Information modeling for the monitoring of existing buildings’ indoor comfort

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Highlights

Building information modelling can provide a valid support to all the phases of retrofit process. The informative model can manage and represent data on indoor hygrothermal comfort. Studying the possibility to use small and smart sensors helping to carry out energy audit is one of the main output of the research.

Abstract

BEMS (Building Energy Management System) and BACS (Building Automation and Control System) make available a high quantity of data on consumptions, indoor and outdoor conditions and users’ profiles of a building that can drive the choice of energy retrofit interventions. Moreover, the current developments in the digitalization of the building process, are leading the diffusion of BIM methods and tools which can provide a valid support to manage all data and information for the retrofit process. The paper is focused on the efficient integration of these systems.

Keywords

Building’s indoor comfort monitoring, Energy Audit, BIM, Integrated multi sensors

1. INTRODUCTION

The adoption of Building Information Modeling (BIM) methodology on renovation and retrofitting projects is still at a basic level [1]. Despite the urgent need to improve the quality and the functionality of the existing building stock, all the processes related to its transformation are still carried out with traditional analogical methods and instruments. The main cause is that an efficient application of BIM methodology needs overcoming a number of critical issues, such as the identification of necessary information for retrofitting, the collection and proper interpretation of monitored data, the handling of uncertainty and the long time and high resources required for creation of the model of an existing building [2]. In these cases the informative
model has to be generated from the actual 'as-built' state with practically none or only scarce documentation and information [3]. Among all the possible sets of information that can be gathered when analyzing an existing building, one of the most complex and detailed regards its energy performance and consumptions (Energy Audit or Energy Diagnosis). It requires first of all the collection of climatic data regarding the building site. They can be affected by the built and natural context surrounding the building, so at least the geometry of the obstructions nearby must be modelled. Then data on the building opaque and transparent envelope must necessarily be collected, together with other derivative thermal quantities such as steady-state and periodic thermal transmittance. Regarding electrical and thermal systems, their main features and consequent energy performance must be collected and/or assessed. Unlike industry audits, where the output of manufacturing processes is precisely defined, buildings audits require also the assessment of the operating conditions of the building and its use profile [4]. Since the main function of HVAC system is providing suitable hygro-thermal indoor conditions and air quality, it is evident that a comprehensive approach to audits cannot avoid their correct assessment [5]. The thermal comfort sensation is basically depending on the heat balance between the human body and the environment, that is a complex phenomenon, so its whole analysis requires the measurement and assessment of different quantities [6] by the use of suitable instruments [7]. The standard procedure for the measurement of the basic variables and the consequent calculation of comfort indexes are carried out with microclimatic monitoring devices that can be bulky and cannot be easily positioned within occupied spaces. For these reasons they do not fit for continuous monitoring of environmental parameters, that is instead a key point for the conversion of the existing buildings into “cognitive” ones [8]. The increasing presence in buildings of BEMS (Building Energy Management System) and BACS (Building Automation and Control System), makes available a very large amount of data on consumptions, internal and external environmental conditions and use profiles that can be of great help in energy audit procedures. It is also possible integrating in buildings components different dedicate sensor able to collect data on indoor thermal conditions. In both case, the measurement uncertainty is much higher than microclimatic monitoring devices. In 2018 regional research body Sardegna Ricerche financed the cluster project PRELuDe³ (protocol for the processing of buildings energy efficiency’s data), whose main task is to link together all the players of the energy retrofit interventions by the use of BIM [9]. In this context, studying the possibility to

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I. INTRODUZIONE

L’adozione della metodologia Building Information Modeling (BIM) nell’ambito degli interventi di riqualificazione e di retrofitting è ancora a un livello embrionale [1]. Nonostante l’urgente necessità di migliorare la qualità e la funzionalità del patrimonio edilizio esistente, tutti i processi correlati alla sua trasformazione vengono ancora effettuati con strumenti e metodi analogici tradizionali. La causa principale consiste nel fatto che un’applicazione efficiente della metodologia BIM si trova ad affrontare una serie di criticità, quali l’identificazione di informazioni necessarie per l’intervento di retrofitting, la raccolta e la corretta interpretazione dei dati monitorati, la gestione dell’incertezza e le elevate risorse necessarie per la creazione del modello dell’edificio esistente [2]. Per gli interventi di riqualificazione degli edifici esistenti il modello informativo deve essere generato dallo stato ‘as-built’ a partire da una scarsissima, se non nulla, documentazione d’archivio [3].

Tra tutte le possibili informazioni che possono essere raccolte durante l’analisi di un edificio esistente, quelle che riguardano il comportamento energetico ed i consumi (Audit energetico o Diagnosi energetica) sono fra le più complesse e dettagliate. La prima fase di tale procedura richiede la raccolta di dati climatici per quanto riguarda il luogo di costruzione. Questi possono essere influenzati dal contesto costruito e naturale che circonda l’edificio, per questo motivo deve essere modellata almeno la geografia delle ostrazioni nelle vicinanze. Successivamente devono essere necessariamente raccolti dati sull’involvero opaco e trasparente, insieme ad altre grandezze come la trasmittanza termica stazionaria e periodica. In merito ad impianti elettrici e termici, devono essere raccolte e/o valutate le informazioni relative alle loro caratteristiche principali e le conseguenti prestazioni energetiche. A differenza degli audit industriali, dove è definito esattamente l’output dei processi produttivi, quelli edilizi richiedono anche la valutazione delle condizioni operative dell’edificio e del suo profilo di uso [4]. Poiché la funzione principale del sistema HVAC è quella di fornire condizioni indoor idrotermiche e qualità dell’aria idonee, è evidente che un approccio globale alle verifiche non può prescindere dalla loro corretta valutazione [5].

La sensazione di comfort è fondamentalmente dipendente dall’equilibrio termico tra corpo umano e ambiente; si tratta di un fenomeno complesso a cui l’analisi richiede la misurazione e la valutazione di quantità differenti [6] tramite l’uso di idonei strumenti [7]. La procedura standard per la misurazione delle variabili di base e il conseguente calcolo di indici di comfort è condotta con dispositivi di monitoraggio microclimatici che...
use small and smart sensors helping to carry out energy audit is one of the main activities. The research, lead by the DICAAR Department of the University of Cagliari together with DIEE Department and Sotacarbo SpA, with the collaboration of Polytechnic University of Milan, is currently focused on the monitoring of the case study building: the Mandolesi Pavilion of the Faculty of Engineering and Architecture in Cagliari. In the frame of this research, the present paper is aimed at investigating how complex comfort indexes can be derived from small sensors measurement and how they can be collected, managed and represented by the use of BIM.

2. STATE OF THE ART

Currently, the main theories regarding thermal comfort in indoor inhabited spaces are two: the first originates from the studies of Fanger [10], while the second is due to the studies on adaptive models [11, 12]. It is generally accepted that the use either of the former or the latter depends on different boundary conditions [13]. The Fanger’s method has been preferred in this study due to its higher complexity requiring a wider set of information.

According to the standard procedures [6], thermal comfort can be defined by one global and few local indexes. In the following only the first will be taken into account. The statistic response of a given number of occupants to a thermal environment can be expressed by the use of PMV (Predicted Mean Vote) or the correlated PD (Percentage of Dissatisfied). Their calculation requires six input quantities. Two depend on occupants: clothing insulation (CLO) and metabolic rate (MET). Four are related to environment: air temperature (ta), relative humidity (RH), air velocity (va), mean radiant temperature (MRT).

The acceptability of different set of environmental and personal variables can be verified calculating PMV and confronting the results with the threshol values given by standards. They are not fixed, but depend on the intended use of the spaces (residential, educational, hospital …): from ± 0,2 (space’s category A) to ± 0,7 (category C) [6].

The measurement of the four environmental quantities has to be carried out with certified sensors (at least a psychrometer, a globe thermometer and an anemometer) that are described in detail in [7].

As already explained, this kind of devices unlikely suits for continuous environmental monitoring. The sensors tested in the present research are characterized by smaller dimensions, possibility to be easily integrated in building components and able to connect to existing Wi-Fi networks.

In the case study of PRELuDE³ project a set of similar sensors has been installed (Figure 3).
Figure 1. Procedure for the evaluation of indoor global thermal comfort according to Fanger's theory and standard ISO 7730 [6].

Figure 2. Full microclimatic station for the measurement of environmental parameters affecting occupants’ global comfort sensation, according to ISO 7726 [7].

Figure 3. Multi sensor room controller installed in Mandolesi Pavilion by PRELuDe³ project.
On the one hand, it is evident that the quality of measurement of the integrated multi sensor is not as high as the one of a certified microclimatic station. On the other hand they can provide continuous measurement that can be easily transferred to a dedicate common data environment by Wi-Fi connections. For the reasons it is authors’ opinion that it is worthy to investigate on a simplified methodology to obtain comfort indexes by small sensors measurement and to represent them by the use of BIM.

3. METHODOLOGY

The case study, the Mandolesi Pavilion, is a contemporary building, nowadays historicized, of particular architectural and iconic value. Designed starting from 1962 by Enrico Mandoles, was completed in 1970 [14]. Inside the building, two offices have been the object of sensorization aimed at detecting parameters useful for defining performance and comfort within the building spaces.

After a reconnaissance work on the available documentation about the building, on the geometric, technical and technological aspects of its components, the work continued with the definition of a conceptual scheme of decomposition of the building into constructive objects categories (PBS). Then, with the choice of alphanumeric contents to be capitalized for each of them, the level of detail of the model can be defined. Finally, a set of parameters to “inform” the model components was selected. The building components were modeled respecting the architectural detail and the current internal distribution scheme.

Furthermore, we proceeded to associate a parametric object in the digital model of the building to each sensor located in the two rooms indicated above. Through the use of the BimOne plug-in, which allows the connection of the digital model database to a spreadsheet, the data coming from the sensors...
and recorded in the spreadsheet can be capitalized and displayed in the room schedules of Revit with a simple updating of the model.

In the following a simplified procedure for the calculation and representation of comfort indexes is proposed. In the next section, the results of its application to the case study will be discussed.

The first step has been the reduction and simplification of the input parameters. The installed sensors are able to measure $ta$ and RH, but MRT and $v_a$ remain substantially unknown. The first can be measured by a globe thermometer, that, despite its precision [15], can unlikely be incorporated in small smart devices. Many studies are nowadays available on possible alternative measurement and calculation of MRT, since it depends on the surface temperature of indoor walls, ceiling and floor and on their geometry, more precisely on the view factors between the point of measurement and each surrounding surface [16]. Some of them take also into account the use of the informative model of the building [17].

The purposes of the present work suggest an even more simplified method that consider MRT equal to $T_a$. Such hypothesis, after having fixed the values of

![Comfort area in January](image)

*Figure 5. Comfort area drawn for winter conditions in an office space. MET=1,2; CLO=1; $v_a=0,1$ m/s; MRT=$t_a$; PMV$_{11}$=-0,5; PMV$_{12}$=0,5 (space category B).*
CLO, MET and va favors the graphical representation of the results because “iso-PMV” conditions can be depicted on a psychrometric chart [18].

MET can be fixed taking into account the activity carried on within the room. It is information that can be easily correlated to the informative model spaces. CLO and va can be set according to the year’s period that can be read by the sensors’ measurements.

Instead of calculating PMV starting from the sensors measurement, an inverse approach has been proposed, in order to better represent the comfort conditions on psychrometric charts. It is a key point of the work, since they can be easily linked to the informative model and give an immediate overview of eventual discomfort occurrences. The workflow proposed is the following.

MET, that depends on activity, thus on the space use, is read from the model room schedule. CLO and va are assigned according to the date registered by the sensors. The PMV thresholds (in the following PMVll and PMVul for the lower and upper acceptable limits) are read from the room space schedule where they are set according to its category [6]. MRT is set equal to $T_a$. Under such hypotheses, by the use of a dedicated spreadsheet that reads the required input data from the model and the CDE, the comfort area can be drawn on a psychrometric chart as in figure 5.

The sides of the comfort area are the iso-PMVll and iso-PMVul lines, while the top and bottom ones are drawn according to the maximum and minimum acceptable RHs that are 70% and 30% [6]. The area is calculated solving the nonlinear system described in [6] and generally used to calculate PMV

distributivo interno attuale. Inoltre, si è proceduto all’associazione, ad ogni sensore collocato nei due locali indicati sopra, di un oggetto parametrico nel modello digitale dell’edificio. Attraverso l’utilizzo del plug-in BimOne, che consente il collegamento del database del modello digitale ad un foglio di calcolo, i dati provenienti dai sensori e registrati nel foglio di calcolo possono, con un semplice aggiornamento del modello, essere capitalizzati e visualizzati negli abachi dei locali.

Di seguito viene proposta una procedura semplificata per il calcolo e la rappresentazione degli indici di comfort. Nella prossima sezione verranno discussi i risultati della sua applicazione al caso studio.

Il primo passo è stato la riduzione e la semplificazione dei parametri ambientali di input. I sensori installati sono in grado di misurare $T_a$ e RH, ma MRT e va rimangono sostanzialmente sconosciute. La prima può essere misurata con globo-termometro, che, nonostante la sua precisione [15], difficilmente può essere incorporato in piccoli dispositivi. Attualmente sono disponibili numerosi studi su possibili misure alternative e sul calcolo della MRT, poiché essa può essere anche calcolata a partire dalla temperatura superficiale delle pareti interne, del soffitto e del pavimento e dalla loro geometria, più precisamente dai fattori di vista tra il punto di misurazione e ogni superficie circostante [16]. Alcuni di essi tengono conto anche dell’uso del modello informativo dell’edificio [17].

Il presente lavoro suggerisce un metodo ancora più semplificato che considera MRT uguale a $T_a$. Tale ipotesi, dopo aver individuato i
4. RESULTS

Currently in Mandolesi Pavilion, two rooms (north and south facing) are equipped with smart sensors collecting data on environmental conditions ($t_a$, RH, illuminance, $CO_2$) and energy consumptions.

Among the data stored in the CDE, two set of environmental measurement starting from the standard six input parameters (see previous section).

Once the comfort area is identified, the spreadsheet compares $t_a$ and RH from the sensor to the drawn limits. If the point is on the left of the area, a too cold condition occurs (“F”). If it is on the right, it means too hot inside the room (“C”). If the point is within both sidelines, but above or under the comfort zone a too humid (label “U”) or too dry (label “S”) conditions are respectively assigned to the point. In case of none of these occurrences, the room is in comfort conditions.

The charts with comfort zones and dotted with measurements are linked to the room schedule. The spreadsheet calculates the percentage of F, C, U and S points on a whole monthly set of measurement. These percentages are shown on the model by a color scheme for each room equipped by sensors.
have been selected for the test of the methodology previously described. They refer to July 2017 and January 2018 and have been measured in the north facing room.

The sensors have an acquisition rate of 5 minutes. Since the response of human body to environment has not such rapidity, hourly averages of ta and RH have been calculated and imported in the dedicated spreadsheet. Then MET, PMV_{ll} and PMV_{ul} have been read from the model. For an office building MET is equal to 1,2 while PMV limits are ±0,5. From the date of the hourly measurements averages the spreadsheet has selected the suitably values for v_a (0,1 m/s for January and 0,12 for July) and CLO (1 for January and 0,5 for July, due to different predicted level of clothing).

In January very few points are below the minimum acceptable, while in July, a conspicuous number of points is on the right of the comfort area.

This representation gives an immediate overview of the measured data, however do not consent to associate them to the moment of acquisition. An alternative representation is depicted in figures 9 and 10.

In those cases it is possible to identify the days in which comfort is not provided. The dotted lines represent the temperature corresponding to PMV_{ll} and PMV_{ul} for a relative humidity equal to the measured one.
The spreadsheet has counted the number of points inside and outside the comfort areas, identifying also their relative position.

In January only 7.8% of hours are beyond comfort limits while in July comfort is reached only for the 38.6% of time. Data collected by the sensors and the relative elaborations have been structured inside the informative model. The creation of a room schedule has allowed the capitalization of historical data recorded by the sensors and of diagrams about the comfort level associated with the various rooms of the building.

In figure 11 it is possible to identify the temperatures recorded in the north-
facing room both in July 2017 and in January 2018.

Figure 12 shows that the room schedule contains parameters for the organization of the diagrams that very clearly represent the comfort conditions of the same room with respect to the required limits.

Finally the use, inside the room schedule, of color schemes has allowed to provide an immediate visualization of the situations of discomfort within the sensorized rooms.

<table>
<thead>
<tr>
<th>HOURS OF COMFORT OR DISCOMFORT (%)</th>
<th>month</th>
<th>January</th>
<th>July</th>
</tr>
</thead>
<tbody>
<tr>
<td>comfort</td>
<td>92,2%</td>
<td>38,6%</td>
<td></td>
</tr>
<tr>
<td>hot (C)</td>
<td>0,8%</td>
<td>59,5%</td>
<td></td>
</tr>
<tr>
<td>cold (F)</td>
<td>7,0%</td>
<td>1,9%</td>
<td></td>
</tr>
<tr>
<td>humid (H)</td>
<td>0,0%</td>
<td>0,0%</td>
<td></td>
</tr>
<tr>
<td>dry (S)</td>
<td>0,0%</td>
<td>0,0%</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Percentage of hours within or beyond comfort limits. The table shows also the reason for an eventual overstepping.

Figure 11. Room schedule and historical temperature data.

Figure 12. Room schedule and data on internal comfort conditions.
5. CONCLUSIONS

Building information modelling can provide a valid support to all the phases of retrofit process. It is evident that BIM can be also a fundamental instrument of information management in the knowledge phase, preliminary to any design proposal, also from the energy point of view. Besides all the information that can be gathered and stored regarding the existing envelope and systems, the paper shows that the model can manage and represent data on indoor hygrothermal selection of appropriately values for va (0.1 m/s per January and 0.12 per July) and CLO (1 per January and 0.5 per July, due to the different levels of clothing hypothesized).

A January few points are below the minimum acceptable, while July a number of points is on the comfort right side of the area comfort. This representation provides an immediate overview of the measured data, but does not allow them to be associated with the time of acquisition. An alternative representation is shown in Figures 9 and 10. In these cases it is possible to identify...
comfort, too. To reach such a goal, it is necessary that a widespread network of monitoring devices is installed. PRELuDE³ project is testing at the moment a system on the case study of Mandolesi Pavilion in Cagliari, able to collect continuously data at least on the basic comfort parameters (air temperature and humidity). Human response at environmental condition is not, however, a simple phenomenon and it is influenced also by other variables. It can be correctly represented only by the use of complex indexes, among which the Predicted Mean Vote is the most frequently employed.

The methodology proposed in the paper provides a simplified workflow for the management of all the data necessary for the assessment of comfort or discomfort conditions during the energy audit process. It shows how it is possible linking the informative model with the data coming from sensors. The first gives useful information on activities carried out in indoor space and can define the PMV thresholds that depend on building use. The latter provide data on environmental parameters and on the period of monitoring on which statistical clothing insulation and air velocity values depend. Starting from these inputs, it is possible to evaluate the occurrence of comfort or, otherwise, the reasons for a probable discomfort sensation from occupants.

The graphs drawn for the case study highlights in a very effective and immediate way that in the monitored room during a winter month, comfort conditions are very often reached while during July the discomfort hours are predominant. Under such conditions, the analyses of energy consumption must necessarily take into account the absence of required thermal quality of the spaces, due probably to an underutilization of cooling systems.

The described study also shows that the comfort temperature range is not fixed, but can sensibly vary from winter to summer and, even in the same month, it can oscillates because of the influence of the other variable, firstly by the humidity. It is well known by the theories on comfort, but it should not be forgotten that still today HVAC systems have generally only one set-point, fixed on a given temperature in summer and in winter. From this point of view the study can give and interesting contribution also on more functional algorithms for systems setting.

The next step of the research activity will be the comparison between the comfort indexes calculated by the simplified methodology and by a certified microclimatic monitoring device. Small sensors can bring a dramatic increase of the number of data acquired, but their quality need to be cautiously verified. Also the estimation of some environmental variable, such as MRT, will be improved. The 3D model can give useful information regarding the geometry of the spaces. Together with the use of suitable algorithm to evaluate the

i giorni in cui il comfort non si rileva. Le linee tratteggiate rappresentano la temperatura corrispondente a PMVₑ e PMV₆ per un'umidità relativa uguale a quella misurata. Il foglio di calcolo conta il numero di punti all'interno e all'esterno delle aree di comfort, identificando anche la loro posizione relativa.

A gennaio solo il 7,8% delle ore supera i limiti di comfort a luglio il comfort è raggiunto solo per il 38,6% del tempo. All'interno del modello informativo sono stati strutturati i dati rilevati dai sensori e le relative elaborazioni. La creazione di un abaco dei locali ha consentito la capitalizzazione di dati storici registrati dai sensori e dei diagrammi circa il livello di comfort associato ai vari locali dell'edificio. Nella figura 11 si possono individuare le temperature registrate nel locale esposto a nord nel mese di luglio 2017 che nel mese di gennaio 2018.

Nella figura 12, invece, si può notare che l’abaco dei locali contiene dei parametri che consentono di capitalizzare anche i diagrammi che rappresentano molto chiaramente le condizioni di comfort dello stesso locale rispetto ai limiti richiesti.

Infine, all’utilizzo, all’interno dell’ambito dei locali creato, di schemi colori ha consentito di fornire una visualizzazione immediata delle situazioni di disagio all’interno dei locali sensorizzati.

5. CONCLUSIONI

La creazione di modelli informativi può fornire un valido supporto a tutte le fasi del processo di retrofit. È evidente che il BIM può essere anche uno strumento fondamentale in fase di conoscenza, preliminare a qualsiasi progetto di progetto, anche per quanto riguarda gli aspetti energetici. Oltre a tutte le informazioni che possono essere raccolte e memorizzate riguardo all’involucro e agli impianti esistenti, il contributo mostra che nel modello informativo possono essere gestiti e rappresentati anche i dati sul comfort igrotermico interno. Per raggiungere tale obiettivo, è necessario installare una rete capillare di sensori di monitoraggio. A tal proposito, con il progetto PRELuDE³, al momento si sta testando un sistema di monitoraggio sul caso studio del Padiglione Mandolesi a Cagliari, in grado di raccogliere dati controllati almeno sui parametri di base del comfort (temperatura e umidità dell’aria). La risposta umana alle condizioni ambientali non è, tuttavia, un fenomeno semplice ed è influenzata anche da altre variabili. Tale risposta può essere rappresentata correttamente solo mediante l’uso di indici complessi, tra cui il più frequentemente impiegato è il “voto medio previsto”.

La metodologia proposta nel presente contributo fornisce un flusso di lavoro semplificato per la gestione di tutti i dati necessari per la valutazione delle condizioni di comfort o disagio durante il
temperatures of indoor surfaces it could bring to a more precise assessment of mean radiant temperature and, thus, of comfort complex indexes. The correlation between energy consumption and comfort conditions can be also investigated. In the case study currently also sensor acquiring information on electrical consumption are installed. Linking these data with comfort could bring to an assessment of the quality of heating and cooling system and on their use profile.

One of the most ambitious future challenges for the research will be the automation of the workflow, reducing the transfer of data towards and from datasheets and implementing the potentiality of visual programming of BIM applications. It is a key step toward the creation of instruments that can be used also by non expert operators.

6. REFERENCES


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