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Performing Diagnosis in Building with Partially Valid Heterogeneous Tests

Houda Najeh, Mahendra Pratap Singh, Stéphane Ploix, Antoine Caucheteux, Karim Chabir, Mohamed Naceur Abdelkrim

***Abstract*—Building system is highly vulnerable to different kinds of faults and human misbehaviors. Energy efficiency and user comfort are directly targeted due to abnormalities in building operation. The available fault diagnosis tools and methodologies particularly rely on rules or pure model-based approaches. It is assumed that model or rule-based test could be applied to any situation without taking into account actual testing contexts. Contextual tests with validity domain could reduce a lot of the design of detection tests.

The main objective of this paper is to consider fault validity when validate the test model considering the non-modeled events such as occupancy, weather conditions, door and window openings and the integration of the knowledge of the expert on the state of the system. The concept of heterogeneous tests is combined with test validity to generate fault diagnoses. A combination of rules, range and model-based tests known as heterogeneous tests are proposed to reduce the modeling complexity. Calculation of logical diagnoses coming from artificial intelligence provides a global explanation consistent with the test result.

An application example shows the efficiency of the proposed technique: an office setting at Grenoble Institute of Technology.

***Keywords*—Heterogeneous tests, validity, building system, sensor grids, sensor fault, diagnosis, fault detection and isolation.

I. Introduction

A conventional rule-based building automation system (BAS) provides alarms based on thresholds. In the domain of diagnoses, these thresholds are related to behavioral constraints and measure the abnormality in building performance. Nevertheless, alarms require further analysis by the facility manager to identify the fault type and their consequences. The fault diagnostic analysis is generated from the modeled behavioral of the system thanks to detection test results. Conversely, there are several situations in which diagnosed faults are not correct due to change in the local context of the tested building site because underlying tests are not context independent. These local contexts are hard to model and lead to invalid diagnosis results. In more general term, the validity of diagnosed fault is always questioned. Isolating fault causes is also a labor-intensive process and require an experienced human interactions.

The next challenge is complexity in testing a whole building system using both rule and pure model-based test. Buildings are complex systems with lots of parameters difficult to calibrate and the relations among the different subsystem are intricated. The systematic approach for test generation ends up with a huge number of tests difficult to handle [4].

In [8], the concept of a contextual model that is valid under certain circumstances and associated with the behavioral constraints is proposed. A combined approach of fault detection and diagnoses (FDD) is presented with the help of heterogeneous test and logical diagnosis. The limitation of the proposed method is that it relies on a strong assumption that is "non-faulty sensors". Moreover, a faulty sensor or measurement could disturb the applicability of proposed methodology. The main objective of this work is to develop a comprehensive whole building fault diagnosis tool that incorporate sensor failures. At the end, a real case study is presented to demonstrate the applicability of the proposed diagnosis method.

This paper is organized as follow: Section II presents the problem statement and research objective. Section III presents a case study for a building system. Section IV discusses the experimental validation of the proposed approach. Finally, concluding remarks and future works are given in Section V.

II. Problem Statement and Proposed Methodology

Current work highlights the following key challenges in building fault diagnoses. The proposed methodology is explained in detail.

A. *Need for Testing in Specific Context*

In the domain of fault diagnosis, a symptom is defined as a measurable change in the behavior of a system from its normal behavior i.e. an indication of fault. Conventional model or rule-based behavioral tests are used to generate only symptoms. These models appear in the behavioral constraints (Definition 1) and it is assumed that the behavioral test could be applied to any situation without taking into account different contexts [8]. However, a model valid for all context is difficult to design and the validity of a test result is always questioned in fault diagnosis.

Let's introduce some definitions to state the problem to be solved. A behavioral constraint is defined as follows.

Definition 1: Behavioral constraint

Let $X_{(t,t+h)}$ be a set of variables covering a time horizon h and $K(X_{(t,t+h)})$ be a set of constraints with $K(X_{(t,t+h)}) \in D_k$ if satisfied, where D_k is a bound domain. A behavioral constraint set modelling the normal behavior *(ok)* is defined as:

$$ok \leftrightarrow \forall t, K(X_{(t,t+h)}) \in D_k \text{ or } \exists t, K(X_{(t,t+h)}) \notin D_k \leftrightarrow \neg ok$$

Houda Najeh, Mahendra Pratap Singh and Stéphane Ploix are with University of Grenoble Alpes, G-SCOP lab, CNRS UMR 5272, Grenoble, France (e-mail: houda.najeh@grenoble-inp.fr, stephane.ploix@grenoble-inp.fr, talk2mpsingh@gmail.com).

Antoine Caucheteux is with Cerema Ouest, 23 Avenue de l'Amiral Chauvin, 49136 Les Ponts de Cé, France (e-mail: antoine.caucheteux@cerema.fr).

Karim Chabir and Mohamed Naceur Abdelkrim are with University of Gabes, National Engineering School of Gabes, Tunisia, Research lab. Modeling, Analysis and Control of Systems (MACS) LR16ES22 (e-mail: karim.chabir@yahoo.fr, naceur.abdelkrim@enig.rnu.tn) .

In contrast, proposed contextual tests, valid in some specific contexts offer an easy way to test the whole building system [2]. A contextual test combining different events is based on validity constraints (Definition 2) for a test. In the field of intelligent diagnosis, the concept of validity constraint was initially introduced in [5].

Definition 2: Validity constraint

Let's introduce another set of constraints $V(X_{(t,t+h)}) \in D_v$ where D_v is a bound domain, to define the validity of a behavioral constraint set (X is assumed to be a superset of the variables appearing either in behavioral or in validity constraint sets i.e. some variables might not appear in both constraint sets). A behavioral constraint set modelling the normal behavior under validity conditions is defined as:

$ok \wedge \left(\forall t, V(X_{(t,t+h)}) \in D_v\right) \rightarrow \forall t, K(X_{(t,t+h)}) \in D_k$ or
$\left(\exists t, K(X_{(t,t+h)}) \notin D_k\right) \wedge \left(\forall t, V(X_{(t,t+h)}) \notin D_v\right) \rightarrow \neg ok$

It's not possible to test $\forall t$. Therefore, tests with validity does lead to soft proofs: the more data for which validity is satisfied, the more likely the test conclusion is. Therefore, one has to estimate the likeliness of ok and of $\neg ok$.

In conclusion, validity is another kind of knowledge about the behavior. In order to launch a valid diagnosis analysis, each test needs to satisfy behavioral and possibly validity constraints (K and V) simultaneously. Table I summarizes the way to combine both constraints.

TABLE I
Table of Validity from Definition 2

K	V	Conclusion
satisfied $\forall t$	satisfied $\forall t$	normal behavior
satisfied $\forall t$	non satisfied	invalid
non satisfied	satisfied $\forall t$	abnormality
non satisfied	non satisfied	invalid
satisfied $\exists t$	satisfied $\exists t$	normal behavior
satisfied $\exists t$	non satisfied	invalid
non satisfied	satisfied $\exists t$	abnormality
non satisfied	non satisfied	invalid

B. Need for Heterogeneous Tests

Modeling of a whole building system including building components require a huge effort and there are various practical limitations. In fact, systematic approach for tests generations ends up with a huge number of tests difficult to handle [4]. For instance, there are several variables shared among the building sub-systems and difficult to model because of their intricated relations. Taking into account the limitations of pure model-based and rule-based approaches it is a challenging job to test the whole building system. In order to deal with building complexity issue, the notion of heterogeneous test is introduced in this work [8].

In general, a test (Definition 3) is a process of yielding symptoms and possible related explanations. Heterogeneous tests can be range, rule or model-based tests. These tests are performed at the same time and a bridge approach [9] with formal diagnosis analysis is used for the diagnostic analysis, handling heterogeneous tests.

Definition 3: Test A detection test is defined by:

1) $K(X_{(t,t+h)}) \in D_k$
2) $V(X_{(t,t+h)}) \in D_v$
3) Support: it is a set of possible explanations in case of inconsistency in terms of component or item states like: ok(item 1) ∧ ok(item 2) ∧ ...
4) A bunch of data $X_{(t,t+h)}$ related to the of variables X = $\{x_1, x_2, ...\}$ covering a time period *(t, t+h)* . It satisfies:
$(\exists t, K(X_{(t,t+h)}) \notin D_k) \wedge (\forall t, V(X_{(t,t+h)}) \in D_v) \leftrightarrow Expl$
$(\exists t, K(X_{(t,t+h)}) \in D_k) \wedge (\forall t, V(X_{(t,t+h)}) \in D_v) \leftrightarrow$ normal behavior
$(\exists t, K(X_{(t,t+h)}) \in D_k) \wedge (\forall t, V(X_{(t,t+h)}) \notin D_v) \leftrightarrow invalid$

Definition 4: Range-based test

Range-based if $K(X_{(t,t+h)}) \in D_k$ is made of intervals belonging checks. It's a simple test derived with the help of upper and lower bounds.

Definition 5: Rule-based test

Rule-based if $K(X_{(t,t+h)}) \in D_k$ is made of "if...then... else".

Definition 6: model-based test:

Model-based if $K(X_{(t,t+h)}) \in D_k$ is made of equations.

III. A Case Study for a Building System

A. Test Bench

The example of study concerns an office in Grenoble Institute of Technology which accomodates a professor and 3 PhD students. The office has frequent visitors with a lot of meetings and presentations all through the week.

The setup for the sensor network includes (see Fig. 1):

- 2 video cameras for recording real occupancy and activities.
- 2 luminosity sensors with different sensitivities
- 4 indoor temperature sensors, for the office and the bordering corridor
- 2 COV+CO2 concentration sensors for office and corridor
- 1 relative humidity sensor
- 4 door and window contact sensors
- 1 motion detector
- 1 binaural microphone for acoustic recordings
- 5 power meters
- outdoor temperature, nebulosity, relative humidity, wind speed and direction, ... from weather forecasting services
- a centralized database with a web-application for retrieving raw data from different sources continuously

B. Design of Tests

The system to be diagnosed is divided into various elements or sub-systems (heating system, occupants, lighting system and many more) and components level (door position, heat exchanger) and associated with the related variables. This analysis is usually done on the basis of prior knowledge of input-output or cause-consequences relations between the variables and sub-systems.

The systematic approach systematically identifies all the possible causes and consequences for each hypothesized deviations of different variables [1], [7]. Deviations of variables from its normal range generate symptoms and signify some problems or disorders in building's operation. The motivation behind combining this approach with model-based diagnosis is, to develop a diagnostic methodology for

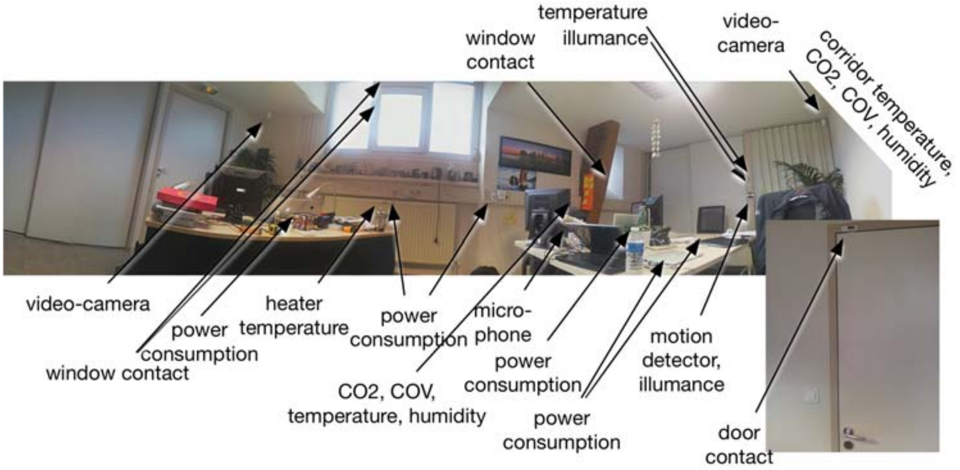

Fig. 1 Sensor test bed at Grenoble INP

buildings, which can cover a maximum number of distinct modeled and non-modeled faults in buildings.

In the present approach, the sensor-level is emphasized. It is not assumed that all sensors are measuring correct value and performing their normal job i.e. mode (ok). The fundamental concern is given to diagnose the faulty sub-system and their components that could affect the overall building performance as well as testing the validity of heterogeneous tests through theses sensors.

In the framework of the office, 9 tests are elaborated:

- Test1: no lighting (range-based test)
- Test2: poor lighting (rule-based test)
- Test3: poor air quality (range-based test)
- Test4: unacceptable room temperature (range-based test)
- Test5: high co2 concentration (range-based test)
- Test6: high electrical consumption (range-based test)
- Test7: no heat (rule-based test)
- Test8: unacceptable heat temperature (range-based test)
- Test9: zonal temperature test (model-based test)

Note that only tests 1, 7 and 9 are presented. Other tests are omitted for reason of space.

Test 1: no lighting (range based test)

Lighting system is an important system in buildings. Testing the illuminance in a building is necessary to maintain the comfort of the occupants. Hence the formulation of this test

It is a range-based test and checks the indoor lighting due to abnormal behavior of a building system. Indoor lighting relies on the normal behavior in the office and sensor measurements. Test function T1 (see Equation 1) generates test results for the deviation of indoor lighting building performance.

$$T1 = \begin{cases} \text{consistent if } (\mathrm{K}(X_{(t,t+h)}) \in D_k) \vee (\mathrm{V}(X_{(t,t+h)}) \in D_v) \\ \text{not obvious if } \neg\, (\mathrm{K}(X_{(t,t+h)}) \in D_k) \vee (\mathrm{V}(X_{(t,t+h)}) \in D_v) \\ \text{invalid otherwise} \end{cases} \tag{1}$$

Now recalling the signification of mode (ok). Not ok represents the complementary fault mode representing the abnormal behavior. In addition, a test needs to satisfy the certain behavioral constraints and validity constraints.

Support: According to an expert, a problem in the lighting system can arise from switch, illuminance sensor, electricity or presence. The concept of fault validity means including sensor that measures the validity in the test support (detected motions sensor in this case). Hence, the support of this test is:

ok(switch) ∧ ok(illuminance sensor) ∧ ok(electricity) ∧ ok(detected motions sensor)

Behavioral constraints K: According to the office, it is considered that lighting should be between the minimin and the maximum value of illuminance.

illuminance ∈[illuminance_min, illuminance_max]

Validity constraints V: the best way to test the illuminance measurements is when it's night, there is no occupants in the office and the light switch is in position off. Hence, the validity constraint is:

presence ∧ night ∧ light switch is in position off

Required sensors for behavior: illuminance sensor

Required sensors for validity: detected motions sensor

Test explanation:

This test determines the illuminance performance of the building. The variable illuminance depends on several building components such as presence and sunset. Test support integrates all major building component that could affect building's illuminance performance as well as sensors that measure the validity. For instance, switch or electricity could be responsible for no lighting. On the other hand, behavioral constraint signifies the normal behavior range for indoor illuminance. Further, there are following validity constraints have been introduced: presence (measured by detected motions sensor) and night.

In order to detect a symptom, the test result must violate behavioral constraints and at the same time it needs to satisfy validity constraints. For instance, if a symptom is detected and valid it signifies that the problem could be caused by switch, illuminance sensor etc... Fault validity signifies that the problem could be from detected motions sensor in this case.

Test 7: no heat (rule-based test)

No heating is a source of discomfort for occupants. Hence, the formulation of this test.

Support: The support for this test is:

ok(Theater sensor) ∧ ok(heating system)

Behavioral constraints: According to the office, it is considered that heater temperature should be higher or equal than Toffice_reference+10. Hence, the constraint behavior is: Theater>=Toffice_reference+10

Validity constraints: the best way to test the heater temperature is when the occupants are present in the office and when it is winter. Hence, the validity constraint is: presence ∧ winter

Presence is measured using detected motions sensor.

Required sensors for behavior: Theater sensor, Toffice_reference sensor

Required sensors for validity: detected motions sensor

Range-based and rule-based tests are limited to certain rules and unable to check the building performance at zonal level. In order to develop a global diagnosis approach the present approach is extended to low level model-based zonal test.

Test 9: zonal temperature test (model-based test)

Modeling the whole building including building components require a huge effort and there are various practical limitations. For instance, there are several variables shared among the building subsystem and difficult to model because of their relations. In this paper, a physical model representing the building behavior is used to predict the inside temperature for the office [3]. By observing the variables included in it, it is clear that the inside temperature is related to different phenomena like the outdoor temperature, the corridor temperature, occupancy, the position of the door and the window and different sources of heat inside the office. In this test, the temperature predicted by the physical model is compared with the measurered temperature.

Likewise, rule and range-based test, model-based tests also have to satisfy the behavioral and validity constraints.

Support: ok(Toffice-wall sensor) ∧ ok(Toffice-reference sensor) ∧ ok(Theater sensor) ∧ ok(door contact sensor) ∧ ok(door opening) ∧ ok(Tcorridor sensor)

Behavioral constraints: Testimated > 19

Validity constraints: presence ∧ door opened ∧ winter

Presence and door opening are measured using detected motions sensor and door contact sensor respectively.

Required sensors for behavior: Toffice-wall sensor, Toffice-reference sensor, Theater sensor, Tcorridor sensor, CO2 corridor sensor

Required sensors for validity: detected motions sensor, door contact sensor

IV. Experimental Validation of Proposed Diagnosis Approach

A. Simulation Scenarios

In order to simulate different fault, a fault-model is used. The fault-model is activated to create a discrepancy in normal behavior of the system. This model includes different building system and able to simulate abnormal behavior in building operation. In this case, few important and most frequent faults are simulated to perform the diagnosis analysis. However, it is important to mention How and When these faults are simulated. In the present context, faults mainly come from failures, abnormal performance or human behaviors. It was mentioned before that validity is determined using a sensor and this sensor can be faulty. The objective of simulated fault scenario is to illustrate if it is easy to detect the fault or not. The detail of simulated fault is given below:

- *Scenario 1: important number of occupants between t=8 and t=12*: is considered as abnormal occupancy i.e. more occupants present than normal. This fault is simulated by injecting number occupants in the different hour.
- *Scenario 2*: Theater sensor gives null values
- *Scenario 3: important number of appliances*: use of additional appliances, causing internal heat gain and over electrical power consumption. This fault is simulated as the use of an additional appliances with the rating 1200 watt-Hour.

B. Bridge Diagnosis

All possible explanations from rule, range and model-based tests are merged into a single signature table (Table III in Appendix) for further analysis. Furthermore, these tests are performed over the set of data.

A symptom could be explained in the terms of a combination of non-zero elements in each row of the signature table 3. Bridge approach develops a row-based test explanations for each non-obvious test. Furthermore, the possible explanations for above symptom could be given as:

Expl(Test2)={¬ (lights), ¬ (illuminance sensor)}
Expl(Test3)={¬ (occupants), ¬(appliances), ¬ (detected motions sensor)}
Expl(Test7)={¬(Theater sensor), ¬(heating system)}

These explanations are considered as all possible set of conflicts that could be responsible for the related faults. A HS set (Definition 7) described in original Reiter work [6], is used for conflict analysis.

Definition 7: Hitting set

A hitting set H for the C(set of explanations) =
{ $Expl_1$, $Expl_2$,..., $Expl_i$, } ⊆ COMPONENTS
if H ⊆ $U_{1\leq k\leq n}$ $Expl_k$ and H ∩ $Expl_k$ ≠ { }

Set H is minimal if and only if ∀ X ⊂ H, X is not a hitting set.

Definition 8: Normalized hamming distance

For given two equal length binary vectors b1 and b2, normalized hamming distance d_H is defined as d_H (b_1, b_2) = (bit-wise changes in b1 and b2) / (number of bits in b1 or b2).

In order to follow the fault isolation process, normalized hamming distance measure the closeness between observed symptom and each column of Table III.

In this scenario, one tests is invalid due to an important number of occupants and only tests 2, 3 and 7 represent inconsistency in the system. In order to diagnose further, all invalid tests are discarded from the diagnosis analysis.

The hamming distance is computed after removing the invalid signature from the theoretical signature table (Table III in Appendix).

d_H(cfm(S1))=0.375
d_H(cfm(S2))=0.625
d_H(cfm(S3))=0.875
d_H(cfm(S4))=0.5
d_H(cfm(S5))=0.5
d_H(cfm(F2))=0.25
d_H(cfm(F4))=0.375
d_H(cfm(F5))=0.25
d_H(cfm(F6))=0.375
d_H(cfm(F7))=0.375
d_H(cfm(F12))=0.5
d_H(cfm(F19))=0.5
d_H(cfm(F22))=0.5
d_H(cfm(F23))=0.5

Using hamming distance analysis it is very obvious that ¬(F2) and ¬(F5) are a declared faults because they have the minimum hamming distance.

The bridge approach goes to the next level of analysis based on test explanations and tries to find a minimum possible explanation for all faults (only the first stage of diagnosis is presented).

minimum diagnoses=

¬(Theater sensor), ¬(occupants), ¬(lights)

The actual fault scenario for this test is an important number of occupants. Due to the violation of validity constraints, Test1 is removed.

The bridge diagnosis show that Theater sensor, occupants and lights are the primary reason for this symptom. They are detected in first stage of diagnosis.

Indeed, diagnoses analysis found occupants sensor could be a possible reason for this scenario. However, it is combined with other components (Theater sensor and lights).

In the present case the diagnosis method is able to detect relatively low sensitive fault i. e it is not easy to detect the fault.

Note that only the scenario 1 is presented. Similar simulation results concerning the other scenarios are omitted for reason of space.

Influence of t in diagnosis analysis

The same example is done by applying the default scenario at t from 13h to 14h. In this interval, the conditions of validity are not satisfied. In fact, there are occupants in the office but the door is closed (see Fig. 2).

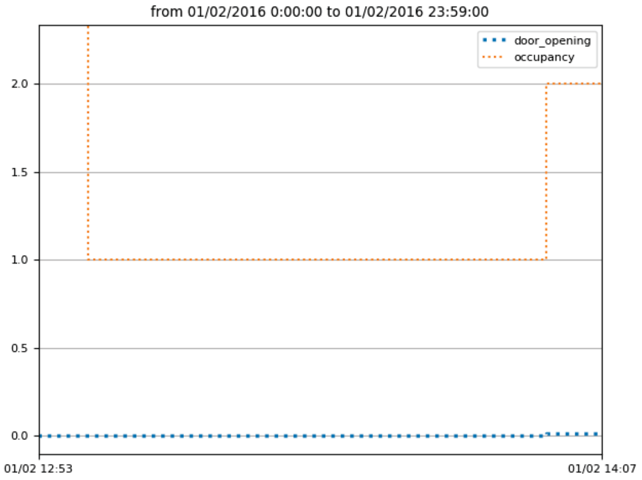

Fig. 2 Occupancy profile and door opening at t from 13h to 14h

In this scenario, tests 1, 3, 4, 5, 8 and 9 are invalid (see Table II). They are discarded from the diagnosis analysis.

TABLE II
INFLUENCE OF T IN DIAGNOSIS ANALYSIS

Tests	simulated fault analysis	validity conclusions	observed symptom
Test 1	K= 0, V ≠ 0	invalid	invalid
Test 2	K ≠ 0, V=0	inconsistent	1
Test 3	K= 0, V ≠ 0	invalid	invalid
Test 4	K= 0, V ≠0	invalid	invalid
Test 5	K= 0, V ≠0	invalid	invalid
Test 6	K= 0, V =0	consistent	0
Test 7	K≠ 0, V =0	inconsistent	1
Test 8	K= 0, V ≠0	invalid	invalid
Test 9	K= 0, V ≠0	invalid	invalid

The hamming distance is the following:

d_H(cfm(S1))=0.66
d_H(cfm(S2))=0.66
d_H(cfm(S3))=0.66
d_H(cfm(S4))=1
d_H(cfm(S5))=0.33
d_H(cfm(F2))=0.33
d_H(cfm(F4))=0.66
d_H(cfm(F5))=0.33
d_H(cfm(F6))=0.66
d_H(cfm(F7))=0.1
d_H(cfm(F12))=0.66
d_H(cfm(F19))=0.33
d_H(cfm(F22))=0.66
d_H(cfm(F23))=0.66

Further, ¬(S5), ¬(F2), ¬(F5) and ¬(F19) have the minimum hamming distance

In order to perform further diagnosis analysis, explanations for these tests are:

Expl(Test2)={¬(lights), ¬(illuminance sensor)}
Expl(Test7)={¬(Theater sensor), ¬ (heating system)}

The minimum diagnoses calculated by bridge method is the following (only the first stage of diagnosis is presented)

The minimum diagnoses=

(¬(Theater sensor), ¬(lights))

The bridge diagnosis shows that Theater sensor and lights are the primary reason for this symptom. The bridge diagnosis leads to an inaccurate results.

V. CONCLUSION

Performing diagnosis in building with partially valid heterogeneous tests is considered as a new contribution to building diagnosis. The proposed methodology incorporates sensor failures in diagnostic analysis. First, the validity of diagnosed fault can be verified easily. Moreover, proposed contextual tests are valid under certain context and relatively easy to apply under real building conditions. Lastly, a minimum set of possible faulty component are derived from the consistency analysis method. The results show that diagnoses obtained from tests with validity are more reliable than those obtained with tests without validity.

The limitation of the proposed method is that it relies only on "automatic tests". Moreover, expert conclusions could improve the results of proposed methodology.

Future works will be around the development of an advancing whole building fault diagnosis tool that incorporates expert conclusions together with automatic tests.

APPENDIX

where:

- $f_{S1} \rightarrow f_1 \vee f_3$
- $f_{S2} \rightarrow f_8 \vee f_9$

TABLE III
REDUCED SIGNATURE TABLE

	S1	S2	S3	S4	S5	F2	F4	F5	F6	F7	F12	F19	F22	F23
test1	1	0	0	0	0	1	1	0	0	0	0	0	0	0
test2	0	0	0	0	0	1	0	1	0	0	0	0	0	0
test3	0	0	0	0	0	0	1	0	1	1	0	0	0	0
test4	0	1	1	0	0	0	0	0	0	0	0	0	0	0
test5	0	0	1	0	0	0	1	0	1	0	1	0	0	0
test6	0	0	0	1	0	0	0	0	0	1	0	0	0	0
test7	0	0	0	0	1	0	0	0	0	0	0	1	0	0
test8	0	0	1	0	0	0	0	0	0	0	0	1	1	0
test9	0	1	1	0	0	0	0	0	0	0	0	1	0	1

- $f_{S3} \rightarrow f_{10} \vee f_{11}$
- $f_{S4} \rightarrow f_{13} \vee f_{14} \vee f_{15} \vee f_{16} \vee f_{17} \vee f_{18}$
- $f_{S5} \rightarrow f_{20} \vee f_{21}$

and

- f1 → not ok(switch)
- f2 → not ok(illuminance sensor)
- f3 → not ok(electricity)
- f4 → not ok(detected motions sensor)
- f5 → not ok(lights)
- f6 → not ok(occupancy)
- f7 → not ok(appliances)
- f7 → not ok(Toffice_wall)
- f9 → not ok(Toffice_reference)
- f10 → not ok(door)
- f11 → not ok(door contact sensor)
- f12 → not ok(office CO2 sensor)
- f13 → not ok(power stéphane)
- f14 → not ok(power khadija)
- f15 → not ok(power stagiaire)
- f16 → not ok(power audrey)
- f17 → not ok(power bloc east)
- f18 → not ok(power bloc west)
- f19 → not ok(power bloc west)
- f20 → not ok(Theater sensor)
- f21 → not ok(heating system)
- f22 → not ok(radiator)
- f23 → not ok(Tcorridor sensor)

NOTATIONS

$\neg$	Negation
$\vee$	Logic OR
$\wedge$	Logic AND
$\forall$	For all
$\exists$	Exists
$\in$	In
$\notin$	Not in
$\subseteq$	Subset

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Houda NAJEH received Eng. degree in electrical-automatic engineering from the National Engineering School of Gabes (ENIG), Tunisia in 2015. Since that, she is a PhD student in the research laboratory for Sciences for the Production, Optimization and Production of Grenoble (G-SCOP) and the research laboratory of Modelling, Analysis and Control Systems of the National Engineering School of Gabes (MACS), Tunisia. Her research interests include fault detection and diagnosis in building systems.

Mahendra Pratap SINGH Dr. Mahendra Singh earned his Ph.D. degree from University of Grenoble, France where he worked on the development of Reactive building management with the key focus on fault diagnosis. He is currently a post-doctoral researcher at Maersk Mc-Kinney Moller, University of Southern Denmark

Stéphane PLOIX is professor at the Grenoble Institute of Technology in the GSCOP lab. After an engineer degree in mechanics and electricity, in 1998 he obtained a Ph.D. from Institute National Polytechnique de Lorraine in control engineering and signal processing and the HDR degrees in 2009. He is a specialist in supervision, monitoring and diagnosis, and his studies focus on human-machine cooperative mechanisms. He is involved in different industrial projects dealing with the supervision of distributed plants, the diagnosis of human skills, iterative diagnosis tool for companies and power management in building.

Antoine CAUCHETEUX Antoine CAUCHETEUX is an Engineer / Researcher at the Center for Studies and Expertise on Risks, Environment, Mobility and Development (CEREMA). It assumes responsibility for the unit of measure for assessing the energy efficiency of buildings and their systems. He participated in the supervision of two theses and was scientific manager, for CEREMA, ANR MEMOIRE and OMEGA projects and the project PCI Energy efficiency of buildings.

Karim CHABIR received the B.Eng. degree in electrical engineering and automatic engineering from The Higher School of Sciences and Technology of Tunis (ESSTT), Tunisia in 2003, the M. Sc. degree in automatic and intelligent techniques from the National Engineering School of Gabes, Tunisia in 2006, and the Ph.D. degree in automatic control from Henri Poincare University, France in 2011. The research works were carried out at the Research Centre for Automatic Control of Nancy (CRAN) and at the Research Unit of Modelling, Analysis and Control Systems of the National Engineering School of Gabes. He was a member of the dependability and system diagnosis group (SURFDIAG). He was a secondary school teacher of Gabes from 2003 to 2007, where he was also an assistant professor in the Faculty of Science of Gabes from 2007 to 2011. He is now assistant professor at the National Engineering School of Gabes (ENIG), Tunisia. His research interests include model-based fault diagnosis and fault-tolerant control.

Mohamed Naceur ABDELKRIM received the B. Sc. degree in electrical construction in 1980, and the M. Sc. degree in electrical construction in 1981 from the High Normal School of Technical Education of Tunis, Tunisia. He also received the Ph.D. degree in automatic control from the National School of Engineers of Tunis, Tunisia in 2003. He began teaching in 1981 at the National School of Engineers of Tunis and since 2003, he has been a professor of automatic control at the National School of Engineers of Gabes, Tunisia. He is currently the head of the research unit on Modeling, Analysis and Control of Systems (MACS), Tunisia. His research interests include diagnosis, optimal control, robust control and robotics.