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A Bridge Approach to Fault Diagnosis in Buildings

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Abstract

Nowadays, building's power consumption represents the most important portion of the global consumption (about 40 – 45%). To use more efficient energy sources, it requires not only the improvement in materials as well as new technology measures using less energy, but requires also the detection of faults that can occur during building life. These faults cause not only serious energy losses, but also human discomfort in the buildings. Thanks to sensor network, discomfort or failure alarms can be detected, which identify some issues in buildings. An alarm must be analysis to identify the faults and fix them as quickly as possible in order to maintain building performance. The aim of this paper is to study for application of diagnostic theories in the building. A Bridge approach is used as a diagnosis tools in the buildings. An application to a smart building is implemented to face this fault diagnosis in buildings problem.

Keywords: Energy Smart-Home, Diagnosis, Fault detection, Bridge approach

1. Introduction

Buildings are becoming more and more complex energy systems consisting of several elements i.e. heating/cooling systems, ventilation systems, lighting and control systems etc. In addition, buildings have multifarious activities and the occupants may have different demands from a building. Even though building ramification is growing, communication between the participants and the building elements during the building life is poor [1]. The building energy system and the monitoring of its energy and environmental performance has been the subject of great interest in recent years. There is an increasing awareness that many buildings do not perform as intended by their designers.

Typical buildings consume 20% more energy than necessary due to faults occurring at a different level of the building life cycle i.e. from construction to operations [2,3]. The building energy management system (BEMS) collects and stores massive quantities of energy consumption data. The goal of BEMS (control of energy uses and costs, while maintaining indoor environmental conditions to meet comfort and functional need) cannot be achieved without uncovering valuable information from the tremendous amounts of available data and transform it into organized knowledge [1]. Hence significant potential exists for better use of BEMS data through fault detection analysis in order to improve operations and save energy. It should focus on all major anomalies including unplanned situations and able to provide corrective actions or recommendation to operator as well as users.

Fault detection and diagnosis is well-proven and known methods for research areas like aerospace, automotive and process industry etc. Since, last few years numerous attempts were made to apply these techniques for buildings. In August 1990 (Revised in 2001), International energy agency (IEA) published Annex-25 i.e. "Building optimization and fault diagnosis source book" [4,5]. This work could be considered as relevant beginning of FDD in smart building research domain. The purpose of this publication was to enlist all technical faults focusing on HVAC and controllers. In more recent works few diagnostic tools were developed to identify the whole building level faults, for example, Automatic building commissioning analysis tool (ABCAT), and Whole building diagnostician (WBD) developed by Texas A&M University and Pacific Northwest National Laboratory (PNNL) respectively [6,7]. Recently a model-based real-time automated FDD tool is developed by Lawrence Berkeley national laboratory [8] and simulation were performed over chiller model. Moreover, these works are either inspired by physical model-based or data based models. In parallel, a contemporary group of researchers also focused on qualitative models for fault diagnosis analysis. In buildings, rule based qualitative model are used to diagnose faults in air handling units or other part of HVAC [9,10,11]. Few works also found

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in literature adopted the rule-based diagnosis models for entire building operation management [12]. A detailed review about FDD methods applied for buildings can be found in [13]. In summary, most of the works related to FDD in buildings are fundamentally concerned about the equipment failures leading to indoor discomforts or maintenance.

The present work is devoted to the problem of fault detection using real building energy consumption data through a Bridge approach which can combine FDI and DX. Experimental results show the effectiveness and usefulness of the proposed approach in automatic detection of abnormal energy consumption. The organization of the paper is as follows. Section 2 provides description of studied building and data information while in Section 3 a brief description of method used in this study is presented. Section 4 describes the methodology and in Section 5 results and discussion are given. Conclusions based on results of this study constitute Section 6.

2. Case study: the Cecp/Cerema building

The building C.E.C.P (laboratory CEREMA) within the department Experimentation, Research, Development and Innovation (DERDI) of the CETE Normandy Centre, was built from May 2011, we setup a platform of 40 rooms (see Figure 1 and 3). This platform was equipped a sensor network included HOBO sensors, BEAN sensors and iRIO-Schneider sensors, which permit to measure temperature, CO_2 concentration, electrical consumption, calorific consumption, window opening and human presence in order to research about thermal building.

Fig. 1. The C.E.C.P/CEREMA building

Indoor air quality (IAQ) is important since up to 90% of a typical people's time is spent indoors, and poor IAQ has been linked to respiratory illness, allergies, asthma, and sick building syndrome. For this platform, IAQ can be regulated by the ventilation system that mixes fresh outdoor air with return air for the air supplied to the indoor space. This ventilation system may provide heat through air/water exchanger thanks to a fuel boiler.

2.1. Ventilation system

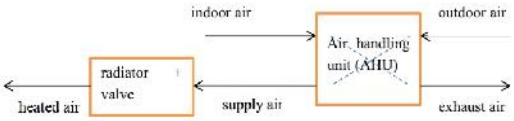

Fig. 2. Ventilation system in C.E.C.P

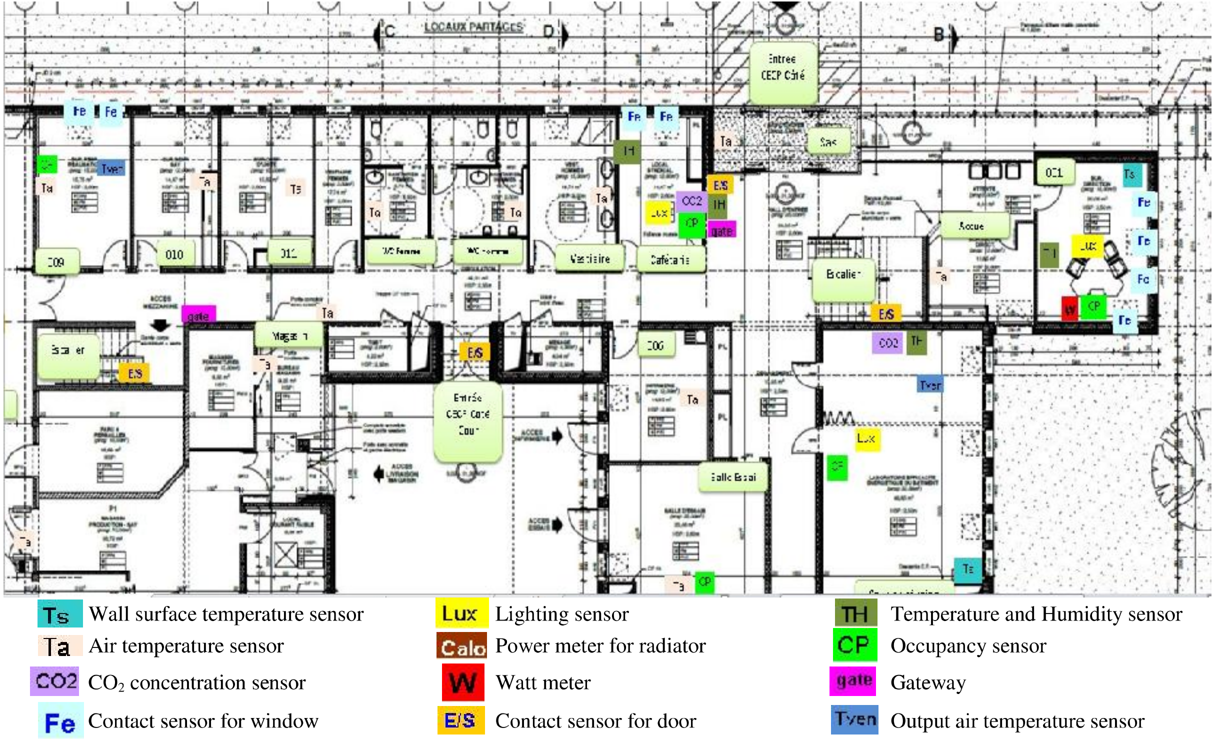

Fig. 3. Plan of the C.E.C.P building

The ventilation system in C.E.C.P (see Figure 2) is dual flow ventilation system. This system allows limiting the heat losses inherent in the ventilation. It uses the heat from stale air before it is expelled from the house to warm the fresh air coming from outside. ($T_{\text{supply\_air}}$), which is computed by following equation:

$$T_{\text{supply\_air}} = (T_{\text{inside}} - T_{\text{outdoor}})\varkappa + T_{\text{outdoor}} \tag{1}$$

with $\varkappa$ is the efficiency of the heat exchanger which is estimated, from measure, by 0.8.

In the case of $T_{\text{supply\_air}} < 22$ °C, the radiator will heat this supply air to 22°C. Then, the energy consumption of the radiator is given as follow:

$$P = m.c.\Delta T \tag{2}$$

where:

- m, mass of air [kg]
- c, specific heat [J/kg.°C]

2.2. Heating system in the C.E.C.P building

The heating system provide heated air to the rooms within the building through air/water exchanger thanks to a water boiler (illustrated in Figure 4).

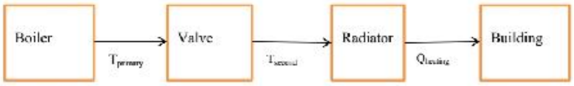

Fig. 4. The heating system in C.E.C.P building

- T_{primary} , the boiler temperature which is adjusted by water law [°C]. This temperature can be computed as follow:

$$T_{\text{primary}} = -2.33T_{\text{outdoor}} + 66.67 \tag{3}$$

- T_{second}, temperature of steam in pipe which is calculated in function of T_{primary} as follow:

$$\begin{cases} T_{\text{second}} = T_{\text{primary}} & \text{if} \quad \text{the boiler works normally} \\ T_{\text{second}} = T_{\text{outdoor}} & \text{if} \quad \text{the boiler is broken} \end{cases}$$

- Q_{heating} , the amount of energy is supplied by thermostat to each room in the building:

$$Q_{\text{heating}} = 1500\left(\frac{T_{\text{rad}} - T_{\text{inside}}}{50}\right)^{1.3} \tag{4}$$

with T_{rad} and T_{inside} are respectively the temperature of the radiator and the air temperature in each room [°C].

3. BRIGE approach to fault diagnosis in buildings

Before 2000s, FDI and DX have been considered as completely isolated groups. Intuitively, both methodologies had their own terminologies and paradigm for fault detection and diagnosis. The FDI approach mainly focuses on dynamic system and utilize two step diagnosis process i.e. Detection and Isolation, whereas DX approach mainly deal with static system and adopt the consistency based diagnosis (CBD). FDI believe, abnormality in modeled behavior implies faults in system, on the contrary, DX assumes that faulty behavior cannot be determined only from behavior, it should involve component discretion. Multiple fault diagnosis is also a challenging task for FDI, though DX can deal with them easily. FDI and DX, require a formalized model that avail the system information. A more detailed comparison between FDI and DX has been presented in [14].

Concurrently, a Bridge approach (illustrated in Figure 5) have been proposed to bridge the data based and physical model-based diagnosis. The mainstay of Bridge approach that is capable of finding the diagnosis with component level explanation. Formal diagnosis or FDI analysis exploits only valid test revealing a behavior abnormality of system, gives an easy mean to fault detection. However, with the notion of Hamming distance and signature table, faults localization is not adequate to address the component or sub-system level faults. Aforementioned, FDI solely rest on ARRs and DX follow the conflict analysis to diagnose the system. In [14] came up with concept of support and scope and tried to establish a link between ARR and conflict.

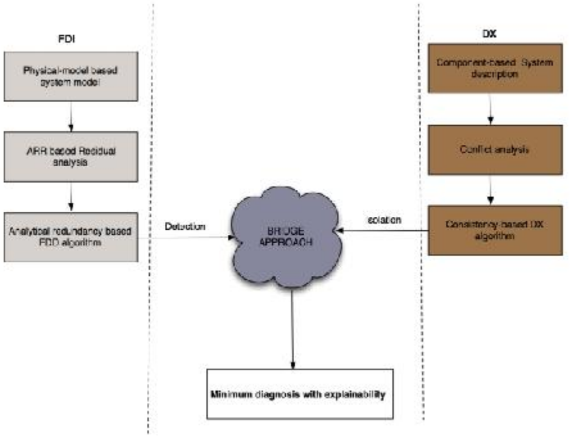

Fig. 5. Bridge approach of diagnosis

4. Application to the C.E.C.P building

4.1. Sources of anomalies in building operation

To understand all the possible sources of anomalies in building operation, the whole building is considered as a complete system-level (upper-level) subject to analysis (see Figure 6). It is further subdivided into primary and secondary sub-systems level. Each sub-system is assigned a variable related to their functionality and corresponding symptoms are analyzed in detail with all feasible fault causes. Eventually, the component level consists in all elementary or "non-divisible" part of a building system. In present, component level approach is not much emphasized. The fundamental concern is given to diagnose the faulty sub-system that affects the occupants discomfort dominantly (in Table 1).

Table 1. The possible faults in the C.E.C.P building

Sub-systems	***Fault***	***Affected parameters***
Building envelope	Window is opening.	- Indoor temperature in the room has window opening. - Indoor temperature in neighbor rooms.
Ventilation system	Ventilation is not running effectively.	- Indoor temperature of all the rooms - Air temperature after air handling unit ($T_{\text{supply\_air}}$).
	The radiator of ventilation system is broken.	- Indoor temperature of all the rooms - Air temperature after radiator of ventilation system ($T_{\text{heated\_air}}$)
	Pipe is pierced or stuck.	- Indoor temperature. - Airflow blown into the room.
Heating system	Boiler is broken.	- Indoor temperature of all the rooms - Boiler temperature (T_{primary}). - Thermostat temperature in all the rooms.
	Pipe of heating system is pierced or stuck.	- Indoor temperature of several rooms. - Thermostat temperature in several rooms.
	Thermostat is broken in a room.	- Indoor temperature in this room. - Thermostat temperature in this room.
Occupants	Abnormal occupancy in a room.	- Indoor temperature in this room. - CO_2 concentration.
Electrical consumption	Unplanned appliances in a room.	- Power meter. - Indoor temperature in this room.

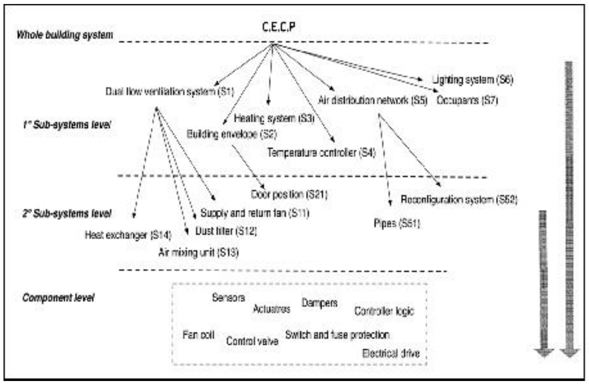

Fig. 6. System-level analysis of C.E.C.P

4.2. The detection tests

To perform, detection each symptom require a set of sensors with certain deciding criteria to confirm the test. Figure 7 shows the test methodology used for detecting the primary symptoms. In this figure sensors (S) are used to measure the building reality and memory unit represents the storage of information fetched from sensors. Further a logic unit decide whether test is valid or not based on respective deciding criteria. The test confirmation unit convert the decisions into binary values i.e., 1 or 0. A test acknowledge the presence of symptom when a symptom abides by the linked criteria. The description of the causes for alarm (detected by sensors) for different test are given below, in further discussion each test with their deciding criteria is explained in detail in Table 2.

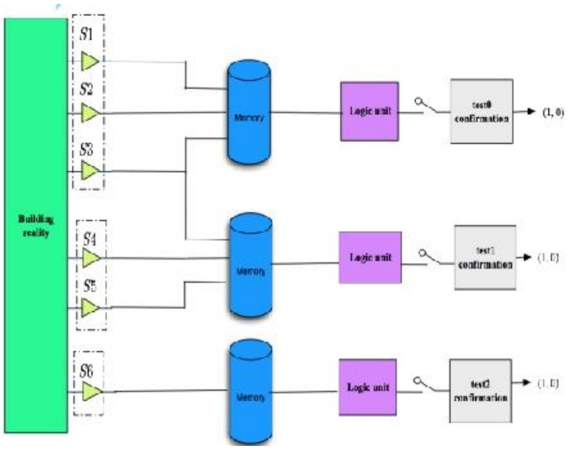

Fig. 7. Test set-up and representation

- **Test 1:** *test indoor thermal discomfort*

Figure 8 shows the test methodology used for detecting the primary symptoms. In this figure, sensors (S) are used to measure the building reality comfort is 18°C to 24°C. However, 19°C is considered as optimum comfort.

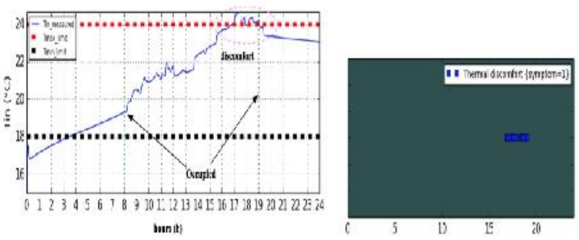

Fig. 8. Test set-up and representation

Causes for alarm:

- Heating system: thermostat is broken, boiler is broken or pipe is broken.
- Ventilation system: Air Handling Unit (radiator of AHU or efficiency), pipe pierced.
- Window opening.
- Ambient temperature more than a threshold (The building don't have cooling system).
- Sensor is faulty.
- Unplanned occupancy.
- Unplanned appliances

- **Test 2:** *test indoor temperature is not following the thermal plan*

Causes for alarm:

- Heating system: thermostat is broken, boiler is broken or pipe is broken
- Ventilation system: Air Handling Unit (AHU) (radiator of AHU or efficiency), pipe pierced
- Window opening in this room or in the neighbor room
- Unplanned occupancy
- Unplanned appliances
- Sensor is faulty

- **Test 3:** *test abnormal consumption in each room*

Causes for alarm:

- Unplanned appliances

- **Test 4:** *test water law for radiator in each room*

Test verifies temperature of radiator by using equation of water law (equation 3).

Causes for alarm:

- Boiler is broken
- Sensor is faulty
- Pipe is broken
- Radiator is broken

- **Test 5:** *test water law for boiler*

Causes for alarm:

- Boiler is broken.

- **Test 6:** *Test window opening*

Causes for alarm:

- Window is open

- **Test 7:** *test temperature of supply air before enter radiator AHU (T_{supply_air})*

Test verifies temperature of supply air by using equation 2.3.

Causes for alarm:

- Poor efficiency
- Sensor is faulty

- **Test 8:** *test temperature in output of radiator AHU (T_{heated_air})*

Test verifies if this temperature is less than 22 ºC or not. If less than 22 ºC, that means radiator AHU is broken.

- **Test 9:** *test occupancy*

Test verifies the number of persons in the room

Causes for alarm:

- Unplanned occupancy

- **Test 10:** *test airflow*

Test verifies the airflow blown in each room with the plan of airflow.

Causes for alarm:

- Loop of ventilation system is broken.
- Some ventilation pipes are pierced.

5. Experimental results

5.1. Scenario:

At 18 hours, window is opening and abnormal electrical consumption in ***office009*** was simulated. Efficiency AHU is simulated by 0.4 less than normal state (0.8). Observed symptom is the temperature in the room "BUR_009" is less than 18 ºC. The concepts and principle mentioned in the previous sections have been implemented into a command line software called DXLAB.

Table 2. Fault signature table

Test	Heating system			Ventilation system				Opening window	Occupancy	Electrical consumption	Exterior temperature
	Main pipe of heating system	Thermostat	Boiler	Efficiency	Radiator	Pipes for studied room	Main pipe of ventilation system				
Test 1	1	1	1	1	1	1	1	1	1	1	1
Test 2	1	1	1	1	1	1	1	1	1	1	0
Test 3	0	0	0	0	0	0	0	0	0	1	0
Test 4	1	1	1	0	0	0	0	0	0	0	0
Test 5	0	0	1	0	0	0	0	0	0	0	0
Test 6	0	0	0	0	0	0	0	1	0	0	0
Test 7	0	0	0	1	0	0	0	0	0	0	0
Test 8	0	0	0	0	1	0	0	0	0	0	0
Test 9	0	0	0	0	0	0	0	0	1	0	0
Test 10	0	0	0	0	0	1	1	0	0	0	0

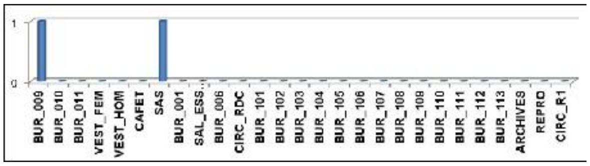

Fig. 9. Result of test 1

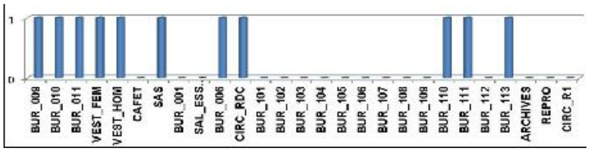

Fig. 10. Result of test 2

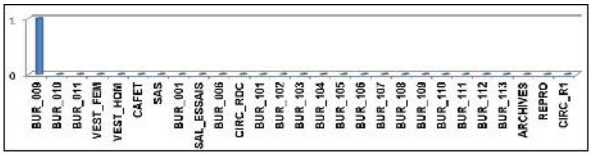

Fig. 11. Result of test 3

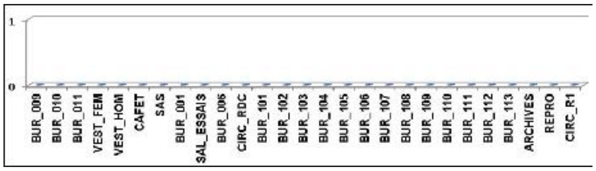

Fig. 12. Result of test 4

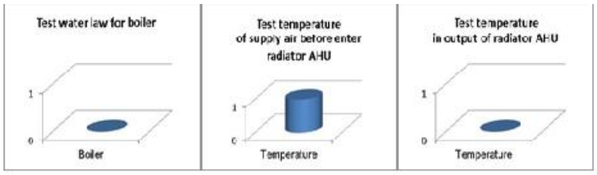

Fig. 13. Result of test 5, 7 and 8

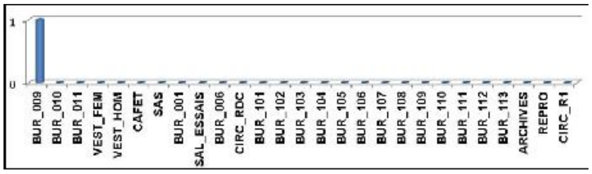

Fig. 14. Result of test 6

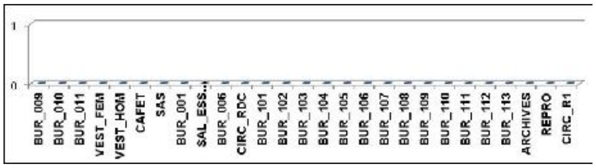

Fig. 15. Result of test 9

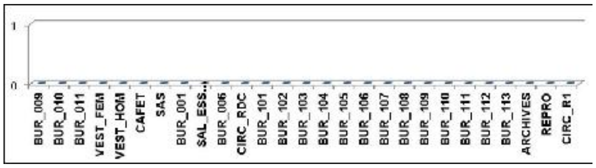

Fig. 16. Result of test 10

5.2. Results:

- *Faults detection for the office009*

From Figure 9 to Figure 16, observed signature for 10 tests are obtained: [1, 1, 1, 0, 0, 1, 1, 0, 0, 0]. The results given by the DXLAB for this scenario as follow: **`{window_BUR009 is not ok - electricalConsumption_BUR009 is not ok - efficiencyAHU is not ok} - score: 100%, apriori: 10%, contextual: 100.0%`**

with:

- **`apriori`**: unreliability of component which assumes that each component has a probability working in a normal state and that probabilities are independent. In this application, the unreliability is fixed as 0.1.

- `contextual`: the measure of coincidence

- *Faults detection for the office010*

With 10 tests above, the DXLAB says: **`{efficiencyAHU is not ok - other_windows is not ok} - score: 100%, apriori: 10%, contextual : 85.71%`**

The component "**`other_windows`**" is then decomposed into sub-components **`window_BUR009, window_BUR011,window_BUR012,window_CIRC_R1`** (that means window in others rooms in the building). In this case, the diagnoses calculated by DXLAB is: **`{efficiencyAHU is not ok - window_BUR009 is not ok} - score: 100%, apriori: 10%, contextual: 85.71%`**

For these diagnoses above, BRIDGE can detect all the fault cause the symptom in the office009. BRIDGE method always starts with a test negative. Therefore, in the cases there are compensable faults, this method does not work.

6. Conclusions

The research aimed at testing the potential of using a Bridge approach diagnosis for an automated fault detection process in building. The study will help building energy management systems (BEMS) by tracking and detecting abnormal energy consumption in building overall energy system. The methodology can be easily integrated with the BEMS to perform fault detection in near real time and can be applied to the buildings with similar end-uses. An application to a smart building of this approach was presented. Experimental results show the effectiveness of the proposed approach in automatic detection of abnormal energy consumption.

Acknowledgements

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