Applied Energy 111 (2013) 602–623

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

An evaluation of robust controls for passive building thermal mass and mechanical thermal energy storage under uncertainty

Sean Hay Kim*

Autodesk, Inc., San Rafael, CA 94903, USA

HIGHLIGHTS

- Building thermal mass and TES are substantial demand-side control instruments.
- MPC is proven to enhance their control performance and thus bring economic advantages.
- Uncertainty in certain operating conditions could diminish their control effectiveness.
- A robust MPC in which relevant uncertainty sources are compiled is proposed.
- Robust MPC presents a stable performance in varied and non-indigenous conditions.

ARTICLE INFO

Article history:
Received 2 February 2013
Received in revised form 6 May 2013
Accepted 12 May 2013
Available online 11 June 2013

Keywords:
Uncertainty
Risk
MPC
Thermal mass
TES
Demand control

ABSTRACT

Passive building thermal mass and mechanical thermal energy storage (TES) are known as one of state-of-the-art demand-side control instruments. Specifically, Model-based Predictive Control (MPC) for this operation has the potential to significantly increase performance and bring economic advantages. However, due to the uncertainty in certain operating conditions in the field, its control effectiveness could be diminished and/or seriously damaged, which results in poor performance.

This study pursues improvements of the control performance of both thermal inventories under uncertainty by proposing a robust MPC in which relevant uncertainty sources are compiled; therefore, it is designed to perform more stable than traditional MPCs under uncertain conditions.

Uniqueness and superiority of the proposed robust demand-side controls include:

(i) Controls are developed based on the a priori uncertainty assessment, such that a systematic modeling approach for uncertainty was taken according to characteristics and classifications of uncertainty.
(ii) The robust MPC reduces the variability of performance under varied and non-indigenous conditions compared to the deterministic MPC, and thus can avoid the worst case situation.

1. Introduction

Employing demand-side control can utilize the building energy supply more effectively and efficiently. The demand-side control is a strategy concerned with adopting measures to alter the system load profile; control measures are used to match demand and supply profiles in frequency and magnitude in a fashion that both demand and supply stakeholders favor. The primary objective of the demand-side control is to modify the demand profile to reduce the variability and even net demand, since large variations in the power demand are more of a strain on the power grid. A driving force of the demand-side control at individual buildings is, therefore, often a utility rate incentive: both utility suppliers and customers prefer shifting the energy demand toward lower the utility rate period as much as possible. Mutual benefits are lower operating costs for demand stakeholders (i.e., customers) and lower infrastructure investments for supply stakeholders (i.e., utility provider).

While load shedding, peak clipping, load shaping and valley filling are technical goals frequently used in modifying the demand profile [1], utilizing thermal inventory, such as passive building thermal mass control and mechanical thermal energy storage (TES), under rate incentives is a well-established technical measure of the demand-side control that can be selected for individual building [2–4].

A successful demand-side control depends in part on how accurately the building power demand is forecasted during the projected control horizon, thus appropriate (and various, if necessary) demand-side control instruments should be placed

---

* Tel.: +1 415 940 2011.
E-mail address: seanhay.kim@autodesk.com

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.05.030

proactively in a harmonized fashion [5]. Model-based predictive controls (MPCs) utilizing both passive and mechanical thermal inventories have demonstrated solid demand-side control performance [2,4,6]. A typical output of the MPC is a supervisory control portfolio for equipment and devices modeled in the MPC. In reality, however, the MPCs are formulated based on the prediction from simulations using building energy models under a specific scenario. Thus, uncertainty can risk the MPCs to perform as designed. If a control strategy is developed not considering the lack of full predictability due to uncertainty, serious side effects can result due to deficient building load prediction, such as inactivated building thermal mass or least load shifting of a Thermal Energy Storage (TES) when occupancy and lighting levels are underestimated [7]. Despite the potential of underperforming deterministic model-based control strategies in practice, there are only a few studies that relate the uncertainty issues to the optimal supervisory controls of HVAC&R systems [8].

A whole building energy analysis, which uses the similar resolution of building energy models used for the MPC, often accounts for uncertainty and risk during design phase [9]. However, temporal and spatial resolution of MPC solutions is drastically finer than that of whole building energy analyses [5]. Therefore, characteristics of uncertainty in the MPCs should be more sharply identified, focusing on the following points:

(i) “Uncertainty” tends to be used narrowly, referring to “noise” in the building supervisory MPC, which appears to be due to the “error” terms conventionally used in local PID controllers.
(ii) The sporadic nature of uncertainty, such as that observed in occupant behavior or microclimate, which has often been undermined in whole building energy analyses, can seriously damage the control performance of the MPC.
(iii) The model calibration tolerance that compliance codes recommend (e.g., Coefficient of Variation of the Root Mean Square (CV-RMSE) of ±30% [10], ±25% [11], and ±20% [12]) still allows significant model uncertainty to the MPC.
(iv) Process-related uncertainty, such as random errors and bias to sensors and actuators, can be another source of critical uncertainty when modeling building systems.

This study aims to propose a robust MPC utilizing the thermal inventory based on the definition of uncertainty specific for the MPC [5], which is designed to perform more stable under uncertain conditions than the traditional deterministic MPCs do. Then the developed robust MPC should be evaluated with respect to legacy control strategies against a test building for which thermal inventory control is designed in accordance with a planned new time of use (TOU) tariff with higher rate incentives.

This paper comprises three parts: In the first part, uncertainty is specifically defined with respect to its potential risk to the MPC applications (Section 2). In the second part, a development of the robust MPC for building thermal mass control and mechanical TES control, which compiles associated uncertainty sources, is discussed in depth (Section 3). In the third and final parts, the developed robust MPC is evaluated against benchmark control strategies (Sections 4 and 5).

2. Uncertainty in the MPC

The prequel of this study [5] reviewed definitions, characteristics and sources of uncertainty that are relevant to the MPC with an in-depth analysis. This section extracts and highlights the two most important characteristics of uncertainty that the robust MPC should deal with.

2.1. Definitions and characteristics of uncertainty in general modeling

General statements suggest that uncertainty is defined indirectly from the definition of certainty, whereas certainty is defined as the condition of knowing *everything* necessary to choose the course of action with the most preferred outcome [13,14]. This study defines uncertainty as the *gap* between certainty and the decision-makers’ “present state of information” [15] as Fig. 1 depicts. Therein, uncertainty is described as a (known and unknown) confidence range of the (imperfect and subjective) information available at the present state [5].

In Fig. 1, the state of precise information indicates the state at which the stakeholder has all the information about the use of model, such that the distribution type and specification of model parameters are perfectly known. However, knowing all information about the model does not mean that there is no uncertainty, since a specific occasion originating from the unpredictable part may or may not happen. Therefore, uncertainty has erratic characteristics in nature (called *sporadic uncertainty*) as well as indefinite characteristics caused by lack of pertinent knowledge to develop computational models (called *imprecise uncertainty*) [5].

2.2. Sources of uncertainty in the MPC

Classifying uncertainty sources helps to efficiently capture their significant behaviors when modeling them into a building energy model used for the MPC [16]. Sources of uncertainties that are often mentioned in modeling buildings and HVAC&R systems can be classified into three categories, as follows, based upon origin elements of the model [5,8].

(i) *Model-inherent uncertainty*: The uncertainty of the various building and system component models, which is caused by inaccurate or incomplete data in the analytic model and/or lack of a reasonable regression fitting in the response model.
(ii) *Process-inherent uncertainty*: The range, due to randomness and bias, within which the control and process variables can be dispersed.
(iii) *Scenario-forecast uncertainty*: The unpredictable discrepancy in forecasting the driving forces located outside the system, called scenarios – mainly weather, building operation, and supply and demand in the energy market.

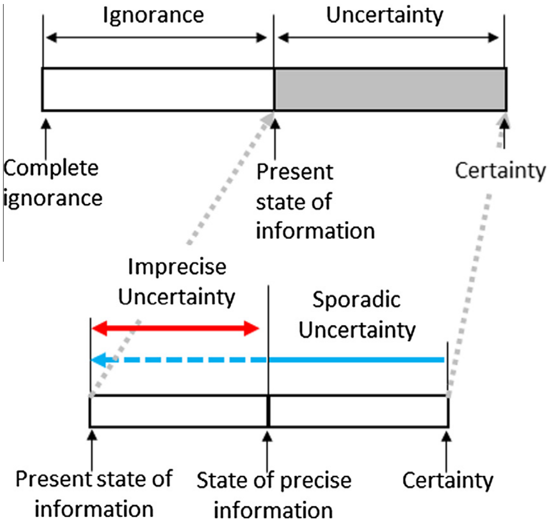

Fig. 1. Characteristics of uncertainty [15].