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A MULTI-DOMAIN MULTI-ZONAL SCHEMA FOR SYSTEMATIC COMPARTMENTALISATION OF BUILDING SYSTEMS CONTROL LOGIC

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SUMMARY: *In order to accommodate the integration requirements of increasingly complex technologies for heating, cooling, ventilation, and lighting of buildings, effective design and configuration methods are needed. Specifically, decisions regarding the environmental control systems' type and devices, the number and extent of control zones, as well as the number and position of sensors need to follow a structured approach with traceable reasoning. Moreover, decision processes in one domain (e.g. thermal control systems) must be coordinated at a deep level with other domains (e.g. visual control systems). The absence of a structured approach in these areas can result in inefficiencies in the design and operation of buildings and their systems. In this context, the present contribution elaborates on the potential of a generative schema for the systematic representation of buildings' systems control architecture, including control devices, control zones, and associated actuators and sensors. The schema is inclusive vis-à-vis multiple control domains and multiple zones and can effectively support the systematic compartmentalisation of control logic in technologically complex buildings. To probe the robustness of the proposed schema in dealing with the multi-faceted and complex systems control circumstances in real buildings, a preliminary experiment was conducted, involving a group of architecture and engineering students. The participants found the method to be effective in supporting the configuration of buildings' technical systems and the communication between architects and engineers.*

KEYWORDS: *building systems, control logic, control zones, systems architecture*

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1. INTRODUCTION

The design and configuration of buildings' control systems does not seem to have 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 do not necessarily follow a structured approach, nor do they always reflect a traceable reasoning. Rather, such decisions appear to be frequently made on an ad hoc basis using implicit – heuristically grounded – knowledge of individual experts. Moreover, in many occasions, the decision processes in one domain (e.g. thermal control systems) are not sufficiently coordinated with other domains (e.g. visual control systems).

It can be argued that such lack of structure and integration may cause considerable inefficiencies in design and operation of buildings and their systems. Specifically, implementations of innovative (e.g. predictive) building systems control strategies may be hampered – amongst other things – due to a lack of transparent and systematic representations of the buildings' systems control architecture. Conventional literature on control theory does not fully address this problem (Mosca 1995, CIBSE 2000, Franklin et al. 2006, Unbehauen 2008). Of the previous – more pertinent – research work in this domain (Mahdavi 2001a, 2004, 2005, Mertz and Mahdavi 2003, Mahdavi and Schuß 2013) cannot be said that it has affected the current state of practice. Hence, a continuation of intensive research and development efforts in this area is in order.

Toward this end, the present contribution elaborates on a general generative schema for the representation of buildings' systems control components and architecture. This schema is inclusive vis-à-vis multiple control domains and associated control zones. Moreover, it has the potential to effectively support the systematic compartmentalisation of control logic in technologically complex buildings. To examine the robustness of the proposed schema in dealing with the complex systems control circumstances in real buildings, a preliminary experiment was conducted, involving a group of architecture and engineering students. Thereby, the schema was found to be effective in supporting the configuration of buildings' technical systems and the communication between architects and engineers.

2. BACKGROUND

2.1 Building systems control components and technology

The review of the pertinent literature does not yield a specific common terminology regarding building systems control. Thus, to facilitate the present treatment, a few terms, definitions, and exemplary instances are provided as per Table 1. Based on a few items from this Table, Fig 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 rule or algorithm) receives sensory information (S) concerning this parameter and manipulates the device's actuator (A). Consequently, the device delivers to (and/or extract from) the control zone some amount of mass and/or energy via the device's terminal (T). We do not assert that the building systems control terminology of Table 1 is entirely free of inconsistencies and ambiguities. Nonetheless, it can be shown to suitably support relevant domain discussions, if a number of conditions, qualifications, and simplifications are considered. Two such qualifications are briefly discussed below.

First, the notion of a "control zone" needs to be properly understood. A recurrent communication problem between control engineers and building design professionals could be avoided, if we view control zones 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 is a flexible entity that can be projected to buildings' constituent spaces and elements, but it is not identical with those. To exemplify this point, Fig 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.

Second, if a control device is to denote an entire HVAC (Heating, Ventilating, Air-Conditioning) system, it cannot be understood merely in terms of 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 would frequently imply a complex (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 properly pressurised ducts, and finally delivered – via multiple terminals – to the building's multiple thermal control 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 represent 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 operation 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.

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

Term	Definition	Instance
Controller	Agent that instantiates a control action	People, software
Control action	Modification of the state of a control device's actuator	Opening a window, switching lights on/off
Actuator	Component of a device that changes its state	Valve, dimmer, people
Control device	A technical entity that delivers to (or removes from) a control zone some quantity of mass and/or energy	Window, luminaire, HVAC
Control device terminal	The interface of a control device 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) in a control zone within a certain range
Control parameter	Indicator of the control zone's relevant state	Air temperature, relative humidity
Actuator state	Position of a control device's actuator	Open/close, dimming level, valve position
Control zone	Physical target domain of a control action	Workstation, room, floor, building
Control state space	The logical space of all possible positions of all relevant actuators	Positions of windows, blinds, luminaires, etc.
Sensor	Monitors the value of a control parameter in a control zone	Thermometer, photometer

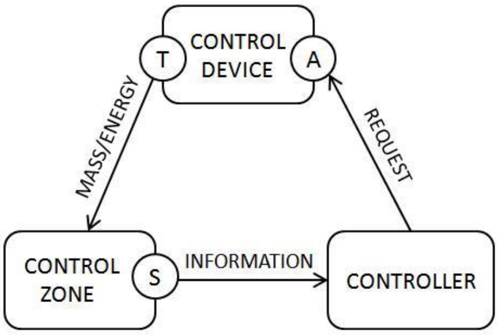

FIG 1: A basic control loop involving a control device, a control zone, and a controller. "T" and "A" denote device's terminal and actuator, whereas S stands for sensor

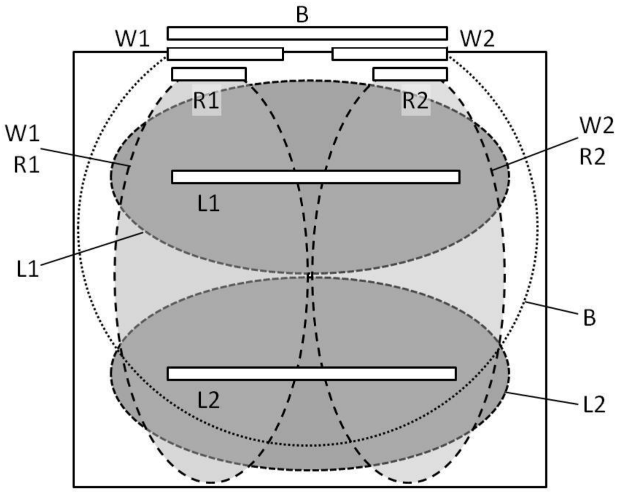

FIG 2: Schematic illustration of a room with multiple devices (B: external shade; W1, W2: windows, R1, R2: radiators; L1, L2: luminaires) together with the schematic depiction of the associated control zones

2.2 Complexity of building systems control architecture

We can now pinpoint one of the primary sources of complexity in designing control systems for buildings. In most practical cases, there is not an exclusive 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 (e.g., window, radiator, shading element). Likewise, the operation of a single device (e.g., 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 due to a number of factors such as system robustness, scalability, flexibility, adaptability, and security. On the other hand, the complex interplay of multiple devices in view of their implications for multiple control zones appears to imply a highly coordinated 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 pertaining to a previously introduced schema for the generation of the overall syntactic architecture of a building's systems control logic (Mahdavi 2004). This schema is primarily intended to support a systematic compartmentalisation of systems control logic in complex buildings.

3. COMPARTMENTALISATION OF CONTORL LOGIC

3.1 General approach

The starting point for systems control logic 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 (flow of mass and/or energy) instantiated by the device controller and acting on the control zone, or the flow of the zone state information (via zone sensor) to the device controller.

Note that the definition of two entity layers and their relationships involves some heuristically-based judgments and associated uncertainties. For instance, small unintentional influences (e.g. heat emission) of a specific device (such as a luminaire) on a specific (e.g. thermal) state of a zone 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. Specifically, we currently develop a simulation-aided methodology toward identification of effective impact zones of projected control devices. However, this method is not addressed in the present treatment.

The distributed architecture of the building systems' control logic is to be cogently derived from this limited set of initial relationships between two entity layers (control zones and control devices) in an automated fashion following a rule-based strategy (Mahdavi 2001a, 2004, Mertz & Mahdavi 2003). This architecture can be seen as a template or framework of distributed compartmentalized nodes, which can contain partial methods and algorithms for control decision making.

3.2 Generation rules

If a control task would only involve one-to-one relationships between control devices and zones, the control logic architecture would be trivially distributed, resulting in a maximally flat hierarchy. As this is rarely the case, deeper logical hierarchies are required.

At a very 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 commands. 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 in a spatial domain 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 (rules, algorithms, etc.).

The following set of steps facilitate the generation of a multi-compartment control logic schema (a unique hierarchical multi-layered configuration of nodes) for a specific control task:

- Step 1: Arrange distinct control zones in terms of the basis layer of the schema. The state of these zones is assumed to be dynamically monitored via respective zone sensors.
- Step 2: Arrange device controllers (DCs) in the next layer. Every individually controllable device is assumed to have a DC, which can – amongst other things – operate the device's actuator in the absence of higher-level requests (e.g., in case of the break-down in the communication system).
- Step 3: Connect device controllers (DCs) to the zones, whose states are appreciably influenced by the operation of DCs.
- Step 4: generate the first layer of logic compartments or nodes (layer of zone controllers) as follows: If more than one DC influences the same zone, a respective zone controller is required to coordinate their operation. Hence, this layer accounts thus for the need for zone-specific coordination across multiple devices.
- Step 5: generate the second layers of logic compartments (high-level controllers) 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. Note that high-level controls that control an identical collection of zone controllers can be merged.

- Step 6: Generate the terminal layer of nodes (meta-controller) as needed: If high-level controllers overlap in terms of devices involved, merge them into one meta-controller.

We do not proclaim that the above set of steps represents the only procedure to achieve a well-structured control logic compartmentalisation. Specifically, step 5 must not necessarily followed with a terminal step. Other, deeper hierarchical structures and associated generative rules are possible. However, the presented formulation of the generative procedure represents in our experience a proper balance between theoretical possibilities and practical applicability.

3.3 An illustrative schema generation example

Consider the illustrative control task pertaining to a simple office space as depicted in Fig 3. Control objective in this case is maintaining the values of a number of zone state indicators within target values. The zone state indicators (control parameters) are in this case air temperature (θ), 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 previously described generative steps, the distributed multi-layered multi-domain systems control schema of Fig 4 emerges. In this schema, layers 1 (zones) and 2 (device actuators) result from steps 1 to 3. Layers 3 (zone controllers) and 4 (high-level controllers) result from steps 4 and 5 respectively. Layer 5 ("meta-controller") emerges following step 6. Control requests communication in this schema is downwards, whereas the flow of information (e.g., sensor values and device actuator states) is upwards.

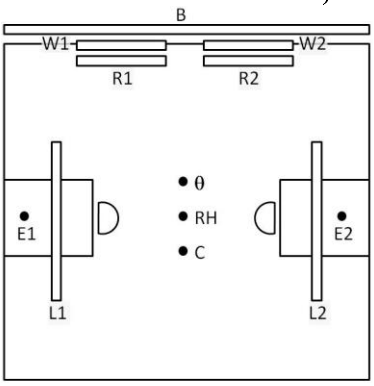

FIG 3: An office space with seven devices (windows W1 and W2, two radiators R1 and R2, two luminaires L1 and L2, and external shade B) and five sensors (illuminance sensors E1 and E2, indoor air temperature, relative humidity, and carbon dioxide sensors θ, RH, and C)

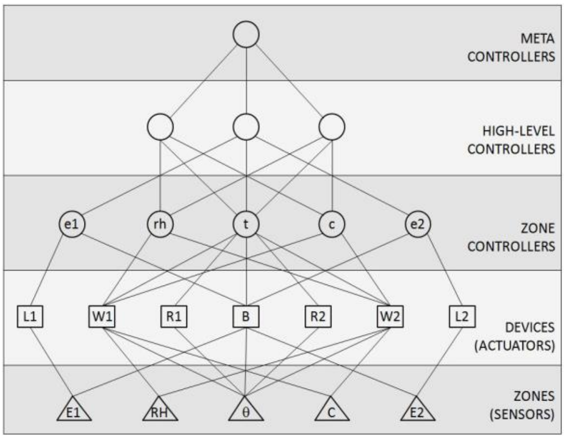

FIG 4: Illustrative distributed multi-layer multi-domain systems control schema for the office space of Fig 3

3.4 Populating the schema with semantics

In the previous section, we described a procedure 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 and within each compartment. 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, distributed, and scalable assembly of control code for large and complex building systems operation scenarios.

It is nonetheless useful to briefly discuss the manner in which the schema could be populated with control semantic. Toward this end, we focus here on the promising option of a simulation-based control strategy (Mahdavi 1997, 2001b, 2008). In the simulation-based control approach, 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 (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. This circumstance 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 (weather, occupancy, preferences). 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 compartmentalised structure. Devices can be equipped with simple methods (e.g., rules) to either autonomously operate their respective actuators (for instance in case system communications break down), or to suggest, to the upper layers, preferable actuator positions. Zone controllers could merge the recommendations they receive, via weight assignments (i.e., 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 proposals 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 (as in the previous examples) 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 to device layer (and higher) via virtual sensors. Likewise, environmental performance criteria (such as CO2 emissions attributable to the consumption of a certain type of fuel) as well as economic performance indicators (such as energy cost) could be effectively accommodated in the schema in terms of corresponding virtual meters and sensors.

4. A PRELIMINARY TEST OF USABILITY

To empirically explore the viability of the scheme generation method, we conducted a preliminary test involving a number of architecture and engineering students. Thereby, participants collected and documented the information for the generation of the control logic distribution scheme for a number of existing spaces. Subsequently, for each space the existing correspondence between zones and devices was documented and a respective control logic compartmentalisation scheme was generated. The results of the experiment provide an initial basis to evaluate the viability of the method in a realistic application context. They suggest that the proposed method can support the detection of inconsistencies in the existing patterns of control zones and device allocations. Moreover, the method can support the development of improved solutions for the design and placement of sensors, devices, and their actuators.

The experiment involved 29 architecture (84%) and engineering (16%) students. 24% of the students did not have prior education regarding buildings' technical systems in their education, whereas the rest had at least some background in this area. More than half of the students (52%) had not been previously exposed to building systems design issues, whereas the rest had some exposure. Most of the architecture students did not have any experience in communicating with building service engineers. Out of those architecture students who did have experience working with engineers, the majority suggested that the latter were open for system design suggestions by architects. All participants stated that architects must know more about buildings' technical systems.

The participants were introduced to the scheme generation method via a three-hour introduction session. Thereby, the theoretical background of the method and examples for its application were presented. The participants were asked to:

1. Select and document an existing space in a building;
2. Identify all control devices in the space and their associated terminals and actuators;
3. Estimate the spatial impact zone of each device;
4. Identify all sensors in the space (note that the actual spaces were rarely equipped with relevant environmental sensors) and specify sensors that should have been ideally installed as part of the system configuration);
5. Generate a proper control logic compartmentalisation scheme for the selected spaces based on information obtained through steps 1 to 4 above and following the scheme generation rules;
6. Fill a questionnaire concerning the scheme generation method (general effectiveness and the usability assessment of the method, common problems faced while generating the scheme, suggestions for improvement of the procedure).

A few weeks after the introductory session, a second session was held, where the participants presented their interim results. These included documentations of the selected spaces together with control distribution schemes, which they considered to be appropriate for the existing spaces and their devices. Based on feedback provided to the participants at this session, the interim results were modified and submitted as final documents. We reviewed these submissions and the questionnaire results to evaluate the fidelity of the generated schemes and the perceived effectiveness and usability of the scheme generation method.

Table 2 provides an overview of the questionnaire results. These results suggest that most of the participants found the proposed scheme generation method useful toward understanding and evaluating buildings' technical systems, improving the communication between architects and engineers, and supporting the improvement of buildings' energy performance.

The questionnaire involved also a few open-end questions. For instance, participants were asked to name the main problems in using the method. The most frequently mentioned problems concerned the correct placing of the sensors and the definition of zones. Participants mentioned also difficulties in defining zone controllers and high-level controllers in the scheme. Moreover, a large number of participants believed that the scheme generation method would become too complicated if applied to larger spaces.

The review of the submitted projects leads to a number of observations pertaining to the scheme generation method's usability and robustness. All participants performed the initial component of the task correctly: This means that the devices, terminals and actuators were properly identified. Participants also identified the spatial target of the devices, i.e. the zones. However, frequently there were problems with the number of identified zones. In a large number of projects, too many zones – and too many associated sensors – were defined. Participants had also problems with placing the sensors in proper locations. For example, in certain cases multiple spatially close rather small impact zones were defined for multiple luminaires. This, although the luminaires are jointly controlled, i.e. they share the same actuator.

Table 2: Overview of questionnaire results

Question	Participants' responses [%] Not at all	Not so much	A little bit	Yes	Yes, very much
Does the method make the understanding of buildings' technical systems easier?	0	16	16	60	8
Does the method help identifying design problems of buildings' technical systems?	0	0	40	52	8
Could the method contribute to energy saving measures in buildings?	0	8	20	56	16
Was it clear and convenient to apply the method to the selected room?	0	16	36	48	0
Can the method improve communication between architects and engineers?	0	4	44	48	4
Could the method be feasibly applied to larger and more complex spaces/buildings?	0	4	24	60	12

In certain instances, the one-to-one mapping between zones and sensors was violated, i.e. multiple sensors were positioned to cover the same zone. Likewise, in a number of cases only one sensor was provided to cover multiple zones. Moreover, sensors were occasionally placed in inadequate positions, i.e. on the periphery or even outside the corresponding zone.

As reflected in the questionnaire results, many participants had problems with the scheme generation process. A common problem concerned the generation of the layer of the devices. Frequently, multiple devices were represented separately, even if they were jointly controlled (i.e., shared the same actuator). If such devices are not combined in the scheme, the second layer of the scheme becomes too large. Hence the entire scheme becomes too complicated because of the numerous connections.

Difficulties were also experienced while generating the layer of high-level controllers. Most participants correctly generated the layer with the zone controllers and mapped the zones to the devices. The subsequent steps involved, however, errors in application of the scheme generation rules. Specifically, the high-level controller layer was often generated in a wrong fashion. For instance, layer generation process was prematurely terminated in that the zone controllers were simply connected with a high-level controller. Such cases suggest that some participants might not have fully understood the meaning and purpose of the associated generation rule.

Certain scheme generation problems were common amongst participants. One common problem was the separate representation of the devices in the scheme. The experiment suggested the potential for further simplifications in the scheme generation process. Presumably, one could argue that devices should be merged together in the scheme if they affect the same sensor (irrespective of them being individually controllable or not).

5. CONCLUSION

This contribution described a method to generate a compartmentalised control logic schema for multi-zonal multi-domain building systems control scenarios. The schema allows breaking down the structure of a complex control task into five layers (zones, devices, zone controllers, high-level controllers, meta-controllers).

Compartments in the zone controllers' layer facilitate zone-specific coordination of multiple devices. Compartments in the high-level controller layer facilitate device-specific coordination across multiple zones. These nodes provide thus containers for the distributed encapsulation of the required control semantic.

A preliminary experiment was conducted to probe the robustness of the proposed schema and its automated generation in dealing with the multi-faceted and complex systems control circumstances in real buildings. Toward this end, a group of architecture and engineering students deployed and evaluated the method using a sample of real spaces.

The participants' impression of the method and its usability was largely positive. The method was found to be effective in supporting the configuration of buildings' technical systems and the communication between architects and engineers. Actual implementation results, however, revealed in some cases a number of problems with the application of the method. This implies the need to develop a more effective communication framework (user interface) for the selection of devices and marking of the zones. Moreover, the envisioned environment shall offer interactive features to the users, such that certain steps in scheme generation could be taken in a semi-automated fashion, thus reducing the probability of generating schemes that are faulty or unnecessarily complex.

Currently, efforts are being undertaken to specifically examine and demonstrate the implementation of control logic distributed across multiple nodes of the multi-layered building systems control schema. Thereby, we explore the potential of a predictive simulation-assisted control semantics toward populating the distributed nodal structure of the proposed building systems control architecture.

6. ACKNOWLEDGMENT

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7. REFERENCES

CIBSE. (2000). Guide H: Building Control Systems. Butterworth-Heinemann; ISBN: 978-0750650472.

Franklin G. F., Powell J. D. and Emami-Naeini A. (2006). Feedback control of dynamic systems – 5.th edition; Pearson Prentice Hall; New Jersey; ISBN: 0-13-149930-0; 910 p.

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. Europia. 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. "Proceedings of the 5th ECPPM conference" (Eds: Dikbas, 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 11th 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.

Mahdavi A. and Schuss M. (2013). *Intelligent Zone Controllers: A Scalable Approach to Simulation-Supported Building Systems Control*. "Building Simulation 2013 - 13th International Conference of the International Building Performance Simulation Association." ISBN: 978-2-7466-6294-0; 1498 - 1505.

Mertz K. and 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.

Schuss M., Zach R., Orehounig K., and 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.