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RESEARCH ARTICLE

Alessandro CARBONARI, Leonardo MESSI, Berardo NATICCHIA, Massimo VACCARINI, Massimiliano PIRANI

Development of a BIM-based holonic system for real-time monitoring of building operational efficiency

Abstract In the wide context of facility management, several processes, such as operations, maintenance, retrofitting, and renovations, ensure that buildings comply with the principles of efficiency, cost-effectiveness, and indoor comfort. Apart from ordinary operation, facility management is responsible for the renovation of and long-term performance improvement of building facilities. In such a scenario, the cyber–physical system (CPS) paradigm with holonic architecture, which is the focus of this study, can successfully guide the operation management and long-term refurbishment processes of buildings. Analogous to the manufacturing field, the developed CPS maximizes holons' self-configuration and self-organization and overall throughput effectiveness metrics to detect the best corrective actions toward system improvements. Consequently, suggestions and lessons learned from the evaluation of building efficiency are redirected to the building information model. Hence, the digital model acts as a repository of currently available equipment for operations management and the history of diagnoses that support decision-making during the maintenance, retrofitting, and renovation processes. Evidently, the repeated detection of a specific issue, which is unaffected by operations management, should be considered an opportunity to act and enhance the performances of existing building components. Similar to a goods-producing industry, the building management system developed in this study applies the aforementioned methodology to provide services related to indoor comfort and building health. This approach indicates that a method for automatic real-time diagnosis is tested in a case study consisting of a multi-use and large public building. The current paper, which is an extended version of the one presented in the Creative Construction Conference 2018, deepens the decision support tool and the supervision policy. Moreover, the developed system is contextualized by providing an example of use case and highlighting the step forward in the field of smart buildings.

Keywords BIM, building management system, cyber-physical system, facility management, holonic system

1 Introduction

In the wide context of facility management, several processes, such as operations, maintenance, retrofitting, and renovations, ensure that buildings comply with the principles of efficiency, cost-effectiveness, and indoor comfort. The relevant research in this field is turning toward challenging goals, which can obtain actual benefits from advanced data management and integration of intelligence, to produce cause-effect, performance, and deterioration modelling that has yet to be extensively surveyed (Volk et al., 2014). Although preliminary applications of performance monitoring have been suggested (Eastman and Sacks, 2011), evidence suggests that digitalization and building information modeling (BIM) should be further developed for general application to improved decision-making in complex facilities for refurbishment and facility management (Volk et al., 2014). Furthermore, the importance of BIM in the assessment of the performances of buildings has recently been discussed, along with the possibility of using structured knowledge to evaluate the condition of existing buildings (Bruno et al., 2018). Lastly, the majority of commercial building management systems (BMS), which

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Alessandro CARBONARI, Leonardo MESSI (✉), Berardo NATICCHIA, Massimo VACCARINI
Department of Civil and Building Engineering and Architecture (DICEA), Polytechnic University of Marche, via Brecce Bianche n. 12, Ancona, Italy
E-mail: l.messi@staff.univpm.it

Massimiliano PIRANI
Department of Information Engineering (DII), Polytechnic University of Marche, via Brecce Bianche n. 12, Ancona, Italy

have been developed in the last decade, achieve indoor building comfort that relies on a centralized and hierarchical framework. The hierarchical structure often comprises the following top–down layers: data acquisition, data transmission, data interpretation, and performance evaluation and optimization (Ma et al., 2010). Strict master–slave relationships between layers imply a top–down control decision, while bottom–up status reporting is implemented (Valckenaers and Van Brussel, 2016). In the operation phase, hierarchical building management systems are often able to reach their goals in an efficient manner and with no faults. However, these systems fail to pursue predetermined targets in the presence of disturbances. Traditional systems cannot pursue an assigned task if any unforeseen events occur. The rigid structure of these systems result in difficulty in addressing unexpected scenarios. The reactivity of low-level modules weakens because such modules have to consult high hierarchy levels in case of a disturbance. Consequently, global decision-making is often based on obsolete information (Valckenaers and Van Brussel, 2016).

This study develops a first holonic computing structure based on cyber-physical systems' technology for the indoor comfort management and medium- and long-term refurbishment processes of a large public building. The diagnosis is based on the measurement of the effectiveness of every device intended as an elementary unit of a system of systems. During operation, an overall throughput effectiveness (*OTE*) metrics measures the subsystems' performances and drives refurbishment design for their enhancement (Bonci et al., 2017). Recommendations, history, and lessons learned from the *OTE* evolutions are redirected to BIM to support decision-making for the performance and design improvement of an entire building. Similar to a goods-producing industry, the building management system developed in the current study applies the aforementioned methodology to provide services related to indoor comfort and building condition. Hence any manager, whether operating in the manufacturing or construction sectors, can leverage the effectiveness indexes and system's history to make the best decision.

The remainder of this paper is organized as follows. Section 2 provides a literature review of the holonic approach and effectiveness indexes adopted in the present research. Section 3 describes the case research methodology. Section 4 describes the case study. Section 5 shows the simulation results. Section 6 provides the conclusions.

2 Literature review

2.1 Holons, agents, and CPSs

The holonic concept, which is the basis of the holonic management systems, was introduced in 1967 by Koestler (1967) to explain the evolution of biological and social systems. In the real world, where nearly everything is simultaneously a part and a whole, each holon can be part of another holon (Valckenaers and Van Brussel, 2016). The word holon is the combination of holos, which means "whole" in Greek; and the suffix on, which suggests "a part" (Giret and Botti, 2004; Verstraete et al., 2006; Wang and Haghighi, 2015). In the manufacturing field, holons are autonomous and cooperative building blocks because they can control the executions of their own strategies and develop mutually acceptable plans (Valckenaers and Van Brussel, 2016). Furthermore, holons consist of an information-processing part and often a physical-processing part (Verstraete et al., 2006; Wang and Haghighi, 2015; Valckenaers and Van Brussel, 2016). The former is responsible for high-level decision-making, collaborating, and negotiating with humans and other holons, whereas the latter is a representative of its linked physical component and responsible for transferring decisions and instructions to the same physical component (Wang and Haghighi, 2015). Koestler (1967) explained that a holonic system (or holarchy) is a hierarchy of self-regulating holons that function (1) as autonomous wholes in supra-ordination to their parts, (2) as dependent parts in subordination to control at high levels, and (3) in coordination with their local environment (Giret and Botti, 2004; Valckenaers and Van Brussel, 2016). Therefore, holonic architecture combines high and predictable performance, which distinguishes hierarchical systems, with the robustness against disturbances and agility that are typical of heterarchical systems (Verstraete et al., 2006). Accordingly, systems' resilience is guaranteed.

The agent, which means "a person who acts" in Latin, 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. Although holons can be composed of other autonomous holons, agents do not immediately apply the recursive architecture (Wang and Haghighi, 2015; Valckenaers and Van Brussel, 2016). A multi-agent system comprises at least two related agents (Giret and Botti, 2004; Valckenaers and Van Brussel, 2016).

In the manufacturing field, cyber–physical systems are systems of collaborating computational entities that are intensively connected with the surrounding physical world (Monostori et al., 2016). The interaction between physical and cyber elements is of key importance to the purpose of the current study. Cyber–physical systems, which are similar to holons, consist of cyber and physical parts. This shared feature makes a holonic paradigm a suitable approach for constructing and modeling a CPS system in the form of a holarchy. A cyber–physical system allows bidirectional coordination of the virtual and physical levels, whereas a holarchy, given its flexibility, guarantees evolutionary self-organization (i.e., resilience) (Wang and Haghighi, 2015). 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 (Akanmu and Anumba, 2015; Yuan et al., 2016). To implement these concepts in real-world applications, agents are key enablers because they act as decision-making and communication entities with agents embedded in other holons and humans as well (Verstraete et al., 2006; Wang and Haghighi, 2015). Holonic management systems, which have been successfully applied in the manufacturing field, can constitute a novel technology to address unforeseen scenario variations. The autonomy and cooperation of these systems' elementary units (i.e., holons) may enable the avoidance of the rigid structure of hierarchical systems and immediate response to disturbances (Valckenaers and Van Brussel, 2016).

2.2 *OEE*, *OTE*, and *OFE* metrics

The overall equipment effectiveness (*OEE*), which was introduced by Seiichi Nakajima for applications in the manufacturing field, measure productivity and perform diagnostics at the equipment level. To address the gap at the factory level, an overall throughput effectiveness (*OTE*) metrics is developed (Muthiah and Huang, 2007). The purpose of *OTE* is twofold: it measures the factory-level performance and can also be used for performing factory-level diagnostics, such as bottleneck detection and hidden capacity identification. Any factory layout can be modeled using a combination of the predefined four subsystems (i.e., series, parallel, assembly, and expansion), thereby enabling the determination of the overall factory effectiveness (*OFE*). Moreover, *OTE* has the potential to automate the performance diagnostics of the entire factory-level, thereby driving a quantitatively continuous improvement of productivity. The current metrics is applied in Muthiah and Huang (2007) to case studies on wafer fab and glass manufacturing and shows that productivity bottleneck and opportunities for improvement can be identified quantitatively. In Stadnicka et al. (2017), the *OTE* metrics is experienced in the control process of kitchen fronts to support the decisions concerning improvements. In Stadnicka et al. (2017), it is performed in a telecommunication service to achieve an improved control of the effectiveness and bottleneck in the supply network. For the purpose of the current study, the described metrics can constitute a useful methodology to determine the possibilities of improvements in indoor climate comfort and future refurbishment.

3 Research methodology

3.1 System architecture

The holonic computing structure developed in this study involves three development environments, namely, MATLAB®/Simulink®, SQL, and Revit® (see Fig. 1).

The Revit® environment concerns the building digital model (bDM; see Section 3.6) as the interface of one of the numerous BIM software available on the market, such as Autodesk® Revit®. The MATLAB® and SQL environments share the decision support tool (DST, see Section 3.3), which assesses the effectiveness of the system of systems and suggest a list of possible corrective actions.

The MATLAB® environment consists of the virtual simulation laboratory (VSL) and supervision policy (SP; see Section 3.5) apart from the previously described DST.

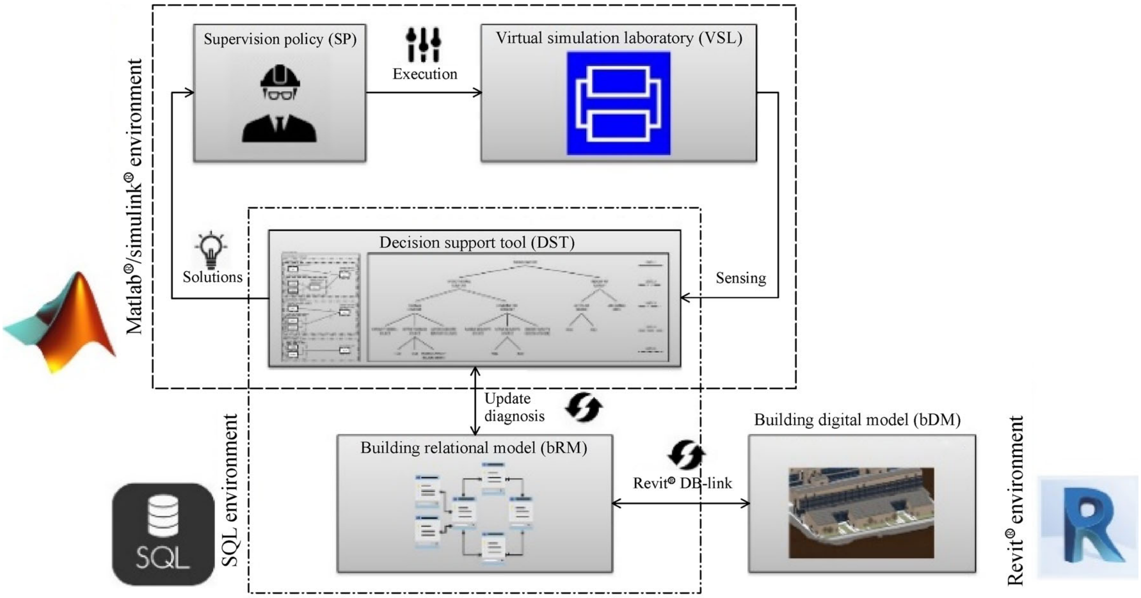


Fig. 1 Architecture of the developed holonic computing structure based on the CPS technology.

VSL is responsible for replacing and emulating a real building by using a detailed building model. This model was developed in the Dymola® programming environment, which is based on the Modelica® language. The building model used in the current research was built upon the open-source Modelica® "Buildings" library (Wetter et al., 2014), which has the level of detail needed to analyze the behavior of each device and subsystem belonging to the building. The measures taken from VSL provide feedback (delayed by 1 step to be realistic) for DST. DST evaluates and updates *OEE* of each cell through SQL queries. Thereafter, this tool updates *OTE* in the entire system's tree and suggests a list of possible actions to SP. Among the actions suggested by DST, SP selects and applies the one to be performed in VSL on the basis of some internal logic/intelligence (see Section 3.5). Similar to situations in which sensors and actuators are distributed around the building, the applied methodology enables the monitoring of the physical variable trends and track inputs (normalized between 0 and 1) of the corrective actions (see Fig. 2).

Apart from DST, the SQL environment involves the building relational model (bRM; see Section 3.6), which is a relational database that bridges DST and bDM and has a double function. The first function is to update DST when bDM changes. The second one is to store effectiveness data received from DST to run diagnostics of the building. Meanwhile, bRM and bDM exchange data in both directions owing to the Revit® DB-Link plug-in. This way, SQL and the Revit® environments are connected.

The holonic computing structure developed and implemented by integrating the Simulink®, SQL, and Revit® environments enables the implementation of any type of desired simulations away from the site.

3.2 Use case

The use case (see Fig. 3), which is considered the starting point of the previously described system architecture (see Section 3.1 and Fig. 1), clarifies the fields of application of the developed technology. Given that a real-world implementation is considered, the system architecture's VRP has been replaced with the real building (RB)

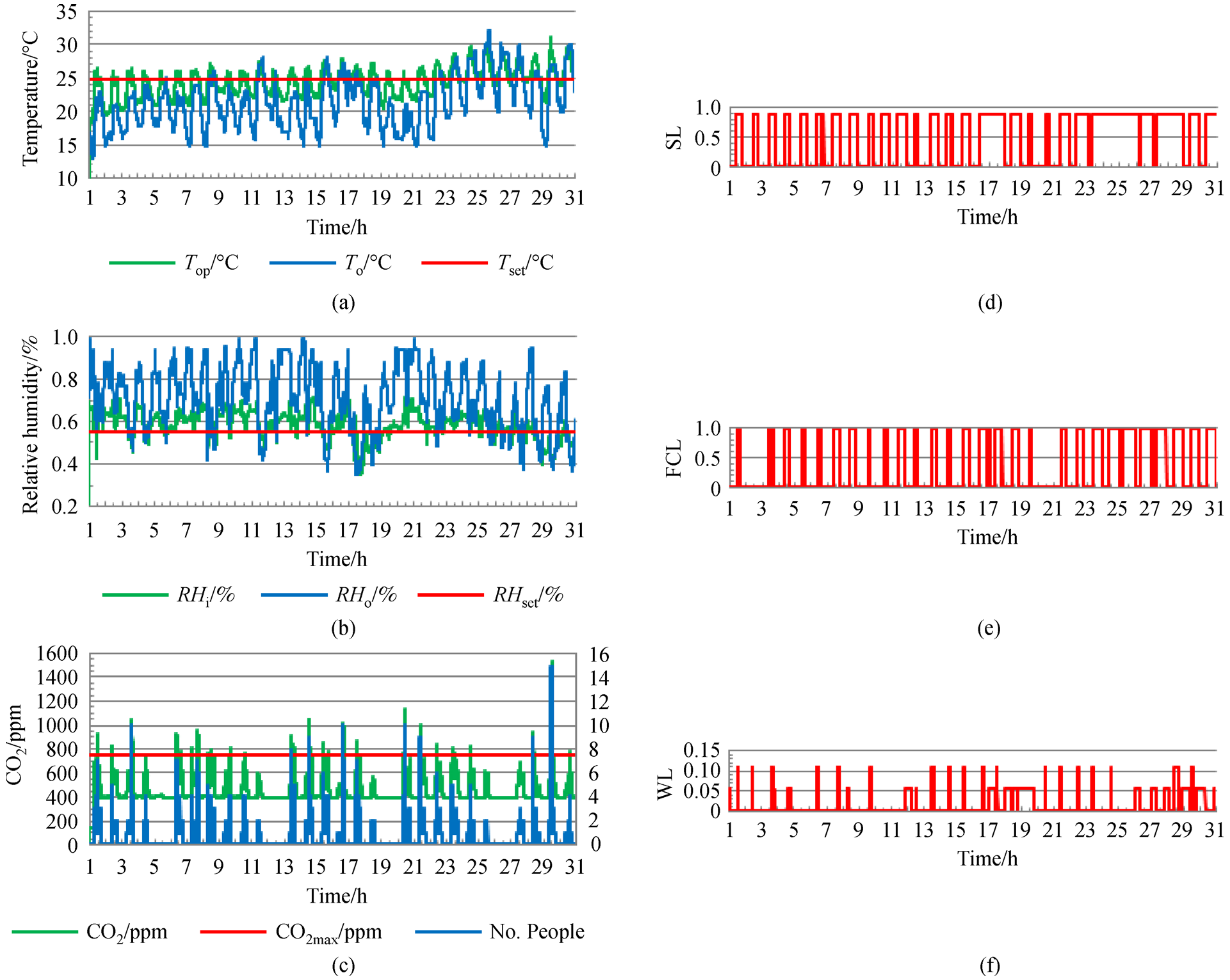


Fig. 2 Results of the operation management for June. Trends of (a) temperature, (b) relative humidity, (c) CO_2 concentration vs number of people inside room no. 90, (d) shading level, (e) fan coil level, and (f) window level.

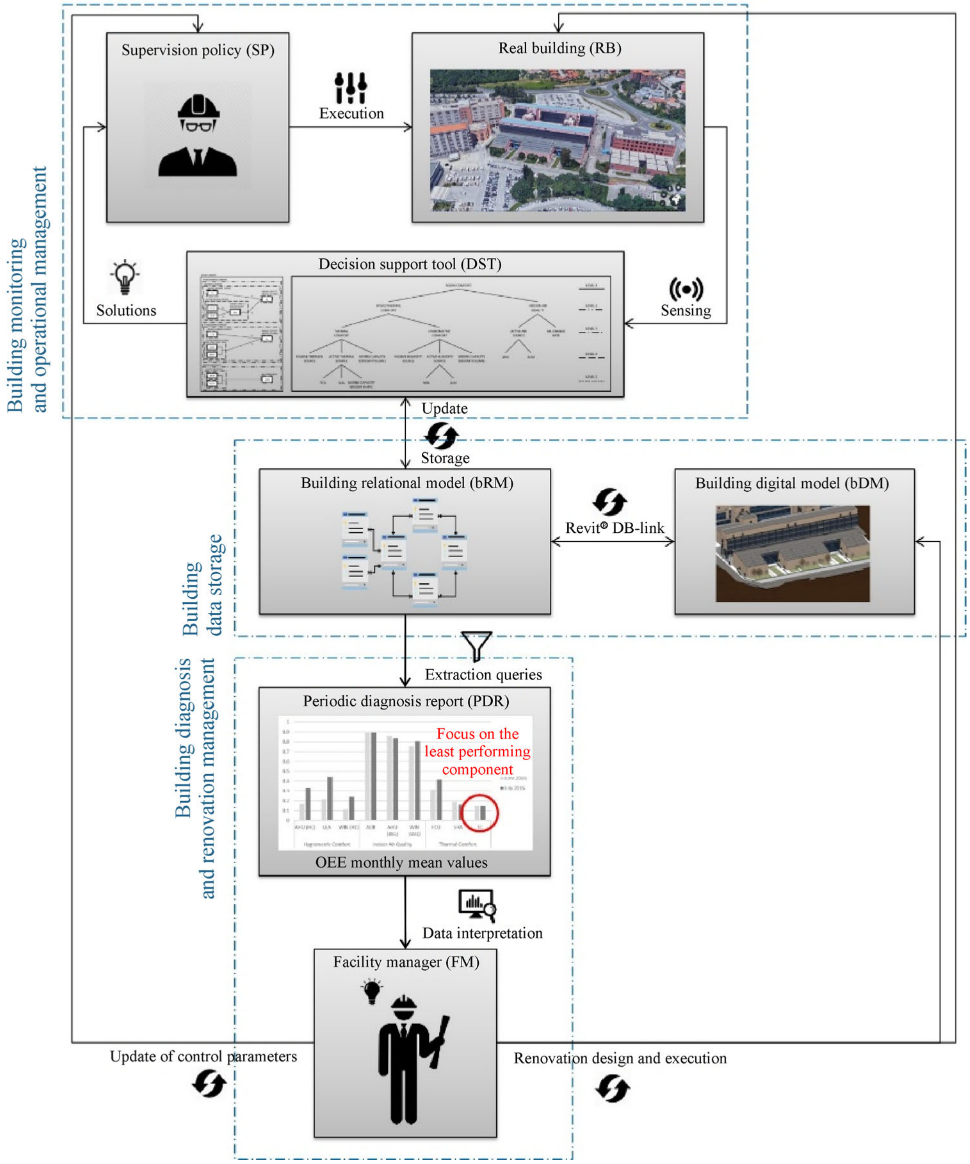


Fig. 3 Use case of the holonic system for operational and renovation management.

populated by distributed sensors and actuators. The building monitoring and operational management are carried out through DST, which processes physical parameters and provides a list of possible corrective actions. Meanwhile, SP applies the best corrective action on the basis of an adopted logic (see Section 3.5). Operational data from DST are stored into bRM and extracted by queries to deliver a periodic diagnosis report (PDR) to the facility manager (FM). The latter reveals to FM the performances of the components measured by the *OEE* values. FM can read PDR as a complete representation of the building behavior, particularly focusing on the least performing components to be modified or substituted. At this point, FM can implement the following actions:

- undertake a renovation process to commission the design phase, thereby implying a bDM update, and lead the renovation execution;
- update the control parameters of SP if after renovation the new building asset requires a different logic for the operational management.

3.3 DST

The operation and maintenance management is led by a pervasive control of the effectiveness of the system of systems, which drives corrective actions toward their improvement (Bonci et al., 2017).

During simulations, the distributed performance metrics, which were inherited from the manufacturing field, defines *OFE*, *OTE*, and *OEE*. These parameters, the values of which are between 0 and 1, are effectiveness indexes that refer to the highest, intermediate, and lowest levels, respectively, of a system's performance.

The *OEE* metrics of one of the lowest production equipment is defined as follows:

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

where the availability efficiency A_{eff} captures the deleterious effects caused by the breakdowns; performance efficiency P_{eff} captures productivity loss owing to reduced speed, idling, or minor stoppages; and quality efficiency Q_{eff} captures loss caused by defects (Bonci et al., 2017).

If a normal operation without breakdown events of devices is assumed for the first application, then the *OEE* metrics is re-adapted from manufacturing to building management:

$$A_{\mathrm{eff}} = \frac{T_{\mathrm{availability}}[\mathrm{time}]}{T_{\mathrm{need}}[\mathrm{time}]} \ (\approx 1 \text{ in normal operation}), \tag{2}$$

$$P_{\mathrm{eff}} = \frac{T_{\mathrm{production}}[\mathrm{time}]}{T_{\mathrm{availability}}[\mathrm{time}]} \ (\approx 1 \text{ in normal operation}) \times \frac{R_{\mathrm{actual\ effect}}[\text{speed or flow}]}{R_{\mathrm{theoretical\ effect}}[\text{speed or flow}]}, \tag{3}$$

$$Q_{\mathrm{eff}} = \frac{N_{\mathrm{good\ production}}[\mathrm{count}]}{N_{\mathrm{actual\ production}}[\mathrm{count}]} (\approx 1 \text{ in normal operation}). \tag{4}$$

Hence, the *OEE* formula re-adapted for buildings is defined as follows:

$$OEE \approx \frac{R_{\mathrm{actual\ effect}}[\text{speed or flow}]}{R_{\mathrm{theoreti\ caleffect}}[\text{speed or flow}]} \quad (1 \text{ in normal operation}). \tag{5}$$

OTE is a recursive function of *OEE* and likewise defines an effectiveness index that refers to any intermediate level of a system's tree. The *OTE* expression depends on four fundamental types of interconnection structures, namely, series, parallel, assembly, and expansion (see Fig. 4). Table 1 describes the *OTE* formulas, which were adapted from (Pirani et al., 2016), for each of the four types of interconnection.

In the buildings operation scenario, the application of these interconnections is set on the basis of the following definitions:

- series: succession of activities on the same part/entity with a specific order;
- parallel: group of activities not on the same part/entity without a specific order;
- assembly: group of parallel-type activities, the outputs of which are mixed following a specific proportion defined by k_i;
- expansion: group of parallel-type activities, the outputs of which are split following a specific proportion defined by k_i.

With reference to the developed system of systems (see Figs. 5(a) and 5(b)), the parent–children relationship, which affects the elements located at different levels of a system, is explained and focuses on the assembly defining the active thermal source subsystem (see red boxes in Figs. 5(a) and 5(b) to locate the subsystem within a system's scheme and system's tree, respectively; see Fig. 6(d) and Fig. 5(c) for an enlarged views of the subsystem from the system's scheme and system's tree, respectively). In this case, the assembly is the proper interconnection because the fan coil unit (FCU) and shading's (SHA) outputs are mixed following a proportion that depends on the room's shape. In the particular case of a regular-shaped room, FCU and SHA can affect the room comfort in the same measure and a parallel interconnection could be used (see Figs. 6(a) and 6(b)). In the most general case of an irregular-shaped room, the mixing capacity, which is the function of the room's morphology, must be considered (see Figs. 6(c) and 6(d)). Moreover, k_i represents how a subsystem's device affects a room based on a 0 to 1 ranking, which is normalized to 1 among all the subsystem's devices.

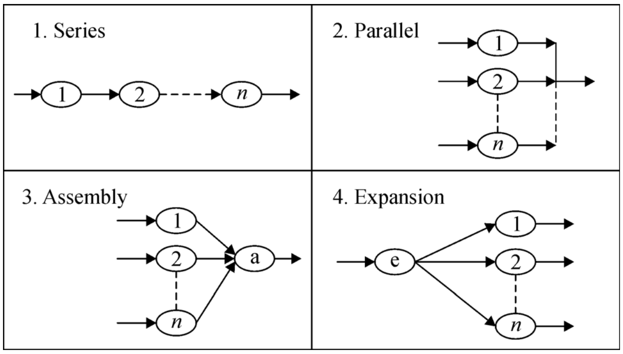
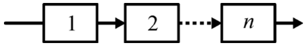
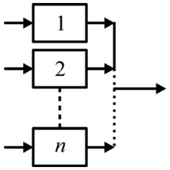
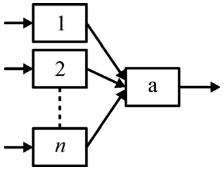
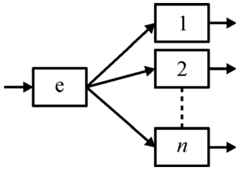
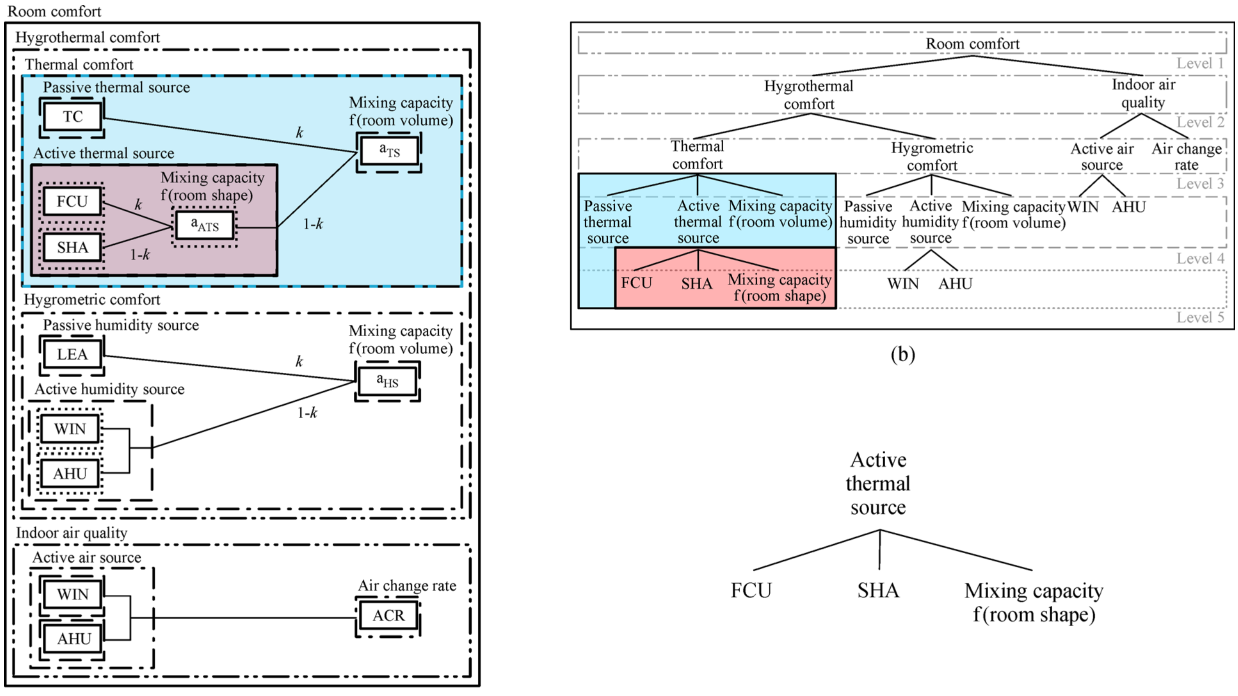


Fig. 4 Four unique subsystems. Adapted from Muthiah and Huang (2007) by permission of Taylor & Francis Ltd.

Table 1 Computing formulas of the *OTE* metrics in recursive form. Copyright(2016) IEEE. Adapted with permission from Pirani et al. (2016)

	Interconnection type	*OTE* of parent holon	R_{th} of parent holon	Q_{eff} of parent holon
Series		$\dfrac{\min\left\{\min\limits_{i=1,\dots,n-1}\{OTE_i\cdot R_{\mathrm{th},i}\cdot\prod_{j=i+1}^{n}Q_{\mathrm{eff},i}\},OTE_n\cdot R_{\mathrm{th},n}\right\}}{\min_{i=1,\dots,n}\{R_{\mathrm{th},i}\}}$	$\min\limits_{i=1,\dots,n}\{R_{\mathrm{th},i}\}$	$\prod\limits_{i=1}^{n}Q_{\mathrm{eff},i}$
Parallel		$\left(\sum\limits_{i=1}^{n}OTE_i\cdot R_{\mathrm{th},i}\right)/\sum\limits_{i=1}^{n}R_{\mathrm{th},i}$	$\sum\limits_{i=1}^{n}R_{\mathrm{th},i}$	$\dfrac{\sum\limits_{i=1}^{n}Q_{\mathrm{eff},i}}{n}$
Assembly		$\dfrac{\min\left\{\min\limits_{i=1,\dots,n}\{OTE_i\cdot R_{\mathrm{th},i}\cdot Q_{\mathrm{eff,a}}/k_{\mathrm{a},i}\},OTE_{\mathrm{a}}\cdot R_{\mathrm{th,a}}\right\}}{\min\left\{\min\limits_{i=1,\dots,n}\{R_{\mathrm{th},i}/k_{\mathrm{a},i}\},R_{\mathrm{th,a}}\right\}}$	$\min\left\{\min\limits_{i=1,\dots,n}\left\{\dfrac{R_{\mathrm{th},i}}{k_{\mathrm{a},i}}\right\},R_{\mathrm{th,a}}\right\}$	$\dfrac{\sum\limits_{i=1}^{n}k_{\mathrm{a},i}Q_{\mathrm{eff},i}}{\sum\limits_{i=1}^{n}k_{\mathrm{a},i}}Q_{\mathrm{eff,a}}$
Expansion		$\dfrac{\sum\limits_{i=1}^{n}\min\{R_{\mathrm{th,e}}OTE_{\mathrm{e}}\cdot k_{\mathrm{e},i}\cdot Q_{\mathrm{eff},i},R_{\mathrm{th},i}\cdot OTE_i\}}{\sum\limits_{i=1}^{n}\min\{R_{\mathrm{th,e}}\cdot k_{\mathrm{e},i},R_{\mathrm{th},i}\}}$	$\sum\limits_{i=1}^{n}\min\{R_{\mathrm{th,e}}\cdot k_{\mathrm{e},i}\cdot R_{\mathrm{th},i}\}$	$\dfrac{\sum\limits_{i=1}^{n}k_{\mathrm{e},i}Q_{\mathrm{eff},i}}{\sum\limits_{i=1}^{n}k_{\mathrm{e},i}}$



(a) (b) (c)

Fig. 5 (a) System's scheme and (b) system's tree developed for the case study; (c) enlarged view of the active thermal source subsystem from the system's tree.

The following relationships are provided once *OEE* of the "children" FCU, SHA, and assembly cell (a_{ATS}) (see Fig. 5(c)) are calculated from the VSL data:

$$OEE_{\mathrm{FCU}} \approx \frac{R_{\mathrm{act,FCU}}}{R_{\mathrm{th,FCU}}}, \tag{6}$$

$$OEE_{\mathrm{SHA}} \approx \frac{R_{\mathrm{act,SHA}}}{R_{\mathrm{th,SHA}}}, \tag{7}$$

$$OEE_{\mathrm{a_{ATS}}} \approx \frac{R_{\mathrm{act,a_{ATS}}}}{R_{\mathrm{th,a_{ATS}}}} \approx (1 \text{ in normal operation}). \tag{8}$$

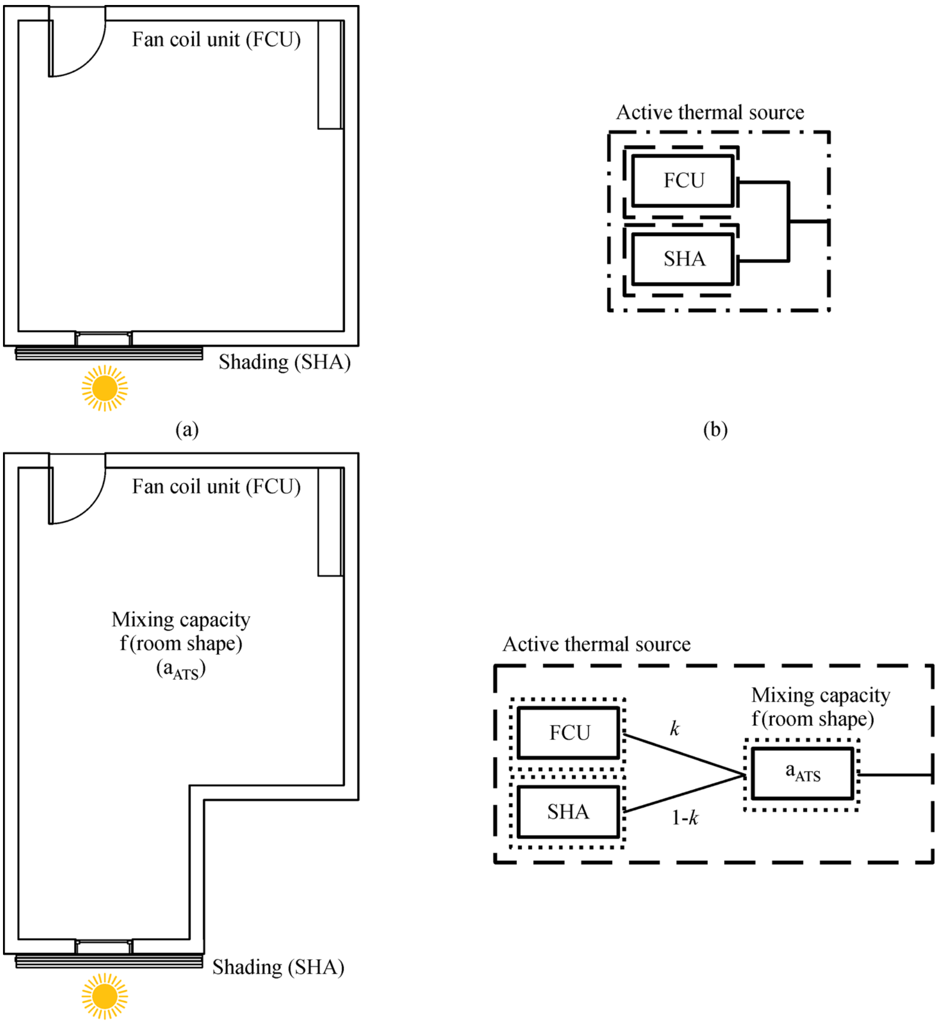
OTE of the "parent" (i.e., the active thermal source subsystem) is calculated using the assembly formula in Table 1 as follows:

$$OTE = \frac{\min\left\{\min_{i=\mathrm{FCU,SHA}}\left\{\frac{OTE_{\mathrm{FCU}}\cdot R_{\mathrm{th,FCU}}\cdot Q_{\mathrm{eff,a_{ATS}}}}{k_{\mathrm{a_{ATS},FCU}}},\frac{OTE_{\mathrm{SHA}}\cdot R_{\mathrm{th,SHA}}\cdot Q_{\mathrm{eff,a_{ATS}}}}{k_{\mathrm{a_{ATS},SHA}}}\right\},OTE_{\mathrm{a_{ATS}}}\cdot R_{\mathrm{th,a_{ATS}}}\right\}}{\min\left\{\min_{i=\mathrm{FCU,SHA}}\left\{\frac{R_{\mathrm{th,FCU}}}{k_{\mathrm{a_{ATS},FCU}}},\frac{R_{\mathrm{th,SHA}}}{k_{\mathrm{a_{ATS},SHA}}}\right\},R_{\mathrm{th,a_{ATS}}}\right\}}. \tag{9}$$

This procedure shows that the entire system's tree is compiled with the *OEE* and *OTE* values to detect the overall system's *OFE*. Thereafter, the event–condition–action (ECA) calculation model described in Bonci et al. (2017) is used as basis to enable DST to provide (for each iteration) a list of suggested corrective actions.

The development of the DST structure follows two necessary and practical steps. The first step involves defining the system's scheme with semantics. The latter could be defined as the closest representation to the human way of thinking (see Fig. 5(a)). Subsequently, the previous scheme is translated into the system's tree, which is defined conversely as the closest representation to the computing structure (see Fig. 5(b)). The system's tree shows the re-configurability, scalability, and robustness that are typical of holarchies (i.e., resilience) and can be adapted to environmental changes. At any level, the tree instance can be changed or dynamically reconfigured on purpose because it is a combination of elementary standard units. That is, if the building changes, the system's scheme will be adjusted using the most appropriate type of interconnection structure.

The system's scheme and tree in Figs. 5(a) and 5(b) are composed of cells (i.e., leaves of the tree), the semantics of



(a) (b)

(c) (d)

Fig. 6 (a) Regular-shaped room and (b) parallel interconnection compared with (c) irregular-shaped room and (d) assembly interconnection.

which in the current research is described as follows:

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

3.4 Holonic nature of the system

The developed architecture (see Fig. 1) clearly embodies the key features of holons described in Section 2.1.

The part-and-whole dualism, which is embodied within the word "holon" characterizes the DST structure (see Figs. 5(a) and 5(b)). For example, the active thermal source (i.e., highlighted in red) is a part of the assembly, which is called thermal comfort (i.e., highlighted in blue). Moreover, the active thermal source is an assembly itself (i.e., a whole) composed of FCU and SHA.

From this structure, another important holonic feature emerges, namely, autonomy and cooperation of holons. For example, FCU is contemporarily autonomous, as a piece of equipment able to provide a cooling power, and cooperative along with SHA and TC to guarantee thermal comfort (see Figs. 5(a) and 5(b)).

The combination of information-processing and physical-processing parts, which is typical of holons, is considerably evident if the use case implementation (see Fig. 3) is considered. In the current system, each building's device has a double form, which is the virtual representation within DST and its linked physical component in RB. The latter is the real device (e.g., the physical FCU), which applies the most convenient corrective action. The former (e.g., the virtual FCU) simulates the component, with all its properties inherited from the bRM and bDM, during the information processing performed by DST on the base of data collected by sensors. Moreover, the information-processing part (i.e., DST) is effectively responsible for high-level decision-making and for collaborating with humans. On the one hand the DST–SP connection provides the corrective action to be performed. On the other hand, the DST–bRM connection enables FM to extract useful data by means of queries.

The application of the holonic key principles to the developed system faces and overcomes the weakness shown by commercial building management systems. Common BMS fails in case of unexpected events because of their rigid hierarchical structure. By contrast, the proposed holonic system succeeds against disturbances. Moreover, the proposed system merges high and predictable performance, thereby distinguishing hierarchical systems with robustness against disturbances and agility, which are typical of a heterarchical system. That is, the current holonic management system guarantees resilience.

3.5 SP

SP represents an intermediate step between DST and VSL and acts similar to a manager. This entity selects, among all the actions suggested by DST, the one to carry out or leaves the status unchanged (no action). Hence, 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. That is, the effects obtained during the previous days suggest confirming or changing corrective actions.

In the simulations, the results of which are depicted in Figs. 2 and 10, 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). That is, if actions are suggested for each subsystem, then the first field of action is thermal comfort, the second is hygrometric comfort, and the third is indoor air quality. This assumption does not imply that a field of action is less important than another because the time step of each iteration is short (i.e., 5 min);
- higher priority to SHA closing than FCU power on and higher priority to FCU power off than SHA opening to pursue thermal comfort according to energy saving principles;
- if low performance persists, then a lower-priority action will be carried out in the following iteration;
- if a higher-priority action is already running, then the selection skips to the lower-priority one;
- if more than one action for the same subsystem is suggested, then the highest-gain action is selected.

3.6 Building relational and digital model

In this study, bRM and bDM are two sides of the same coin, which are the practical and formal sides, respectively. In particular, bDM is the building information model in its native environment and represented by a BIM software working interface (see Fig. 9(a)). By contrast, bDM of a building under analysis was developed using Autodesk® Revit® and translated thereafter into its congenital relational structure (see Fig. 8(b)), namely, bRM, to explicitly show its database nature. In addition, bRM works as an open repository of any type of building's data to be re-directed to bDM.

The bRM–DST connection provides the possibility of defining the DST scheme or updating it if the building changes. By contrast, the same link provides the possibility to carry out self-diagnosis of the developed holonic management system. BIM becomes a repository of the facility history or the potential actions of improvement concerning a building. Indirectly, a bi-directional communication channel is set up, that is, a learning phase of the VSL from the BIM repository and the storage of real-time data from VSL into the building information model.

Accordingly, the relational potential of BIM has to be completely 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 Darwen (2009). In RM, everything is a relational variable (relvar). Tables, attributes, and database schemas cannot frequently 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. Through homomorphic mapping between bDM and its relational representation, we obtain the opportunity to develop new structured types that make it possible to record relational information and data. 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 obtained, enriched, and a reasoning system can be integrated into the relational model of the building. Consequently, BIM becomes the core of short-term control and medium- and long-term design evolutions and adaptations on the building endowed with intelligence. After the fabrication, a digital twin of the building will continue to survive. The building digital model, which is constantly updated according to the status of the building itself, becomes the basis for FM's actions (Russell and Elger, 2008). The life of the building will be mirrored in BIM, which is assumed as a type of virtual twin. The last progress in the area of ubiquitous computing enables buildings to be increasingly networked. The building of the future will be equipped with an increasing number of sensors to monitor all types of activities. Hence, lighting, heating, air conditioning, and other services can be monitored and actually controlled. Sensors and services can relay their status in real-time to BIM, which serves as a living document of the facility throughout its life cycle (Russell and Elger, 2008). When renovations or modifications are required, the last version of bDM provides an excellent basis for the necessary design activities. When the built facility reaches the end of its life cycle and is going to be demolished, the digital twin provides detailed information about the materials used in its construction, in order to plan their environmentally-sound recycling or disposal (Borrmann et al., 2018). The dualism, which is building relational-digital model, is a first example of digital twin and represents the initial step toward the development of the analogue prototype. In the future, the real analogue building and its digital twin will be intelligent. They will exist parallel with one another and exchange information with one another (Russell and Elger, 2008).

As a first experiment, the best available technology on DBMS has been used as a proof of concept. To interact bi-directionally with bDM, it has been mapped to an SQL Server® DBMS using the Revit® DB-Link plug-in (see Fig. 7). It permits the flow of information between Autodesk® Revit® and the DBMS in both directions. Thus, BIM is updated with changes applied from the reasoner or controller and receives the real-time data from the virtual or physical models or sensors. A workaround to the limited relational possibilities has been temporarily 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.

A system's *OEE* history from DST, which is stored inside the SQL environment in a SQLiteStudio® DBMS, can be processed by queries (see Table 2) to make diagnoses (see Fig. 7). As an example, cell 9's *OEE* values can be copied from the entire history into the table "ID_995898" (see "Filter by #cell = 9" query in Table 2 and Fig. 8(a)). Once exported in SQL format, it is redirected into the SQL Server® DBMS (see "Copy table" query in Table 2). Thereafter, SHA's *OEE* mean value, which is updated in real-time for each iteration, can be stored inside bRM, thereby filling the specific attribute inside table "GenericModels" (see "Compile *OEE* mean value" query in Table 2 and Fig. 8(b)). Note that the SHA component in front of the case study room corresponds to cell 9 of the system of systems (i.e., "SHA" in Figs. 5(a) and 5(b)) and to the Revit element whose ID is 995898. Lastly, SHA's *OEE* mean value can be re-directed to the bDM using Revit® DB-Link plug-in and displayed inside Autodesk® Revit® as SHA's parameter (see Fig. 9(a)).

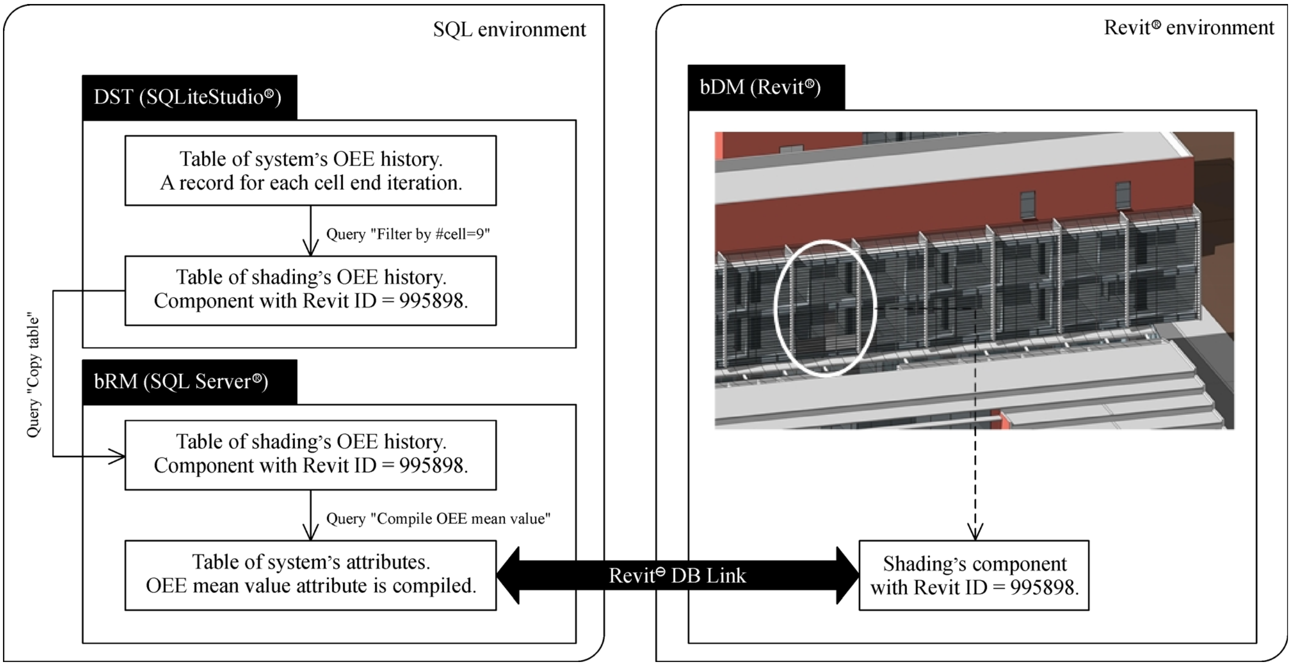
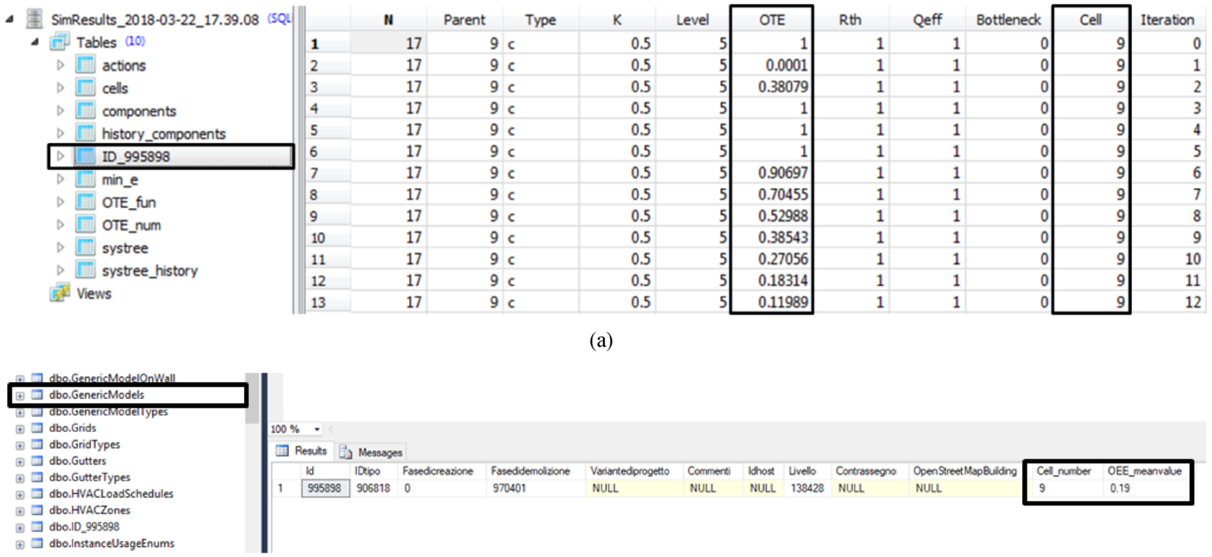


Fig. 7 DST–bRM and bRM–bDM connections.

Table 2 Queries to process and link data in the SQL environment

Query name	Query text
Filter by #cell = 9	CREATE TABLE ID_995898 (N INTEGER, Parent INTEGER, Type CHAR, K INTEGER, Level INTEGER, OTE REAL, Rth REAL, Qeff REAL, Bottleneck INTEGER, Cell INTEGER, Iteration INTEGER DEFAULT 0); INSERT INTO ID_995898 SELECT * FROM systree_history WHERE Cell == 9;
Copy table	CREATE TABLE [provaDBlink].[dbo].[ID_995898] (N INTEGER, Parent INTEGER, Type CHAR, K INTEGER, Level INTEGER, OTE REAL, Rth REAL, Qeff REAL, Bottleneck INTEGER, Cell INTEGER, Iteration INTEGER DEFAULT 0); INSERT INTO [provaDBlink].[dbo].[ID_995898] (N, Parent, Type, K, Level, OTE, Rth, Qeff, Bottleneck, Cell, Iteration) VALUES (17, 9, 'c', 0.5, 5, 1, 1, 1, 0, 9, 0); […] INSERT INTO [provaDBlink].[dbo].[ID_995898] (N, Parent, Type, K, Level, OTE, Rth, Qeff, Bottleneck, Cell, Iteration) VALUES (17, 9, 'c', 0.5, 5, 0.0001, 1, 1, 0, 9, 8641);
Compile OEE mean value	ALTER TABLE [provaDBlink].[dbo].[GenericModels] ADD Cell_number INTEGER; ALTER TABLE [provaDBlink].[dbo].[GenericModels] ADD OEE_meanvalue DECIMAL; UPDATE [provaDBlink].[dbo].[GenericModels] SET Cell_number =(SELECT Cell AS Cell_number FROM [provaDBlink].[dbo].[ID_995898] WHERE Iteration = 0) WHERE Id = 995898; UPDATE [provaDBlink].[dbo].[GenericModels] SET OEE_meanvalue =(SELECT avg(OTE) AS OEE_meanvalue FROM [provaDBlink].[dbo].[ID_995898]) WHERE Id = 995898; SELECT * FROM [provaDBlink].[dbo].[GenericModels] WHERE Id = 995898;



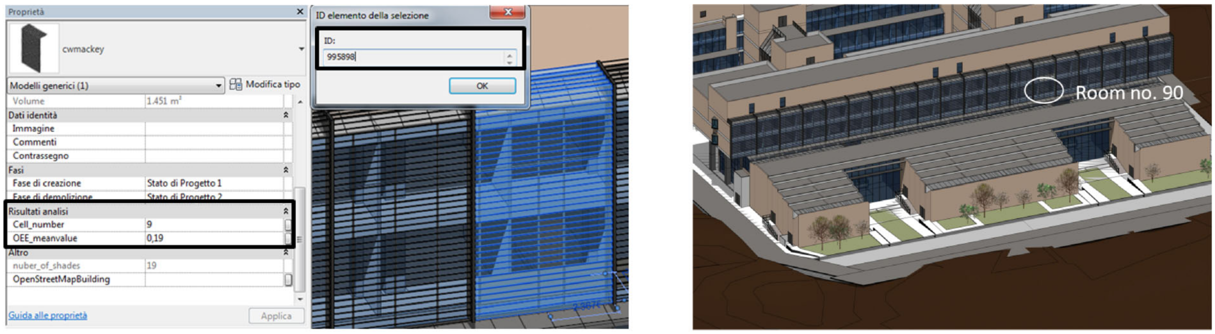
	N	Parent	Type	K	Level	OTE	Rth	Qeff	Bottleneck	Cell	Iteration
1	17	9	c	0.5	5	1	1	1	0	9	0
2	17	9	c	0.5	5	0.0001	1	1	0	9	1
3	17	9	c	0.5	5	0.38079	1	1	0	9	2
4	17	9	c	0.5	5	1	1	1	0	9	3
5	17	9	c	0.5	5	1	1	1	0	9	4
6	17	9	c	0.5	5	1	1	1	0	9	5
7	17	9	c	0.5	5	0.90697	1	1	0	9	6
8	17	9	c	0.5	5	0.70455	1	1	0	9	7
9	17	9	c	0.5	5	0.52988	1	1	0	9	8
10	17	9	c	0.5	5	0.38543	1	1	0	9	9
11	17	9	c	0.5	5	0.27056	1	1	0	9	10
12	17	9	c	0.5	5	0.18314	1	1	0	9	11
13	17	9	c	0.5	5	0.11989	1	1	0	9	12

(a)

	Id	IDtipo	Fasedicreazione	Fasedidemolizione	Variantediprogetto	Commenti	Idhost	Livello	Contrassegno	OpenStreetMapBuilding	Cell_number	OEE_meanvalue
1	995898	906818	0	970401	NULL	NULL	NULL	138428	NULL	NULL	9	0.19

(b)

Fig. 8 (a) Results of "Filter by #cell = 9" query applied inside SQLiteStudio® workspace (DST) and (b) "Copy table" and "Compile *OEE* mean value" queries applied inside SQL Server® (bRM).



ID: 995898

Volume 1.451 m³

Dati identità
Immagine
Commenti
Contrassegno

Fasi
Fase di creazione Stato di Progetto 1
Fase di demolizione Stato di Progetto 2

Risultati analisi
Cell_number 9
OEE_meanvalue 0,19

Altro
nuber_of_shades 19
OpenStreetMapBuilding

(a) (b)

Fig. 9 (a) *OEE* monthly mean value for June displayed inside Autodesk® Revit® as a shading's parameter and (b) the room No. 90 in a 3D view of the Eustachio's building information model (bDM).

4 Case study

Eustachio building is the location of the Faculty of Medicine of the Polytechnic University of Marche in Ancona, Italy. This structure is a large and multi-purpose building composed of two main blocks, thereby creating a clear division between the main fronts (i.e., north and south). The heating system is a two-pipe type and the air-handling system serves separately the north and the south fronts. Consequently, the building has some symptomatic discomfort problems, such as high temperatures during winter, low temperatures during summer, and mid-season temperatures out of control.

The focus of this study is one office room (i.e., room no. 90), which is located on the third level of the south front and used as an office (Fig. 9(b)). Its net surface is approximately 19 m^2 and the three-modules window is approximately 7 m^2 large, one of which is operable. Room no. 90's air handling unit causes just air recirculation because the humidifier is not working. The fan coil unit is a FC200 type. For the purpose of this research, only the cooling function in the summer is considered. In addition, a shading system is included. The application to this room has been used as a proof of concept for further simulations to the whole building. The described methodology (see Section 3) enables the immediate diagnosis of the causes of the building's limitations in terms of indoor climate comfort and plan future refurbishment.

5 Simulation results

The holonic management system in this study was applied in June and July 2016. In this period, weather data define dynamic boundary conditions that considerably affected the system. The simulations for this representative scenario aim to prove the proposed system's ability to perform short-term operation management in real-time and diagnoses building with regard to medium- and long-term refurbishment. 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 detail, bRM can perform the following tasks:

- store system of systems' time data, such as the *OEE*, *OTE*, and *OFE* time values, thereby creating a repository of the facility history;
- store (see Fig. 8(b)) and redirect the *OEE*, *OTE*, and *OFE* mean values, which are continuously updated according to the last iteration, to bDM (see Fig. 9(a)) to visualize them inside the Revit® environment (e.g., during refurbishment design of building).

The low monthly mean values of *OTE* and *OEE* highlight the entities that cannot pursue the assigned target toward room comfort. Figure 10 shows the *OEE* monthly mean values of the system's cells (the leaves of the tree, see Fig. 5(b)) for June and July 2016. Considering the month of June, the histograms point out the highest effectiveness of the indoor air quality subsystem. The room assumed as case study has a good air change rate (OEE_{ACR} = 0.89), while the window ($OEE_{\mathrm{WIN(IAQ)}}$ = 0.76) and air handling unit ($OEE_{\mathrm{AHU(IAQ)}}$ = 0.86) ensure a satisfactory ventilation. By contrast, the room's external partitions are not effective in terms of thermal conduction (OEE_{TC} = 0.15) for indoor thermal comfort because they are made of glass and metal. The shading (OEE_{SHA} = 0.19) and the fan coil unit (OEE_{FCU} = 0.31) 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. In June, the results of the hygrometric comfort point out a dual aspect: the window ($OEE_{\mathrm{WIN(HC)}}$ = 0.11) and the air handling unit ($OEE_{\mathrm{AHU(HC)}}$ = 0.17) do not ensure sufficient contribution to the optimal indoor relative humidity. Meanwhile, the room's external partitions are not effective because of air leakage (OEE_{LEA} =

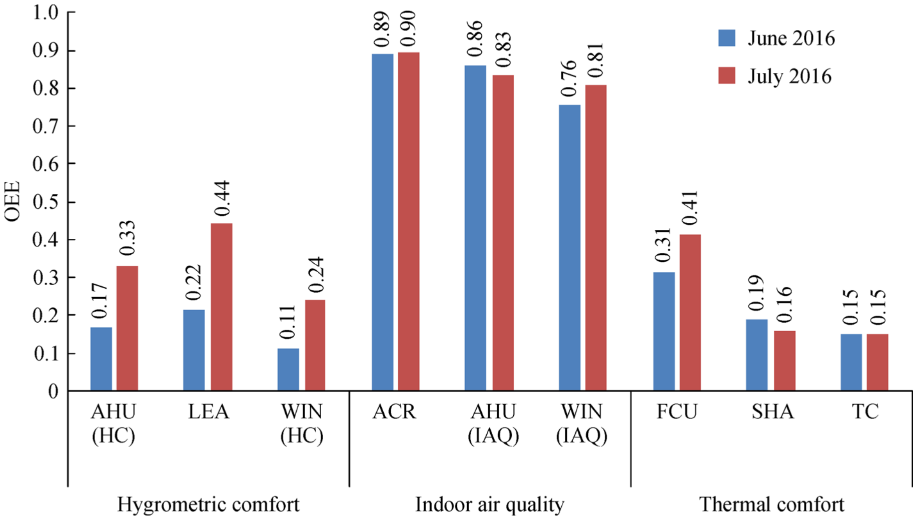


Fig. 10 OEE monthly mean values for June and July 2016.

0.22). In July, the subsystems concerning the indoor air quality and the thermal comfort show a similar behavior to June, whereas the hygrometric comfort one improves, since *OEE* values are doubled. The evolution of the building behavior, displayed in a chart month by month, drives the diagnosis and renovation process, detecting isolated cases and confirming bad performances. SHA and TC denote a constant shortage and the need to act to improve thermal comfort.

6 Conclusions

The holonic computing structure based on the CPS technology, which involves the MATLAB®/Simulink®, SQL, and Revit® development environments, is experienced in a room used as an office. The latter has been used as a proof of concept for further simulations to the whole building. The methodology described in this study makes it possible to diagnose quickly the causes of building's shortcomings in term of indoor climate comfort and plan future refurbishment. The diagnosis is based on the measurement of the effectiveness of every device, intended as a system of systems' unit, in terms of *OEE* values. During simulations, DST provides the *OFE* and *OTE* values as measures, respectively, of the entire system and subsystems' effectiveness and drives the enhancement of the refurbishment design. Furthermore, bRM has been considered a repository, in which system of systems' effectiveness values are stored. Lastly, these values are redirected to bDM and displayed inside Autodesk® Revit® as construction elements' parameters.

The current study represents a striking contribution toward the development of a smart building, characterized by a physical facility linked to its digital twin. The proposed technology supports the monitoring and operational management of the building and its data storage as well to easily perform diagnosis and manage the renovation process.

To conclude, similar to a goods-producing industry, the building management system developed in this study combines the CPS technology, holonic approach, and the *OTE* metrics to provide a service relating to indoor comfort and building health. Hence, any manager, whether operating in the manufacturing or construction sectors, can leverage effectiveness indexes and system's history to make the best decision.

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