Energy and Buildings 142 (2017) 111–127

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Economic impact of persistent sensor and actuator faults in concrete core activated office buildings

Joachim Verhelst[a,b,c,*], Geert Van Ham[b,d], Dirk Saelens[a,e], Lieve Helsen[a,c]

[a] EnergyVille, Belgium[1]
[b] KULeuven, FIIW, Technology Campus Geel, Belgium
[c] KULeuven, Department of Mechanical Engineering, Belgium
[d] KULeuven, Department of Electrical Engineering, Belgium
[e] KULeuven, Department of Civil Engineering, Belgium

ARTICLE INFO

Article history:
Received 26 August 2016
Received in revised form 23 January 2017
Accepted 23 February 2017
Available online 27 February 2017

Keywords:
HVAC
MPC
Errors
Persistent bias
Fault impact
Sensitivity
CCA

ABSTRACT

Sensor and actuator degradation occurs frequently in office buildings. These can have a large impact on HVAC performance, both on energy use and thermal (dis)comfort. The degree of impact depends on the faulty component(s), fault type(s) and fault severity and has a significant non-linear relation with the control strategy and comfort constraints. Concrete core activated (CCA) office buildings typically have a high thermal inertia, high comfort requirements and they are equipped with low exergy and low capacity production systems. This allows the inclusion of renewables, thermal storage and flexible load shifting, but this also augments the effects of small perturbations in control output.

In this paper, the economic fault impact is investigated by dynamic simulations using an emulator model of a CCA office building in combination with four different control strategies. A virtual test-bed is developed, consisting of two emulated office zones and a temperature modulated concrete core activation HVAC system, augmented with persistent faults in temperature sensor and hydronic flow rate actuators. Both the fault free (FF) performance and the fault present (FP) performance are investigated and compared through the relevant, control-associated costs using an economic framework. This methodology is able to determine the fault sensitivity of different supervisory control strategies and assists with the selection of the most economical, fault-robust controller for a certain building type. Also, the most critical sensors and actuators are identified.

The evaluated faults are shown to be detrimental for the control performance. The relative economic impact of simultaneous (realistic, randomly distributed and non-correlated) sensor and actuator faults, ranged from +7% to +1000%. By adhering to an appropriate commissioning frequency, this impact can be reduced. The optimal commissioning period for sensors and actuators was determined to be between 2.8 and 5.0 years (case study, controller and assumption dependent). The lowest financial impact due to degradation faults, for this case study and assumptions, is attained by the closed loop model predictive control (CL-MPC) supervisory algorithm, which incurred only a 15% relative increase of total present cost, as opposed to increases above +100% for the other investigated control strategies over the controller lifetime.

This study highlights the relevance of taking faults into account when evaluating long term HVAC control performance and quantifies the economic impact of simultaneous persistent sensor and actuator faults on control performance.

1. Introduction and background

In modern office buildings, the increased uptake of renewable, moderate temperature technologies lead to ever more dynamic interactions between the different HVAC components. While installation and control settings are often kept unchanged over the building lifetime, many building usage parameters, such as number of occupants, preferences and schedules tend to vary drastically over the office building life cycle.

The control performance of dynamic systems varies significantly with operating conditions, especially if control settings are not tuned correctly to the system dynamics of the controlled plant. Low-level HVAC systems control is usually of the P(I)D

* Corresponding author.
E-mail address: Joachim.Verhelst@kuleuven.be (J. Verhelst).

[1] www.energyville.be

http://dx.doi.org/10.1016/j.enbuild.2017.02.052
0378-7788/

Nomenclature

add	additive (or offset) fault
AHU	air handling unit
AN	(amplitude of) normally distributed noise
B	bias, see add
BEMS	building energy management system
BAS	building automation system
CAV	constant air volume (ventilation)
CCA	concrete core activation
CLC	control life cycle (evaluation period)
CL-MPC	closed loop MPC
CT	controller type
EM(C)S	energy management and control system
ESCO	energy servicing company
FC	faulty component
FDDe	fault detection, diagnosis and evaluation
FF	fault free
FI	fault impact
FP	fault present (situation)
rFP	random fault propagation
$FP_{FC,FT,FS}$	fault type *FT* present, in faulty component *FC* with severity *FS*
FS	fault severity large, medium or small
FT	fault type bias, noise or scale fault
HC	heating curve
HVAC	heating, ventilation and air conditioning
KPI	key performance indicator
MPC	model predictive control
M, mult	multiplicative (or scaling) fault
PC	net present cost
OS	optimal start-up
OL-MPC	open loop MPC
PID	proportional, integrative and differential
RBC	rule base control
R-MPC	robust (min–max) MPC
TABS	thermally active building systems
TRV	thermostatic regulating valve
VAV	variable air volume (ventilation)
WF(s)	weighting factor(s)
WN	white noise

type, which can be notoriously sluggish or oscillatory, if badly tuned [1–3]. Poorly maintained, degraded, and improperly controlled equipment leads to an estimated 15–30% of extra energy use in commercial buildings [4]. There are many different causes for these degradations: building design and construction is a highly competitive, price-driven industry. The application of large safety margins and rules of thumb in HVAC design often lead to equipment over-sizing, causing cycling behavior of equipment, which result in increased energy use and mechanical wear compared to properly-sized equipment [5].

Especially for heavy, concrete core activated buildings, optimal control is challenging [6], since building, installation and user dynamics span a large frequency range[2] and since many underlying states are unknown and un-actuated [7].

The effect of persistent degradation faults on energy use is highly dependent on the type of fault and the fault severity. System performance was reported to be significantly lower when in the presence of faults or when they were induced on purpose. Roth [8] refers to a fault-related "energy waste" in HVAC, lighting and large refrigeration systems between 4% and 20%. Li [9] investigated the detection and diagnosis of 6 occurring hydronic faults on weather compensated control, optimal start-up and thermal regulation valves on a two-zone school building emulator. In this study, also a questionnaire was sent to 46 maintenance experts of heating systems in France to assess the impact and occurrence of faults in HVAC systems. On average, faults in HVAC installations lead to a 15–40% increase of yearly energy use [10,9] compared to the fault free situation. These high percentages and wide ranges strengthen our hypothesis that faults should be taken into account in the evaluation of controller performance in office buildings over their lifetime.

The combined effects of uncertainty and control settings for model based controllers have been investigated by Privara [11], Maasoumi [12] and others [13–15]. This research has mainly focused on the impact of model error mismatch due to imperfect parameter estimation and unidentified building dynamics. They documented large swings in control performance, often deteriorating, but sometimes a performance improvement, depending on the degree of model mismatch and the reference used. Also, while some controller formulations had negligible sensitivity even to large model mismatches, others controller algorithms were very sensitive. Castilla [16] made a comparison of thermal comfort predictive control strategies and their possible trade-offs. These observations strengthen our hypothesis that apart from energy use evaluation, also comfort evaluation and supervisory controller types should be taken into account when evaluating control performance in office buildings over their expected lifetime.

Only a limited amount of completed research was found in the area of modeling strategies for common HVAC faults. The development of diagnostic fault models is severely hampered by the scarcity of measured data on the (in-operation) effects of individual faults on HVAC equipment performance. Several studies exist on FDDe performance evaluation in offices, but these fault models and performance evaluations mainly focus on single HVAC-installations (AHU, chiller, boiler). Haves [17] modeled common chiller faults using a first principle model (white box) and an empirical approach (black box model) based on measurements of known (induced) fault states. Braun [18] made a shortlist, frequency table and analysis tool for chiller related faults. Basarkar [19] used the Energy Management run-time Scripting (EMS) functionality in Energyplus (EP) to model and evaluate the energy impact of several VAV box damper failure. Basarkar [19] implemented 5 common AHU faults in Energy Plus using custom EMS schedules. Trcka [20] developed a custom Trnsys type to model common hydronic heating circuit faults. However, faults also occur in building-integrated distribution (e.g. active hydronic controllers) and/or emission systems (e.g. FCU, CCA) and may have a performance impact beyond the system they originate in. In these studies, there was no clear description of what type and severity of persistent faults should be considered when evaluating the economic impact of faults on building-wide HVAC (control) performance in office buildings.

The building-wide impact of (white or colored) sensor- and actuator-noise, additive and multiplicative faults on closed loop HVAC control performance is investigated less often in full building and installation emulations. To the authors knowledge, only Visier [21] investigated faults commonly encountered in six hydraulic heating systems in medium to large size residential and non-residential multi-story buildings, for space heating as well as for domestic hot water heating. A heat generation plant with non-condensing gas boilers, with a design temperature around 90 °C were assumed in this study, including boiler control and sequencing, scheduling of occupancy periods and adaptive control for the temperature setpoint of each secondary loop (RBC) with secondary loop flow control by thermostatic flow-regulation control valves (TRV). An optimum start-stop algorithm for the primary circuit and

[2] From 5.6×10^{-3} Hz (0.05 h) for low level control and disturbances, up to 3.9×10^{-6} Hz (72 h) for heavy building element dynamics.