

# IZ-CON: an intelligent zone controller for building systems operation

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## **Abstract:**

This paper describes the concept of an intelligent zone controller (IZ-CON) for integrated operation of building systems. IZ-CON is intended to deploy a predictive control methodology with embedded simulation capability. Thereby, the scalability problem of predictive simulation-assisted control method toward accommodating large and complex buildings is addressed. Moreover, the IZ-CON is inspired by a specific approach to building's control scheme involving the division of the target building into a number of well-formed sub-domains. Toward this end, a generative scheme for representation of buildings' systems control architecture is developed that allows for a structured distribution of systems' control logic. The scheme is cogently derived from a limited set of initial relationships between two entity layers. The first entity layer comprises of building zones subject to environmental control actions. The second layer comprises of technical devices responsible for control functionality. The entire control scheme – including the IZ-CON nodes – is derived in an automated fashion based on the relationships between the above two layers.

## **Keywords:**

simulation-based building systems control, zone controller

## **1. Introduction**

This paper describes the concept and structure of an intelligent zone controller (IZ-CON) for integrated operation of building systems. IZ-CON approach to building systems operation may be summarized as follows:

- i)* IZ-CON applies a predictive control methodology, which is powered with embedded simulation capability (Mahdavi 2008). In contrast to the majority of conventional control algorithms (e.g., rule-based methods, PID), the simulation-based control approach is proactive, rather than reactive. The simulation-based approach is also to be distinguished from the model-predictive control (Richalet et al. 1976, García et al. 1989), as it involves the explicit and run-time deployment of numeric simulation in the control logic. Previous work and associated small-scale implementations of the approach have been shown to be effective (Schuss et al. 2011). However, there are some doubts about its feasibility in terms of scalability toward accommodating large multi-zone buildings with multiple systems. We believe that the IZ-CON approach is well-suited to effectively address the scalability problem of predictive simulation-assisted control method.

- ii) IZ-CON deployment is based on a specific approach to the generation of building's control scheme and, specifically, the division of the target building into a number of well-formed sub-domains. Toward this end, we have developed a generative scheme for representation of buildings' systems control architecture that allows for an integrated and structured (hierarchical and traceable) distribution of systems' control logic. The scheme is cogently derived from a limited set of initial relationships between two entity layers. The first entity layer comprises of building zones subject to environmental control actions. The second layer comprises of projected devices responsible for control functionality. Once sub-domains are defined in a consistent manner, a network of communicating yet independent zone controllers (IZ-CONs) can be assigned to them.
- iii) IZ-CON involves user in the control process in a threefold manner: *a)* user behavior patterns and tendencies are used as the basis for corresponding predictive models; *b)* users are provided with zone state information pertaining to, for example, indoor climate (e.g., temperature, relative humidity, air quality) and positions of control devices such as luminaires, shades, and fans; *c)* users are provided with individual control possibilities, including the option to override the automated control regime.

The work on IZ-CON is motivated by certain inadequacies in current approaches to building systems control. We argue that the design methods of systems control architecture in buildings have not kept pace with the integration requirements of increasingly complex technologies for heating, cooling, ventilation, and lighting of buildings. Decisions regarding the environmental control systems' type and devices, the number and extent of control zones, as well as the type, number, and position of sensors neither follow a structured approach, nor reflect a traceable reasoning. Rather, such decisions seem to be frequently made on an ad hoc basis. Moreover, decision processes in one domain (e.g. thermal control systems) are rarely coordinated with other domains (e.g. visual control systems). Such lack of structure and integration is likely to cause inefficiencies in design and operation of buildings and their systems. Specifically, implementations of innovative (e.g. predictive) building systems control strategies may be hampered in part due to a lack of transparent and systematic representations of the buildings' systems control architecture. Classical literature on control theory does not address this problem (Mosca 1995, CIBSE 2000, Franklin et al. 2006, Unbehauen 2008). Previous – more pertinent – research work in this domain (Mahdavi 2001a, 2004, 2005, Mertz and Mahdavi 2003) has not affected the current state of practice. We thus need more research and development efforts in this area.

## 2. Basic terminology

There is a lack of a universally agreed-upon terminology in building systems control. Thus, to facilitate the present treatment, a few terms, definitions, and exemplary instances are adapted as per Table 1. Figure 1 illustrates a basic control loop: A device is assigned to control a certain parameter of a control zone. The controller (seat of the control algorithm) receives sensory information (S) concerning this parameter and manipulates the device's actuator (A). Consequently, the device delivers to (or extracts from) the control zone some amount of mass and/or energy via the device's terminal (T). The building systems control terminology of Table 1 is not free of inconsistencies and ambiguities. Nonetheless, it works fairly well, if certain conditions, qualifications, and simplifications are applied. Two such qualifications are briefly discussed below.

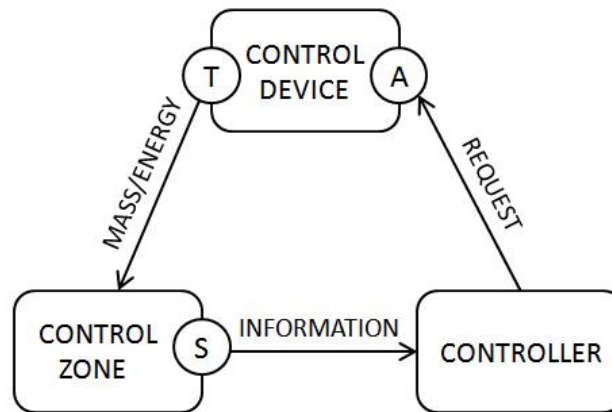


Figure 1. A basic control loop involving a control device, a control zone, and a controller. Here "T" and "A" denote device's terminal and actuator, whereas "S" stands for sensor.

Table 1. Selected terms for building systems control (based on Mahdavi 2001a, 2004, with modifications).

Term	Definition	Instance
Controller	Agent that sets control actions	People, software (algorithm)
Control action	Induced change in the state of a control device's actuator	Opening a window, switching lights on/off
Actuator	Component of a device that, acting upon a control command, brings about device state changes	Valve, dimmer, people
Control device	A technical element or system, whose purpose is to deliver to (or remove from) a control zone some quantity of mass and/or energy	Window, luminaire, HVAC
Control device terminal	The technical component of a control device that acts as its interface to the control zone	Radiator, diffuser
Control objective	To maintain a certain state in a control zone by keeping the respective control parameter in a certain range	Maintaining air temperature (or illuminance levels) in a control zone (a space, or a task plane) within a certain range
Control parameter	Indicator of the control zone's relevant state	Air temperature, relative humidity, carbon dioxide concentration, illuminance
Actuator state	Position of a control device's actuator	Open/close, dimming level, valve position
Control zone	Target domain of control action	Workstation, room, floor, building
Control state space	The logical space of all possible positions of all relevant actuators	All possible positions of windows, blinds, luminaires, etc.
Sensor	Reports the actual value of a control parameter in a control zone	Thermometer, photometer

First, the notion of a "control zone" needs to be properly understood. Recurrent miscommunications between control engineers and building design professionals could be avoided, if control zones are seen as the physical targets of control actions and not necessarily as architectural entities such as rooms. Perhaps it would be helpful to think of a control zone as a fluid (i.e., flexible) entity that can be projected to buildings' constituents spaces and elements, but it is not identical with those. To exemplify this point, Figure 2 illustrates the case of a simple open plan office space with multiple devices and multiple overlapping zones. In this case, the devices include external shade (B), windows (W1, W2), radiators (R1, R2), and luminaires (L1, L2). As the schematic depiction in this Figure demonstrates, the devices may have different and overlapping intended impact areas (control zones). Thus, zones may be associated with parts, whole, or aggregations of architectural spaces. Moreover, zones need not always imply three-dimensional volumes, but can refer to two-dimensional planes, as in the case of illuminance control on a horizontal task surface.

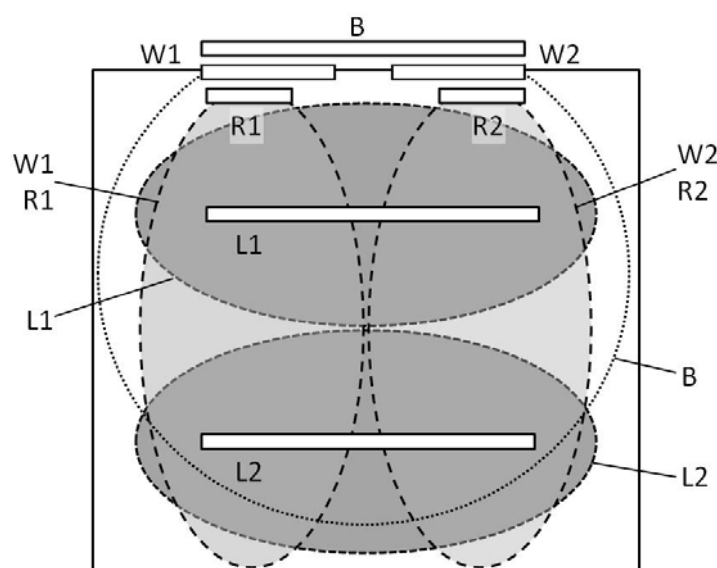


Figure 2. Illustrative depiction of a simple office space plan with multiple devices (B: external shade; W1, W2: windows, R1, R2: radiators; L1, L2: luminaires) and associated control zones.

Second, a control device (if the term is to cover entities such as an HVAC system) is not necessarily a simple stand-alone technical component (such as window or luminaire) that has just one actuator with a simple set of distinct states. Rather, it is frequently a complex and nested (hierarchically organized) technical system. For example, a building's mechanical ventilation system consists of numerous components at multiple levels. Large amounts of conditioned air mass may be centrally prepared, distributed around the building over an extensive network of ducts, and finally delivered – via multiple terminals – to the building's multiple thermal zones. Terminals may in turn possess embedded, individually controllable, generative elements (such as reheat coils).

A simplification of this complexity would be beneficial for the purposes of the present discussion. Toward this end, we suggest to view a complex device in terms of a black box, whose virtual actuator is realized at the location of the device's terminal (i.e., its interface with the control zone). The assumption is that the complex device's machinery within the

black box is controlled in a way such that, upon request (i.e., upon manipulation of the device's virtual actuator) modulated amounts of mass and/or energy would be released to (or extracted from) the target control zone. In other words, the control device in the present discussion can be regarded as a zone-specific terminal of an overarching nested system, which is represented in the proposed generative control schema through its virtual actuator.

### **3. A schema for the structured representation of the control logic**

#### ***3.1. Defining the problem***

The previous discussion allows us to pinpoint one of the primary sources of complexity in designing control systems for buildings. In most practical cases, there is no one-to-one mapping between devices and control zones. Rather, the control parameter (e.g., air temperature) in a target control zone (e.g., in a room) may be influenced – intentionally or unintentionally – by the operation of multiple devices such as windows, radiators, and shading elements. Likewise, the operation of a single device such as shading element may influence two or more distinct control parameters representing different control zones (e.g., indoor air temperature and task illuminance). In other words, devices and zones could maintain one-to-one, one-to-many, and many-to-one relationships. Thus, more often than not, the control task in a building must address a many-to-many pattern of relationships between control devices and control zones.

The problem can now be framed as follows. On the one hand, a decentralized distribution of control logic appears attractive in view of considerations pertaining to system robustness, scalability, flexibility, adaptability, and safety. On the other hand, the complex interplay of multiple devices in view of their implications for multiple control zones appears to imply a rather concentrated organization of control logic. In the extreme, where all devices can influence all zones, the control logic will have to be highly centralized. To address this problem, the present contribution reports on the recent developments regarding a previously introduced schema for the architecture of a building's systems control logic (Mahdavi 2004). This schema is primarily intended to support a systematic distribution of control logic in complex buildings.

We envision a simple generative schema is that allows for the high-level representation of a building's systems control logic. The starting point for schema generation is the unambiguous definition of two entity layers, namely control zones and control devices. Subsequently, the relationships between these layers must be established. A relationship denotes either a physical intervention involving mass and/or energy flows instantiated by the device controller and acting on the control zone, or zone state information flow via zone sensor to device controller. Note that the definition of two entity layers and their relationships involves some heuristically-based judgments and associated uncertainties. For instance, unintentional minor impact of a specific device such as heat emission of a luminaire on a specific zone state indicator such as air temperature may be neglected, as the purpose of a luminaire is not to heat a zone, but to illuminate it. Moreover, the assumed impact zone of a device and its actual impact area may be different: The impact regions of control devices can be rarely defined in terms of sharp boundaries. Computational methods to support the design task with these uncertainties are conceivable and partially under development. However, we shall not deal with them in the present treatment.

We suggest that the distributed architecture of the building systems' control can be derived cogently from the aforementioned limited set of initial relationships between two entity layers, control zones and control devices, in an automated rule-based fashion (Mahdavi 2001a, 2004, Mertz & Mahdavi 2003). This architecture can be seen as a template of distributed nodes, which can contain partial methods and algorithms for control decision making.

### 3.2. *Generation rules*

If a control task involves only one-to-one relationships between control devices and zones, the control logic architecture would be trivially distributed (maximally flat). At this basic level, every device can be thought as having a device controller (DC). The task of DC is to operate the Device's actuator autonomously, in the absence of higher-level requests. However, as previously argued, the real world building systems control tasks often involve many-to-many relationships. In the theoretical extreme case, where every one of  $p$  devices would influence every one of  $q$  zones,  $p \times q$  relationships between devices and zones would have to be reckoned with. While real cases might not be nested as much, there is still a great deal of interdependency. Consequently, the design of a required complex control code structure could be supported, if it could be broken done into a manageable number of clearly defined segments or nodes. Generative rules could be applied to derive such nodes in the control schema for the accommodation of well-formed pieces of control logic in terms of rules, algorithms, and simulation code. We propose a set of such generative rules toward generating a multi-nodal control logic schema, i.e., a unique hierarchical multi-layered configuration of nodes for a specific control task:

- Step 1: Arrange distinct control zones as the basis layer of the schema. The state of these zones is captured via respective zone sensors.
- Step 2: Arrange device controllers (DCs) in the next layer. Every individually controllable device is assumed to have a DC with access to the Device's actuator.
- Step 3: Connect device controllers (DCs) to the zones, whose states are appreciably influenced by the operation of DCs.
- Step 4: generate the zone controllers' layer (IZ-CONs) as follows: if more than one DC influences the same zone, a respective zone controller is required to coordinate their operation. This layer accounts thus for the need for zone-specific coordination across multiple devices.
- Step 5: generate the high-level controllers (HC) layer as needed: If a DC receives requests from more than one zone controller, a high-level controller (HC) is generated. This layer accounts thus for the need for device-specific coordination across multiple zones.
- Step 6: If high-level controllers overlap in terms of devices involved, merge them into one meta-controller.

Such a schema may be generated for an entire building or any part of a building that may be regarded as closed (well-bounded) in terms of control actions and their implications.

### 3.3. An illustrative schema generation example

Consider the illustrative control task pertaining to a simple office space as depicted in Figure 3. Control objective is maintaining the values of a number of zone state indicators or control parameters within target values. These are in this case air temperature ( $\theta$ ), relative humidity (RH), carbon dioxide concentration (C), and illuminance ( $E_1, E_2$ ). The control task is to be accomplished via the operation of two windows (W1, W2), a shading device (B), two radiators (R1, R2), and two luminaires (L1, L2). Following the steps described in section 3.2, the distributed multi-layered multi-domain systems control schema of Figure 4 emerges. In this schema, layers 1 (zones) and 2 (device actuators) result from steps 1 to 3. Layers 3 (IZ-CONs) and 4 (high-level controllers) result from steps 4 and 5 respectively. Layer 5 (meta-controller) results from step 6. In this schema, the direction of control requests is downwards, whereas the sensor information flows upward.

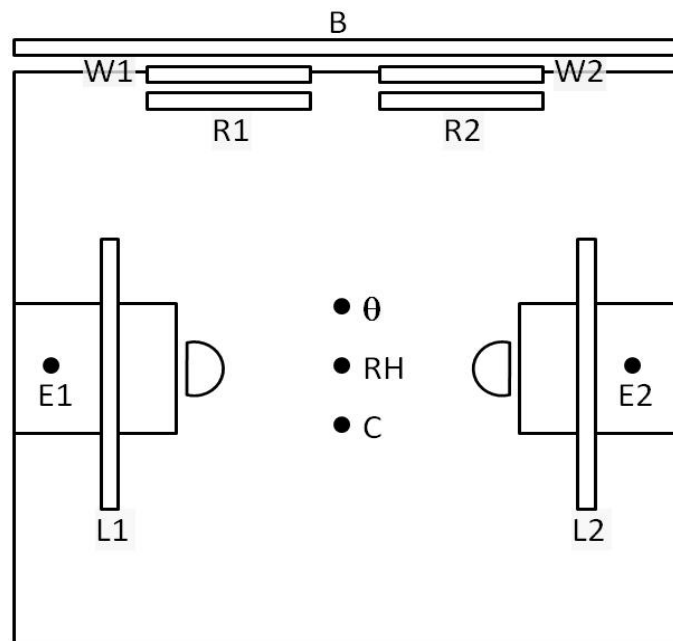


Figure 3. An office space with seven devices (windows W1 and W2, two radiators R1 and R2, two luminaires L1 and L2, and external shade B) and five sensors (illuminance sensors E1 and E2, indoor air temperature, relative humidity, and carbon dioxide sensors  $\theta$ , RH, and C).

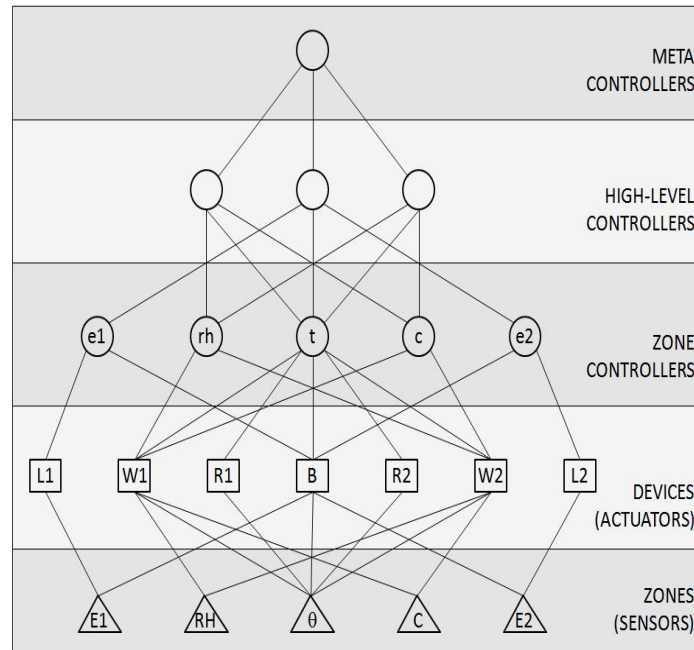


Figure 4. Illustrative distributed multi-layer multi-domain systems control schema for the office space of Figure 3.

### 3.4. Populating the schema with semantics

In the previous section, a process was described to generate schemata for building systems control. However, it is important to emphasize that the schema does not predetermine what kind of control method or style is applied at each instance. Rather, the nodes in this schema represent containers or place-holders for pertinent parts (code segments) of the overall control logic. Consequently, the nodes can accommodate a variety of rule-based and/or algorithmic control solutions. A crucial benefit of the schema can be seen in its potential to provide a structured platform for a modular and distributed assembly of control code for large and complex building systems operation scenarios. The manner in which the schema could be populated with control semantic could be further discussed with reference to the promising option of a simulation-based control strategy (Mahdavi 1997, 2001b, 2008). According to this strategy, control decisions are made upon evaluation of the computed implications of virtually enacted control options. This implies that at each control decision making instance, available control options, i.e., the alternative actuator positions, are virtually realized via simulation. The simulation results, which are the projected values of the control parameter for a specific point of time in future, are then compared to identify the most promising option. Thus framed, the control task can be seen as navigation of the control state space. In case of multiple devices with a large number of possible states, the computational handling of the control state space may become infeasible. A circumstance that is further aggravated due to the necessity to conduct such computations on a recurrent basis: The control process is of course a dynamic one, given the changing nature of relevant boundary conditions such as weather, occupancy, as well as user preferences and priorities. Hence, the optimal combination of device actuator positions must be arrived at in an ongoing manner. To reduce the size of the control state space, various methods from operation research and optimization can be applied (Mahdavi 2008, Schuss et al. 2011).



To semantically populate the proposed generic system, the simulation-based control strategy could make good use of the nodal structure. Devices can be equipped with simple methods to either autonomously operate their actuators (for instance in case system communications break down), or to suggest, to the upper layers, preferable actuator positions. IZ-CONs could merge the recommendations they receive by comparing the advantages of operating one device versus another. Alternatively, they could use partial system models to predict, compare, and evaluate the performance implications of recommendations from the lower layer. Similarly, meta-controllers could evaluate submitted options via some performance criteria (e.g., the pertinent devices' energy use), or they could independently conduct whole system simulations for all or a part of the recommendations they receive.

An attractive feature of the proposed schema is its capability to flexibly accommodate multiple evaluation criteria toward optimal control decision making. Thereby, evaluation criteria can be represented not only in terms of real sensors but also in terms of calculated, derived, simulated, aggregated, and virtual sensors. For example, performance indicators such as mean radiant temperature, PMV (predicted mean vote), and various glare indices could be computed real-time and the results could be reported by the sensors to the higher levels of systems control hierarchy. Likewise, environmental performance criteria such as CO<sub>2</sub> emissions attributable to consumption of a certain type of fuel as well as economical performance indicators such as energy-related expenditures could be effectively accommodated in the schema in terms of corresponding virtual sensors.

### ***3.5. A prototypical implementation instance***

Currently, an actual implementation of the proposed IZ-CON approach is being prepared within the framework of the EU-supported CAMPUS 21 project (CAMPUS 2011). Toward this end, the Environmental Research Institute (ERI) Building of the University College Cork (UCC) is selected. An open office space in this building will be used for the prototypical implantation. The ERI Building (Figure 4) has an up to date building automation system and a fairly comprehensive monitoring infrastructure. The selected south-facing space (Figure 5) is located in the first floor (Figure 6).



Figure 4. The ERI Building.

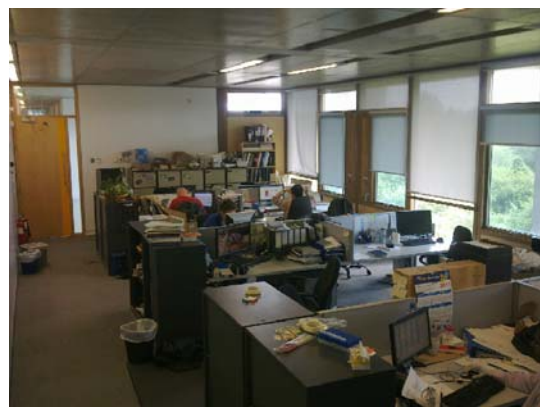


Figure 5. Selected open office space.

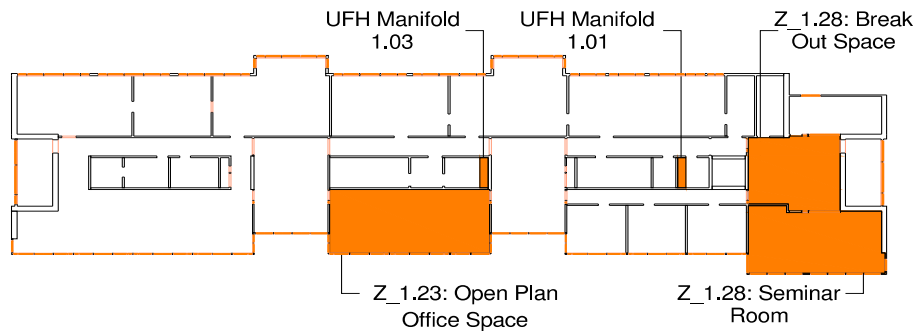


Figure 6. ERI Floor plan with demonstration room Z\_1.23

The documentation of the original control setup does not reveal an explicit analysis of the complex relationships between devices, actuators, zones, and sensors. The first step in the implementation of the control task is thus to capture and represent such relationship. As the schematic representation in Figure 7 shows, the space has the following individually controllable devices: 4 blinds (B1 to B4), 4 operable windows (W1 to W4), and 4 sets of 2 luminaires (L1A/L1B to L4A/L4B). Moreover, the space is supplied with a constant volume air system (V) and a floor heating system (H). The control objective is maintaining the values of a number of zone state indicators or control parameters within target values. In this case, the control scheme is based on the assumption of 4 lighting zones (represented by illuminance sensors E1 to E4), and two compound hygro-thermal and indoor quality zones represented by two sets of sensors for air temperature, relative humidity, and carbon dioxide concentration ( $\theta_1$ , RH1, C1 and  $\theta_2$ , RH2, C2). Following the steps described in section 3.2, the distributed multi-layered multi-domain systems control schema of Figure 8 emerges. In this schema, layers 1 (zones) and 2 (device actuators) result from steps 1 to 3. Layers 3 (IZ-CONs) and 4 (high-level controllers) result from steps 4 and 5 respectively. Layer 5 (meta-controller) results from step 6. Note that, for simplification purposes, secondary (relatively less essential) device influences on zones (dotted lines in Figure 8) were neglected in the scheme generation process. Hence, the resulting schema consist one meta controller for the coordination of the two high level controllers from the two hygro-thermal and air quality zones.

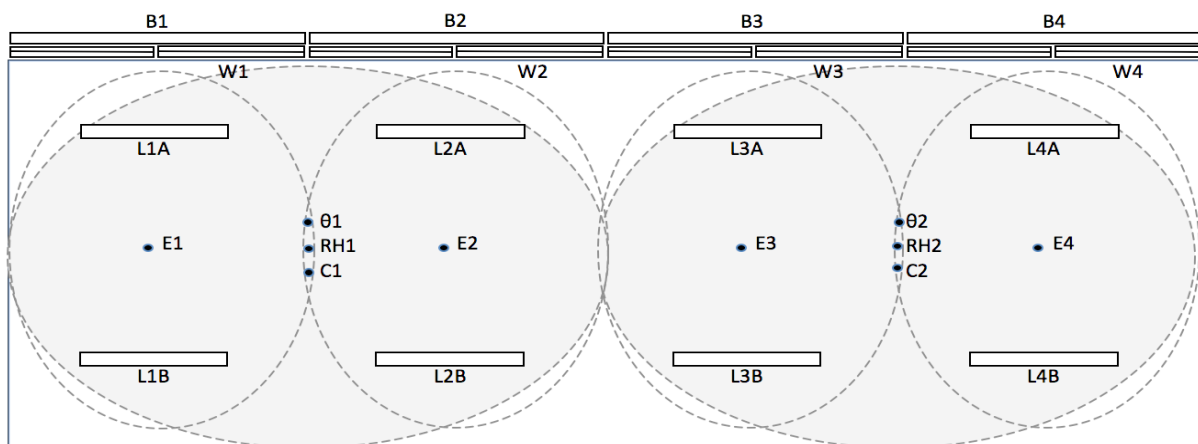


Figure 7. The ERI office space (Z\_1.23) with devices (windows W1 to W4, luminaires L1 to L4, and external shade B1 to B4) and ten sensors (illuminance sensors E1 to E4, indoor air temperature  $\theta_1$  and  $\theta_2$ , relative humidity RH1 and RH2, and carbon dioxide sensors C1 and C2).

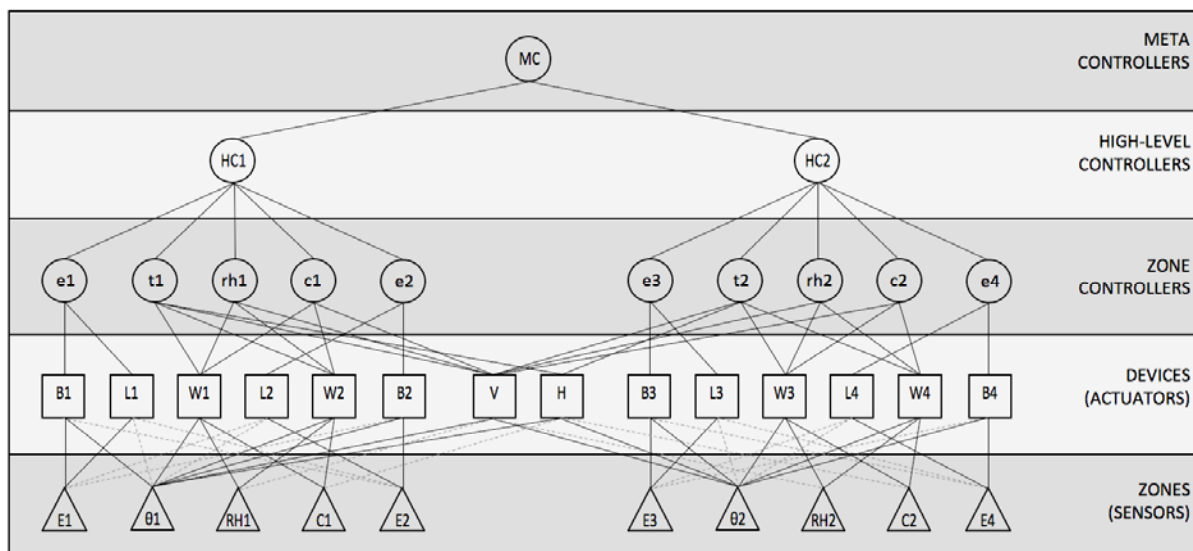


Figure 8. Illustrative distributed multi-layer multi-domain systems control schema for the open office space (Figure 7).

#### 4. conclusion

This contribution described a method to generate a schema for the control architecture of multi-zonal multi-domain building systems control scenarios. The schema allows breaking down a complex control task into five layers (zones, devices, IZ-CONs, high-level controllers, and meta-controller). IZ-CONs facilitate zone-specific coordination of multiple devices. Nodes in the high-level controller layer facilitate device-specific coordination across multiple zones. These nodes provide thus containers for the distributed encapsulation of the building systems control semantic. An illustrative real-world instance of the schema deployment was presented.

#### References

- CAMPUS 2011. Control and Automation Management of Buildings and Public Spaces in the 21st Century. <http://zuse.ucc.ie/campus21/>.
- CIBSE 2000. Guide H: Building Control Systems. Butterworth-Heinemann; ISBN: 978-0750650472.
- Franklin, G. F., Powell, J. D., Emami-Naeini, A. 2006. Feedback control of dynamic systems – 5.th edition; Pearson Prentice Hall; New Jersey; ISBN: 0-13-149930-0; 910 p.
- García, C. E., David M. Prett, D. M., Manfred Morari, M. 1989. Model predictive control: Theory and practice—A survey. *Automatica*. Volume 25, Issue 3, May 1989, Pages 335-348. Elsevier Science Ltd. Garcia 1989
- Mahdavi, A. 1997. Toward a Simulation-assisted Dynamic Building Control Strategy. Proceedings of the Fifth International IBPSA (International Building Performance Simulation Association) Conference. Vol. I, pp. 291 – 294.
- Mahdavi, A. 2001a. Aspects of self-aware buildings. *International Journal of Design Sciences and Technology*. Europa: Paris, France. Volume 9, Number 1. ISSN 1630 – 7267. pp. 35 – 52.

- Mahdavi, A. 2001b. Simulation-based control of building systems operation. *Building and Environment*. Volume 36, Issue 6, ISSN: 0360-1323. pp. 789-796.
- Mahdavi, A. 2004. A combined product-process model for building systems control. "eWork and eBusiness in Architecture, Engineering and Construction: Proceedings of the 5<sup>th</sup> ECPPM conference" (Eds: Dkbas, A. – Scherer, R.). A.A. Balkema Publishers. ISBN 04 1535 938 4. pp. 127 – 134.
- Mahdavi, A. 2005. Space, Time, Mind: Toward an Architecture of Sentient Buildings. (Keynote paper). *Computer Aided Architectural Design Futures 2005*. Proceedings of the 11<sup>th</sup> International CAAD Futures Conference (Martens, B. and Brown A.: Editors). Springer, The Netherlands. ISBN-10 1-4020-3460-1. pp. 23 – 40.
- Mahdavi, A. 2008. Predictive Simulation-Based Lighting and Shading Systems Control in Buildings. *Building Simulation, an International Journal*. Volume 1 / Number 1 / March 2008. pp. 25 - 35. ISSN 1996-3599.
- Mertz, K. & Mahdavi, A. 2003. A representational framework for building systems control. Proceedings of the 8th International IBPSA Conference, Eindhoven, Netherlands; ISBN: 90-386-1566-3; pp. 871 - 878.
- Mosca, E. 1995. *Optimal, predictive and adaptive control*. Prentice Hall; New Jersey; ISBN: 0-13-847609-8; 477p.
- Richalet, J., Rault, A., Testud, J.L., Papon, J., 1976. Model Predictive Heuristic Control: Application to Industrial Processes, 4.th IFAC Symposium on Identification and System Parameter Estimation. Tbilisi USSR
- Schuss, M., Zach, R., Orehounig, K., Mahdavi A. 2011. Empirical evaluation of a predictive simulation-based control method. Proceedings of the 12th International IBPSA Conference 14 – 16 November 2011, Sydney, Australia.
- Unbehauen, H. 2008. *Regelungstechnik. 1. Klassische Verfahren zur Analyse und Synthese linearer kontinuierlicher Regelsysteme, Fuzzy-Regelsysteme*; Vieweg+Teubner; Wiesbaden; ISBN: 3-8348-0497-5; 401p.

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