Renewable and Sustainable Energy Reviews 76 (2017) 673–686

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Model selection for continuous commissioning of HVAC-systems in office buildings: A review

Verhelst J.[a,b,*], Van Ham G.[a], Saelens D.[a,b], Helsen L.[a,b]

[a] KULeuven, Celestijnenlaan 300C, 3000 Leuven, Belgium
[b] Energyville, Celestijnenlaan 300C, 3000 Leuven, Belgium

ARTICLE INFO

Keywords:
HVAC
Control
Office building
Review
Model
FDDe
Continuous commissioning

ABSTRACT

This paper presents an overview of literature and procedures about real-life, state-of-the-art implementations of model-based (MB) Continuous Commissioning (CCx) in office buildings. The focus is on the building- and HVAC-models used for each of three distinct CCx-domains: The identification of energy conserving opportunities (ECOs), fault detection, diagnosis, evaluation and overhaul (FDDe) and model-based control (MBC). For each domain, the relations between chosen model structure, model order, parameter estimation procedure, available sensor data quality and calculation power are highlighted. These insights are critical for office building managers, BEMS manufacturers and researchers involved or interested in the selection and implementation of MBCC strategies.

The analyses indicate that the chosen model order and parameter estimation technique depend highly on available calculation power and data availability. Full model-sharing between different subtopics is rarely performed, presumably due to the diversity of model requirements for each CCx-domain. Several model structures and parameter estimation procedures -e.g. multi-step-ahead and subspace identification- are recurring frequently within one domain -e.g. MBC-. Also, both within and between CCx-domains, the exchange of available expert knowledge and measurements for parameter estimation improves the accuracy of the resulting models.

1. Introduction

Heating, ventilation and air conditioning (HVAC), used to reach and maintain indoor comfort during occupied periods, is responsible for around 40% of the energy use in office buildings [1]. The annual primary energy use in office buildings in Europe varies from 100 to 1000 kWh/m^2/y of conditioned floor space [2]. This large spread can be explained by variations in building usage, location, orientation, status and control of HVAC and lighting installations, use and type of office equipment and operating schedules [3].

Many buildings and HVAC are operated today in a suboptimal manner. Several studies (e.g. [4,5]) mention average energy conserving opportunities (ECOs) between 15% to 30% of building energy use, through improvements of operational strategies, on top of savings associated with major retrofits in the same buildings. Roth et al. [6] estimated potential savings of 3–17 billion (per year for the top 13 ECO implementations (ECOI) in the USA alone [7]. In Europe, potential electrical savings alone are estimated between 61 to 100 kWh/m^2/y for office buildings, resulting in potential cost savings above 6 billion € per year when extrapolated to all office buildings in Europe [1].

The process of following up and improving building and HVAC performance during their lifetime is grouped under the label "Commissioning" (Cx). A US industry survey (in 2000) in California estimated that only 0.03% of existing buildings and 5% of new construction had been commissioned (PECI 2000). A follow-up survey in 2005 estimated that well below 5% of existing buildings and as much as 38% of new constructions had been commissioned [8]. These figures indicate that there is a rising awareness of the importance of CCx, at least for new buildings. But also for existing installations, there is a daunting potential for improvement. In a small study (20 chillers) in California [9], 70% of the investigated systems were impacted by faults and about 40% had more than one fault. Servicing was economically justified for about 40% of the units.

The CCx process is a long, continuous, active monitoring and correction process, comparable to the PDCA circle often found in industrial evaluation cycles (see Fig. 1). Note that Cx of buildings always involves people, and not just technology [10]. Model based

* Corresponding author at: KULeuven, Celestijnenlaan 300C, 3000 Leuven, Belgium.
E-mail address: joachim.verhelst@kuleuven.be (Verhelst J.).

http://dx.doi.org/10.1016/j.rser.2017.01.119
Received 20 November 2015; Received in revised form 23 December 2016; Accepted 17 January 2017
1364-0321/

Nomenclature

AECf	Annual Energy Consumption Impact of a fault
AFT	Accellerated failure time
AHU	Air handling unit
ARMAX	Autoregressive-moving-average model with exogenous input
ARX	Autoregressive model with exogenous input
BB	Black box
bEQ	Building energy quotient-programme (US)
BREEAM	Building research establishment environmental assessment method (UK)
BL	Building level controller implementation (multiple energy flows)
BM	Benchmark
CCA	Concrete core activation
Cx	Commissioning
CCx or CC	Continuous commissioning
CE	Certainty Equivalence
DD-AHU	double deck AHU (hot and cold supply air)
DMPC	Distributed MPC
EARM-OAM	Energy Assessment and Reporting Methodology-Office Assessment Method, (UK)
ECO(s)	Energy conservation opportunity (opportunities)
ECOI	Energy conservation opportunity identification
EUI	Energy use intensity
FCU	Fan coil unit
FDDe	Fault detection, diagnosis and evaluation
fl	Number of floors considered in implementation
GB	Grey box
HLC	Heat loss coefficient
HMM	Heat map model
HW	Hardware
ISABELE	In-situ assessment of the building enveLope performances (EU project)
KPI	Key performance indicator
LEED	Leadership in Energy and Environmental design (US)
LS	Least square error minimisation
MI	Mixed integer
MBCx	Model based commissioning
MBCC	Model based Continuous commissioning
MPC	Model predictive control
MTTF	mean time to failure
MQC	model quality criterion
ML	Machine Learning
ML	Maximum likelihood (method)
MLE	Maximum likelihood estimation
MRI	(Multi-step prediction) MPC relevant identification
NMPC	Non linear MPC
PL	Plant level controller implementation (one energy carrier)
[RAD	Radiative terminal unit (radiator or convector)
RC	Resistive-capacitive analogy
PE	Performance Evaluation
PEM	Prediction error minimisation
RL	Room level controller implementation
RMSE	Root mean Square error
SCOP	Seasonal coefficient of performance
SE	Schneider Electric
SEER	Seasonal energy efficiency ratio
SD-AHU	Single duct AHU (only one supply duct)
Sota	State of the art
SS	State space
SSTR	subspace trust region solve
STEM	Short Term Energy Monitoring
SW	Software
TABS	Thermally active building system
TB	Toolbox
TRL	Technology readiness level
WB	White box
WBM	whole building model
WCC	Weather compensated control
QFDT	Qualitative Fault Detection Tool (commercial software)
#z	Number of zones considered in implementation
#y	Number of considered observations (measurements, inputs)
#x	Number of controlled states
#u	Number of controlled input signals
#d	Number of considered disturbances
#p	Number of estimated parameters

continuous commissioning (MBCC) can assist, enhance and support the decision quality and ease of implementation of most of these phases, as will be shown in implementation examples in this paper, but will not -yet? - replace the requirement for human involvement [11].

Fig. 1. CCx is a cyclical process of Planning, Doing, Checking and Acting (or adjusting) that can be represented schematically by the PDCA-circle.

Each of these evaluation cycles can drive the implementation of ECOs or other energy saving strategies.

1.1. Objectives of this review

This paper aims to present an overview of literature and procedures about state-of-the-art implementations of model-based (MB) Continuous Commissioning (CCx) in office buildings. The focus is on the building- and HVAC-models used for each of three distinct CCx-domains: The identification of energy conserving opportunities (ECOs), fault detection, diagnosis, evaluation and overhaul (FDDe) and model-based control (MBC). For each domain, the relations between chosen model structure, model order, parameter estimation procedure, available sensor data quality and calculation power are highlighted.

1.2. Drivers for Commissioning (Cx)

There are multiple drivers that explain the increasing implementation of Cx for HVAC systems in buildings, especially in the last decade. Compared to older office buildings, most modern buildings have more stringent comfort demands, increased complexity of HVAC systems,