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Rule based Fault Detection & Diagnosis for high performance buildings: application to a positive energy building in France

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Abstract

Fault Detection & Diagnosis (FDD) is at the heart of the PERFORMER European FP7 project that aims at reducing the gap between expected and actual energy performance. The purpose of the article is to describe the FDD methodology used within the Performer project and illustrate the benefits of its application to a positive energy building. The rules were defined according to the Building Manager's requirements and were applied to the data collected from the BMS. The proposed approach is very easy to apply and to use in any type of building, including nearly zero energy buildings. Expert rules address very technical and recurring issues in buildings and the work undertaken within PERFORMER is to help Building Managers in their decision-making process by giving them an accurate picture of the level of performance of their buildings. The whole study and final results will be available by the end of the year.

Keywords - fault detection, expert rules, performance gap, threshold, actual value.

1. Introduction

By improving the energy efficiency of buildings, European total energy consumption could be reduced by 6% and CO₂ emissions by 5%. Although efforts have been made at the national level to improve building performance, significant discrepancies remain between the targets defined at the design stage and the actual performance both in terms of energy efficiency and users' comfort. The PERFORMER FP7 project addresses those issues by developing an innovative integrated concept for monitoring and evaluating building energy performance which will help reduce the gap between predicted and actual performance in a performance guarantee perspective.

FDD (Fault Detection and Diagnosis) is one of the key methods used in the project to achieve its objectives and the technique identified to support the FDD approach is the expert rules-based method. Although FDD is often investigated in research projects and is integrated in many solutions, the expert rules method remains underexploited, though. While the building industry is seeking even smarter and sophisticated solutions to reach a high level of performance, expert rules are more simple and straightforward

to implement, and they address very operational matters in Building Managers' daily life.

Many reports and articles deal with FDD and, to a lesser extent, expert rules. The International Energy Agency has published several reports (“Annexes”) which highlight the benefits of FDD methodologies and techniques, and in particular, Annexes 25 [1], 31 [2], 34 [3] and 40 [4] that were very valuable to conduct our study. However when we tried to apply the knowledge to practical cases, we pointed out some limits of the literature. Most of time, the expert rules topic is analysed only as a piece of a whole FDD method and is therefore not detailed enough. Moreover, the field of knowledge is often reduced to specific equipment such as HVAC (e.g. IEA's Annex 34), whereas other recurring issues are actually raised by Building Managers and they do not necessarily comes from the systems themselves.

The added-value of our work on expert rules is firstly embedded in the use case we are developing. We have built up a methodology to define the rules that is directly linked to one of the project's pilot sites, the Woopa Office Building (Lyon, France). This building was put into operation in 2011 and is a high-performance building with efficient systems, which is a distinguishing feature. Indeed, most of the existing case studies are often focused on old or low-performance buildings, while our study demonstrated that the same problems and other recurring issues remain in new efficient buildings. Moreover, our approach follows a well-defined process included in a global project, and integrates key stakeholders and valuable experience feedbacks. The purpose of our work is not to deliver further academic features but to rather provide the Building Managers with a consistent method, easy to apply to achieve their performance targets. All this gives meaning to our the study.

2. Methodology

a. The expert rules methodology in Performer

Expert rules were included in a first instance in the PERFORMER energy performance assessment methodology to provide functional requirements and specifications towards the development of the solution and the expert system. The process we chose to implement expert rules follows three main steps : (1) the definition of the expert rules addressing the issues raised by the Building Manager, (2) the development of the algorithms to test the rules on the pilot (off/online), and (3) a set of recommendations to help the decision-makers when they want to use and apply the rules. The approach is a top-down approach targeting the end user needs, i.e. the Building Managers or the Facilities. It has been broken down into several steps (Figure 1) in order to devise a consistent and robust framework.

[Step 1] We collected all the most recurring and impacting symptoms and faults that were previously listed in the literature and existing case studies.

[Step 2] We analyzed the faults and selected the ones that were the most impacting in terms of energy consumption and users' comfort which are key primary KPIs defined in PERFORMER. These indicators support the overall process for energy performance monitoring and assessment, and are expected **to assess energy performance** by

comparing expected and actual value of energy performance, and to check that expected energy consumption, CO2 emissions and economic targets are reached, and **to manage energy performance** by explaining any gap between expected and actual values, and to ensure the continuity of energy performance. We also used secondary KPIs (specific to FDD) to define the thresholds for the application of expert rules in order to detect any performance gap between actual and predicted values :

Table 1: Indicators for global performance of systems and FDD

Heating Systems	System efficiency
	Pumps energy consumption for distribution
	Indicator of optimal start test (EN NF12098-1)
	% successful starts
	Local hourly average operative temperature for the 1 st hour of occupancy
Cooling Systems	Temperature differential between local hourly average operative temperature and local set point temperature
	System efficiency
	Pumps energy consumptions for distribution
	Indicator for optimal start test
	% of successful starts
DHW Systems (Hotels)	Local hourly average temperature for the 1 st hour of occupancy
	Temperature differential between local hourly average operative temperature and local set point temperature
	DHW system efficiency
AHU/ventilation	Thermal solar collector efficiency
	Supply temperature from hot water tank
	Fans energy consumptions
	Status of the fan
	Pumps battery consumption
Lighting	Ratio of supplied flow rate and hygienic ventilation flow rate
	Pressure drop across AHU filters
Lifts	% of time when the lights are “on” when the building is not occupied
	% of time when the lights are “on” when the building is occupied
Lifts	Lift energy consumption per month and year
	Working monthly hours in non-occupancy

[Step 3] Other feedback from the other pilot sites helped us to write the expert rules methodology and provide specifications for the expert rules development and application. In order to deliver a practical use case, we worked closely with the Building Manager of the Woopa Office Building to define some rules for specific faults. We finally came up with a set of recommendations presenting a list of specific rules tailored to detect and diagnose the malfunctions raised by the Building Manager.

[Step 4] The simulation models realised in another module of the project [5] should also help to adjust the rules and make them more accurate (this task has not been completed yet and will be used within a verification process once the rules are practically applied to the building.

[Steps 5-6] We have already started to test some rules on the data collected from the BMS of the Woopa Office building to check their validity and efficiency. These tests are off-line driven

[Step 7] The whole work described above will have to be integrated in the on-line expert module of the Performer tool.

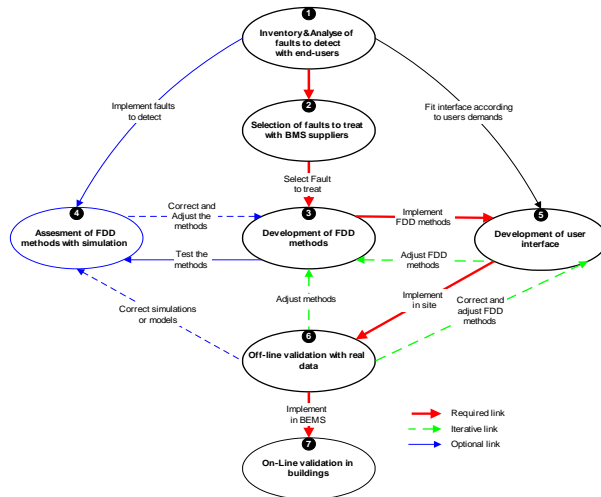


Fig. 1 – The FDD approach followed within the PERFORMER project [6]

b. Case study and experience feedback

The method has been applied to the Woopa Office Building [7]. It is located in Lyon (France) and is a NZEB building (BEPOS). The office building covers a 11,000m² area over 7 floors. The notions of sustainability and high energy performance were included since the conception of the building until its delivery in 2011. Efforts were made on the thermal and visual comfort (external insulation, triple glazed windows, atrium) and on the integration of high performance systems (active floor system using groundwater only, balanced ventilation with 80% of energy recovery, highly efficient individual lighting systems). The building also produces energy from its renewable energy systems in place: an rapeseed oil cogeneration, 3 biomass condensation boilers, one gas condensation boiler for backup and more than 800m² of photovoltaic modules. Its BMS records data every 15 minutes and every 24 hours with an accurate granularity for each usage. It also generates 691 csv files per day and each file contains up to 13,000 data. 312 sensors were initially installed in order to measure the consumptions of the systems per usage : heating, ventilation, comfort & occupancy, lighting, hot water for sanitary use, fan coils, lifts and auxiliary equipment. Although the building is globally highly efficient, several issues regarding its BMS performance were flagged. Among the problems related to the BMS, some sensors are not properly connected and others deliver unreliable data. Some data collected to measure the energy consumption from the solar panels and the micro-cogeneration are so unreliable that the Building Manager has to report them manually. And we finally identified lots of programming errors that impacted the writing and the application of some rules. These issues acted as a brake on our work and one of our conclusions was to focus our future

investigation much more on the quality and the reliability of the data than the systems themselves.

The rules off-line tests were conducted within a process around 5 main steps as following: the transfer of data from BMS database to FDD database (Acquisition interface), the removal of irrelevant values in order to filter data (Data filtering), the definition of the building's operating mode (Building's mode definition), the definition of the expert rules to detect any symptom of fault or deviation to an expected behavior, the application of the expert rules on the values transferred to the database (rules application) and the diagnosis of the malfunctions by listing the potential causes (diagnostic and final step of the process).

The main added-value of our methodology is the way we address the Building Manager's requirements and needs. In this case, the Building Manager is the end user and also a proactive stakeholder in the whole process. Although the Woopa building is highly efficient and is equipped with high quality systems, lots of remaining and recurring issues hold back the improvement of its energy performance. Our methodology aims at delivering a comprehensive methodology and an easy-to-use toolkit to the Building Manager so that he can detect, understand and fix the malfunctions in the building. Beyond the quantitative results, it is also valuable to show how relevant and efficient expert rules can be when conducting – for instance - an Energy Performance Contract study in high energy performance buildings to avoid any further drift, and to come from a corrective to a preventive maintenance.

3. Method

The proposed application of expert rules consists in the analysis of measured data to detect any equipment malfunction or energy performance drift. A diagnosis process based on relevant indicators is defined to detect faults and drifts as early as possible and to guide the Building Manager through the potential causes and help him make a decision. Several rules can be applied to a given building. The following rules have been identified for the Woopa Office building:

- R1: Checking of heating systems start optimization at start of occupancy (1st hour) over the heating season
- R2: Checking of the operative temperature in occupancy over the heating season
- R3: Checking of the hourly programming system – 3 modes of the heating set-point temperature over heating season
- R4: Checking of the hourly programming ventilation system
- R5: Checking of air-treatment filtration system
- R6: Checking of photovoltaic production
- R7: Checking of cogeneration production
- R8: Checking of the cascade of boilers
- R9: Checking of the command of pumps with respect to the heating system status
- R10: Checking of specific appliances consumption drift

In order to illustrate the approach we chose the R2 rule and analysed the measurement of indoor temperatures used to support building energy performance mastering. As presented in step 4 of the application process, the rules have to be described before their application. We defined a set-point temperature variable $T_{sp}(t)$ of a given time t based on the functional analysis of the building; the set-point temperature varies depending on the outside temperature and the building occupancy. We then defined two thresholds $T_{OH}(t)$ and $T_{UH}(t)$ based on $T_{sp}(t)$ and tolerances δ_{OH} for overheating and δ_{UH} for underheating. To implement the rule, Boolean indicators were defined to check the compliance between the theory (“temperature should be between 19°C and 22°C”) and the real values (“temperature is 18.5°C”). Equations (1) and (2) define the indicators I_{OH} and I_{UH} as the truth values of comparison between the actual zonal temperature $T(z,t)$ of a given zone z and a given time t and the corresponding thresholds. A fault occurs when an indicator is *True*, i.e. the temperature is over the overheating threshold or under the underheating threshold.

$$I_{OH}(z,t) = \{ T(z,t) > T_{OH}(t) \} \quad (1)$$

$$I_{UH}(z,t) = \{ T(z,t) < T_{UH}(t) \} \quad (2)$$

To simplify the visualisation of indicators, Boolean values are encoded in binary (True=1, False=0) which allows averaging indicators every hour, day or week. The average indicator is then an evaluation of the fault rate. Once the rules have been described, those indicators are used to detect and analyse the faults. We follow a funnel approach from a big picture to a detailed analysis through four main steps:

- (1) *Global alarm*: To notify the building manager on a specific fault, we worked on two global indexes: the overall building fault rate and the number of units, where the weekly fault rate is over 50%. In our case, the temperature level is under the underheating threshold for more than 50% over the occupancy period.
- (2) *Spatial localisation*: To understand the coherence of the results we provide a zoning of the building with zonal fault rates. The user can identify entire faulty floors and/or facades indicating a global cause (not enough insulation on the north side...) or isolated faulty zones for a local cause (open window, heater malfunction...).
- (3) *Temporal localisation*: When the user identifies a fault, he has to understand how the indicator behaves in time. By selecting a faulty zone, the user can go deeper in the visualisation details and look at the indicator with a more accurate granularity (daily or hourly average). If there are regular faults on the same pattern, then specific causes can be listed: for example temperature fault in the morning can be due to a heating system starting too late.
- (4) *Diagnosis*: We finally come up with a list of possible causes to explain the detected fault, and with other detailed visuals depending on the rule we selected. The user can compare our analysis with the events that occurred in the building to understand the fault and undertake an action plan to mitigate it and/or prevent it.

4. Results

Over the heating season, temperature can be used as a proxy for the comfort of occupants. The analysis of the temperature levels enables to check whether both the programming and regulation of the heating system are compliant with users' requirements in terms of comfort and, when appropriate, to adapt it to the building environment and people activities. This can provide the Building Manager with an efficient and operational support, based on the analysis of measurement generally available for large office buildings. Here is an example of application for an expert rule based on the analysis of indoor temperatures during occupancy in a heating period. This analysis is split into the identification of overheating (OH) and underheating (UH). To simulate the operational use, expert rules were applied to the BMS weekly data (collected and filtered according to steps 1 and 2 of methodology). The building manager can therefore monitor the performance every week and undertake actions to improve it or fix any faulty piece of equipment.

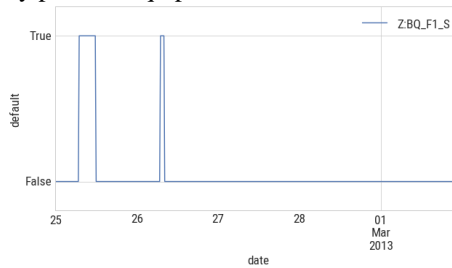


Fig. 2 – Underheating issue of the Temperature in zone BQ_F1_S

Rule R2 was applied to the Woopa Office building (temperature data recorded every 15 minutes) with tolerances $\delta_{OH}=2^{\circ}\text{C}$ and $\delta_{UH}=1^{\circ}\text{C}$, and indicators I_{OH} and I_{UH} were therefore calculated. In order to make the visualisation easier, we illustrated this step with the underheating indicator I_{UH} over the working week from 25th February to 1st March 2013. An underheating problem has been tracked for each zone: an example is presented in Figure 2.

Although the graph shows the required information, it does not match operational purposes though, especially when the manager wants to monitor the temperature of every room in a large building. It is therefore important to simplify the process and provide a global overview to give the user a perspective to find the underlying causes of the fault. Based on the calculated indicator I_{UH} we followed the four steps described in the method above.

(1) *Global alarm*

In the Woopa Office building case study, the overall building fault rate is **18%** and **10 zones** have a fault rate higher than 50%: this results encourages the manager to go deeper into the fault analysis.

(2) *Spatial localisation*

We can see the indicator's zonal weekly average for one of the floors (see Figure 3 where temperature in white areas is not monitored). In Figure 3, high (resp. low) fault rates are represented in dark red color (resp. light yellow). We can see that the fault rate

is higher in zone “BN_F3_N” (north-west of the lower part of the figure): this means that the set point temperature is hardly met in this zone. The results in the other floors (not presented here) show that other northern zones of the building are working properly: it seems therefore to be an **isolated issue**.

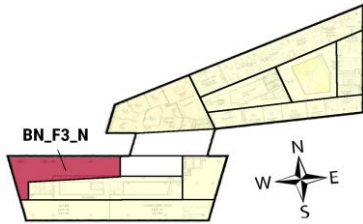


Fig. 3 - Weekly average of Temperature underheating faults on building map (Floor 3)

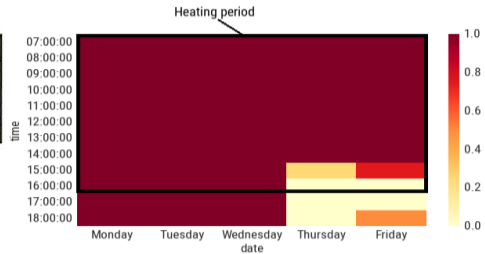


Fig. 4 - Heatmap of hourly underheating indicator (zone BN_F3_N) [1: Fault]

(3) Temporal localisation

Figure 4 shows the hourly average of underheating fault indicator during the considered week in the selected faulty zone (BN_F3_N). The fault rate level is represented by a color on the scale on the right hand side, where 1 means that the indicator is “True”, i.e there is a fault. The days are on the X-axis while the Y-axis shows the time slots (from 07:00-08:00 to 18:00-19:00). The heating period (beginning before 07:00 and ending at 17:00) is displayed so that the manager knows if the heating is on or off. The underheating fault happens every day during this week: it seems to be a **recurrent issue**. The low fault rate observed on Thursday and Friday afternoon should motivate the Building Manager to understand what happened at this specific time (more activity, action on the heating system...) and fix the fault observed during the rest of the week.

(4) Diagnosis

To further analyse the faulty zone, the user is provided with a global overview of the indoor temperatures relating to the outdoor temperatures. This shows whether the low or high indoor temperature levels can be explained by low or high outdoor ones. The chart below gives an overview where the dots are the tuples {Indoor Temperature ; Outdoor Temperature} for the faulty zone: the straight grey line is the set point temperature, the blue (resp. red) area shows the default area for underheating (resp. overheating) and the grey area represents outdoor temperatures below the reference temperature used for sizing (-11°C for the Woopa Building). Below this point, the building cannot be considered as “faulty”. Figure 5 shows that even for relatively high outdoor temperatures (>5°C) the system is not able to meet the set point temperature.

The fault is **isolated** and **recurrent**: the user can collect information to know what happened and the state of the systems in the zone. Monitoring this specific zone for several weeks can also help understand the cause of the fault. For the fault illustrated above, potential causes can be: sensor failure, regulation valve locked, faulty settings on local controller, broken/open window.

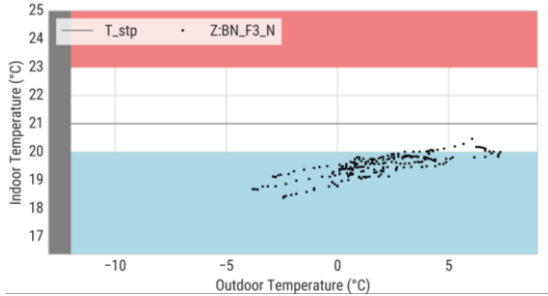


Fig. 5 - Scatter plot of Indoor and Outdoor Temperatures with set point temperature (T_{stp})

5. Discussion

To implement R2 we chose overheating and underheating thresholds of 2°C and 1°C to adapt the rule to the heating season: underheating faults can be more impacting on the occupant's comfort. Those values could be a parameter that the user can tune according to the level of detection accuracy he wants to achieve. The impact of such faults on KPIs has not been fully addressed yet but is essential to drive the Building Manager towards better fault treatment: it can help quantify the overconsumption or user lack of comfort due to a temperature fault, for example. We displayed a picture of the proposed methodology to detect the faults and guide the Building Manager to the possible causes. It is based on the interaction between the automatic evaluation of indicators and the manual selection of objects and group of objects to be further analysed. This work is on-going and will continue to build an operational tool based on the presented concept. The development of the tool and the rest of the implementation process will involve the Building Managers to ensure that their needs and expectations are met. For example the analysis could be more relevant on a monthly basis or with more detailed visualisation charts. To balance the importance of a fault we thought of a trust indicator based on the data quality received by the BMS: this enables the user to prioritise the actions to undertake and fix the most probable and impacting faults. Such a methodology is also able to store the fault history for a given object and use this information to guide the user to this specific object if a fault often occurs. The automatic detection of patterns to identify the temporal and spatial regularity of faults is also in the scope of this development.

6. Conclusion

The main purpose of the article was to focus on the first steps of the methodology, that is to say the building data analysis, the expert-rules definition and the application of those rules to the collected data in order to detect any localised or recurring fault. The technical part is only focused on one rule among others. It was our choice to go in depth on the indoor temperature issues for a better comprehension rather than giving a brief overview of all the rules that we identified for the Woopa office building. The work on FDD is an on-going process in the PERFORMER project and the involvement of the

Building Managers is fundamental to ensure that the entire process meets specific requirements in an energy performance guarantee perspective. The other rules are being tested off-line and the team has to work on the next steps of the FDD methodology and particularly on the connection aspects including the integration of the expert-rules into the BMS hierarchy, the energy management control system and the use of sensors.

The user interface is also an important component of the whole FDD chain that the team has to develop as it has to provide the end user with all the information that helps him conduct the detection and diagnosis work. The Building Manager has to see straight away if there is any system or piece of equipment which does not work properly and where in the building the fault occurred. The user interface has to display the most relevant visualisation tools for the end users, both in terms of skills and details. It has to be considered as an operational tool that provides the most accurate representation modes of the situation of the building in real time and as a decision-making tool to help Building Managers in the fault diagnosis process. In order to ensure that the rules are working properly, it is therefore important to test them by creating artificial faults. This testing phase should include: a fault-free test procedure, sensor validation procedure, the list of the specific faults to be tested, threshold settings, alarm handling, etc.

The results from the simulation work will be also used to adjust the accuracy of the rules. As an overall recommendation, expert rules should not be considered just as an easy way to conduct a FDD approach but as the key technique to ensure that the specific faults identified with the Building Managers will be detected and diagnosed in a very accurate manner and as the best operational method that includes all the stakeholders into the process.

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