Towards the cognitive building: 
information modeling for the energy audit

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Highlights
The research focuses on the concept of cognitive building which identifies in the “digital twin” of the building the ideal interface between man and building to allow internal conditions and provided services adaptation by focusing on the user. The base of the research is the digitization of the building that permits the gathering, transmission, filtering and analysis of extracted information in order to promote the minimization of waste, maximization of comfort and optimization of energy flows that necessarily should be flexible, adaptable and customized. The contribution aims at testing the use of the BIM methodology in order to make energy audit procedures more efficient.

Abstract
The new paradigm of smart building requires the accomplishment of occupants needs through the analysis of data gathered within the building, which switches from activities host to provider of customized services for occupants. The digitalization supports this new approach, as the implementation of Building Management Systems (BMS) in Building Information Modelling (BIM) environment allows to link the information collected to a database. The contribution is focused on a case study of the University of Cagliari, the Mandolesi Pavilion, and it is aimed at implementing and improving energy audit procedures by the use of Building Information Modelling.

Keywords
Energy retrofitting, Cognitive building, Energy audit procedures, BIM, BMS

1. INTRODUCTION

Analysing the broad definition of Industry 4.0, it is worthy to note that this is leading to “a confluence of disruptive digital technologies that are set to change the manufacturing industry in an unrecognizable way. The key elements of this change are the surprising growth in computing power, and connectivity, the emergence of advanced analysis and business intelligence functionality, new forms of human-machine interaction and the improvements in the transfer of digital instruction to the physical world, such as advanced robotics and 3-D printing “[1][2]. One element that appears with the greatest transparency is the fact that Cyber-Physical Systems (CPS) seem to be supply chain systems [3]. Industry 4.0 is based on principles of flexibility
of production and the individualization of products, which in real time are subject to the specific expectations of individual customers. Technologies and concepts are allowing the machines and algorithms of future societies to make decisions and carry out independently learning activities with minimal human-machine interaction [4]. These expressions introduce the paradigm of the Fourth Industrial Revolution in the Construction Sector in terms of supporting the semi-autonomy of decision-making processes.

This opens up to the concept of cognitive building which identifies in the “digital twin” of the building the ideal interface between man and building allowing conditions and provided services adaptation by focusing on the user in a specific and predictive way.

A monitoring and actuating network system permeating the building supports and derives by the ability to control conditions and enforce constraints in the indoor environment where generated and interfered flows are analysed. The crucial assumption on which the cognitive concept is based is the digitization of the building that permits the gathering, transmission, filtering and analysis of extracted information in order to promote the minimization of waste, maximization of comfort and optimization of energy flows that necessarily should be flexible, adaptable and customized. The application of advanced data analysis methods implemented through automated algorithms is conceivable by machine-readable and formerly computational data that can be collected, organized, visualized and networked within the building through a BIM system.

The implementation of the cognitive systems in the construction sectors appears really interesting: the availability of sensorized building components with “intelligence” during the manufacturing process, their installation and, above all, their useful life of service appears a very effective support in decision-making processes. In the Operations & Maintenance phase, the sensorized component would generate substantial information flows relating to its performance. In this way the original manufacturer would become a service provider: in particular, within performance-based contracts.

Furthermore, the so-called Cognitive & Living Built Asset is essential since the new real estate or infrastructure product places the user at the centre of the business. The concept of cognitive building is integrated with sensing technologies, distributed intelligence and IoT. It introduces in the building new possibilities of interaction and autonomization with alternative models of management during building life cycle in order to optimize in real-time all kind of intervention. The driver of these processes can be the energy optimization from which environmental impacts and management costs.
derive. It is important to centralize the processes of verification and control of the internal conditions, of the functioning of the energy management systems and of the flows of the occupants that define the conditioning needs (Personal Cloud or Cloud Cast of SEN-SEable City Lab at the Massachusetts Institute of Technology’s) [5].

However, this workflow is valid when the cognitive building crosses all phases: from the embryonic concept to the definitive design and execution phases. For the existing building heritage, conceived according to the traditional canons, often unknown in terms of components, performance, consumption, etc., the path to the cognitive building paradigm inevitably passes through intermediate steps. A complete survey on the existing building is necessary to correctly set up all the maintenance or retrofit interventions, in order, as far as possible, to “automate” the processes. The backwardness of the construction sector in terms of knowledge process and existing asset management, makes it far away from the paradigm of Industry 4.0. One of the main areas in which these limits are clearly shown is that of improving the energy performance of the assets. The results are strongly influenced by the margins of uncertainty on the evaluation of the residual performance of the building. The necessary knowledge process, synthetically called “energy audit”, is mostly based on flows that, although regulated [6], are still conducted in an artisanal way and without strong links with the other phases of the building process. The audit is aimed at developing a calibrated physical model (baseline) which represents the energy performance of the building at the current state and allows a reliable estimation of the effects of the possible efficiency measures [7]. Actually, what is required by the regulations is still too limited quantitatively and qualitatively to be concretely used in the simulation phases [8]. If the techniques that characterize the most refined diagnostic levels, such as simulation [9], are implemented, the amount of information requires digital management, as well as a close correlation with the geometrical and constructive data.

The paper tests the use of Building Information Modelling methodology in order to improve the energy audit process on the building envelope. The informative model of the building capitalizes the outputs of the energy audit process and represents an efficient knowledge base for the following analysis about possible intervention scenarios. The research group is applying the cognitive paradigm to a case study of particular architectural interest: the Mandolesi Pavilion which actually hosts the laboratories of the Departments of Civil and Environmental Engineering and Architecture and Mechanical Engineering, Chemistry and Materials of the University of Cagliari. The application of digital paradigms to a case study strongly characterized consistenti flussi informativi relativi alle proprie prestazioni, conosciuto l’originario produttore dierebbe erogatore di servizi: in particolare, all’interno dei performance-based contract. Oltre ai componenti sensorizzati, tuttavia, è il cosiddetto Cognitive & Living Built Asset a contare, poiché il nuovo prodotto immobiliare o infrastrutturale pone l’utente al centro del business, servizizzando la produzione. Il concetto Cognitive, dunque, si integra con la sensorizzazione, l’intelligenza distribuita e l’IoT introducendo nella costruzione nuove possibilità di interazione e di autonomizzazione che introducono modelli predittivi di gestione, costitutivi, performance, consumi, etc., per impostare correttamente tutti gli interventi di manutenzione straordinaria o di retrofit, nell’ottica, quanto più possibile, di “automatizzarne” i processi. Ciò che ancora appare molto lontano da quanto, in altri settori produttivi, sta consentendo il materializzarsi del paradigma dell’Industria 4.0 è, sicuramente, l’avventura nel settore delle costruzioni delle logiche connettive e di gestione degli asset esistenti. In questo senso uno dei principali ambiti in cui questi limiti stanno mostrandosi, in maniera evidente, è quello del miglioramento prestazionale energetico del patrimonio. I risultati ottenibili sono, infatti, fortemente influenzati dai margini di incertezza sulla valutazione delle prestazioni residue del costruito, che ancora al giorno d’oggi, sono estremamente ampi. Le necessarie procedure connettive, che possono essere ricondutte sincretisticamente nel termine “diagnosi energetica”, sono per lo più basate su processi che, per quanto normati [6], sono sempre condotti in maniera artigianale e senza forti collegamenti con le altre fasi del processo edilizio. La finalità della diagnosi, è ormai assodato, è quella di fornire una base per la successiva fase di costruzione di un modello fisico calibrato (baseline) che sia rappresentativo della prestazione...
by “traditional” constructive and management logics, involves important challenges. The first is related to the knowledge of the asset and the digital management of information. This led to the study of the building monitoring techniques and methodologies, in order to acquire, at a later stage, information regarding the building’s internal conditions and occupation as well as the flows of the people occupying the building during the use of spaces.

2. METHODOLOGY

2.1. THE CASE STUDY

The Mandolesi pavilion was designed by Enrico Mandolesi in 1962 and it was approved by the Technical Administrative Committee of the Public Works Department of Sardinia on 21 November 1962. The pavilion was built between 1964 and 1970 in order to host the Institute of Mining Engineering and Applied Chemistry of the University of Cagliari. It is articulated in an underground floor, a pilotis ground floor and two upper floors. The pilotis floor, along with the roof, constitutes the leisure areas and serves as a mediator space between the two upper floors and the underground floor. There are many differences between the slabs of each level of the building: the slab of the second floor is made of concrete and hollow blocks; the slab of the first floor is divided into a central span made of concrete with hollow blocks, and two cantilever spans made of reinforced concrete.

Figure 1. The Mandolesi Pavilion (Photo by Pierluigi Dessì).
The roof of the building is made of a double concrete slab reinforced along the two directions with the joists laid in situ. The external wall consists of only 6 cm thick prefabricated concrete panel, with a layer of 3 cm of glass wool, an air gap of 17 cm and a layer on the inside made of solid square bricks 6x6x24, obtained by cutting in half the “double UNI” brick. The concrete panels are fixed on the edge of the slab by “T” elements in profiled iron embedded when the slab is cast. The iron frame is not only the support for the concrete panels but also for the windows that close the slot between the slab and the underlying concrete panels. There are three types of “mono-block” windows: half-height, resting on the panels; full-height, fixed directly to the floor slab; full height with vertical shading blades in fired enamelled aluminium which can be adjusted from the inside.

2.2. THE BIM MODEL

BIM method involves the elaboration of a parametric model of the building, with the integration of virtual items (“families”) that accurately simulate those of the building. Therefore, the construction of the model of the Mandolesi Pavilion formed an important part of the work. It can gather the information that should be shared between all the subjects involved in building management. However, before the development of the model, some important preparatory actions had to be made. Starting from the careful analysis of the propriety information, the selection of the subject for the parametric modelling was carried out. The work focused on defining the most appropriate detail level of the model. This phase, defined as pre-modelling, is considered to be fundamental as it specifically determines the degree of graphic and information detail (LOD and LOI) needed to achieve the set goals. Depending on the purpose, the model can have different characteristics, ranging from the geometric ones to the alphanumeric ones. In the specific case of the Mandolesi Pavilion, due to its particular architectural value, the pre-modelling phase achieved a rather high level of detail for each technical element.

The complexity of the modelling of the Mandolesi Pavilion is related to the irregularity of particular elements of the building such as the pillars, beams with round edges and the internal staircase. The need to keep track of this irregularity resulted in the almost exclusive use of the “in place families” of the Revit software. The “in-place families” have the peculiarity of being created in the current project, they have the disadvantage of not being able to use them in other projects, and their massive also generates a very heavy model file. Despite the recognized disadvantages, their use made it possible to obtain the best result for the management approach of the Mandolesi Pavilion: the
faithful representation of the various components of the building at the level of complexity and geometric peculiarity. Avoiding excessive simplifications allowed preserving precious details for the planning of restoration and re-functionalization work.

The particular shapes of the components of the building within the modelling frame were reproduced, by using commands such as extrude, join and revolve. An important feature of the model is that it can be updated and integrated at any time in the life of the building. This aspect solves a further critical issue, namely the difficulty of ensuring the “information requirements” for the management of the building after the restoration works. The model, in fact, creates the structure which organises all the data and information that are produced during any new intervention work and that is functional to the innovative management of the building.

2.3. THE ENERGY AUDIT AND THE BIM MODEL

As already said, the present paper is aimed at experimenting the use of Building Information Modelling methodology to optimize the energy audit procedures, with a specific focus on the building envelope. The goal is the capitalization and organization of the audit outputs in a building information model that allows their accurate representation, functional to the simulation of retrofit interventions.

According to standard UNI CEI EN 16247-2:2017 [6], the data to be collected on the building envelope during the energy audit phase are:

- Thermal transmittance values with possible improvements and limits;
- Solar shading conditions with possible improvements and limits;
• Thermal inertia;
• Air tightness;
• Presence of joints and thermal bridges.

In the work, with specific reference to the case study, the issues, for which the correlation with the information model was investigated, were the first and the last. They were analyzes by the use of instrumental surveys such as heat-flux measurements [10] and IR thermographies [11]. For both the information, coming from the tests and that could be properly stored within the building model or in a supporting Common Data Environment, were identified.

Once the above-mentioned tests were carried out and the geometrical and constructive model was created according to design drawings, it was possible to associate to each element the features described in the cited European standard on energy audits [6]. With regards to external walls, the planar structure and the absence of internal thermal bridges, allowed to obtain the thermal conductivity values for all the elements and compare them with the thermal transmittance measurements, according to the calculation described in [12]. The workflow is showed in Figure 3.

With reference to the slabs, the necessity to reduce their weight by hollow blocks or air cavities, due to the peculiar static scheme adopted for the building, required a numerical calculation [13] because of the presence of two-dimensional components of the thermal flux. In that case the workflow is showed in Figure 4.

The estimation of the case study thermal bridges was quite important, due to the presence of several fair-faced concrete elements. The linear thermal transmittance values were associated to the model elements affected by the resultano funzionali ad una gestione innovativa dell’edificio.

2.3. L’AUDIT ENERGETICO ED IL MODELLO BIM

Come già preannunciato, il presente contributo mira a sperimentare l’impiego della metodologia Building Information Modelling al fine di efficientare le procedure di audit energetico, con specifico riferimento all’involucro edilizio. L’obiettivo è la capitalizzazione ed organizzazione degli esiti del processo di audit in un modello informativo dell’edificio che ne consenta una rappresentazione fedele e funzionale alla simulazione di interventi migliorativi.


• I valori di trasmittanza termica degli elementi con eventuali miglioramenti e restrizioni;
• Le condizioni di ombreggiamento con eventuali miglioramenti e restrizioni;
• L’inerzia termica;
• La tennuta all’aria;
• La presenza di giunti e ponti termici.

Nel presente lavoro, e con riferimento al caso di studio citato, gli aspetti di cui si è studiata la correlazione con il modello geometrico e costruttivo dell’edificio sono stati principalmente i primi e gli ultimi, che sono stati analizzati anche attraverso indagini strumentali, quali misure termofluessimetriche [10] e termografiche [11]. Con riferimento ad entrambe sono state individuate le informazioni che hanno caratterizzato le prove che possono essere opportunamente integrate all’interno del modello informativo o di un Common Data Environment di supporto.

Una volta condotte le misure descritte e realizzato il modello geometrico-costruttivo sulla base degli elaborati grafici progettuali, è stato possibile
thermal bridges and the calculation started from their geometrical modelling. The workflow is showed in figure 5.

Figure 4. Workflow for the input of thermal properties of the case study slabs (L2D: thermal coupling coefficient; U: thermal transmittance).

Figure 5. Workflow for the input of thermal bridges properties in the case study (Ψ: linear thermal transmittance).

3. RESULTS

The IR thermographies highlighted the low performance of the envelope, pointing out the presence of some thermal bridges. It successively required their accurate survey, according to the workflows described in the previous section.

The analyses of the building architectural plans, particularly of the variations during the works, made possible to define accurately the geometrical and constructive features of the envelope that was the starting point to assess its present thermal performances. The heat-flux tests carried out on the facade measured a thermal transmittance equal to 1,28 W/m²K. That, compared with the data calculated starting from the conductivity values of the external verticali, la struttura ad elementi piani paralleli e l’assenza di ponti termici interni ad esse, ha consentito di ricavare i valori di conduttività di tutti gli elementi e verificarli con le misure di trasmittanza, secondo il calcolo previsto dalla [12]. Il flusso di lavoro è rappresentato in Figura 3. Per quanto riguarda gli orizzontamenti, la presenza di casseforme a perdere in laterizio o di intercapedini d’aria atte ad alleggerire il peso, a causa del particolare schema statico adottato, ha richiesto una modellizzazione numerica [13] per la presenza di componenti bidimensionali del flusso termico. Il flusso di lavoro, in questo caso, è rappresentato in Figura 4.

La valutazione dei ponti termici nel caso in oggetto è stata di particolare importanza, vista la presenza di numerosi elementi strutturali in calcestruzzo armato a vista. I valori di trasmittanza termica lineica sono stati associati agli elementi del...
partition’s materials, pointed out the low residual performance of the glass wool insulation. Assuming that the thickness of the insulating layer is still 3 cm, as foreseen by the design schemes, the residual conductivity is equal to 0.11 W/mK, quite higher than the value at the moment of the laying.

All the data coming from thermographies and heat-flux measurements were stored in the building information model, specifically in the schedule of the related constructive elements, in order to make them available to all the operators of a hypothetic retrofit intervention on the building. The details of all the information integrated in the model are listed in figure 6. Specifically, both the numerical data (such as the measured thermal transmittance) and the links to external images or graphs were inserted, as well as the links to the raw data acquired.

![Figure 6](image_url)

**Figure 6.** Collection and management of the energy audit data through the building information model. In the centre: the schedule of the elements highlighted in the model (1). Fields for the storage of data regarding thermal bridges (2), IR images (3) and heat-flux measurements (4) were created.

The finite elements modelling of heat exchanges brought to the estimation of a thermal transmittance equal to: 3.53 W/m²K for the lower slab in the cantilever section and 0.79 W/m²K for the same slab in the central span as well as for the slab separating the first and second floor, 1.53 W/m²K for the
roof in the cantilever section and 1,00 W/m²K in the central span. The different values derive from the different layers adopted during the construction phase, necessary to comply with the peculiar static scheme, not sufficiently addressed during the design phase. The building information modelling firstly made the elements sections available with a proper level of detail. Those were the base of the geometrical inputs for the finite elements solver. Then it was possible to assign exactly to each building elements its thermal performance value, as well as all the calculation files that brought to the assessment of such values (Figure 6).

Those highlighted the scarce insulating capacity of the slabs, with some very critical points, such as the cantilever span of the lower slab that will require surely additional insulation in the future (Figure 7).

The envelope is also affected by several thermal bridges, due both to the openings and to the fair-facet structural elements. Again the model provided the geometrical details of the joints and the thermal properties (conductivity, specific heat and density) of the materials. The finite elements solver allowed to estimate the thermal coupling coefficient and, thus, the linear thermal transmittance (Ψ), as described in the previous section. That was assigned in the model to all the elements delimited by a given node (Figure 6).

As is normal in building energy performance calculation, linear thermal transmittance of nodes delimiting opaque elements was equally divided between them, while the thermal bridge between openings and opaque surfaces was completely assigned to the former. In the case of the joint between the external walls and the lower slab, the linear thermal transmittance calculated was 1,43 W/mK and was equally halved between the former and the latter (Figure 6).
4. CONCLUSIONS

The work presented so far illustrates only some of the research activities carried out on the case study building. In particular, the methodology proposed to record and analyze some of the data related to the envelope energy audit through the building information model was described. It showed to be useful firstly as the base for all the geometrical data, provided that the level of detail of the model is adequate. The possibility to extract the geometrical sections, as showed, is useful for all the thermal modelling of the complex elements or the nodes that represent thermal bridges. By the creation of a CDE (Common Data Environment) it is possible to execute such modelling with dedicate solvers and link afterwards the results to the elements in the building model.

The same can be said for the instrumental surveys that can give a more or less detailed overview on the envelope. Generally, those data are lost, or, better, condensate in the only value of transmittance. Instead, the possibility to associate the measure, not only as the final value, but also as the tabular data recorded or the IR image, with the object representing a given element in the model, increase the set of information that remain available for future operations on the building.

The next steps of the research will focus on data, such as hourly air changes or shading factors, that are listed among the ones compulsory in energy audit standard procedures and that can be integrate in the building model as well. All these information are essential to carry out a correct planning and simulation of the energy retrofit interventions. It is also true that, regardless of the detail level of such simulations instruments, the baseline information set need to be associated with the asset model and it is not necessarily prerogative of the only simulation phase.

5. REFERENCES

il profilo energetico. È anche vero però che, al di là degli strumenti più o meno dettagliati per eseguire tali simulazioni, il corredo informativo di partenza deve essere associato al modello del cespite e non necessariamente appannaggio della sola simulazione.