window shades (expressed in terms of the normalized relative frequency of occupant-based closing shades actions) as a function of the incident global vertical irradiance on the respective building facades.

The compound results of these case studies are expected to lead to the development of robust occupant behavior models that can improve the reliability of building performance simulation applications and enrich the control logic in building automation systems (particularly those pertaining to simulation-based building systems control methods).

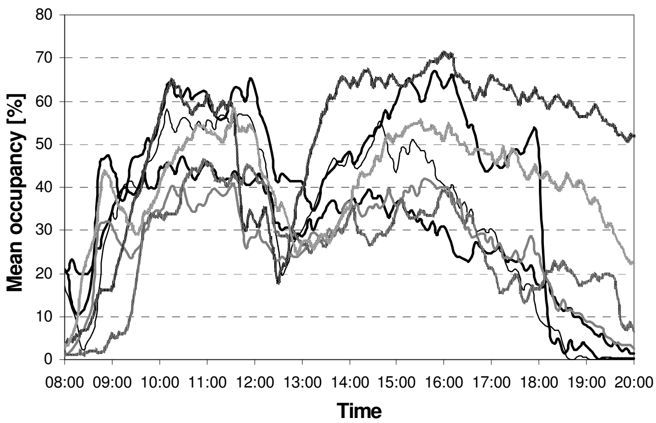

FIG. 9: Observed occupancy levels in 7 different offices in an office building for a reference day

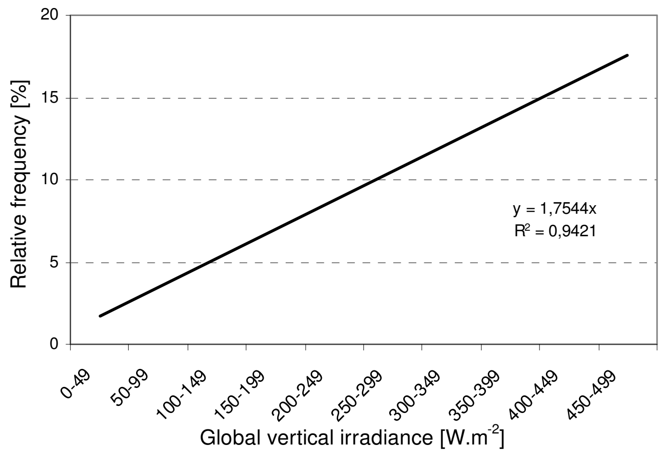

FIG.10: Illustrative simulation input data model for normalized relative frequency of occupant-based closing shades actions as a function of the global vertical irradiance (based on data collected in two office buildings)

7. AN ILLUSTRATIVE IMPLEMENTATION

As noted earlier (section 2), a cogitative system can use its internal representational system to autonomously and preemptively examine the implications of its own interactions with a dynamically changing environment and use the results of such virtual experiments to determine the course of its actions. The generic process toward the utilization of this faculty toward environmental systems control in buildings was discussed in section 4. In our past research, we have applied this process, amongst others, in the lighting and shading systems control domain (Mahdavi 2008, Mahdavi et al. 2005). A recent implementation involved a test bed (Figure 11) in the building physics laboratory of our Department. The objective was, in this case, to implement and test a simulation-based lighting and shading control strategy. Relevant control devices are two suspended dimmable luminaires and a window shading system (Figure 12). Daylight is emulated via a special flat luminaire (STRATO 2008) placed outside the window of the test room. The luminous flux of this source is controlled dynamically according to available external global illuminance measured via a weather station installed on top of a close-by university building. The simulation-assisted control method operates as follows:

At time t_i, the actual state of the virtual model is used to create candidate options for the state of the building in a future time point t_{i+1}. These options include six different positions of shading device and six discrete dimming positions for each of the two luminaires. The options are then simulated using the lighting simulation application RADIANCE (Ward Larson & Shakespeare 2003). Thus, values of various building performance indicators (e.g. horizontal illuminance at multiple locations in the space, illuminance distribution uniformity, different glare indicators, electrical energy use for lighting) are computed for a future time step t_{i+1}. The prediction results are subsequently compared and evaluated based on objective functions set by building users and operators.

To illustrate the control functionality and performance of this approach, Figure 13 shows the recommendations of the system (the dimming position of the two luminaires and the deployment position of the shading device) over the course of a reference day (office working hours). Figure 14 shows the corresponding values of the external global illuminance and the values of the relevant control parameter (i.e., mean workstation illuminance level, derived as the arithmetic average of the illuminance at points E_1, E_2, and E_3 as shown in Figure 11).

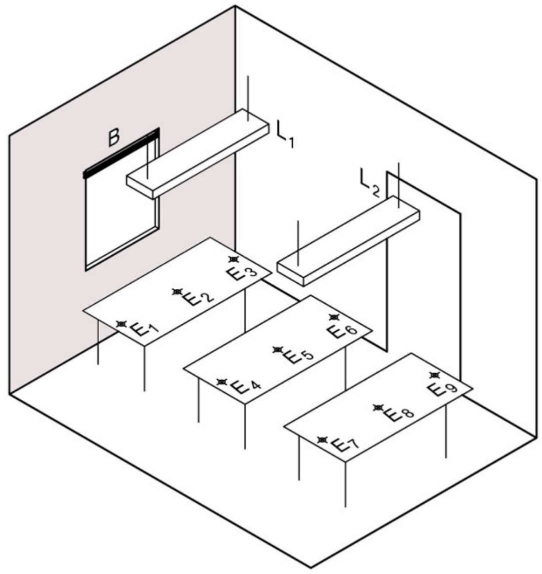

FIG.11: Schematic illustration of the test bed with the two luminaires (L1, L2), the shading device (B), and the workstation with reference points (E1, E2, E3) for workstation illuminance

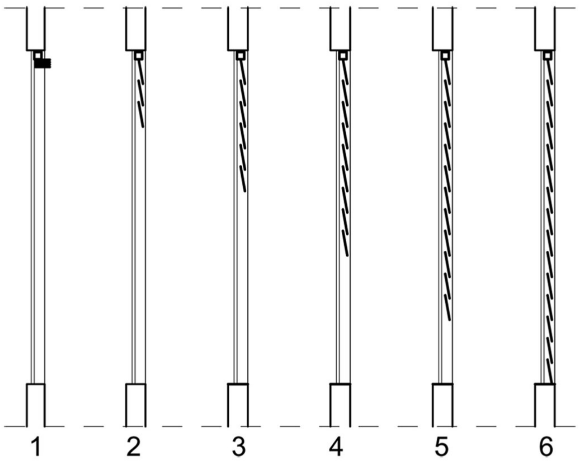

FIG.12: Illustration of the six discrete control states of the shading device in the test bed

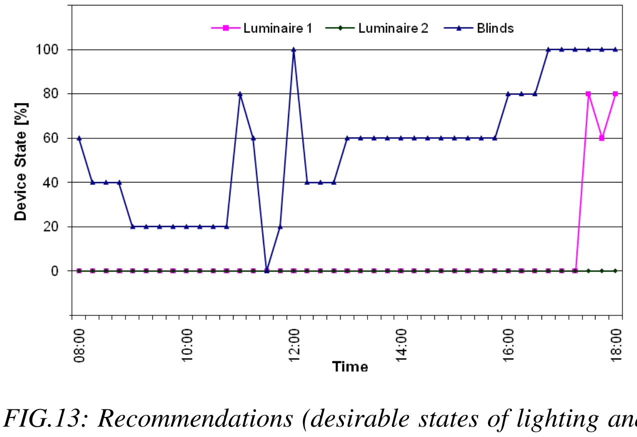

FIG.13: Recommendations (desirable states of lighting and shading devices) of the simulation-assisted lighting and shading control system for a reference day

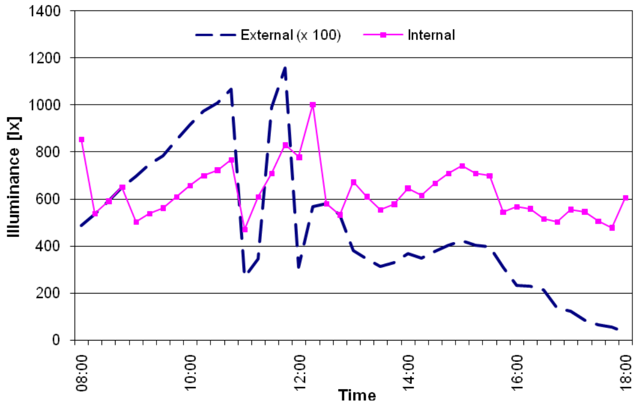

FIG.14: Predicted values of the relevant control parameter (workstation illuminance level) together with the prevailing external global illuminance

For the above experiment, the objective function required the optimization of workstation illuminance level (see Figure 15 for the corresponding preference function), while minimizing electrical energy consumption for lighting. Parallel measurements of the maintained illuminance levels throughout the test period showed a very good agreement with the predicted results, confirming once more the potential of the proposed methodology as a promising contributor to a cogitative building's self-regulatory control functionality.

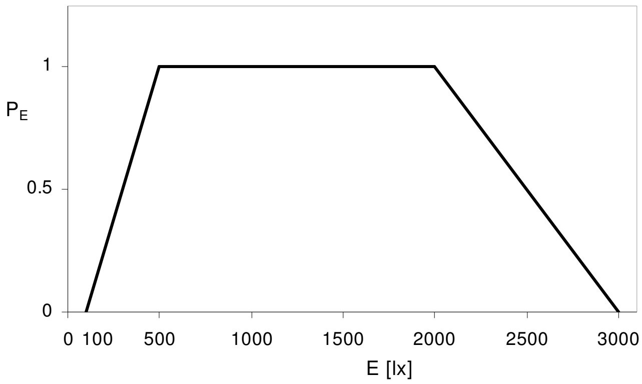

FIG. 15: Illustration of the assumed preference function for workstation illuminance

8. CONCLUSION AND REFLECTIONS

This paper provided an overview concerning the definition, features, technologies, functionalities, and prototypical implementation instances of cogitative buildings. Specifically, the important role of a cogitative building's self-updating dynamic representational system and its utility toward predictive self-regulatory operations were described. However, to better appraise both the critical potential and the associated challenges of presented approach, a number of general reflections concerning recent developments in the building delivery and maintenance process could be beneficial: buildings are subject to complex and dynamic changes of different kinds and cycles. Environmental conditions around building as well as organizational needs and indoor-environmental requirements of building occupants change continuously. Increasingly, buildings include more flexible, moveable, and reconfigurable components in their structures, enclosures, and systems. Moreover, building parts and components age over time, and are thus modified or replaced repeatedly. Likewise, buildings are frequently overhauled and adapted in view of new services and functions (Mahdavi 2005). Under these dynamically changing conditions, provision of functionally, environmentally, and economically desirable services represent a formidable planning, control, and management challenge. The proactive and auto-regulatory control faculties of cogitative buildings have the potential to effectively address certain aspects of this challenge. These faculties can result from a creative synthesis of advanced information modeling techniques (involving both building products and processes), pervasive environmental monitoring and location sensing features, and a simulation-based predictive control logic. Given the recent advances in these areas, the fulfillment of the technological prerequisites for the emergence of cogitative buildings is a realistic proposition.

Nonetheless, cogitative buildings, both as vision and as program, cannot be exempted from a multi-faceted critical discourse that is not limited to technical matters. Such discourse cannot be comprehensively addressed in the present – primarily technical – contribution, but at least two common concerns should be briefly mentioned.

A recurrent objection to the cogitative buildings vision maintains that intensive technology application cannot replace careful and effective building design. An overdependence on technological devices makes buildings in fact not only complex and susceptible to failures and breakdowns, but also energetically inefficient. This possibility is not to be offhandedly brushed aside. However, such heavy-handed technology-dependence would not represent a proper instance of implementing truly cogitative buildings: Application of "soft technologies" (sensor networks, soft-ware) can, in fact, reduce the overt dependence on resource-intensive hardware (e.g. for environmental controls). Note that biological intelligent and cogitative systems are not energetically inefficient. Given the complex occupational, technical, and organizational requirement profile of contemporary buildings, utilization of passive environmental control methods would be unrealistic, unless, as the cogitative buildings vision suggests, advanced sensory and computational tools and methods are applied.

A second common criticism concerns the notion of an all pervasive dynamic self-updating building model that continuously monitors occupants' presence and actions. This is, for some, reminiscent of circumstances in an Orwellian "surveillance state" and could pose, as such, a threat to occupants' privacy and integrity. Moreover, the occupants of buildings that "have their own mind" may become entirely dependent on (and patronized by) a complicated and opaque control hierarchy. These concerns must be taken seriously. As with many other technological advances (e.g. internet, mobile telephony), the threat of data misuse is present and must be understood and effectively addressed. Cogitative building technologies should act – and be seen as – efficient and enabling. Incorporation of sentience in building operation should empower, not patronize inhabitants. Occupants of a cogitative building should find an efficiently operating indoor-environmental context that is accommodating of their individual preferences and requirements.

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