Holonic Management Systems for Resilient Operation of Buildings

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Abstract –

Building management systems monitor and control building performances in real-time. Most control systems, which have been developed in the last decade, achieve the required performances relying on a centralised and hierarchical framework. In the regular operation phase, these systems are usually able to efficiently reach their goals, whereas they often fail to stick to pre-determined targets in the presence of unforeseen disturbances. As a matter of fact, traditional control systems suffer complex unforeseen scenarios that cannot be modelled by the analytics and knowledge integrated in these systems, because hierarchical systems strive to keep full control at any level.

As an alternative, holonic management systems, which have been successfully applied in the manufacturing field, can tackle this type of drawbacks. The flexibility of their elementary units, the holons, makes it possible to avoid the rigid structure of hierarchical systems so as to respond quickly to disturbances and dynamically re-arrange their structure.

In this paper, a first holonic computing structure is developed for indoor comfort management in an office room. The structure developed can drive both the operation management phase and the medium- and long-term measurement of performances. The former is implemented by means of a sequence of specific minimum cost actions which is based on the overall throughput effectiveness (OTE) metrics. The latter exploits the same OTE metrics to suggest corrective and improvement actions. Finally, OTE diagnoses are re-directed to a BIM model to support decision making for long-term improvement actions on the building facility.

Keywords –

Intelligent Buildings, Building Management System, Holonic System.

1 Introduction

Building management is the process of monitoring and controlling the operating systems within building facilities. In the case of indoor comfort control, it includes heating, air conditioning, ventilation and shading units. Most commercial control systems, which have been developed in the last decade, achieve building indoor comfort relying on a centralised and hierarchical framework. Their hierarchical structure is usually made up of the following top-down layers: data acquisition, data transmission, data interpretation, performance evaluation and optimisation [1]. Strict master-slave relationships between layers imply top-down control decision, whereas bottom-up status reporting is implemented [2]. In the operation phase, hierarchical building management systems are usually able to reach their goals in an efficient way and with no faults, whereas they fail to stick to pre-determined targets in the presence of disturbances. In fact, traditional systems cannot pursue the assigned task if any unforeseen events occur. Their rigid structure makes it very difficult to tackle unexpected scenarios. As low-level modules have to consult higher hierarchy levels in case of a disturbance, their reactivity becomes weak. Furthermore, global decision-making is often based on obsolete information [2].

In this paper, a first holonic computing structure based on CPS technology is developed for the indoor comfort management in a room used as an office in a large public building. The operation management is managed by a control based on the measurement of the effectiveness of every device intended as a unit of the system of systems which applies a well-defined sequence of specific minimum cost actions. During simulations, an overall throughput effectiveness (OTE) metrics measures the subsystems' performances and drives corrective actions for their enhancement [3]. Finally, suggestions, history and lessons learnt from the OTE evolutions are re-directed to a BIM model to support decision making for the improvement of the whole building performance and design.

This paper is organised as follows. Section 2 provides a literature review of the holonic approach that was adopted in the present research. Section 3 describes the case research methodology. Section 4 provides a description of the case study. Section 5 shows the simulation results. Section 6 is devoted to conclusions.

2 Literature Review

The holonic concept, which is the basis of holonic management systems, was introduced in 1967 by Koestler [4]to explain the evolution of biological and social systems. Likewise, in the real world, where almost everything is at the same time a part and a whole, each holon can be part of another holon [2]. In fact, the word holon is the combination of "holos", which in Greek means "whole", and the suffix "on", which suggests a part [5], [6], [7]. In the manufacturing field, holons are autonomous and cooperative building blocks, since they can both control the executions of their own strategies and develop mutually acceptable plans [2]. Furthermore, holons consist of an information-processing part and often a physical processing part [2], [5], [6]. The former is responsible for high-level decision making, collaborating and negotiating with humans and other holons, while the latter is a representative of its linked physical component and responsible for transferring decisions and instructions to it [5]. According to Koestler, a holonic system or holarchy is then a hierarchy of self-regulating holons that function (i) as autonomous wholes in supra-ordination to their parts, (ii) as dependent parts in subordination to control at higher levels, and (iii) in coordination with their local environment [2], [4], [7]. Therefore, holonic architecture combines high and predictable performance, which distinguishes hierarchical systems, with the robustness against disturbances and the agility typical of heterarchical systems [6]. In this way, systems' resilience is guaranteed.

The agent, which in latin is "a person who acts", is a software-based decision making unit embedded with internal knowledge. Unlike holons, no such separation of physical and information processing parts exists in agents' structure. Furthermore, whereas holons can themselves be made up of other autonomous holons, agents do not immediately apply the recursive architecture [2], [5]. A multi-agent system is made up of two or more related agents [2], [7].

Cyber-physical systems, in the manufacturing field, are systems of collaborating computational entities which are in intensive connection with the surrounding physical world [8]. The interaction between physical and cyber elements is of key importance to the purpose of this paper. As a matter of fact, cyber-physical systems, similarly to holons, consist of a cyber part and a physical part. This shared feature makes holonic paradigm a suitable approach for constructing and modelling a CPS system in the form of a holarchy. Therefore, on the one hand, a CPS system permits bidirectional coordination of virtual and physical levels and, on the other, the holarchy, with its flexibility, guarantees evolutionary self-organisation or, in other words, resilience [5]. Moreover, CPS systems provide an opportunity for changes in the physical structure to be captured and reflected in the virtual model. Conversely, changes in the virtual model can be communicated to sensors embedded in the physical world [9], [10]. To implement these concepts in real world applications, agents are key enablers, since they act as decision-making and communication entities with agents embedded in other holons and also humans [5], [6]. Holonic management systems, which have been successfully applied in the manufacturing field, can constitute a novel technology to tackle unforeseen scenario variations. Indeed, the autonomy and cooperation of their elementary units, the holons, makes it possible to avoid the rigid structure of hierarchical systems and therefore respond quickly to disturbances [2].

3 Research Methodology

The holonic computing structure developed in this paper involves three development environments, Matlab®/Simulink®, SQL and Revit® (see Figure 1). The Revit® environment concerns the BIM Digital Model (BIM DM, see Section 3.2), as the interface of one of the numerous BIM softwares available on the market, such as Autodesk® Revit®. The Matlab® and SQL environments share the Decision Support Tool (DST, see Section 3.3), which has the function to assess the system of systems' effectiveness and suggest a list of possible corrective actions.

In addition to the DST, the SQL environment involves the BIM Relational Model (BIM RM, see Section 3.2), i.e. a relational database that acts as a bridge between the DST and BIM DM and has a double function. The first function is to update the DST when the BIM DM changes. The second one is to store effectiveness data received from the DST to run building diagnoses. The BIM RM and BIM DM exchange data in both directions, thanks to the Revit® DB-Link plug-in. In this way, the SQL and the Revit® environments are connected.

The Matlab® environment consists of the Supervision Policy (SP, see Section 3.4), the Virtual Simulation Laboratory (VSL, see Section 3.1) and the

DST block.

The measures taken from the VSL provide feedback (delayed by 1 step in order to be realistic) for the decision support tool. The DST evaluates and updates the OEE of each cell by means of SQL queries, then it updates the OTE in all the system's tree and suggests a list of possible actions to the Supervision Policy. Among the actions suggested by the DST, the Supervision Policy selects and applies the one to be carried out in the Virtual Simulation Laboratory based on some internal logic/intelligence.

In Figure 1 all these entities and their relationships are depicted.

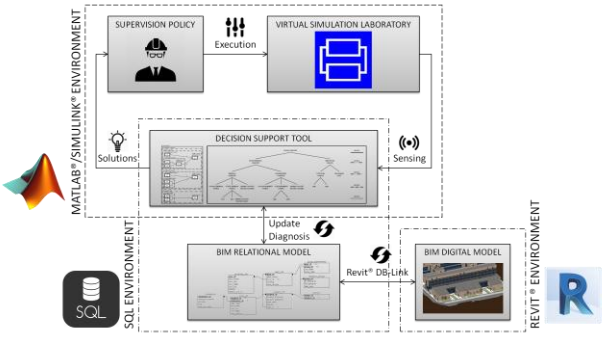


Figure 1. The architecture of the holonic computing structure developed based on CPS technology.

The holonic computing structure developed and implemented by integrating Simulink®, SQL and Revit® environments makes it to carry out any type of desired simulations away from the site.

3.1 Virtual Simulation Laboratory

The Virtual Simulation Laboratory is in charge of replacing and emulating the real building by using a detailed building model. This model was developed in the Dymola® programming environment, which is based on the Modelica® Language. Traditional simulation tools for thermal modelling are usually domain-dependent modelling environments. Whereas, Modelica® brought in relevant innovations allowing for equation-based modelling using program-neutral model description, domain-independent solution methods and the capability of exporting models as Functional Mockup Units (FMU).

The building model used in this work is built upon the open-source Modelica® "Buildings" library [11] and it has the level of detail that is necessary to analyse the behaviour of each device and sub-system belonging to the building. For the purpose of this paper, but without loss of generality, a model of the building restricted to the third floor is considered. However, a preliminary comparison of the comprehensive model with the one restricted to the third floor showed negligible differences. The model was then translated and compiled as a FMU so as to be embedded in the VSL through the Functional Mockup Interface (FMI).

By exploiting the capability of the FMI Kit for Simulink®, provided with Dymola® 2018, the VSL was integrated in the cyber physical system depicted in Figure 1 as an FMI block in co-simulation mode. The selected control inputs for the VSL are three actuator inputs normalised between 0 and 1: the shading level (SL), the fan coil level (FCL) and the window level (WL). The variables measured are both from indoor and outdoor. Indoor measures taken from the controlled room are: air temperature, relative humidity, CO_2 concentration, cooling power, AHU air flow rate, number of people. Outdoor measures are collected by a weather station included in the VSL which provides: air temperature, relative humidity, barometric pressure, wind speed and solar radiation on the horizontal plane.

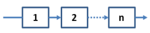
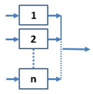
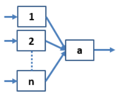
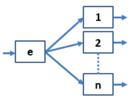
3.2 BIM Relational and Digital Model

In this paper the BIM Relational Model and BIM Digital Model are two sides of the same coin, the practical and the formal side, respectively. The BIM DM of the building under analysis was developed using Autodesk® Revit® and then translated into its congenital relational structure, namely the BIM RM. Hence, the BIM Model works as a repository of any types of data that belong to the building analysed.

The connection BIM RM-DST, as mentioned, provides the opportunity to define and update the scheme of the DST after changes to the building. In addition, the same link provides, in the other direction, the possibility of auto-diagnosis of the holonic management system developed. Actually, the BIM model becomes a repository of the facility history or of the potential actions of improvement concerning the building. Indirectly, a bi-directional communication channel is set up, i.e. a learning phase of the VSL from the BIM repository and the storage of real-time data from VSL into the BIM model.

In order for this to happen, the relational potential of the BIM has to be fully expressed. The underlying BIM representation of the information can be leveraged and further extended to create a mapping between a relational database. Note that the full Relational Model (RM) is intended in the sense described in [12]. In the RM everything is a relational variable (*relvar*). Tables, attributes and database schemas cannot usually be operated relationally. In current SQL-based database management systems (DBMS), these operations are implemented with non-standard host language proprietary extensions for the specific DBMS implementation. By a homomorphic mapping between

Table 1. OTE metrics computing formulas in recursive form adapted from [13].

Interconnection type		OTE of parent holon	R_{th} of parent holon	Q_{eff} of parent holon
Series		$\frac{\min\left\{\min_{i=1,\dots,n-1}\left\{OTE_i \cdot R_{th,i} \cdot \prod_{j=i+1}^{n} Q_{eff,i}\right\}, OTE_n \cdot R_{th,n}\right\}}{\min_{i=1,\dots,n}\left\{R_{th,i}\right\}}$	$\min_{i=1,\dots,n}\left\{R_{th,i}\right\}$	$\prod_{i=1}^{n} Q_{eff,i}$
Parallel		$\left(\sum_{i=1}^{n} OTE_i \cdot R_{th,i}\right) \Big/ \sum_{i=1}^{n} R_{th,i}$	$\sum_{i=1}^{n} R_{th,i}$	$\frac{\sum_{i=1}^{n} Q_{eff,i}}{n}$
Assembly		$\frac{\min\left\{\min_{i=1,\dots,n}\left\{OTE_i \cdot R_{th,i} \cdot Q_{eff,a} / k_{a,i}\right\}, OTE_a \cdot R_{th,a}\right\}}{\min\left\{\min_{i=1,\dots,n}\left\{R_{th,i} / k_{a,i}\right\}, R_{th,a}\right\}}$	$\min\left\{\min_{i=1,\dots,n}\left\{\frac{R_{th,i}}{k_{a,i}}\right\}, R_{th,a}\right\}$	$\frac{\sum_{i=1}^{n} k_{a,i} Q_{eff,i}}{\sum_{i=1}^{n} k_{a,i}} Q_{eff,a}$
Expansion		$\frac{\sum_{i=1}^{n} \min\left\{R_{th,e} \cdot OTE_e \cdot k_{e,i} \cdot Q_{eff,i}, R_{th,i} \cdot OTE_i\right\}}{\sum_{i=1}^{n} \min\left\{R_{th,e} \cdot k_{e,i}, R_{th,i}\right\}}$	$\sum_{i=1}^{n} \min\left\{R_{th,e} \cdot k_{e,i}, R_{th,i}\right\}$	$\frac{\sum_{i=1}^{n} k_{e,i} Q_{eff,i}}{\sum_{i=1}^{n} k_{e,i}}$

the BIM and its relational representation, we obtain the opportunity to develop new structured types that make it possible to record relational information and data. For example, in a BIM entity, it is possible to completely record the real-time history of parts of the building equipment as obtained from sensors. Moreover, it is also possible to record a tracking of the BIM structural changes over time. With data mining, knowledge extraction and representation techniques, some information can be grown upon, enriched, and a reasoning system can be integrated into the relational model of the building. This allows us to make BIM the core of short-term control and medium- and long-term design evolutions and adaptations on the building endowed with intelligence.

As a first experiment, the best available technology on DBMS has been used as a proof of concept. In order to interact bi-directionally with the BIM, the building digital model has been mapped to an SQL Server DBMS using the Revit® DB-Link plug-in. It permits the flow of information between Autodesk® Revit® and the DBMS in both directions. In this way BIM is updated with changes applied from the reasoner or the controller, and receives the real-time data from the virtual or physical models or the sensors. A workaround to the limited relational possibilities has been temporary created by extending some of the basic elementary BIM attributes with a numeric type that creates a primary key to some relations that can store real-time data tables or even a complete (nested) database schema.

3.3 Decision Support Tool

The operation management, as anticipated, is led by a pervasive control of the effectiveness of the system of systems. In other words, during simulations, an overall throughput effectiveness (OTE) metrics measures the subsystems' performances and drives corrective actions towards their improvement [3].

The distributed performance metrics, inherited from the manufacturing field, defines the overall factory effectiveness (OFE), the overall throughput effectiveness (OTE) and the overall equipment effectiveness (OEE). These parameters, whose values are between 0 and 1, are effectiveness indexes referring respectively to the highest level, intermediate levels and the lowest levels of a system's performance. The OEE metrics of one of the lowest production equipment is defined as follows:

$$OEE = A_{eff} \times P_{eff} \times Q_{eff}, \tag{1}$$

where the availability efficiency A_{eff} captures the deleterious effects due to breakdowns, the performance efficiency P_{eff} captures productivity loss due to reduced speed, idling or minor stoppages, and, finally, the quality efficiency Q_{eff} captures loss due to defects [3]. Subsequently, by applying the formulas in Table 1, the effectiveness of every system's cells is determined.

Note that OTE is a recursive function of OEE. This means that OTE is equal to OEE at the leaves of the recursive system's tree. OTE expression depends on four fundamental types of interconnection structures: *series*, *parallel*, *assembly* and *expansion*. In Table 1 we adapt the formulas and the structures from [13] that determine the four kinds of interconnection.

The parent-children relationship affecting elements located at different levels of the system is explained focusing on the assembly that is associated to the active thermal source (see Figure 2 and Figure 3). Once the OEE of the "children" fan coil unit (FCU), shading (SHA) and *assembly* cell (a_{ATS}) are defined, the OTE of the "parent" active thermal source is calculated using the *assembly* formula in Table 1. This is the procedure by which the whole systems tree is compiled with OEE/OTE values. Afterwards, by means of the Event-Condition-Action (ECA) calculation model described in [3], the DST provides, for each iteration, a list of suggested corrective actions.

The development of the structure of the DST follows two necessary and practical steps. The first one consists in defining the system's scheme with semantics. It could be defined as the closest representation to the humans' way of thinking (see Figure 2). Subsequently, the previous scheme is translated into the system's tree, defined, conversely, as the closest representation to the computing structure (see Figure 3). The system's tree shows the reconfigurability, scalability and robustness typical of holarchies, in other words, resilience. Indeed, it can be adapted to environment changes. At any level of it, the tree instance can be changed or dynamically reconfigured on purpose.

Both the system's scheme in Figure 2 and that in Figure 3 are made up of *cells* (the leaves of the tree) whose semantics is described as follows:

- TC: thermal conduction affecting external room's partitions;
- FCU: fan coil as a piece of equipment that is able to provide a cooling power;
- SHA: shading as a device that is able to reduce solar radiation, providing a fraction of it;
- LEA: air leakage through external room's envelope;
- WIN: window as a piece of equipment that is able to provide a moisture content variation and air flow;
- AHU: air handling unit as a piece of equipment that is able to provide a moisture content variation and air flow;
- a_{ATS}: room's mixing capacity of cooling power from thermal sources, function of room's shape and whose specific proportion is defined by k;
- a_{TS}: room's mixing capacity of cooling power from thermal sources, that is a function of the room's volume and whose specific proportion is defined by k;
- a_{HS}: room's mixing capacity of moisture content from humidity sources, function of room's volume and whose specific proportion is defined by k;
- ACR: air change rate defined by the amount of fresh air flowing in the room and its volume.

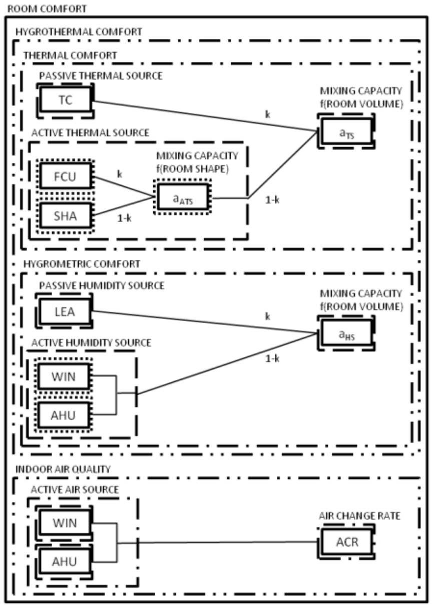


Figure 2. System's scheme developed for the case study.

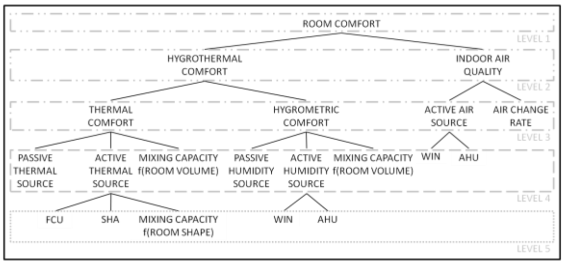


Figure 3. System's tree developed for the case study.

3.4 Supervision Policy

The Supervision Policy (SP) represents an intermediate step between the DST and the VSL (see Section 3.3and Section 3.1) whose function is similar to the one of a manager. Indeed, this entity selects, among the actions suggested by the DST, the action to carry out or leaves the status unchanged (no action). Hence, the SP defines the criterion by which the system acts or does not act. In addition, this "manager" has the ability to learn from the past (i.e. from the BIM, see Section 3.2). The effects obtained during the previous days suggest confirming or changing corrective actions.

In the simulations discussed in Section 5, the policy assumed for short-term operation management sets:

- high priority to thermal comfort (achievable by means of shading closing/opening and fan coil unit power on/off), average priority to indoor air quality (achievable by means of window opening/closing) and low priority to hygrometric comfort (achievable by means of window opening/closing). This means that, if actions are suggested for each sub-system, the first action field is thermal comfort, the second one is hygrometric comfort and the third is indoor air quality. This assumption does not imply that a field action is less important than another one, since the time step of each iteration is short (i.e. 5 minutes);

- higher priority to shading closing than fan coil unit power on and higher priority to fan coil unit power off than shading opening, in order to pursue thermal comfort according to energy saving principles;
- that a lower-priority action will be carried out in the following iteration if the related low performance persists;
- that if a higher-priority action is already running, the selection skips to the lower-priority one;
- that if more than one action for the same sub-system is suggested, the highest gain action is selected.

4 Case Study

Eustachio is the building where the Faculty of Medicine of the Polytechnic University of Marche, Ancona, Italy, is located. This is a large and multi-purpose building composed of two main blocks that create a clear division between the main fronts: the north and the south ones. It is equipped with a traditional building management system (BMS). The heating system is a two-pipe type and the air-handling system serves the north and the south fronts separately. Consequently, the building has some symptomatic discomfort problems like, for example, too high temperatures during winter, too low temperatures during summer, while mid-season temperatures are out of control.

In this paper, the focus is on one office room (i.e. room no. 90), located on the third level of the south front and used as an office (Figure 4). Its net surface is approximately 19 m^2 and the three-module window is about 7 m^2 large, with one module operable. The air handling unit in room no. 90 causes just air recirculation, since the humidifier does not work. The fan coil unit is a FC200 type and, for the purpose of the paper, only its cooling function in the summer season is considered. In addition, a shading system is also included. The actual BMS manages the cooling phase triggering both the fan coil unit and the shading device at the setpoint temperature of 26 °C.

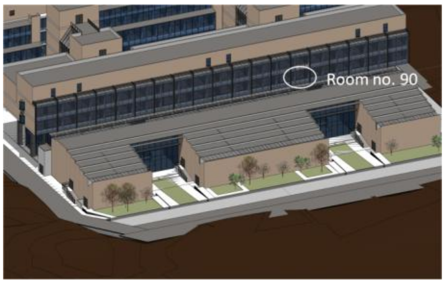


Figure 4. Room no. 90 in a 3D view of the Eustachio building's BIM digital model.

5 Simulations Results

The holonic management system, described in this paper is experienced for the month of June 2016. In this period, weather data define really dynamic boundary conditions able to strongly urge the system. The simulations for this representative scenario aim to prove the system's ability to perform short-term operation management in real time and diagnoses of building with regard to medium- and long-term refurbishment. Such diagnosis ability differentiates the holonic management system at issue from common BMS.

5.1 Operation Management of Building

The holonic management system accounts for building operation, regulating shading level (SL), fan coil level (FCL) and window level (WL) towards indoor comfort. In other words, it can put into practice instructions from the DST, i.e. suggested actions to reach system's improvement, according to the supervision policy (see Section 3.4). Although simulations were carried out for the whole month of June, in this paper only the simulation results of one day are discussed. The following charts show simulation results for the 17th of June. When operating temperature T_{op} exceeds the setpoint T_{set} (see Figure 5.a), the system reacts at first by closing the shading (see Figure 5.b, SL = 0.900) and then switching on the fan coil unit (see Figure 5.e, FCL = 1.000). The shading remains closed longer, giving priority to fan coil unit power off, according to the supervision policy aiming to save energy. When indoor relative humidity RH_i is far from the setpoint RH_{set} and, at the same time, outdoor relative humidity RH_o can help to improve it (see Figure 5.b), the system reacts by opening the window (see Figure 5.f, WL = 0.056). Finally, the system reacts to room overcrowding, which causes too high CO_2 concentration (see Figure 5.c), by opening the window (see Figure 5.f, WL = 0.112).

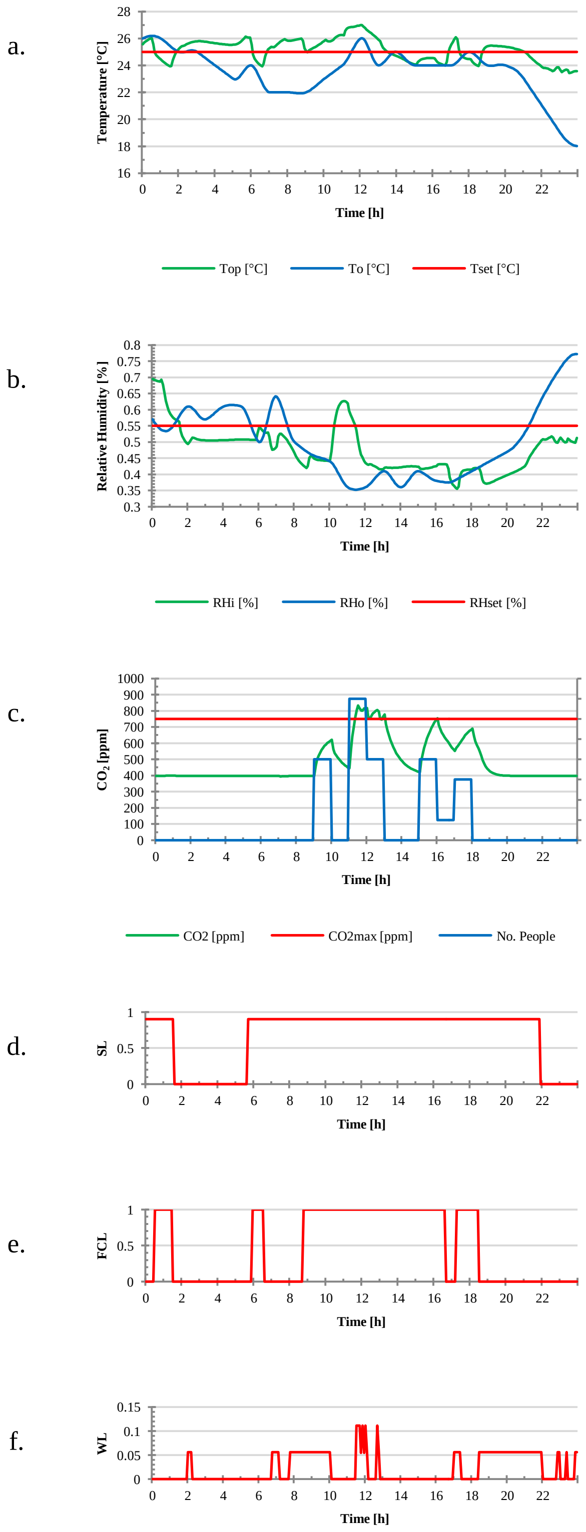


Figure 5. Operation management results for the 17th of June. Trends of a) temperature, b) relative humidity, c) CO_2 concentration vs number of people inside room no. 90, d) shading level (SL), e) fan coil level (FCL) and f) window level (WL).

5.2 Diagnosis of Building

The holonic management system makes it possible to carry out diagnoses on buildings by focusing on the system of systems' and cells' effectiveness mean value. In fact, BIM RM (see Section 3.2) can:

- store system of systems' time data, such as OTE/OEE time values, creating a repository of the facility history;
- store and re-direct their mean values, which are continuously updated according to the last iteration, to the BIM DM (see Section 3.2) in order to visualise them inside Revit® environment (e.g. during refurbishment design of building).

Low mean values of OTE and OEE highlight entities that cannot pursue the assigned target towards room comfort. Figure 6 shows OEE monthly mean values (June 2016) for the system's *cells* (the leaves of the tree) whose semantics is described in Section 3.3. The histograms point out the highest effectiveness of Indoor Air Quality sub-system. In fact, the room assumed as case study has a good air change rate (OEE_{ACR} = 0.90) and window ($OEE_{WIN(IAQ)}$ = 0.76) and air handling unit ($OEE_{AHU(IAQ)}$ = 0.86) ensure a satisfactory ventilation in June. Whereas, the room's external partitions are not effective in terms of thermal conduction (OEE_{TC} = 0.16) for indoor thermal comfort, since they are made of glass and metal. The shading (OEE_{SHA} = 0.19) and fan coil unit (OEE_{FCU} = 0.32) show possibility of improvement, since the former can be extended to the whole glass façade (both the transparent and the glazed part) and the latter can be boosted up. Results about hygrometric comfort point out how the window ($OEE_{WIN(HC)}$ = 0.67) and air handling unit ($OEE_{AHU(HC)}$ = 0.62) ensure a good enough contribution to optimal indoor relative humidity and room's external partitions are not effective, because of air leakage (OEE_{LEA} = 0.34).

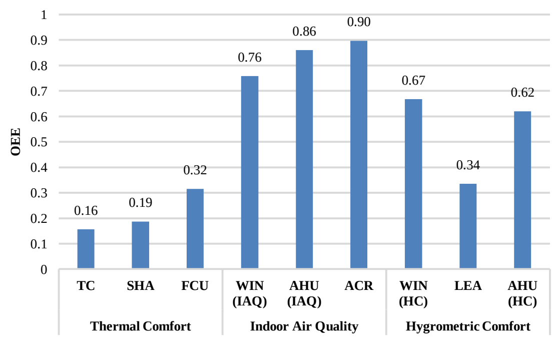


Figure 6. OEE monthly mean values (June 2016).

6 Conclusions

The holonic computing structure, which involves Matlab®/Simulink®, SQL and Revit® development environments, is experienced in a room used as an office. This computing structure works in two directions, the short-term management of building operation and the medium- and long-term diagnoses and refurbishment. In fact, the system shows its ability to reach a target, managing different parameters and devices and following an agreed policy. Besides, the connection of the above mentioned environments ensures diagnoses of buildings based on data history regarding system of systems' effectiveness.

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