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
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 threshold 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 of Dissatisfied). Il loro calcolo richiede sei grandezze di input. Due dipendono dagli occupanti: isolamento dell’abbigliamento (CLO) e tasso metabolico (MET). Quattro sono legate all’ambiente: temperatura dell’aria (t), umidità relativa (RH), velocità dell’aria (va), temperatura radiante media (MRT). L’accettabilità di differenti set di variabili può essere verificata calcolando il PMV e confrontandolo i risultati con il soglia dati dalle norme. Questi non sono fissi, ma dipendono dalla destinazione d’uso degli spazi (residenziale, educativo, ospedaliero ...): da ± 0,2 (categoria A dell’ambiente) a ± 0,7 (categoria C) [6].

La misurazione delle quattro grandezze ambientali deve essere effettuata con sensori standard certificati (almeno uno psicrometro, un termometro a globo ed un anemometro) descritti dettagliatamente in [7]. Come già anticipato, questo tipo di dispositivi difficilmente si adatta ad un monitoraggio ambientale continuo. I sensori testati dalla presente ricerca sono di ridotte dimensioni, possono essere facilmente integrati nei componenti dell’edificio e risultano in grado di connettersi alle reti Wi-Fi esistenti.

Nel caso di studio del progetto PRELuDe³ è stata installata una serie di sensori simili (figura 3). È evidente che la qualità della misurazione del multi sensore integrato non è elevata come quella di una stazione microclimatica certificata. D’altra parte tali sensori forniscono misurazioni continue che possono essere facilmente trasferite in un ambiente di condivisione dati dedicato tramite connessioni Wi-Fi. Per le ragioni sopra esposte, è opinione degli autori che sia opportuno investigare su una metodologia semplificata per ottenere indici di comfort mediante l’utilizzo di piccoli sensori le cui misurazioni saranno rese disponibili mediante l’uso della modellazione informativa degli edifici.
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 \( t_a \) 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

3. METODOLOGIA

Il caso studio è il Padiglione
Mandolesi, nel campus della Facoltà
di Ingegneria, una importante
architettura contemporanea ormai
storicizzata, progettata a partire dal
1962 dall’ing. Enrico Mandolesi e
conclusa nel 1970 [14]. All’interno
e dell’edificio sono stati scelti due
uffici che sono stati oggetto di
sensorizzazione atta a rilevare
parametri utili per la definizione
delle prestazioni e del comfort
e dell’intero degli spazi dell’edificio.

Dopo un’accurata ricognizione
in merito alla documentazione
disponibile dell’edificio, dei
relativi aspetti geometrici, tecnici
e tecnologici dei suoi componenti il
lavoro è proseguito con la definizione
de uno schema concettuale di
scomposizione del manufatto in
categorie di oggetti costruttivi
(PBS), con la scelta dei contenuti
alfanumerici da capitalizzare per
ciascuno di essi e, di conseguenza,
correlato alla definizione del livello di
dettaglio del modello. Infine, si è
proceduto alla selezione di un set di
del dettaglio architettonico e lo schema

![Figure 5. Comfort area drawn for winter conditions in an office space.](image)

\[
\text{MET}=1.2; \ CLO=1; \ v_a=0.1 \text{ m/s}; \ MRT=t_a; \ PMV_{ul}=-0.5; \ PMV_{ll}=0.5 \text{ (space category B).}
\]
CLO, MET and \( v_a \) 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 \( v_a \) 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 \( v_a \) are assigned according to the date registered by the sensors. The PMV thresholds (in the following PMV\(_{\text{ll}}\) and PMV\(_{\text{ul}}\) 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-PMV\(_{\text{ll}}\) and iso-PMV\(_{\text{ul}}\) 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.

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**Figure 6.** Workflow for the proposed methodology. The assessment of comfort in indoor spaces exploits the model for both input data and output representation.
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.

### 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

![Figure 7. Comfort area in January with \( t_a \) and RH measurements.](image-url)
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\textsubscript{ll} and PMV\textsubscript{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\textsubscript{ll} and PMV\textsubscript{ul} for a relative humidity equal to the measured one.
Figure 9. Indoor temperatures measured in January compared with comfort limits. Tu and Tl are the temperatures corresponding to PMVll and PMVul for a relative humidity equal to the measured one.

Figure 10. Indoor temperatures measured in July compared with comfort limits. Tu and Tl are the temperature corresponding to PMVll and PMVul 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.

| HOURS OF COMFORT OR DISCOMFORT (%) | January | July  |
|-----------------------------------|---------|-------|
| comfort                           | 92,2%   | 38,6% |
| hot (C)                           | 0,8%    | 59,5% |
| cold (F)                          | 7,0%    | 1,9%  |
| humid (H)                         | 0,0%    | 0,0%  |
| dry (S)                           | 0,0%    | 0,0%  |

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 conditions with selected appropriate values for (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 hypothetically). In January few points are below the acceptable minimum, while in July a large number of points are on the right of the comfort area. This representation provides an immediate overview of the measured data, but does not allow them to be associated with the acquisition moment. 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
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.

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