A CYBER-PHYSICAL SYSTEM APPROACH FOR BUILDING EFFICIENCY MONITORING

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ABSTRACT

Digitalised models can play a key role in the management of building life-cycle. This paper focuses on the challenges connected to the operation phase of buildings, when the adoption of BIM can make information retrieval and management easier and more efficient. More specifically, a BIM-based cyber-physical system for the automated monitoring of buildings during their regular operation is proposed and tested by means of a customised simulator. The system automatically works out key performance indicators based on the overall throughput effectiveness (OTE) metric, assessing both the overall efficiency and the efficiency of every sub-system integrated in the building. Thus, assessments of the contribution of every sub-system to the operation of the building are performed in real-time. In addition, the metric proposed can help manage multi-objective real-time control. The system is self-reconfigurable thanks to the self-similarity assumption of the computational structure that is designed as a holarchy of holonic systems. The first application reported in this paper shows that when intelligence is embedded at both lower and higher levels, it is possible to generate information that is then used to update the digital model, developed as a BIM. As a result, the digital model becomes the mirror of the physical system and stores the actual performances recorded by the building to support facility managers in making decisions.

KEYWORDS: building management; BIM; performance assessment; cyber-physical systems; holonic systems; OTE/OPE.

1. INTRODUCTION

The architecture, engineering and construction (AEC) industry is asked to contribute to the transition towards a low-carbon economy, where resource usage is limited and infrastructures are more resilient, so as to face the effects of environmental changes [1]. To this purpose, a set of established and emerging challenges have been defined, covering all the phases of the life cycle of a building, where the integration of digitalised processes plays a key role. Among these challenges, in this paper particular attention is given to those regarding building management, which requires that sufficient information is made readily available to operators, in order to facilitate the retrieval of specific knowledge and exchange of information [2]. In other words, data automatically collected during the operation stage of buildings must be filtered and analysed to extract knowledge and relevant information that can support the tasks in charge of operators and building managers. Recently, more ambitious and specific objectives in the field of building management have arisen out of the advent of digitalisation and related technology. Indeed, building management can be enhanced thanks to the adoption of improved performance measurement approaches. These approaches should include both the automated collection of data and their arrangement into performance indicators, which must be referred to by operators and facility managers to assess a building in its life-cycle [3]. Such an aim requires a good transfer of performance information throughout the life cycle of a building, so as to regularly assess actual performance levels [4]. Within this context, Building Information Modelling (BIM) can play a key role as a mutual channel for information exchange among operators during the various phases of the life cycle of a building. As a consequence, relevant research is turning towards another challenging goal in facility management, which can get real benefits from advanced data management and integration of intelligence, so as to produce cause-effect, performance and deterioration modelling, which has not extensively been surveyed yet [5]. Although preliminary applications concerning performance monitoring have been suggested [6], there is evidence that digitalization and BIM must be further developed to be applied to improved decision making in complex facilities for refurbishment and facility management in general [5]. Furthermore, the importance of BIM in the assessment of the performances of historical buildings has recently been discussed, along with the possibility of using structured knowledge in order to perform inference about the health of existing buildings [7].

Within the context above, this paper reports on the preliminary development of an intelligent system architecture which is able to structure tools for the automated assessment of actual performances. In addition, the proposed architecture is able to generate a list of potential improvements in the operation phase of buildings, so as to provide useful feedbacks to building managers. At the same time, the system architecture can perform multi-objective real-time control in the operation phase of buildings.

The approach proposed in this paper exploits the cyber-physical system (CPS) concept, which is a major paradigm that underlies the introduction of intelligence, control, and networking in physical systems in a pervasive way. In the last decade, cyber-physical systems have played a leading role in industrial transformation strategies (e.g. Industry 4.0 in Europe). However, the exploration of the benefits and applicability of cyber-physical systems to the construction industry is still at an initial stage [8]. In [9] it is acknowledged that a better modelling of cyber-physical systems is still a need in the AEC domain.

As a powerful complement to the CPS approach, BIM can lay the basis of a bridge towards the increased digitalisation required by the CPS framework. The new functionalities BIM needs to have for it to adhere to the CPS concept can be summarised by following a recent classification [10], according to which BIM should:

1. be integrated into its environment: it should be physically embodied and positioned in order to record and evaluate physical data from sensors, act or react to events with actuators;
2. be efficient in its environment: it should be specific to an application domain and enhance the capabilities and possibilities of the overall environment;
3. be connected to its environment: it should be connected to a global network and to other cyber-physical systems in order to use and provide data and services;
4. cooperate with its environment: it should be equipped with multimodal human-machine and machine-to-machine interfaces.

The application of the CPS concept to buildings requires a rethinking of the whole facility architecture. In fact, buildings must be modelled as a set of agents, where every agent interacts with other agents and with any high level reasoning unit to reach a common goal. They must be equipped with local intelligence and tools or rules for interaction, so as to be able to advance towards their common objective in the next time step. They must be made able to react to the decisions of a possible high level control unit and aware of a direct communication with a mirror of the real system, which can be represented by a digital model (e.g. the BIM one). Finally, for cyber-physical systems to be feasibly applied to the building and construction field, a lean approach that better links humans and information and communications technology (ICT) must be found.

In order to deal with this need for a lean approach, in the last twenty years holonic structures have been exploited in an attempt to render complexity treatable in manufacturing and beyond [11]. To enhance the CPS concept towards the re-organisation of systems, the holonic approach can be integrated into the CPS architecture. In order to introduce artificial intelligence (AI) into the CPS concept, the holonic approach must be associated to the multiagent system (MAS) paradigm and its engineering [12] to be effective; this is known as the concept of holonic MAS [11, 13, 14]. The main benefits to be brought to AEC by the holonic approach are self-adaptation to the unexpected, dynamic aggregation of units, self-similarity as simplification of complex systems. Cyber-physical systems and holons can be used to determine a reference architecture for building management systems, on which intelligent control policies can be developed and enforced.

In [11] several case studies on holonic multi-agent systems and holonic management systems proposed over the last twenty years are surveyed and critically weighted. In the view of the authors, major takeaways from these studies can be summarised in the following:

- the holonic MAS is a promising tool for the control and design of complex systems-of-systems;
- there has been no clear winning software engineering paradigm so far;
- the design of the control must take into account the unexpected to render a system really flexible and resilient;
- design for the unexpected requires specifying a constraint, a rule or a specific implementation at the latest phase and being ready for change.

In this paper, a reference architecture that can integrate the CPS approach in the management of buildings is developed and tested. More specifically, an open-ended and simplified plug-in system is provided for the automated performance assessment of existing buildings and the detection of necessary improvements, while preserving its integration in a BIM model. The automated system is based on the overall throughput effectiveness (OTE) approach, which was originally developed as an enhancement of the overall equipment effectiveness (OEE) metric [15].

In the following, Section 2 provides the scientific background. Section 3 illustrates the methodology, materials and concepts that are relevant to the approach presented. In Section 4, the approach developed in Section 3 is applied to a real test case. Section 5 is dedicated to conclusions. Acknowledgments and references close the paper.

2. SCIENTIFIC BACKGROUND AND RELATED WORK

2.1 Building information modelling and intelligent management systems

The importance of integrating BIM and management processes has been stressed by several authors. Not many years ago, Fischer [16] described how formalised construction knowledge can lead to self-aware virtual elements that “know” what affects their design and behaviour and are able to react to it. Although a complete formalisation of construction knowledge has not been performed yet, BIM may help to start from atomic parts of it and provide value. An example is provided by the application of cyber-physical systems to temporary structures in construction sites [8]. The high degree of integration between a computing (e.g. virtual or BIM) system and a physical system may lead to a framework where the former embeds models to timely alert the physical system to risks or actions that need to be urgently taken; the latter is complemented by an integrated sensor network to feed the models in charge of dynamically estimating its own status. Thanks to the CPS approach, a bi-directional coordination between the physical system and the virtual model was set, facilitating the management of the physical system, while improving safety, efficiency, accuracy of performance assessment.

Great benefits have been achieved since the implementation of information systems to manage collaborative standardised processes in manufacturing industries. Whereas, the AEC industry is struggling to make the information generated and organised in BIM models compatible with task-specific processes. Towards this direction, information delivery manuals have been developed as a business process modelling language whose double purpose is both to report information that needs to be exchanged to perform a task in a process and to model and to re-engineer AEC processes [17].

Furthermore, in the field of energy management the role of the BIM-based virtual model is to accommodate, create, transform and transfer information according to evolving needs during the life cycle of a building. To this purpose, a specific study was conducted in the field of integration between BIM and building energy management systems, so as to facilitate interoperability between BIM and energy simulation tools, which would speed up the overall design process [18]. In particular, the adoption of a novel interface between BIM software tools and Modelica-based thermal models, along with a semantic enrichment process has been suggested, to allow designers to perform a quick verification of design assumptions while developing their BIM models. The information can then be easily retrieved and updated during the life-cycle of a building, which would dramatically benefit from the integration of advanced energy management and control systems to optimise the operation. One of the reasons is that building energy management systems usually operate according to predefined energy control strategies. This approach results in an overall loss in energy efficiency of 10-15% that could be recovered by adopting automated and self-adapting systems [19]. The development of such automated and self-adapting systems requires the adoption of holistic approaches, advanced monitoring, seamless integration of users, ICT devices and computational resources as well as enhanced BIM tools that can support knowledge generation and extraction, which asks for the enhancement of digitalisation and BIM. Furthermore, some cases of successful BIM implementation applied to the facility management process are now available [20]. These examples show that the development of BIM tools cannot be decoupled from construction and facility management tasks. Also, the formalisation proposed at the various phases of the process must allow the automatic transfer of relevant data and information.

The extension of BIM towards the “management” concept has been surveyed even in the field of historic buildings. One of the goals mentioned is to aid the diagnosis of building health status, which requires the integration of many technical challenges, such as smart knowledge acquisition, collection and notification of performances, cognitive automation and artificial intelligence (AI). Therefore, the main goal claimed in scientific contributions about introducing diagnostics and monitoring of existing buildings in BIM models is to give a contribution to support decision making processes [7].

Further studies have suggested that standardisation alone cannot be enough unless BIM evolves towards new, harmonised, innovative solutions which involve all stakeholders, improve the way they communicate and re-think processes and communication channels. These considerations led to the application of a process-centred approach supported by conceptual process modelling and systems-thinking (i.e. causal dependencies are explicitly identified), including a system-of-systems (SoS) method, which is capable of identifying synergies of related systems [21]. As a result, the development and use of BIM-SoS has provided several organisational and technological advantages, such as better collaboration between different processes or tasks, better standardisation, facilitated exchange of implicit data that can be determined from explicit data, model sharing among stakeholders acting in the different phases of the overall construction process. In conclusion, this methodology combines the advantages of conceptual process modelling and the holistic power of the systems-thinking concept of SoS.

A further paper explored the evidence, showing how digital collaboration technologies are being used in the delivery of major building and infrastructure projects. The main trajectories that characterise their development and use include visualisation, coordination, automation, integration and transformation. The evidence suggests that the integration of people, processes and systems is the predominant underlying theme in a majority of projects. However, instead of a truly integrated approach, projects have often used digital technologies to achieve partial integration and applications have been more often targeted towards design and construction phases than towards operation and facility management. Also, digital technology implementations addressing sustainability issues have received limited attention, in spite of current government and industry focus on that agenda [22]. As a result of the review in [22], it is clear that a uniform approach needs to be established. In addition, BIM appears to be the emerging leading paradigm for dealing with the challenge of interoperability and process automation.

In this paper, an approach that is able to automate the assessment of building performance and enhancement potential is developed. This approach can thus support building operation and facility management. It is developed on top of a BIM-based digital model which plays the role of organising knowledge to reason and support decision making in both regular operation and renovation planning. The semantics of the approach exploits the self-similarity assumption of holonic systems, hence it is invariant over the several layers which any building can be modelled into. Thanks to the abstraction and general framework offered by the SoS paradigm, the computation is not affected by any change the building may undergo in its life-cycle due to renovations. In addition, it is conceived to support collaboration between humans and machines and is inspired by the latest advances observed in the manufacturing industry.

2.2 Holistic, human-centric and proactive automation of processes and services with CPSs

A major challenge currently being addressed in the manufacturing sector is finding a common ground technology or framework that would allow the interoperation of a plethora of already existing automation solutions. In this framework, humans should be allowed to intervene and collaborate in the processes at every level, depending on their nature and complexity. The actual objective at hand is a fully compliant collaboration between humans and machines, in which humans can intervene with their highest flexibility, cognitive capabilities and sentiments in the less repeatable phases of the processes [23]. This implies a search for a common human-to-machine and machine-to-machine language. Web technology, for example, has already achieved many results in this sense. Indeed, web-like technology is a state-of-the-art approach where humans and machines have to interoperate pervasively [24]. Unfortunately, web-like solutions cannot scale well at the lowest levels of computing on tiny and very low cost devices, which are a clear trend for cyber-physical systems.

In order to overcome the above mentioned limitations, database languages are promising declarative means that can provide at least a new simplified starting point towards the holistic control and programming of cyber-physical systems. Recently, the expressiveness of the available embedded database language when used to confront a typical holonic manufacturing system (HMS) problem was shown [25]. The approach presented implies also refreshing a well-known but mostly neglected link between logic programming and database languages [25]. Notably, this problem was already clearly solved with the introduction of the Datalog language [26]. Datalog is a real database language. Expressing queries and views in database language is quite intuitive and fascinating from the viewpoint of users, and it also makes it possible to access large quantities of data stored in mass memory [26]. Also, BIM can be made informationally equivalent to a database. In this sense, database language is a major candidate to render BIM perfectly and seamlessly integrated into the CPS framework, as explained in [25]. BIM is going to assume an active role in the CPS concept by integrating itself into the overall management system.

Despite the encouraging results it is possible to infer from the discussion above, the complexity of the management of services and processes remains an open question. A language itself can be only a handy means but the information model is still inherently intractably complex. In this sense, the work performed in [27] has been proven useful in the advanced manufacturing context. In [27] a well-known performance metrics method has been recalled and extended to fit the characteristics of a holonic management system. Being based on the inherent self-similarity assumption, holonic systems can provide a viable and computationally simple means useful to tackle the problem of control of complex SoS. The question about how well the holonic and self-similarity assumptions can be useful in practical applications for AEC has not been investigated yet. Preliminary applications in manufacturing [11, 28] resulted so promising that the methodology has been inspected further for the dynamic management of a service process [29] and for the management of a highly flexible human-centred manufacturing context [30]. Eventually, the methodology has been proven to provide a complete though simple deterministic performance improvement procedure, beyond traditional bottleneck-driven heuristics [31].

In this work, the methodology is tested in the AEC context for the first time and a link to the BIM framework is enforced.

3. MATERIALS AND METHODS

3.1 Towards a holonic approach against complexity

Holons are autonomous self-reliant units constituting a stable subsystem, which have a degree of independence and handle contingencies without necessarily asking higher authorities for instructions. At the same time, holons are subject to control from higher authorities – the so-called *Janus effect*. In its implementations as an artificial agent, any holon consists of an information processing part and, often, a physical processing part. This characteristic matches the CPS concept. Another important feature is that a holon can be part of another holon. The strength of holonic systems is fully expressed within the possibility of a definition of a holonic hierarchy (i.e. holarchy) to dynamically adapt itself and reconfigure for resilience. Holarchies are not holons, or physical systems of holons, but are conceptual arrangements of holons that represent the basic formal entities for a holonic interpretation of the structures and dynamics of "Reality" [32].

Holonic systems are constructed from stable intermediate forms, also called holons, where this composition repeats in a self-similar manner until the constituents become simple [11]. Self-similarity is indeed a searched property. Holons can contain other inferior levels of holons, which can also be contained in another superior level of holons, resulting in a recursive architecture. Each element from a given level retains the similar structural properties of the preceding level, to which new elements are added based on specific rules. These rules should remain invariant between the levels.

A few more references about recursive agent architectures are available in literature [14, 33]. Nevertheless, having agents whose internal structure is composed of self-similar entities has proven useful in many applications within manufacturing contexts [27, 28, 29, 30]. The self-similarities at each level of the holarchy are constituted by behaviours and dynamics; they are transposed to different levels of abstraction using transformation properties that give a reality to each holarchy level [33]. In a holonic MAS, a decentralised recursive multi-agent approach is an answer to the multiscale organisation of large scale complex systems [33]. The aggregation hierarchy is not bound to any fixed solution, however the tree-shaped hierarchy with augmented structures was successfully applied [28]. Finally, the approach proposed heads for a cutting-through simplification of the general CPS problem applied to the management of complex SoS by exploiting the self-similarity assumption.

3.2 Development of the system architecture

3.2.1 Requirement analysis

Nowadays, the holonic MAS approach can represent a good ground for the development of proactive and resilient systems. The active holarchy has a coordinated goal and holons collaborate towards it. With this approach the grade of autonomy and proactiveness is within a fair range, because the agents implementing holons are not allowed to behave selfishly and to disrupt the holarchy and the stability of the whole system. Nevertheless, the holons should be provided with a collaborative common sense in which they communicate with nearby levels and reason deliberately on their local domain, each holon having its local micro-theory of the domain. A micro-theory is a contradiction-free set of concepts and facts about a particular domain of knowledge (like an ontology) supporting inheritance [34]. In the application proposed in this paper, the proactiveness of the holonic MAS presented consists in the communication of the need for changes in the holarchy in response to a lack of performance. Such information is used to make decisions about improvement actions, which eventually leads to adaptation and resilience.

On the basis of previous works on self-similar processes and systems and the need for the design of a resilient infrastructure, the holonic paradigm has been proven to be appropriate when in the presence of bounded rationality and dynamic/competitive environments. In this case flexible hierarchies (i.e. holarchies) will dominate [11].

Moreover, the evolution of systems and their response to disturbances shall be translated into a BIM history record suitable to the extraction of best practices and lessons learnt for an iterative and adaptive improvement of physical systems. This shall allow the BIM model of the building to become the centre of the evolution of control and management systems.

3.2.2 The overall CPS architecture for automated diagnosis

The first application presented in this paper aimed at the improvement of the management of a building room having particular regard to comfort and air quality. The solution proposed was developed according to a holistic approach and was conceived to be able to manage both long and medium term objectives and real-time control (Fig. 1). The main vertical split of the elements in this figure separates the longer term actions from the short-term ones.

The short-term actions (on the left side of Fig. 1) are the supervised operations on an existing physical structure. The course of the actions happening in the short term are then recorded in a history repository (on the right side of Fig. 1). The presence of the repository makes it possible to perform some analyses and detecting flaws and opportunities that can be used for planning renovation actions.

In addition, two major levels (or layers) of concern are split horizontally in the same figure. The higher knowledge representation and reasoning (KR&R) concerns the intelligent and proactive part, while the lower one is the automation serving operation. The reasoning and representation layer is the context of artificial intelligence. This is the unit where the ontologies and the description of the problem domain are elaborated to produce the necessary procedures and control policies for automation. This is the expert and intelligent part, too. The lower level determines the control that is affected by the policy established at the upper level. The dotted line identifies the link to the BIM component. Basing on the lessons learnt and the information obtained in the operation phase of a building, specifications are transferred to the BIM model in the form of actual KPIs for the improvement of the performances of the sub-systems contributing to the overall objective.

Please insert Figure 1 here.

Nevertheless, the scheme in Fig. 1 denotes a typical layered approach that does not necessarily exploit nor take advantage of the recursive and self-similar potential of holonic systems. Schemes like the one in Fig. 1 typically overcommit to some of the technologies to be applied to perform the control and to reasoning parts. For the application here presented there is the need to redefine the reasoning and automation parts in a nested and recurrent way. If the reasoning is used to produce planning, then automation is used to execute the actions of the plan. Nonetheless, the split between plan and action occurs again if an action is so complex that it requires some recurrent planning before being executed. Moreover, in a cyber-physical context, there is the need to continuously monitor and re-plan at some level in case of contingencies and lack of complete and deterministic environmental information. Planning and acting are not easily separable contexts and their mixture recurs at different action levels and domains [35]. This flexibility is even more necessary when the objectives in the SoS context are multiple, simultaneous but operating at different systems' frequencies, which are namely:

- long term, in which design actions will change the structure of the domain; a building sub-system can be enhanced on the basis of some previous experience and lessons learnt from the actual conduction and the management of the building;
- middle term, in which the building system is continuously monitored and possibly improved, basing on the history of the temporal evolutions and the actual use of the building;
- short term, in which the automated and human (dwellers or maintainers) actions are applied to maintain a desired state (e.g. indoor conditioning).

As a result, the building sub-systems can improve the success rate determined by control objectives by adapting and reconfiguring themselves. In fact, they work as a holarchy.

In order to figure out an agent-like implementation of the holonic entities in the overall BIM holarchy, a good starting point can be the definition of intelligent being (IB) and intelligent agent (IA) found in [11], in the context of holonic MAS. IB will be here associated with the procedures and possibly their emergent behaviour, and IA to active (dynamic or evolving) intelligence. The architecture of a holon should have at least one of the following three fundamental parts: IA, IB, and PHY. PHY is the physical part (Fig. 2). The intelligent being is that part of a holon that mirrors reality (e.g. by sensors and simulations) but also actuates control actions on the physical or virtual world. These actions are to be considered intelligent as they transform some a-priori expertise and intelligence into effective and efficient procedures or control programs (e.g. switching on and off any actuator). Nevertheless, the performances of the actual procedures should be evaluated by an active (proactive and reactive) intelligent part that ponders and reasons as a designer and a decision maker. The decision process needs for a continuous check of the effectiveness of the actions performed on the environment. Due to the possible and random changes occurring in real situations, the model of the environment must be continuously refined to produce a better and resilient controller that features the same variety of the controlled system [36]. The capability of reasoning about the models of the world is attributed to the intelligent agent, which may start a deliberate reasoning or learning process to arrive to new procedures when needed. In fact, an IA should be capable of reasoning about its capabilities at the meta-level reasoning. Thus, holons and humans become more interoperable and collaborative.

Please insert Fig. 2 here.

Fig. 2 depicts a clear separation between the declarative part and the procedural part of any holon:

- in the declarative part the data and knowledge about the domain are separated from the inference (induction and deduction) mechanism that is domain independent;
- in the procedural part there is a database of facts, events and conditions that are domain-specific and depend on the cumulative current knowledge of the programmer about the domain.

As a result, a functional correspondence between the scheme on the left side of Fig. 1 and the holon in Fig. 2 can be noted. As recalled in sub-section 3.2.1, the holon is inherently associated to a recursive tree-shaped relation within a holarchy. To the purpose of holonic simulation, reality is not made up of systems or interrelated elements that form structures, rather it is made up of relationships of inclusion among structures or elements [31]. In other words, not all the levels of the holarchy need be in direct relationship with something physically observable, but with some subjective relationships that group some functional features. The detail and the semantics of this representation can undergo some dynamic evolution as well. Beyond recursion properties, if a self-similar functionality is associated across all the levels of the holonic tree, a great simplification of the structure and an easy way to control the actions for its improvements are obtained. By "self-similarity" it is meant the invariance of the structure of performance computation (which will be reported in section 3.3), which remains the same at every level of the recursion and of the holarchy.

When self-similarities can be exploited as a part of a holarchy, that part can leverage the methodology for performance improvement [27, 28, 29, 30, 37,]. This technique, briefly recalled in the next section, relies mostly on the definition of a tree hierarchy, where the nodes are active components that participate in the overall performance, in relation to the goals assigned and managed from the upper layer.

On intermediate levels, a system has a parent and possibly several children. Such a system owns the computing and performance of its children and is in turn controlled by its parents. The computing of the performance proceeds in a bottom-up manner. In the first action phase, new values of performance are received from the lower levels and are then transmitted (i.e. published) to the parent system (i.e. the subscriber). With this information, the parent recalculates its own information about the performance of the structure it owns and publishes its information to an upper level (if any). This constitutes a first action phase. Each system is then able to suggest or order improvement actions to the children systems owned, depending on the information received. This is a second subsequent action phase. This second communication proceeds downwards, in the opposite direction with respect to the first phase (Fig. 3). Technically, during Phase I, the STATS() procedures publish the actions suggested to be used for the improvement [30]. In Phase II the improvements are carried out depending on the overall strategies and goals. This behaviour is triggered by means of the IMPROVE() procedures. The two phases identify the sensing and actuation of automation, although in between there is room for a reasoning activity. The reasoning is done to make decisions about which improvement should eventually be performed, after considering the goals, the strategies and, possibly, the planning of the operations. The input hierarchy is scanned through the STATS() procedures, while the IMPROVE() procedures trigger changes in the lower levels. This is a major device that renders the control of complex systems effective. It must be noted that this methodology is agnostic with respect to the technology or the specific knowledge representation used for the reasoning. It acts as an automation that resides at a meta level with respect to a specific knowledge representation and reasoning level. It represents an automation of the management in which the manager can be any intelligent agent, being it human or artificial.

Please insert Fig. 3 here.

3.3 Description of the self-similar computing structure

The technique presented in this paper is based on a holonic management system that exploits the self-similarity characteristics that can be imposed on a holarchy. Thanks to this self-similarity, the definition of recursive agents that implement the holon at a certain level is extremely simplified.

The holarchy here presented is a tree hierarchy of holons for which the relationship between their n-th level and the (n+1)-th and (n-1)-th levels is a functional interpretation that expresses also their container/contained relationships [31]. In this case, the relationship is operative. According to the operative interpretation, the holon embodies an operator or operation involving any process carried out autonomously, depending on its inputs obtained from higher levels and the environment.

Two holons at level n are operationally connected only through their parent holon at a higher level. The holarchy structure filters and regulates the flow of information and limits it to what is relevant for a certain holon, which depends form the specific interpretation and purposes assigned to the holon by the domain of the problem.

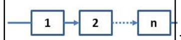
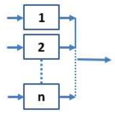
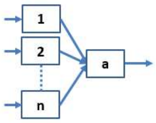
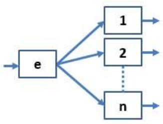
The holarchy interpretation is constructed so as to assign a performance measure to every holon. The result is a mechanism that can be associated to a distributed multi-agent implementation oriented to decision support in the management of the controlled process. Like in other contexts, the introduction of distributed agents for cyber-physical systems renders the complexity treatable in principle. The approach here presented is tested against its efficacy in giving a viable solution to the complexity and interoperability problem in CPSs for building and construction. A similar approach that used the self-similarity approximation, was formerly used in the context of smart manufacturing [27, 28, 30].

Indeed, an analogy between manufacturing and building management is accepted, because, while manufacturing is meant to provide products, buildings are meant to deliver services. In this sense, there may be an analogy between the effectiveness of a production process, which depends on the number and quality of the artefacts and on the capability to adapt to fluctuations in market demand, and the effectiveness of a building. The essential value handled by the elements in the system is a combination of three factors and some control variables, which compose the well-known OEE concept. In the application proposed in this paper, overall process effectiveness (OPE), which is treated similarly to OEE, is defined as follows [15]:

$$OPE = Aeff \times Peff \times Qeff \qquad (1)$$

where the meaning of the three factors can assume different semantics depending on the interpretation (in formal logic sense) adopted for them. The only requirement is for each factor to be a dimensionless quantity in the interval (0-1). Typically: Aeff - "availability efficiency" - captures the deleterious effects due to breakdowns, time delays, setups and adjustments of a process, Peff – "performance efficiency" - captures a performance loss due to reduced speed, idling and minor stoppages in performing a task, while Qeff - "quality efficiency" - captures the loss due to mistakes or reworks in a task.

In the complexity of the processes, the improvement of a specific "unit" performance might not bring effects to the "production" system as a whole. OTE is a suitable holistic metric that can be defined recursively to match the OPE coefficient at the bottom, ranging from a single production cell (or production unit) to the whole system-of-systems [15, 27]. OTE is attributed to the higher-level holons, other than the leaves in the hierarchy tree. The leaves are measured with OPE and are the only holons that can be physically acted upon to make the holarchy metric improve. The relationship between a holon and the holons it contains at the next descending level is a coordinating one and in [32] it is called integrative property rule of internal coordination level. Indeed, OTE is a recursive function of OPE, whose formulation depends on four fundamental types of interconnected structures: series, parallel, assembly and expansion. In Tab. 1 the formulas and the structures determine the four kinds of interconnection.

Internal coordination type		OTE of parent holon	R_{th} of parent holon	Q_{eff} of parent holon.
Series		$\dfrac{\min\left\{\min\limits_{i=1,\ldots,n-1}\left\{OTE_i \cdot R_{th,i} \cdot \prod_{j=i+1}^{n} Q_{eff,i}\right\}, OTE_n \cdot R_{th,n}\right\}}{\min_{i=1,\ldots,n}\left\{R_{th,i}\right\}}$	$\min\limits_{i=1,\ldots,n}\left\{R_{th,i}\right\}$	$\prod\limits_{i=1}^{n} Q_{eff,i}$
Parallel		$\left(\sum\limits_{i=1}^{n} OTE_i \cdot R_{th,i}\right) \Big/ \sum\limits_{i=1}^{n} R_{th,i}$	$\sum\limits_{i=1}^{n} R_{th,i}$	$\dfrac{\sum\limits_{i=1}^{n} Q_{eff,i}}{n}$
Assembly		$\dfrac{\min\left\{\min\limits_{i=1,\ldots,n}\left\{OTE_i \cdot R_{th,i} \cdot Q_{eff,a} / k_{a,i}\right\}, OTE_a \cdot R_{th,a}\right\}}{\min\left\{\min\limits_{i=1,\ldots,n}\left\{R_{th,i} / k_{a,i}\right\}, R_{th,a}\right\}}$	$\min\left\{\min\limits_{i=1,\ldots,n}\left\{\dfrac{R_{th,i}}{k_{a,i}}\right\}, R_{th,a}\right\}$	$\dfrac{\sum\limits_{i=1}^{n} k_{a,i} Q_{eff,i}}{\sum\limits_{i=1}^{n} k_{a,i}} Q_{eff,a}$
Expansion		$\dfrac{\sum\limits_{i=1}^{n} \min\left\{R_{th,e} \cdot OTE_e \cdot k_{e,i} \cdot Q_{eff,i}, R_{th,i} \cdot OTE_i\right\}}{\sum\limits_{i=1}^{n} \min\left\{R_{th,e} \cdot k_{e,i}, R_{th,i}\right\}}$	$\sum\limits_{i=1}^{n} \min\left\{R_{th,e} \cdot k_{e,i}, R_{th,i}\right\}$	$\dfrac{\sum\limits_{i=1}^{n} k_{e,i} Q_{eff,i}}{\sum\limits_{i=1}^{n} k_{e,i}}$

Tab. 1. OTE metric computing formulas in recursive form (adapted from [27]).

The measurement of performances through the OTE/OPE KPIs highlights bottlenecks in the process. Due to the structure of the operators and formulas adopted, these bottlenecks become, at the same time, a focus on the opportunities for process improvements. By acting around the bottleneck elements prompt and effective improvements can be obtained. Bottleneck detection is the driver of the proposed management procedure for performance improvement and it is the basis for a consistent improvement algorithm and of a decision support system [31].

Actually the OTE of a parent system is now obtained from the OTE values of its children. When a child can be considered as a composition of other sub-systems, a hierarchical tree of systems is obtained for which the OTE index can be computed at every level.

If sub-systems do not admit further decompositions, they constitute the leaves of the tree. In this case, their OTE index coincides by construction to OPE. In Fig. 4 the variables s, a and p are children of an expansion parent system at the first level (root) of the tree. In turn, at the second level, s1 and s2 are children of the series system s, while p1 and p2 are the children of the parallel system p and a1, a2, a3 are the children of the assembly system [27].

The set of possible structures at each level is finite and shown in Tab. 1: *series*, *parallel*, *assembly*, and *expansion*. This implies that, at each level of the tree, the computation of the OTE index is obtained by picking one of the recursion formulas within a unique conditional algorithm (e.g. a switch-case statement [27]). The uniqueness of the algorithm at every level constitutes the structural self-similarity in the OTE computation. The lightweight nature of the computing required by this technique, along with its distributable nature, makes the algorithm a candidate for a contribution in the context of the programming and the engineering of multi-agent systems for pervasive cyber-physical systems [25, 27]. In such a structure, the computing from [25] and [27] can now be used to implement:

- the STATS() procedure, which recursively determines the OTE/OPE of each holon and thus the performance bottlenecks;
- the IMPROVE() procedure, which, at each level, communicates the actions to be performed to the lower levels, in order to improve the OTE index of the subsystem.

The IMPROVE() process requires an "expert" decision. Depending on the STATS(), each holon might be asked to choose among several alternative actions.

Please insert Fig. 4 here.

This choice policy is a very simplified form of planning in AI context [38]. Finally, the resulting system is a complete embodied, distributed agent (human or artificial) system with integrated AI and automation.

3.4 Development of the computing structure

The architecture of the simulator developed to implement the BIM-based holonic management system described in this paper is depicted in Fig. 5. It involves three development environments, namely Matlab®/Simulink®, SQL and Autodesk®/Revit®. The role of this infrastructure is to assess the capabilities of the architecture suggested in this paper by means of simulations of real scenarios [39, 40, 41]. It is to be noticed that the virtual simulator laboratory (VSL) is the component that is in charge of estimating the actual evolution of the environment tested. As a proof of concept, the physical part of the framework proposed is simulated by means of the model implemented in the VSL component. Moreover, the authors are committed to develop a suitable and reusable simulation tool that can evaluate the database-centric approach, which is the foreseen underlying technology for commercial implementation, as described in [37]. As it will be reported in Section 4, the computing structure described in this sub-section is used to test the application of the system to the management of a portion of a building, showing how the several components interact with each other. The overall goal of the control is focused on thermal comfort and air quality.

Technically, the simulator is implemented in Matlab/Simulink by interfacing it with the SQL database and Revit. The Revit environment concerns the building digital model (bDM), as the interface of one of the numerous BIM software tools available on the market, such as Revit. The Matlab and SQL environments share the decision support tool (DST) implemented in a Matlab function block, which plays the role of assessing the effectiveness of the system of systems. The DST implements the distributed OTE metric reported in Section 3.3, which has been developed for the case study reported in sub-section 4.1, according to the scheme shown in Fig. 5. This scheme explains the system's semantics in which the building is thought as a service provider. This representation facilitates the development of the computing structure. Thanks to this scheme, the DST suggests a list of possible corrective actions that follow from the OPE and OTE parameters updated at each iteration, whose values are between 0 and 1. They are effectiveness indexes referring to the intermediate levels (OTE) and lowest levels (OPE) of the system's tree, as described in Fig. 6. Once the OPE values of a cell are determined, the OTE value of every subsystem is obtained by following the formulas in Tab. 1 and the event-condition-action (ECA) style of computation [27, 31]. Then, for each iteration the DST provides a list of possible actions towards enhancing the performance of the system of systems.

Besides the DST described above, the Matlab environment consists of the supervision policy (SP) and the aforementioned VSL. The VSL is in charge of emulating the actual behaviour of the building by using a detailed building model. This model is developed in the Dymola® programming environment, which is based on the Modelica language. Modelica allows equation-based modelling using program-neutral model descriptions, domain-independent solution methods and the capability of exporting models as functional mockup units (FMU). The building model used in this work is built on the open-source Modelica "Buildings" library [40] and it has the level of detail that is necessary to analyse the behaviour of each device and sub-system belonging to the building. The measures taken from the VSL provide one-step-delayed feedback to the decision support tool.

The DST evaluates and updates the OPE index of each cell by means of SQL queries, then it updates the OTE parameter in the whole tree of the system and suggests a list of possible actions to the SP. The possible actions provided from the DST are outputs to the IMPROVE() procedure. Only one action at time can be chosen [31]. The choice of the most appropriate action is context and time dependent. The SP unit is in charge of choosing the most viable action. Viability of actions might depend on the availability of the resource that applies or implements it on the physical system, on the actual cost of the action to be enforced, on the particular risks depending on other facts not present in the model (but from external and contingent sources of knowledge). The SP function can be a simple set of rules, as exemplified in [31] with algorithmic nature. This solution can approximate a certain set of contexts, when the complexity can be taken under control.

The usefulness of the proposed architecture is to provide the manager with an automation that timely suggests actions for specific parts of the system, each of which can improve the performance of the process. In addition, the manager is provided with a tool and an approach that can be framed into the systems thinking framework, the management cybernetics, and in viable system models that assume the policy layer as the higher [42]. The SP can also be seen and implemented as a collective entity or agency that embodies the normative personality of an organisation of holons, as the personality of a collective agency can be defined in cybernetics terms in [43].

The SQL environment involves the BIM relational model (RM), which is a relational database acting as a bridge between the DST and the bDM and has a double function. The first one is to update the DST when the bDM changes. The second one is to store effectiveness data received from the DST in order to run building diagnosis. The bRM and bDM exchange data in both directions, thanks to the Revit DB-Link plug-in. In this way, the SQL and the Revit environments are connected. This computing structure makes it possible to carry out any type of desired off-site simulation. By exploiting the capability of the FMU Kit for Simulink and Dymola 2018, the VSL is integrated into the cyber physical system as an FMU block in co-simulation mode. The control inputs selected for the VSL are actuator inputs normalised between 0 and 1 (e.g. the shading level, the fan coil level and the window level). The variables measured are both indoor (e.g. air temperature, relative humidity, CO_2 concentration, cooling power) and outdoor measures (e.g. air temperature, relative humidity, solar radiation on the horizontal plane). It is to be noticed that, when a change occurs in the building to be managed, the Revit DB-Link automatically updates the bRM that changes the system's scheme (Fig. 6) and the computation formulas included in the DST are rearranged automatically. This reconfiguration is a typical property of holonic systems, which are able to revise their structure according to the evolution of the physical system.

Please insert Fig. 5 here.

3.5 Knowledge extraction and the central role of BIM

As in most of the problems involving knowledge representation and reasoning, the main issue remains the automation of information gathering and its semantics structures. This activity is usually performed through data mining automation in the form of online analytical processing (OLAP) and online transaction processing (OLTP). To provide a seamless link between the reasoning tools and the declarative structure of the BIM information, SQL (and, in the future, the Relation Model language) is considered an effective solution which can even encompass OLAP and OLTP in a unified way. By linking the reasoners to the database it is possible to avoid some software technological impedance and to demonstrate that the implementation of an intelligent system can be reduced to a well-designed DBMS also for tiny embedded cyber-physical systems [27]. A valuable example that maps ontologies and databases is the Ontop protégé plug-in, which can already be considered among the promising tools for the framework here developed [16].

In this paper, it is established and put forth that the bRM and the bDM are the two sides of the same coin, where the BIM model works as a relational repository of any type of data and information.

The connection between the bRM and the decision support and control, as explained in section 3.4, provides an informational online loop between the building and the BIM holarchy where intelligence is applied. In order for this to happen, the relational potential of BIM needs to be fully expressed by means of an appropriate relational model. By a homomorphic mapping between BIM and its relational representation, it is possible to develop new structured types that allow the recording of relational information and data. For example, in a BIM entity, it is possible to record the complete real-time history of the parts of the building equipment as obtained from sensors, that is a typical OLTP activity. 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 generated, enriched through OLAP techniques 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.

4. SIMULATION AND RESULTS

4.1 The case study

The first prototype of the BIM-based holonic management system developed as described in Section 3 was tested in an office room of a big public building which hosts one of the faculties of Università Politecnica delle Marche (Ancona, Italy). The building is arranged on six floors above ground, it is 16,900 m^2 large and it is devoted to classrooms, offices, laboratories, library and other faculty-related activities. It dates back to the nineties and is composed of two longitudinal blocks, whose longer sides are the main facades, facing north and south. The envelope facing south is a double-glazing unit divided into three modules by aluminium uprights. The horizontal bland below the glazed surface is internally covered with a 5-mm thick steel sheet. The surrounding partitions are made of plasterboard and plastered hollow bricks.

The office room used for this study is located on the 3rd floor of the south block (i.e. Room no. 90 in Fig. 7-a) and measures approximately 3.52 x 5.46 x 3.00 m (W x D x H). In the building a conditioning and regulation system, which includes a fan coil that is manually controllable by a thermostat, is installed. Mechanical air supply is provided by AHUs installed on the roof, and no local control is installed in the office rooms. A complete BIM model of this building was developed and integrated into the bDM unit of the architecture depicted in Fig. 5, which contains the information necessary for the operation phase and serves as a repository of the actual state of the facility.

The curtain wall facing south is affected by intense overheating in the warm season, which was observed during an experimental campaign [44] performed for the thermal characterisation of the same office room used for the case study presented (Fig. 7-b). The results of that experimental campaign supported the development of a Dymola/Modelica model of the building [45], which was validated against experimental data and integrated into the VSL unit of the architecture depicted in Fig. 5.

Please insert Fig. 6 here.

4.2 Development of the whole framework

Basically, the architecture depicted on Fig. 5 can be split into two main sections. The first one, which involves the SQL and Revit environments, is devoted to the management of information and is represented by the components at the bottom of Fig. 5. The second one, developed mainly in Matlab and secondly in SQL, is devoted to real-time computation and is represented by the components at the top of Fig. 5. The first section is in charge of:

- supporting the multi-objective control, which is performed by the computation section, through the arrangement of the necessary information, that is retrieved from the bDM;
- continuous update of the history of the performances of every sub-system of the building object of control, which is useful to rank and plan both short- and long-term potential improvements for the building;
- transferring the OEE history of any sub-systems and any other update generated by the physical part of the CPS to the bDM.

A scheme of the information flow is depicted on Fig. 7. The bRM is an SQL-based database management system (DBMS) enhanced with non-standard host language proprietary extensions. In the bRM every unit (e.g. tables, attributes and database schemas) is a relational variable. Thanks to this property, a homomorphic mapping between the bRM and bDM is obtained, so a bi-directional flow between the two databases is set up by means of the DB-Link plug-in. Thus, the facility manager of the building is allowed to track the history of every sub-system in the BIM environment (i.e. the Revit component in the case of Fig. 7), and to input information about the building in this same environment, because the bRM is automatically synchronized. As depicted on Fig. 7, functional characteristics and numerical parameters of the sub-systems involved in the control policy (i.e. ventilation units, windows and shading units) are imported into the bRM through the import function of the DB-Link and exposed for the next computational steps. In this phase, the OEE parameters of the current step are still unknown, until a new iteration in the computation section is performed and results are exported back to the DBMS to update the bDM through the DB-Link.

Please insert Figure 7 here.

The DST, which plays a key role in the whole process, is stored inside the SQL environment in a SQLiteStudio DBMS and interfaced to the Matlab environment. It includes the STATS() and IMPROVE() functions (please ref. to sub-section 3.3), which are executed in Matlab/Simulink. The outcomes to STATS() function at the current time step are stored in the folder "systree" of the DBMS, whereas the previous outcome is moved in the folder "systree.history", which thus expands over time and stores the history for medium and long-term assessment of the building and is kept available for answering specific queries, as described in the next sub-section. The outcomes to IMPROVE() function, which are potential actions, are arranged by the DST and transferred to the SP to work out the best control policy available. In this workflow, the performance fields of the building's systems in the bDM are updated with the moving average values of the "systree.history" folder, thus mirroring the dynamic status of the building.

The second section of the architecture is depicted on Fig. 8. It is made up of the DST, the SP and the VSL. This section of the proposed architecture is in charge of:

- performing real-time sensing to track the evolution of the CPS;
- applying policies to be implemented in the multi-objective optimization of the system;
- integrating self-adaptation features to possible changes in the building structure, that can occur during the operation phase.

Please insert Figure 8 here.

Self-adaptation is mainly determined by the self-similar computation structure that is built within the DST, from the model described in sub-section 3.3. To this purpose, the building must be modelled as a combination of recursive elementary systems, which can be combined according to four basic coordination types: series, parallel, assembly and expansion. Then, OTE/OEE computations follows from the rules listed in Tab. 1. Fig. 9 is a scheme of the system of systems representation of a representative room of the building, where there are several parent-children relationships. As a general rule, parents are the groups of systems responsible for delivering performances within pre-determined objectives (i.e. thermal comfort, air quality and hygrometric comfort). Their efficacy is conditioned upon the actual contribution provided by the sub-systems. Among the four basic combination types, the "assembly" was used when the outputs of two or more sub-systems are mixed following a specific proportion k_i; the "expansion" was used any time the outputs of two or more sub-systems are split following a specific proportion k_i; the "parallel" was used for sub-systems whose action on a specific part or entity does not follow a specific order; the "series" succession was used any time two or more sub-systems act on a part or entity following a specific order. This scheme is input for the development of the system's tree integrated in the DST depicted on Fig. 7, which gets its inputs from the outcomes of the computation performed by the VSL. This component is in charge of emulating the real building by simulating its dynamics through a model developed in the Dymola programming environment, which is based on the Modelica "Buildings" library [46]. This model was detailed enough so as to simulate the behaviour of each device and sub-system relevant for the control of the thermal and hygrometric comfort and air quality of the building. In this computation, all the necessary parameters are provided by the DB-Link between the bDM and the bRM, as mentioned above. Then, virtual sensors part of the VSL provide one-step-delayed feedback to the DST. That part of the DST implemented in Simulink computes the distributed performance metrics (OEE) of each elementary system, i.e. the lowest level. This assessment is performed by means of Eq. (1), where "productivity" is calculated as the ratio between:

$$P_{eff} = \frac{R_{act}}{R_{th}} \qquad (2)$$

Please insert Figure 9 here.

This general formula denotes with "R_{th}" the type of output that should be provided by any sub-system, in order for the control objectives to be met within the next time step. This value is computed by the operational benchmark depicted on Fig. 8. Then, the output that the system can actually provide (i.e. "R_{act}") is estimated by the VSL and is related to R_{th}. As an example, air quality needs change over time according to several parameters, such as the number of people in a room, air leakages, the quality of outdoor air. R_{th} in eq. (2) is the air flow that should be provided by the air conditioning system at any time step in order to set the value of air quality within the desired and pre-determined quality threshold. R_{act} in eq. (2) is the maximum allowable air flow that the specific system operating in the building can actually provide, according to the dynamic behaviour of the building as computed by the Modelica model in the VSL.

These inputs are then redirected to the DST, where the system's tree is implemented and the other OEE and OTE values for combined systems and the whole building are computed. As a result, at every step the DST provides a list of OEE and OTE values from the IMPROVE() function, which constitute a ranking of the necessary control steps to fully meet the multi-objective control the building's systems are in charge of.

However, not all the control policies can be applied concurrently, because actuators are often shared by different objectives which might be adversely affected by their activation. So, there is a higher level whose final aim is making decisions about which of the wished control policies must be applied first. This task is in charge of the SP component, which, as described in sub-section 3.4, is in charge of choosing the most viable action. The SP developed in this paper applies the algorithmic approach. Operationally, the SP 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 one 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 as short as 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 manage thermal comfort according to energy saving principles;
- a lower-priority action will be carried out in the next-step iteration if the related low performance persists;
- if a higher-priority action is already running, the selection skips to the lower-priority one;
- if more than one action for the same sub-system is suggested, the action which is expected to lead to the highest gain is selected.

4.3 Results and discussion

In this section, the double advantage provided by this approach is shown. In fact, this platform is able to control the operation of the system in real-time. In addition, the BIM model plays the role of facilitating information exchange among the actors involved in the building operation phase. Such information is automatically generated and can be used to perform diagnoses for long-term refurbishment. The results presented in the following sections are related to the case study described in sub-section 4.1 and simulated by means of the simulator depicted in Fig. 5 and described in sub-section 4.2.

4.3.1 Operation Management

Fig. 10-a shows the simulated temperature of room no. 90 during the week from 23rd to 29th June when the system could hardly guarantee to keep the required temperature set-point (T_{set}), not only because of high outdoor temperature (T_o), but also because of intense solar radiation. As a result, the indoor operative temperature (T_{op}) fluctuates around the set-point only when no intense solar radiation levels are measured in the room. On the contrary, when high solar radiation levels and high outdoor temperatures are combined, the indoor temperature increases above the set-point. This phenomenon is even more evident in the zoomed diagram depicted in Fig. 10-b, which is the proof that the system is not always able to provide the comfort parameters required and, therefore, needs to be improved through long-term enhancement actions.

Please insert Figure 10 here.

The sub-systems responsible for temperature control are the fan coil unit and the shading component. The control platform actuates the shading as a first reaction to temperature increase at about 8 a.m., as shown in Fig. 11-a. Then, about one hour later, it switches on the fan coil unit at its maximum speed. The reason is that the control logic gives priority to low-consumption energy saving control policies, as reported in sub-section 4.2. However, the combined use of both the sub-systems in this room is not effective enough to reach comfort conditions. One of the reasons could be that the shading component only partially covers the envelope. In fact, it covers the top half of the envelope, which is transparent, and does not cover the bottom part, which is not transparent but is made of a lightweight sandwich panel. Another reason could be that the cooling power of the fan-coil unit is insufficient.

In the simulator, the plots depicted are generated by the VSL, which handles the actuators according to the suggestions based on the policy managed by the SP. The VSL also transfers the sensor measurements to the DST, which evaluates the performances of every subsystem and makes these data available to the SP for it to make decisions.

In the meantime, the multi-objective control implemented in the platform can manage other actuators, such as the windows, which contribute to control internal humidity (Fig. 11-b) and CO_2 (Fig. 11-c). The policy applied by the SP to control Relative Humidity (RH) in the time period considered in the figure is clearly to open the window (when WL is close to 1) every time the external humidity is higher than the internal one, in order to help reach the set-point. However, during the midday hours, approximately from 10 a.m. to 1 p.m., the level of window opening fluctuates between 0 and 0.7, because the policy suggested by RH is in contradiction with the one suggested by CO_2, which prevails. Apparently, outdoor RH cannot help increase indoor RH, as needed to get closer to the set-point. Nonetheless, room overcrowding during those hours (Fig. 11-c) requires indoor air to be refreshed. Of course, the control inertia and system stability can be modified according to the control policy implemented in the SP.

Please insert Figure 11 here.

4.3.2 Assessment and recording of the building effectiveness

While the simulation is running, at every simulation step the bRM stores all the OTE/OPE values computed within the routine implemented in the DST unit. Hence, a repository of the facility history is created, which sums up the components that fail to meet required performances. Fig. 12 shows the histogram of the OPE monthly mean values worked out in June and July. These parameters can be used to assess the effectiveness of every component. Of course, the diagnosis changes with time, because the components are operated differently according to the season, and the continuous update process of these values can be integrated into the bDM.

Please insert Figure 12 here.

Fig. 12 shows that all the sub-systems perform better in July than in June in terms of humidity control, which is one of the parameters that strongly depend on outdoor conditions. On the contrary, indoor air quality and thermal comfort do not dramatically differ in the two months. The control system is quite effective in the control of air quality, whereas it struggles to meet the requirements imposed by thermal comfort goals. The main responsible for this failure is the envelope (TC), whose thermal characteristics are likely to be inadequate to respond to the very intense solar radiation and high temperature. In addition, the shading device (SHA) and fan-coil unit (FCU) look like they are not able to balance the thermal loads in the warm season.

These data are a synthetic representation of all the information stored in the bRM, which can be used by any facility manager to analyse the real performances of the control system and plan medium and long-term renovation. Queries inside the SQL environment in a SQLiteStudio DBMS can be performed to check the history of any component, as reported in Table 2, and according to the following general prompts:

- "Filter by #cell=" is used to locate the history of the particular component;
- "Copy table" is used to export the located data in SQL format and re-direct them into SQL Server DBMS;
- "Compile OPE mean value" is used to definitively store the data copied inside bRM, filling the specific attribute inside the table "GenericModels".

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 OPE mean value	ALTER TABLE [provaDBlink].[dbo].[GenericModels] ADD Cell_number INTEGER;
	ALTER TABLE [provaDBlink].[dbo].[GenericModels] ADD OPE_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 OPE_meanvalue=(SELECT avg(OTE) AS OPE_meanvalue FROM [provaDBlink].[dbo].[ID_995898]) WHERE Id=995898;
	SELECT * FROM [provaDBlink].[dbo].[GenericModels] WHERE Id=995898;

Tab. 2. Queries to process and link data in the SQL environment.

For example, a facility manager that wants to check the history of the shading device in room no. 90, first must consider that this component is identified in cell no. 9 of the system of systems scheme in the SQL Server DBMS. Then, the bRM automatically matches this component with its Revit identifier "ID 995898". When the procedure described above is put into place, the first query gives back the result shown in Fig. 13-a and the remaining second and third queries give back what is shown in Fig. 13-b, where the history of this element is copied in the specific attribute inside the table "GenericModels". Finally, the OPE mean value of shading can be re-directed to the bDM using Revit DB-Link plug-in as a shading parameter, therefore it can be visualised through the standard Revit user interface, by opening the "property" window. It must be noticed in Fig. 14 that the value was updated at the end of each month as its moving average. The values displayed here are the same reported in the histogram in Fig. 14 (SHA), but in this case the BIM model itself can be updated in real-time according to the actual performances of the building and no specific skills in database management are required to handle it.

Please insert Figure 13 here.

Please insert Figure 14 here.

5. CONCLUSIONS

The platform developed in this paper was shown to be able to automate the assessment of a building performance during its operation phase, besides providing multi-objective real-time control. The first service is of great interest to all the people involved in the management of the facility; the second service is able to apply any control policy, even balancing several contradictory requests. One of the main components of the platform is the BIM digital model, which mirrors the actual state of the building over time and which is related to a relational database, which serves as an interface between the building, the higher reasoning level and the physical component of the control system (e.g. the measurement setup). As a result, the digital model of the building, which usually consists in a BIM model, becomes the repository of information over the several phases of the building life-cycle and is, therefore, useful to keep the facility at high performance levels and support decision making for its improvement.

Another important component of the platform is the decision support system, which exploits a self-similarity assumption to calculate the effectiveness of the overall system and of the intermediate and lowest layers. This approach was borrowed from the manufacturing industry, where the real-time control of the effectiveness of many concurrent automated sub-systems interacting along a production line is of utmost importance in making sure that resources are used effectively. In the process of adaptation of the approach to the construction field, every building was thought as a set of interacting sub-systems which are supposed to provide the user with some services. The OTE/OPE approach made it possible to uncover performance inefficiencies. This feature cannot only save time for facility managers, but it can also take advantage of the recursion formulas integrated into the computing structure. This is generated by the assembly of four basic computing structures, which can be combined within the overall one as a direct consequence of a system's scheme which reflects the semantics of the physical system under analysis. If the building is subject to changes and the scheme is promptly updated, the computing structures can self-reconfigure and are able to reflect the updated configuration. Self-configuration and adaptation to changes of the physical model is typical of holonic systems.

In addition, the simulator included a virtual simulation model, which emulates the dynamics of a real building. Sensors and probes are also integrated into the emulation model, in order to realistically analyse the potentials of this management architecture. Moreover, the room is modelled as a set of agents, where every agent interacts with other agents and the high level reasoning in several ways: they all communicate to the DST the contribution they can provide to every comfort goal in the next time step, they react to the decisions the control policy unit makes at every step, they are aware of their own status and capabilities by means of the direct communication channel with the building digital model, which may change over time, they can make their own decisions, in case there are no hints from the higher level reasoning. This integration between hardware and software parts into agents complies with the definition of cyber physical systems. Thus, intelligence was integrated both at the lower and higher levels of the overall system, provided that the building is thought as a series of (self-) reconfigurable agents, all interacting and contributing to some pre-defined goals. This approach can provide the building with a higher degree of automation and flexibility, thus being able to manage even unexpected occurrences or rare occurrences for which it was not explicitly designed.

6. ACKNOWLEDGMENTS

This research work was supported by a special Grant awarded by Università Politecnica delle Marche in favour of a joint research project carried out by the staff of DICEA and DII Departments (Contract 2017 – III/6, no. 0000331 on 10th January 2017).

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LIST OF CAPTIONS:

Fig. 1: Overall conceptual scheme of the BIM-based holonic management system architecture

Fig. 2: The conceptual scheme of the holon as intended in the architecture presented

Fig. 3. The two phases of system improvement control.

Fig. 4. An example of a tree derived from the nested structure of the systems.

Fig. 5. The architecture of the holonic computing structure developed based on CPS technology.

Fig. 6. BIM model of the building containing room no. 90 as a case study (a) and picture of the measurement setup installed in the room during a previous experimental campaign (b).

Fig. 7. Information workflow within the CPS for building management.

Fig. 8: framework in charge of computation in the CPS.

Fig. 9: System's scheme as a combination of assembly, expansion, series and parallel rules.

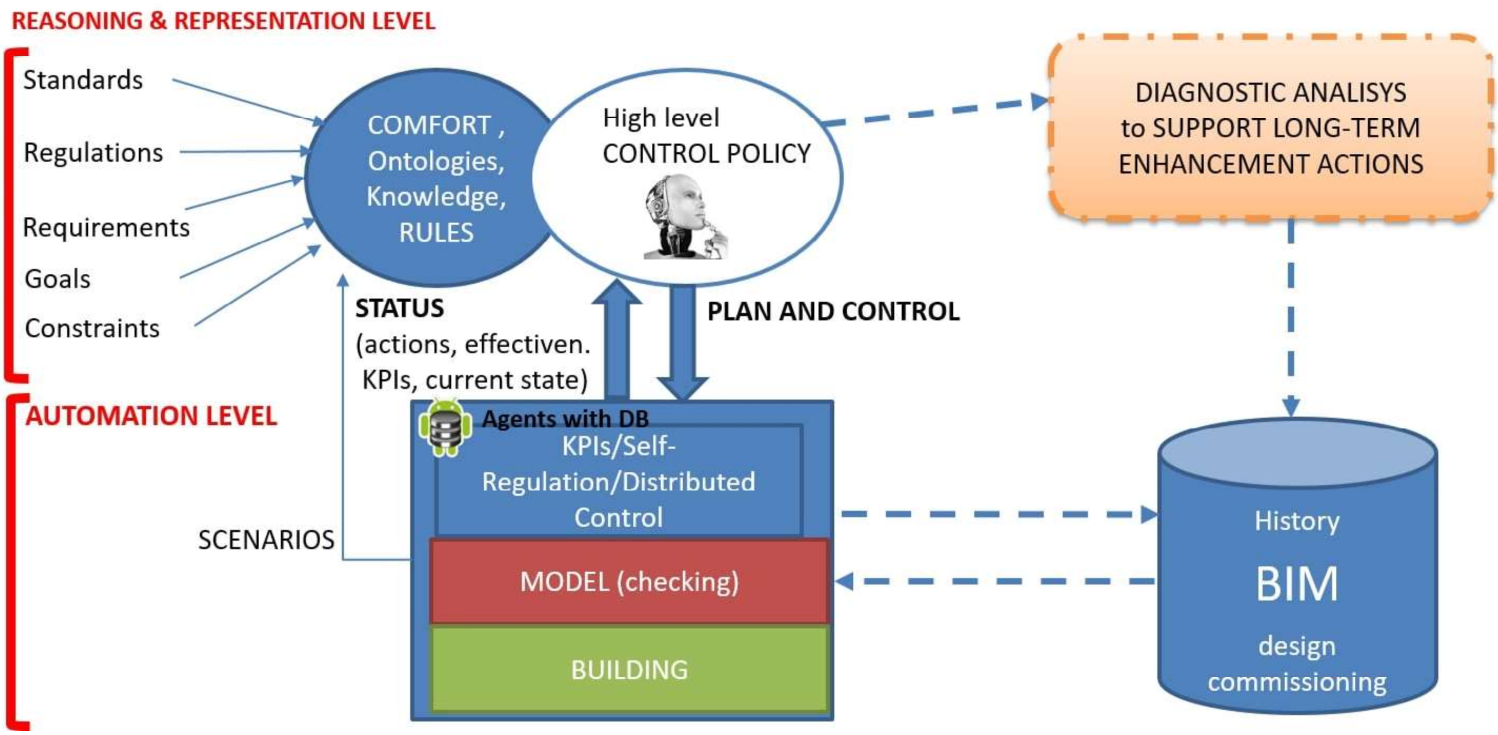
Fig. 10. Temperature plot in the week from 23rd to 29th June (a) and zoom on 29th June (b).

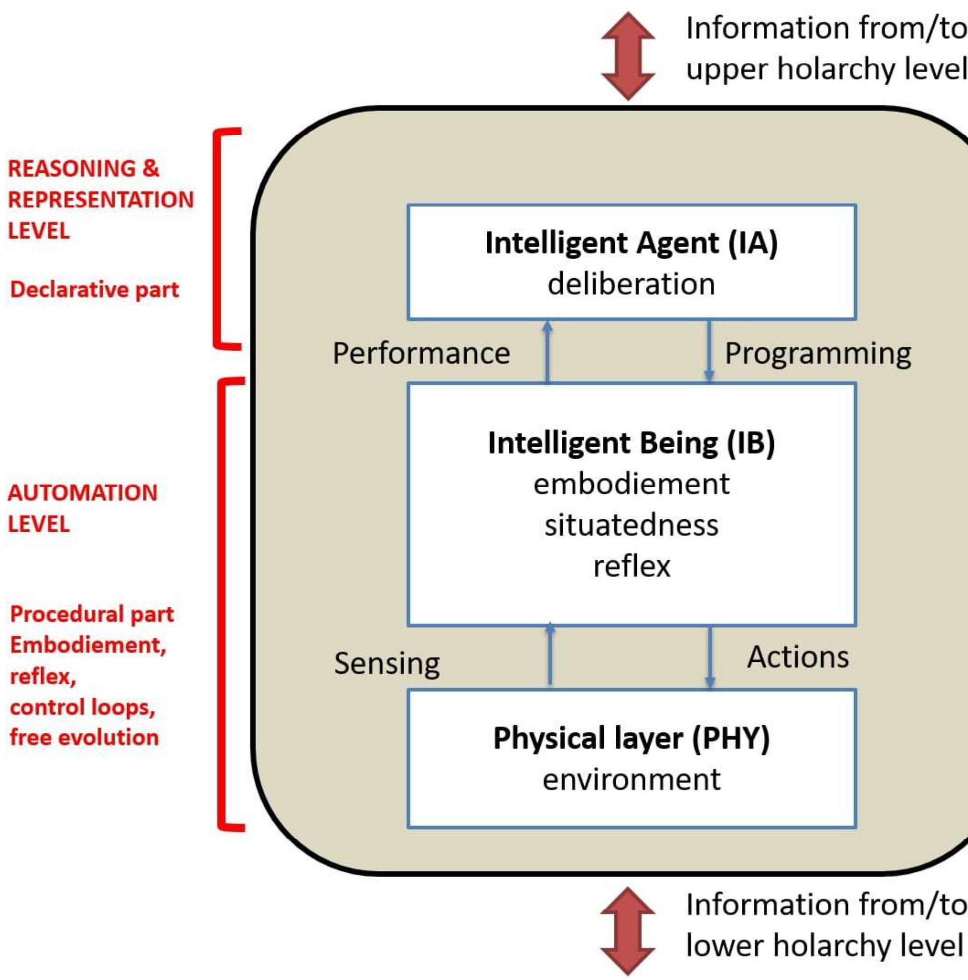
Fig. 11. Shading and fan coil levels on 29th June (a), relative humidity (b) and CO2 levels (c) plotted against window opening on 29th June.

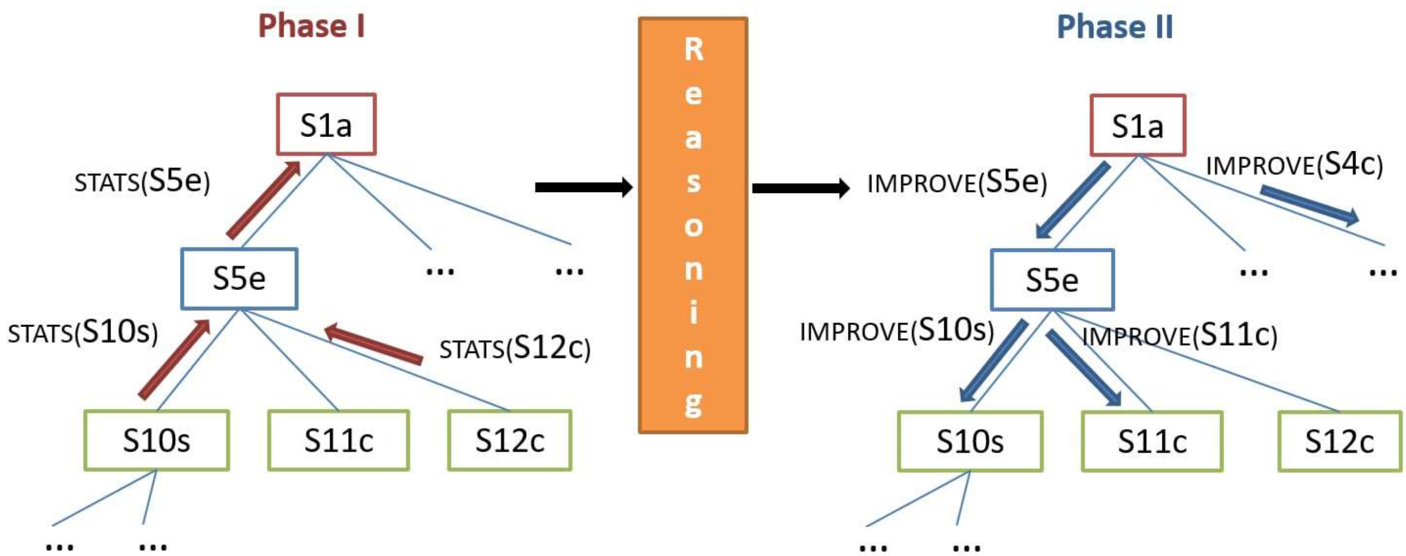
Fig. 12. OPE monthly values related to the months of June and July.

Fig. 13. Results of "Filter by #cell=" (a) and of "Copy table" and "Compile OPE mean value" queries (b) relative to the history in the month of June.

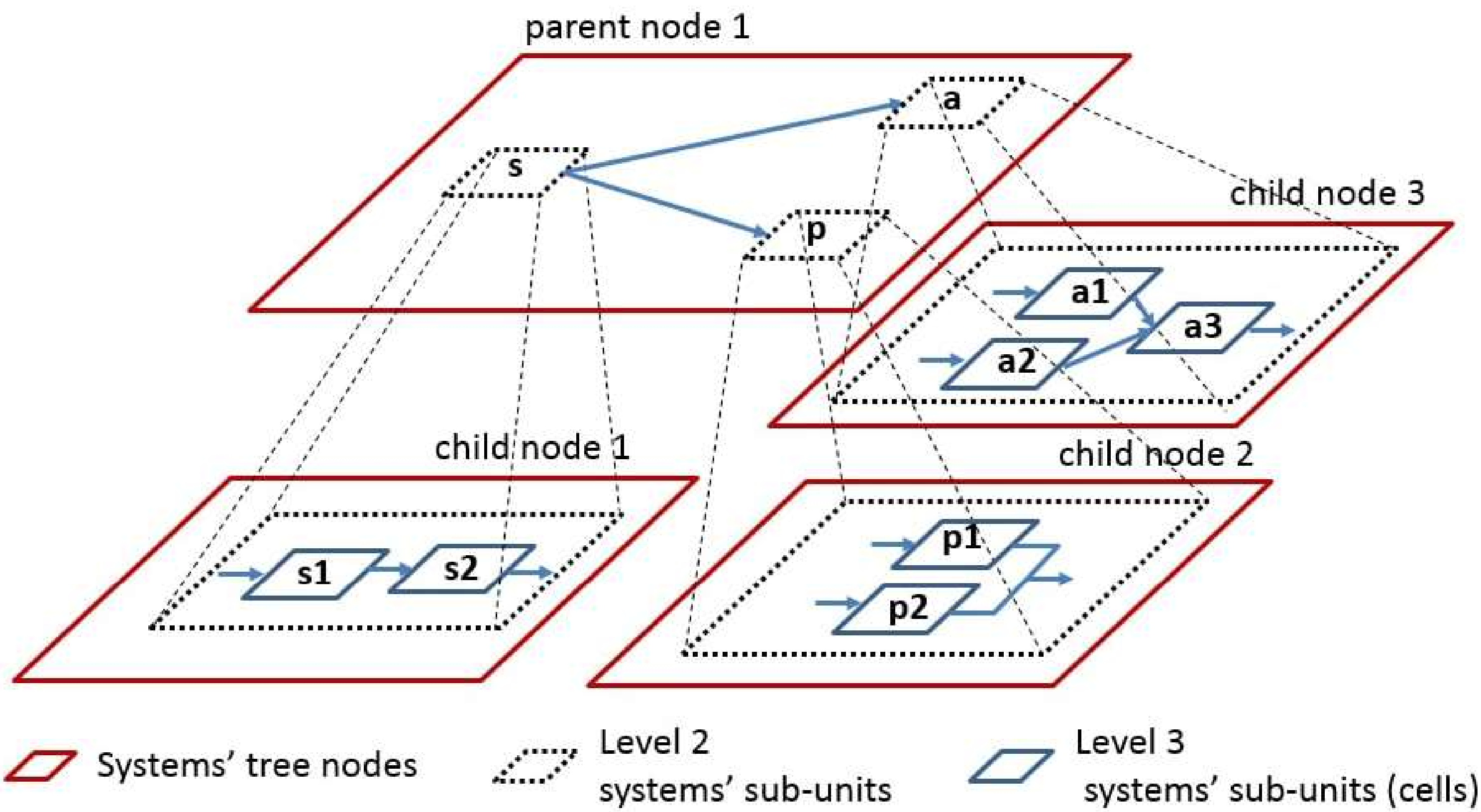
Fig. 14. The OPE mean value of shading displayed inside Autodesk Revit as a shading parameter at the end of June (a) and updated after the month of July (b).


REASONING & REPRESENTATION LEVEL
Standards
Regulations
Requirements
Goals
Constraints
COMFORT ,
Ontologies,
Knowledge,
RULES
High level
CONTROL POLICY
DIAGNOSTIC ANALISYS
to SUPPORT LONG-TERM
ENHANCEMENT ACTIONS
STATUS
(actions, effectiven.
KPIs, current state)
PLAN AND CONTROL
AUTOMATION LEVEL
Agents with DB
KPIs/Self-
Regulation/Distributed
Control
SCENARIOS
MODEL (checking)
BUILDING
History
BIM
design
commissioning

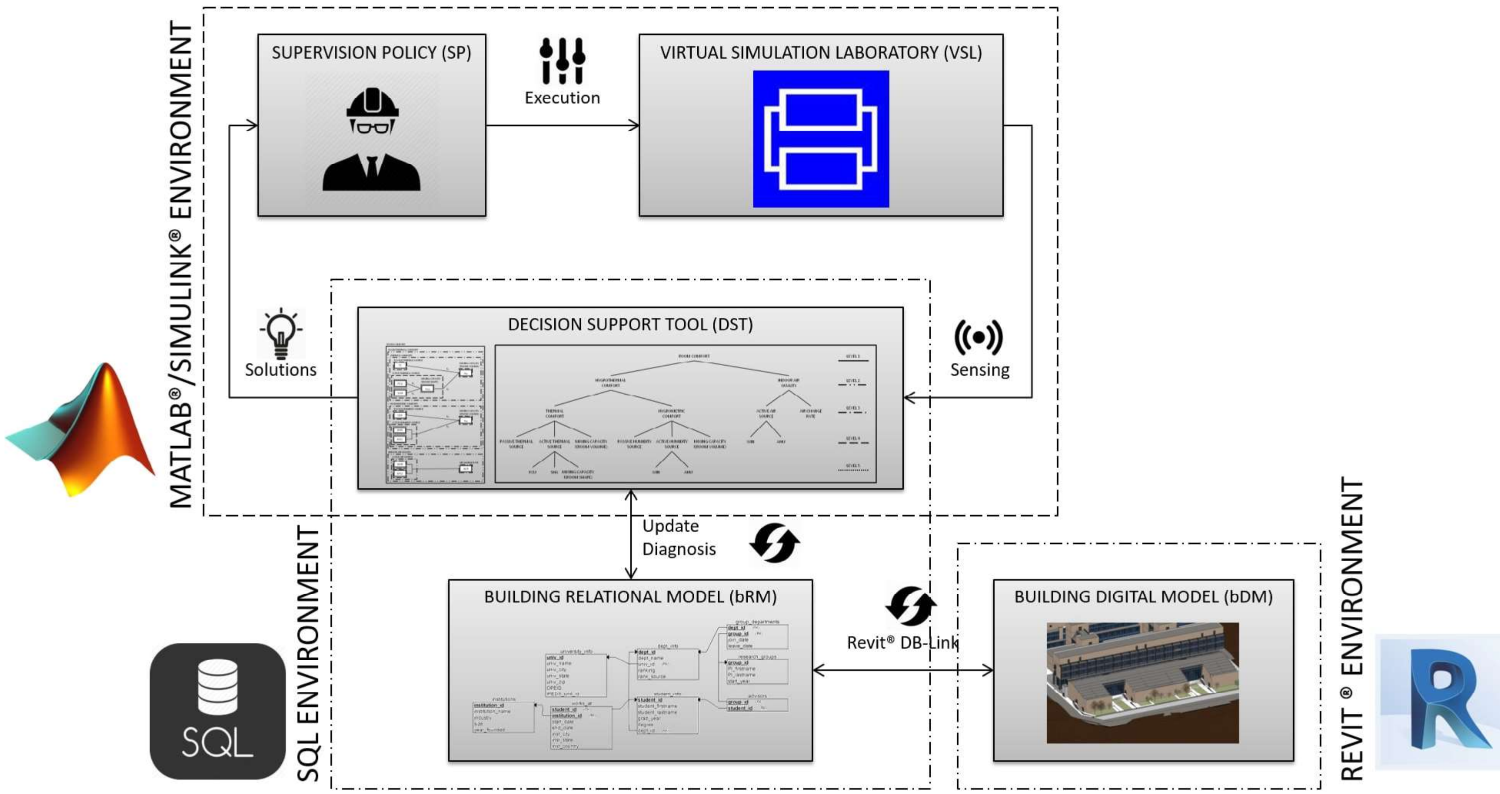

Information from/to
upper holarchy level
REASONING &
REPRESENTATION
LEVEL
Declarative part
Intelligent Agent (IA)
deliberation
Performance
Programming
AUTOMATION
LEVEL
Intelligent Being (IB)
embodiement
situatedness
reflex
Procedural part
Embodiement,
reflex,
control loops,
free evolution
Sensing
Actions
Physical layer (PHY)
environment
Information from/to
lower holarchy level

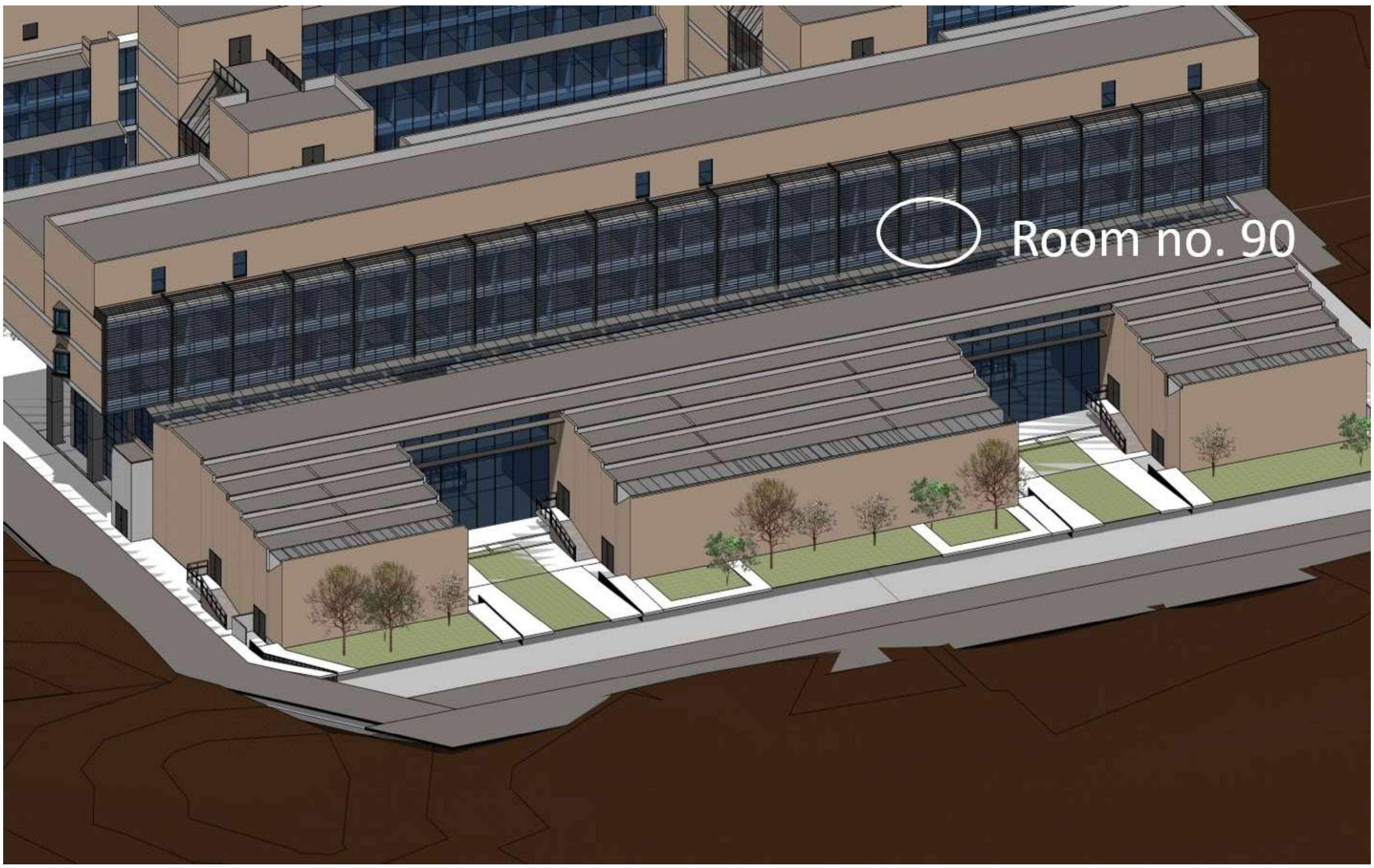


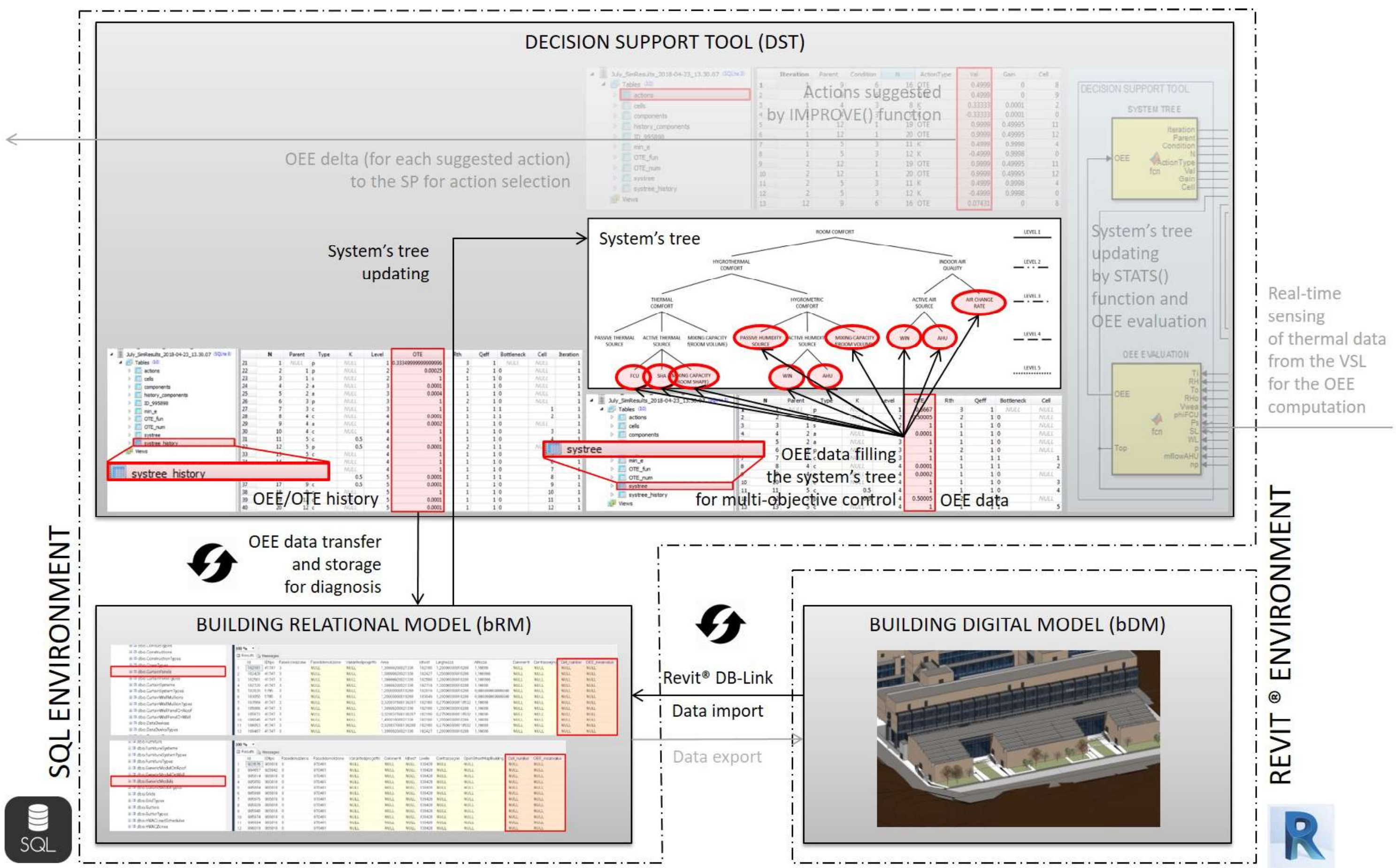
Phase I
S1a
STATS(S5e)
S5e
STATS(S10s)
STATS(S12c)
S10s
S11c
S12c
Reasoning
Phase II
IMPROVE(S5e)
IMPROVE(S4c)
IMPROVE(S10s)
IMPROVE(S11c)

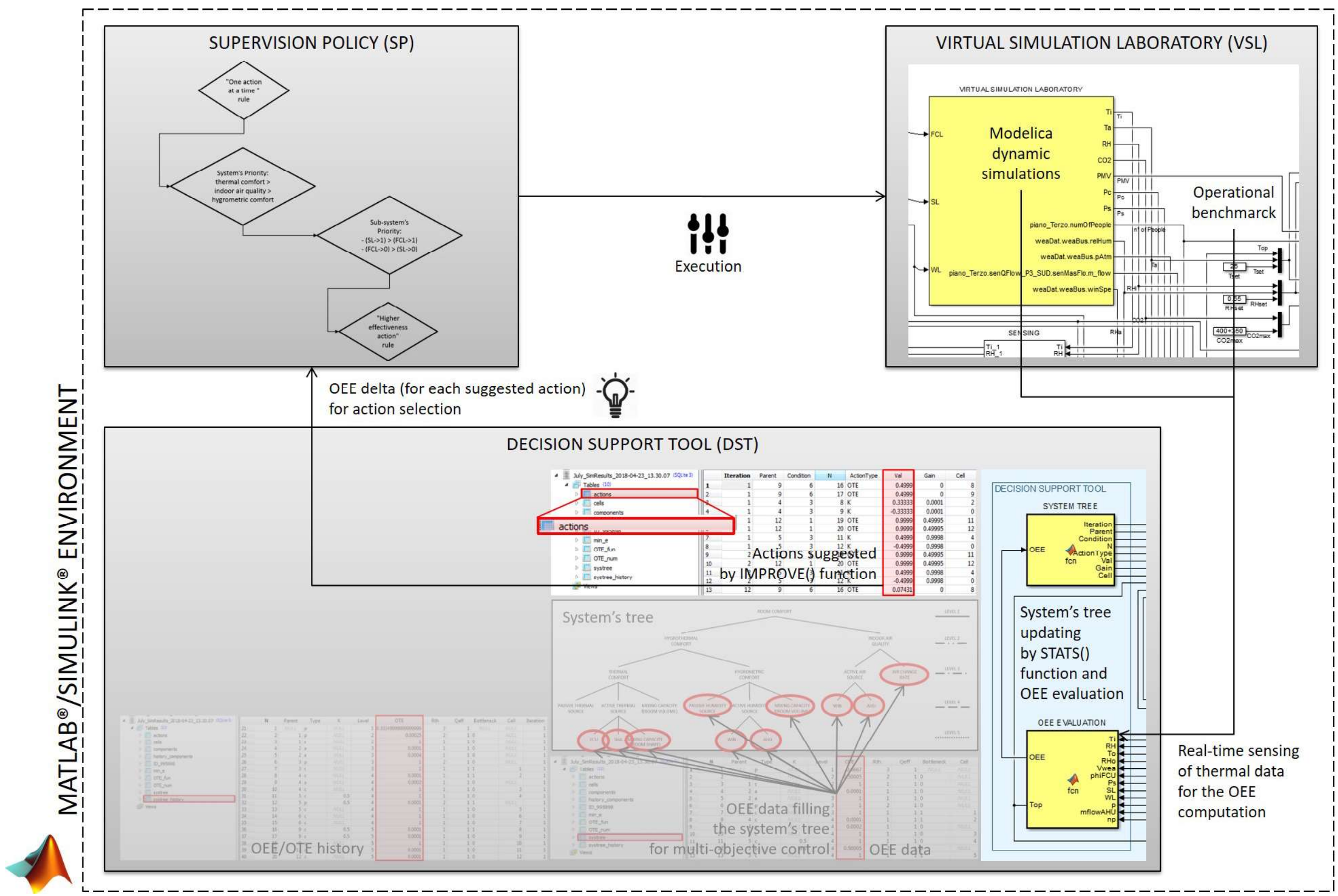


parent node 1
a
s
p
child node 3
a1
a3
a2
child node 1
child node 2
s1
s2
p1
p2
Systems' tree nodes
Level 2
systems' sub-units
Level 3
systems' sub-units (cells)

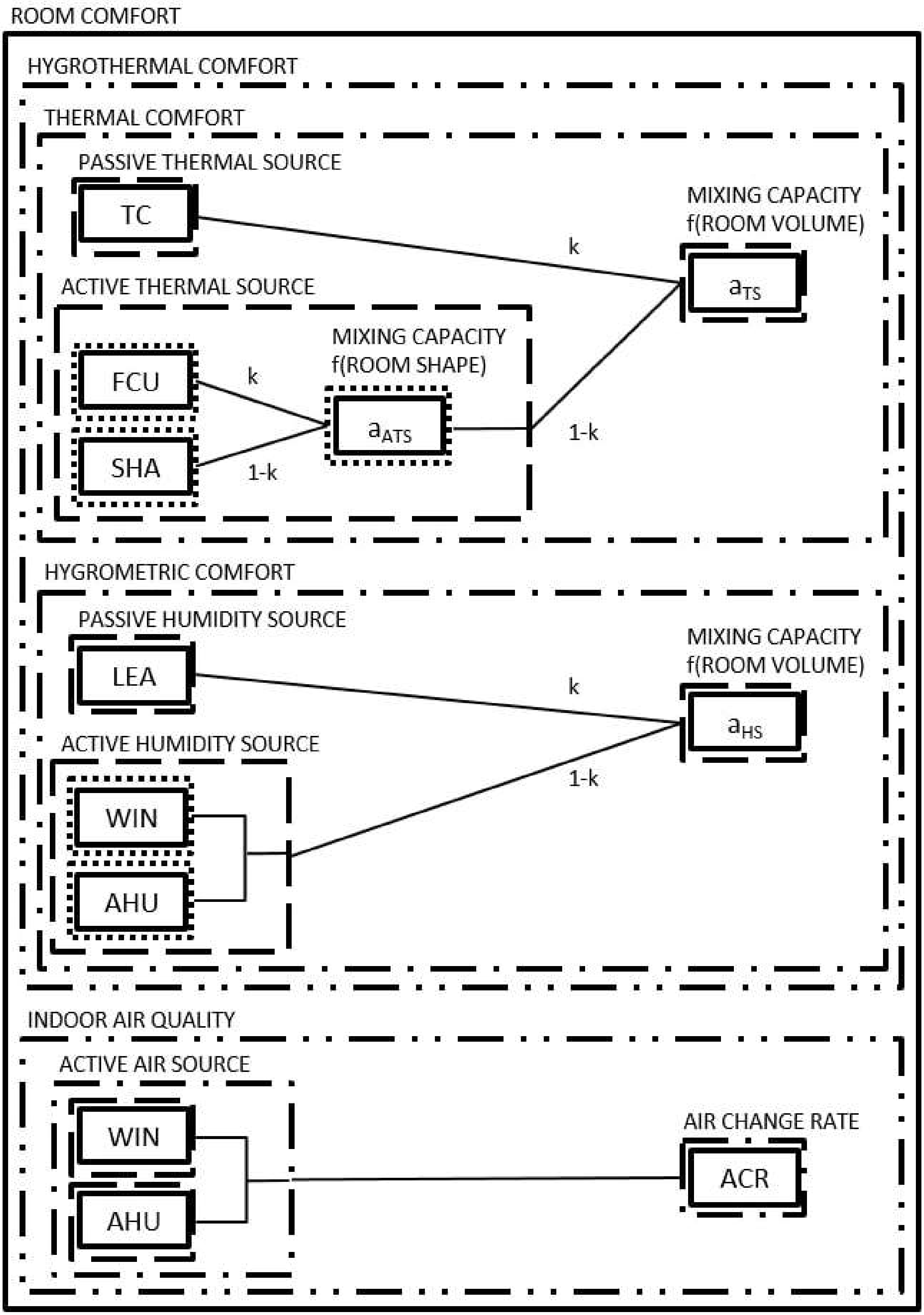

MATLAB®/SIMULINK® ENVIRONMENT
SUPERVISION POLICY (SP)
Execution
VIRTUAL SIMULATION LABORATORY (VSL)
DECISION SUPPORT TOOL (DST)
Solutions
Sensing
Update
Diagnosis
SQL ENVIRONMENT
SQL
BUILDING RELATIONAL MODEL (bRM)
Revit® DB-Link
BUILDING DIGITAL MODEL (bDM)
REVIT ® ENVIRONMENT


Room no. 90

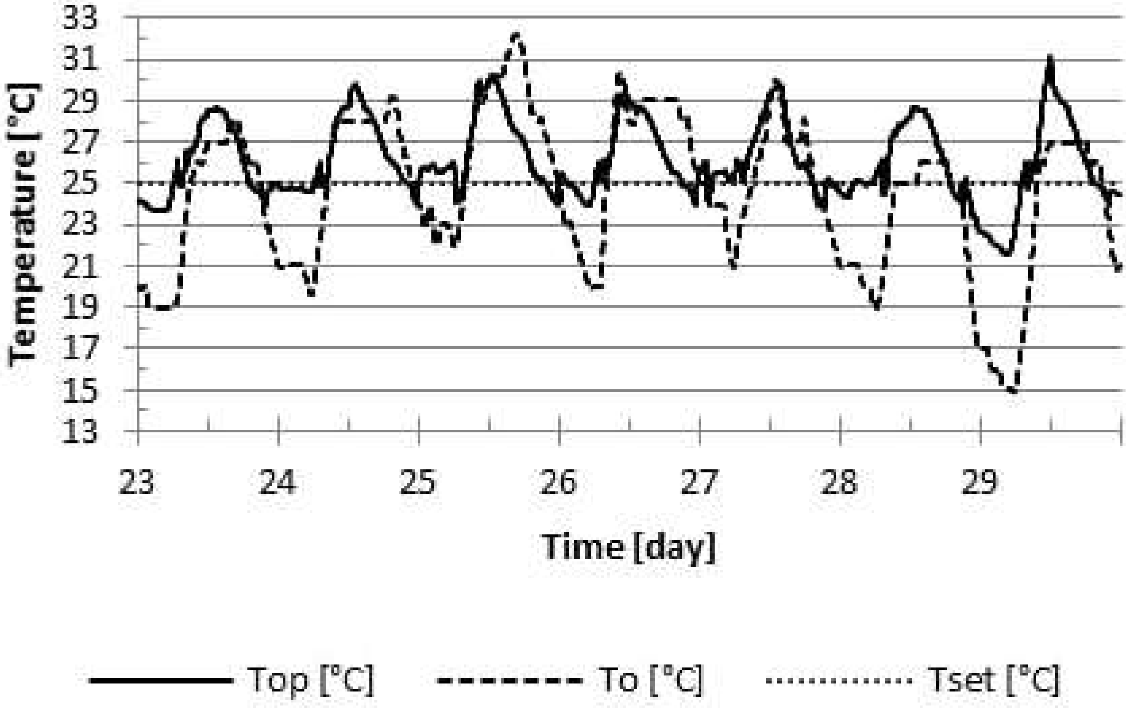

DECISION SUPPORT TOOL (DST)
Actions suggested
by IMPROVE() function
OEE delta (for each suggested action)
to the SP for action selection
System's tree
updating
System's tree
System's tree
updating
by STATS()
function and
OEE evaluation
Real-time
sensing
of thermal data
from the VSL
for the OEE
computation
systree_history
OEE/OTE history
systree
OEE data filling
the system's tree
for multi-objective control
OEE data
OEE data transfer
and storage
for diagnosis
BUILDING RELATIONAL MODEL (bRM)
Revit® DB-Link
Data import
Data export
BUILDING DIGITAL MODEL (bDM)
SQL ENVIRONMENT
SQL
REVIT ® ENVIRONMENT



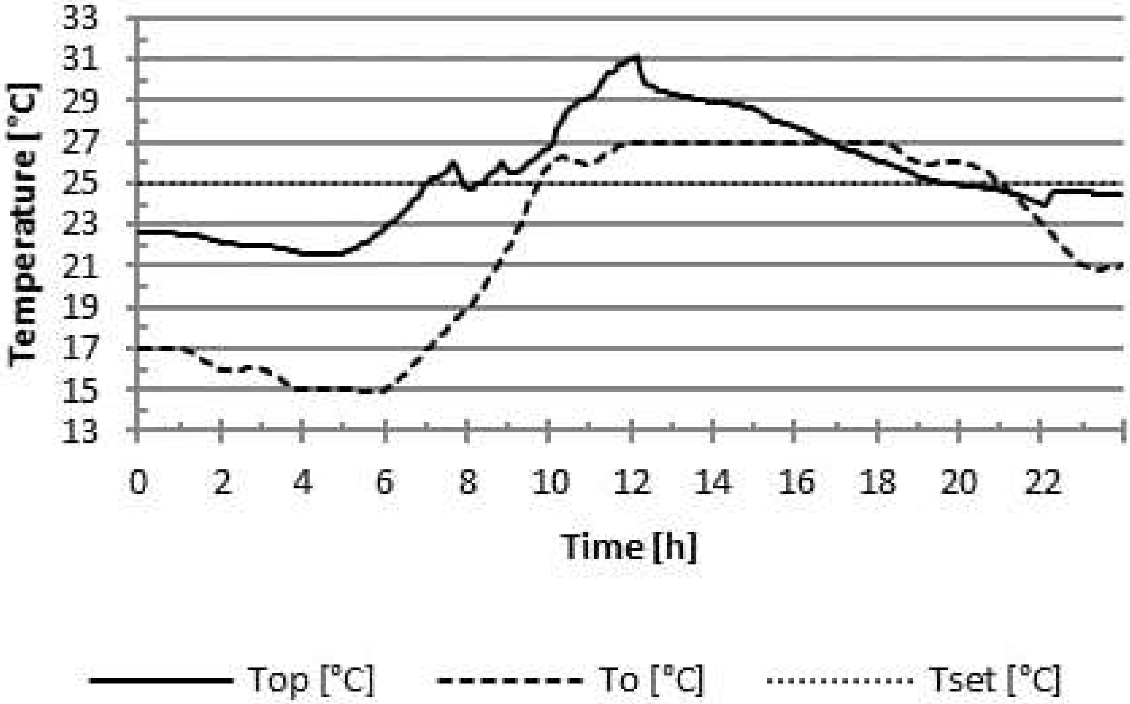
MATLAB®/SIMULINK® ENVIRONMENT
SUPERVISION POLICY (SP)
"One action at a time" rule
System's Priority: thermal comfort > indoor air quality > hygrometric comfort
Sub-system's Priority: - (SL->1) > (FCL->1) - (FCL->0) > (SL->0)
"Higher effectiveness action" rule
Execution
VIRTUAL SIMULATION LABORATORY (VSL)
Modelica dynamic simulations
Operational benchmarck
OEE delta (for each suggested action) for action selection
DECISION SUPPORT TOOL (DST)
actions
Actions suggested by IMPROVE() function
System's tree
System's tree updating by STATS() function and OEE evaluation
DECISION SUPPORT TOOL
SYSTEM TREE
OEE EVALUATION
Real-time sensing of thermal data for the OEE computation
OEE data filling the system's tree for multi-objective control
OEE data
OEE/OTE history



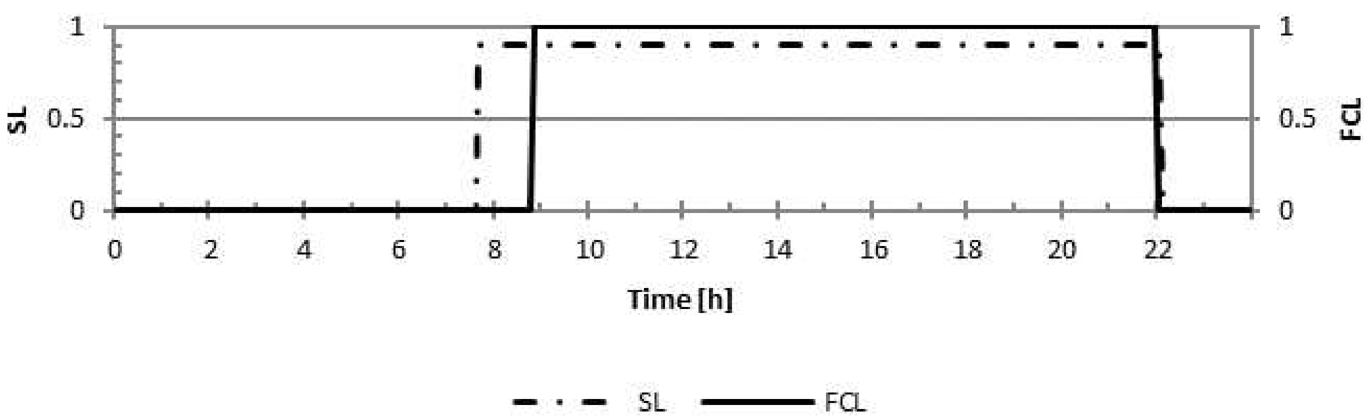
ROOM COMFORT
HYGROTHERMAL COMFORT
THERMAL COMFORT
PASSIVE THERMAL SOURCE
TC
MIXING CAPACITY
f(ROOM VOLUME)
k
a_{TS}
ACTIVE THERMAL SOURCE
MIXING CAPACITY
f(ROOM SHAPE)
FCU
k
a_{ATS}
SHA
1-k
1-k
HYGROMETRIC COMFORT
PASSIVE HUMIDITY SOURCE
MIXING CAPACITY
f(ROOM VOLUME)
LEA
k
a_{HS}
ACTIVE HUMIDITY SOURCE
1-k
WIN
AHU
INDOOR AIR QUALITY
ACTIVE AIR SOURCE
AIR CHANGE RATE
WIN
ACR
AHU



33
31
29
27
25
23
21
19
17
15
13
Temperature [°C]
23
24
25
26
27
28
29
Time [day]
Top [°C]
To [°C]
Tset [°C]



33
31
29
27
25
23
21
19
17
15
13
Temperature [°C]
0
2
4
6
8
10
12
14
16
18
20
22
Time [h]
Top [°C]
To [°C]
Tset [°C]



SL
FCL
Time [h]
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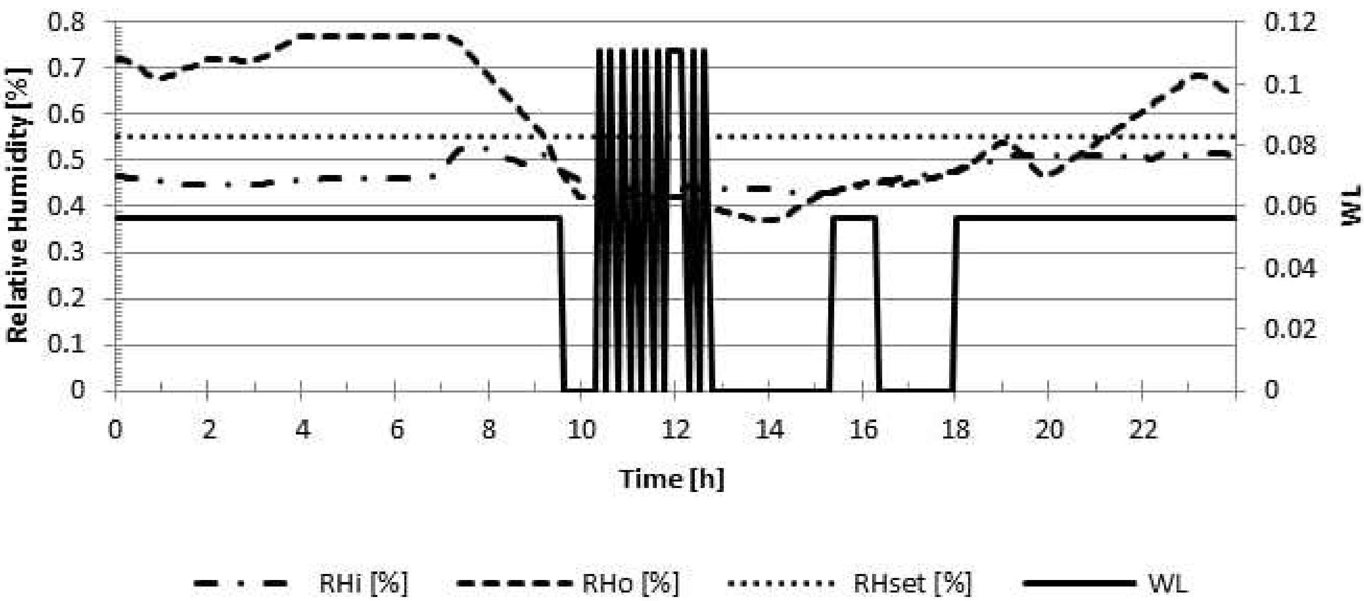
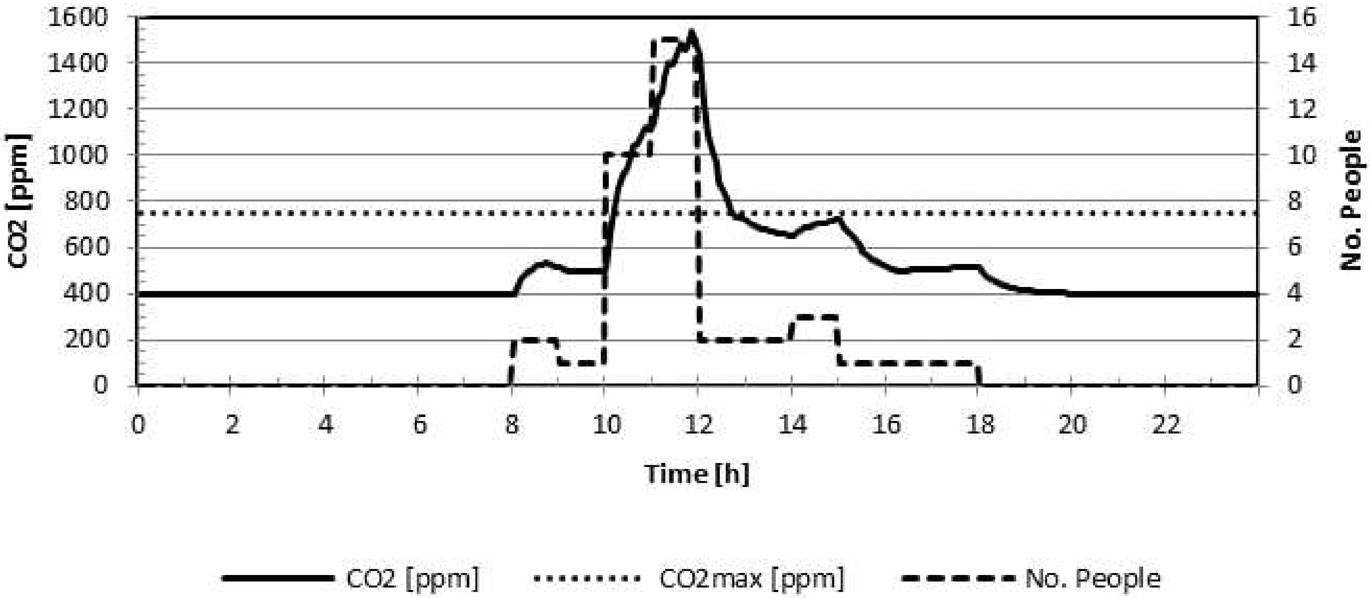
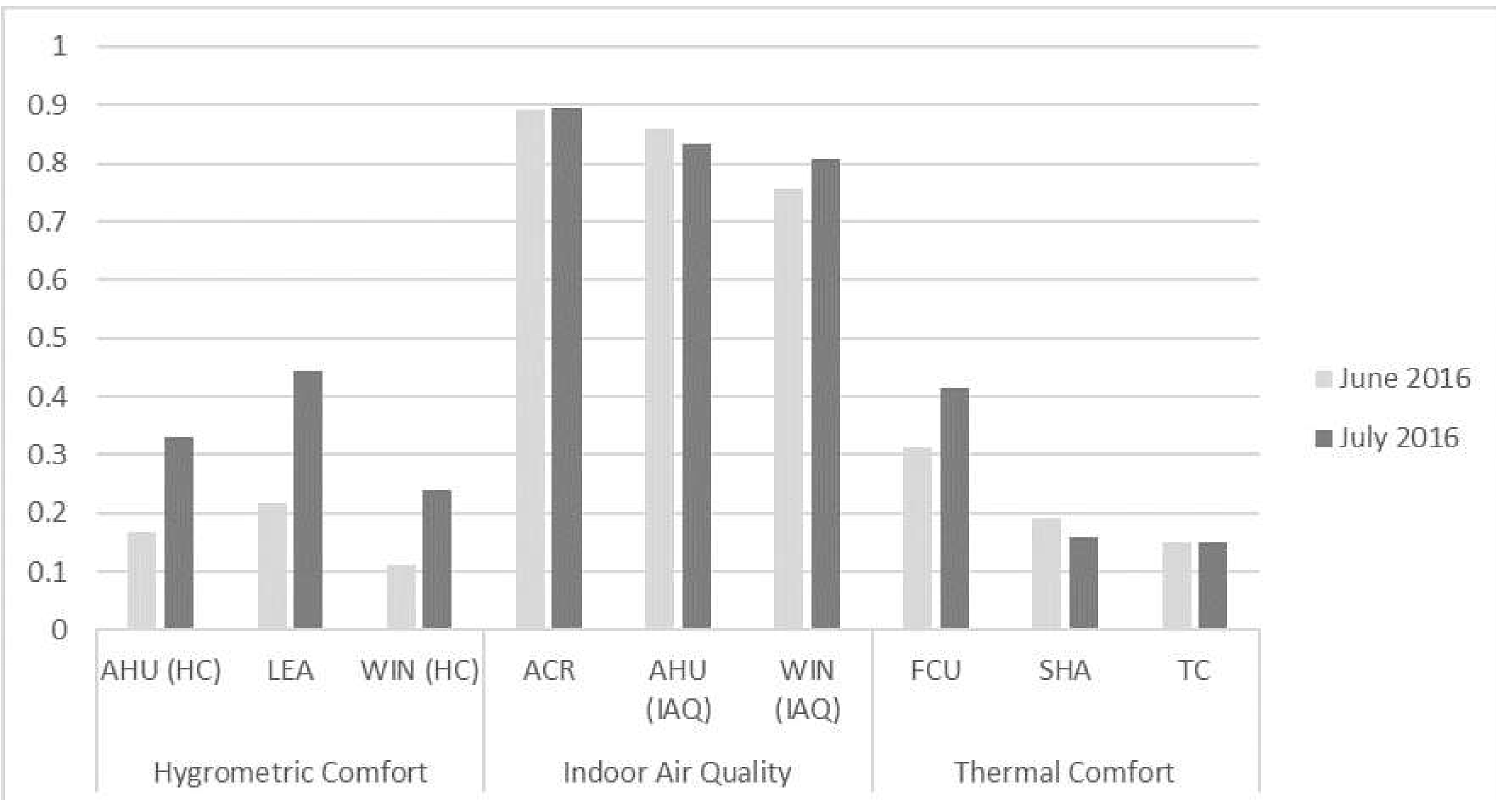
2
4
6
8
10
12
14
16
18
20
22
1
0.5
0
SL
FCL



Relative Humidity [%]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.12
0.1
0.08
0.06
0.04
0.02
0
WL
0
2
4
6
8
10
12
14
16
18
20
22
Time [h]
RHi [%]
RHo [%]
RHset [%]
WL

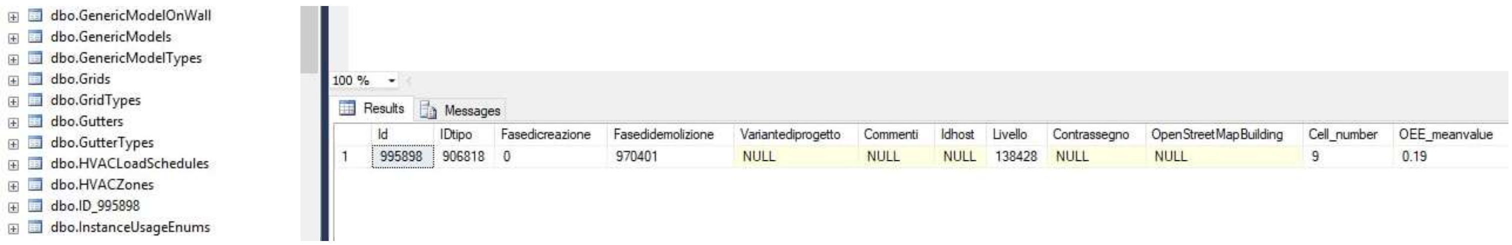


CO2 [ppm]
1600
1400
1200
1000
800
600
400
200
0
No. People
16
14
12
10
8
6
4
2
0
0
2
4
6
8
10
12
14
16
18
20
22
Time [h]
CO2 [ppm]
CO2max [ppm]
No. People

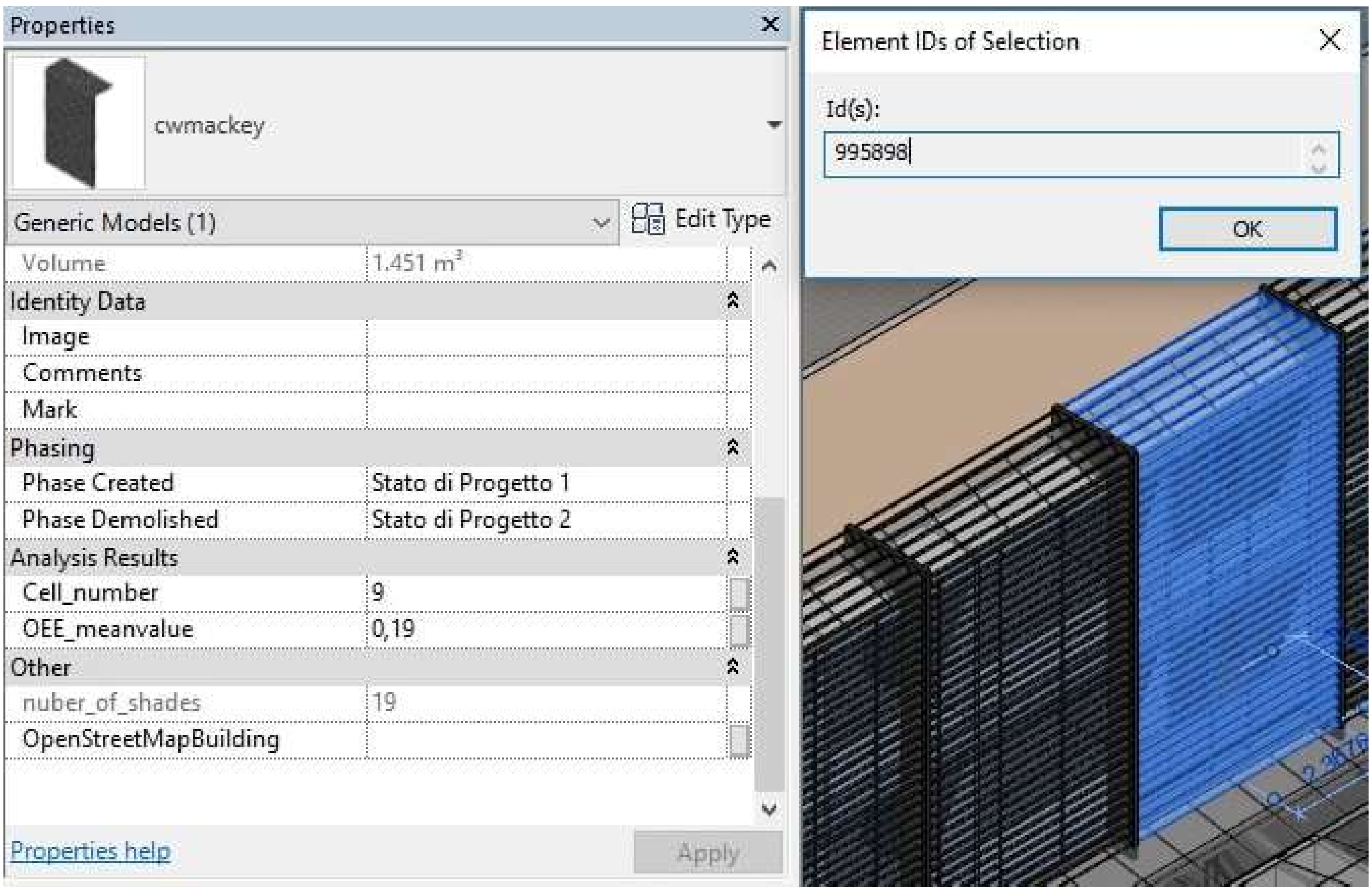

1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
AHU (HC)
LEA
WIN (HC)
ACR
AHU (IAQ)
WIN (IAQ)
FCU
SHA
TC
Hygrometric Comfort
Indoor Air Quality
Thermal Comfort
June 2016
July 2016

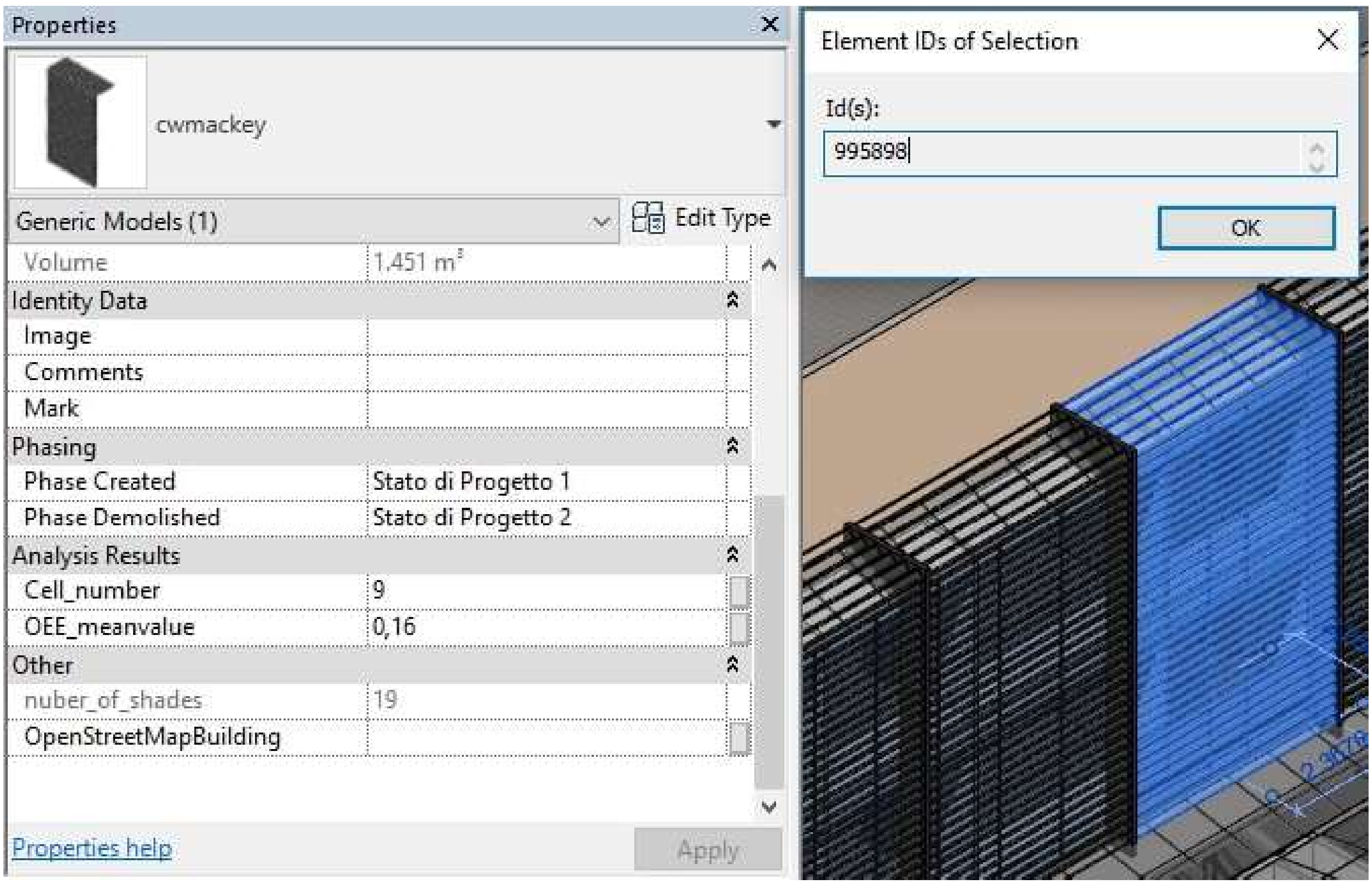
- Tables (10)
  - actions
  - cells
  - components
  - history_components
  - ID_995898
  - min_e
  - OTE_fun
  - OTE_num
  - systree
  - systree_history
- Views

	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



	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


Properties
cwmackey
Generic Models (1)
Edit Type
Volume
1.451 m³
Identity Data
Image
Comments
Mark
Phasing
Phase Created
Stato di Progetto 1
Phase Demolished
Stato di Progetto 2
Analysis Results
Cell_number
9
OEE_meanvalue
0,19
Other
nuber_of_shades
19
OpenStreetMapBuilding
Properties help
Apply
Element IDs of Selection
Id(s):
995898
OK


Properties
cwmackey
Generic Models (1)
Edit Type
Volume
1.451 m³
Identity Data
Image
Comments
Mark
Phasing
Phase Created
Stato di Progetto 1
Phase Demolished
Stato di Progetto 2
Analysis Results
Cell_number
9
OEE_meanvalue
0,16
Other
nuber_of_shades
19
OpenStreetMapBuilding
Properties help
Apply
Element IDs of Selection
Id(s):
995898
OK