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An integrated control-oriented modelling for HVAC performance benchmarking

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ABSTRACT

Energy efficiency in building heating, ventilating and air conditioning (HVAC) equipment requires the development of accurate models for testing HVAC control strategies and corresponding energy consumption. In order to make the HVAC control synthesis computationally affordable, such control-oriented models are typically a simplified version of more elaborate building simulation environments (e.g. EnergyPlus, Modelica, TRNSYS). Despite their simplicity, control-oriented models must effectively catch all the interactions between HVAC equipment, in order achieve system integration and avoid fragmentation in HVAC modelling and control synthesis, which is one of the main causes of suboptimal performance in the building sector. In this work we propose an integrated control-oriented modelling for HVAC performance benchmarking. The following HVAC equipment and their interaction are modelled: condensing boiler, radiator, air handling unit, heat pump, chiller, fan, pump, pipe, duct, and multiple thermal zones. The proposed modelling approach is modular so that the user can add and remove as many components as desired, depending on the building to be modelled. Appropriate procedures for synthesis of control strategies and benchmarking are proposed. Extensive simulations demonstrate the effectiveness of the proposed methodology, which can lead to improvements in occupants' thermal comfort while at the same time consistently attaining energy savings.

1. Introduction

Heating, Ventilation and Air Conditioning (HVAC) systems, widely used in residential and commercial buildings, are responsible for a large part of the energy consumption worldwide. According to the estimates published by the U.S. Energy Information Administration and by the European Commission in 2014, more than 40% of total U.S. and Europe energy consumption was consumed in residential and commercial buildings, half of which was used for HVAC operation [1,2]. It has been widely recognized that in order to enable energy efficiency in HVAC equipment it is crucial to develop accurate models for testing HVAC control strategies and their relative energy consumption [3,4]. Nowadays, there is plenty of software tools used for building energy simulation purposes, among which EnergyPlus [5], Dymola-Modelica [6], TRNSYS [7]. These tools are very precious for energy simulation purposes, but they give limited insight on how to actually design HVAC control strategies for minimization of HVAC energy consumption. To this purpose, simpler models, often referred to as control-oriented models, need to be developed so as to make use of the rigorous tools of systems and control theory [8]. In order to make the control synthesis computationally affordable, such control-oriented models are typically a simplified version of the more elaborate building simulation environments EnergyPlus, Dymola-Modelica and TRNSYS. Despite their simplicity, control-oriented models must effectively catch all the interactions between HVAC equipment, in order to have an integrated environment and avoid fragmentation in HVAC modelling and control, which is often the first source of suboptimal performance in the building sector [9]. This fragmentation implies that control strategies are developed without accounting for possible HVAC component interactions, thus resulting in suboptimal energy performance. A typical example is control of air handling units (AHUs) for heating purposes [10]: the temperature of a room is not only affected by the heating coil used to regulate the temperature of the inlet air, but also by a radiator system. Both the heating coil and the radiator might be driven by the same boiler. As a result, control must carefully integrate these components by taking into account their interaction.

In order to better illustrate this fragmentation, let us look at the state of the art and industrial practice in HVAC modelling and control: unfortunately, HVAC interactions are often neglected. Components are often modelled separately, as illustrated by this

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overview on recent implementations of modelling and control strategies for HVAC systems: a chiller alone [11], a radiator alone [12], an AHU alone [13–15], a heat pump alone [16], AHUs with multiple zones [17–19], floor heating with multiple zones [20]. Some efforts toward HVAC integration can be recognized in works such as [21] (chiller and AHU), [22,23] (AHU with chiller, fans and multiple zones), [24] (boiler, heat pump and chiller), even if many other HVAC components are still not integrated. This overview shows that HVAC system-wide control integration is far from being reached. In this work we aim at covering this gap by proposing an integrated control-oriented modelling for HVAC performance benchmarking. The following HVAC equipment (and their interaction) is modelled: condensing boilers, radiators, air handling units, heat pumps, chillers, fans, pumps, pipes, ducts, and thermal zones. The proposed modelling approach is modular so that the user can add and remove as many HVAC components as desired, depending on the building to be modelled.

Modelling is only the first step toward HVAC system integration: in fact, the final goal is HVAC energy efficiency via improved controls. To this purpose, the second step is the selection of the HVAC control parameters in an optimal way. In this work we finally overcome the aforementioned HVAC fragmentation by exploiting the proposed modelling approach to synthesize and evaluate integrated HVAC control strategies. In particular, after adopting a control architecture commonly used in the building sector (a lower proportional-integral-derivative control layer, and an upper optimization-based control layer to optimize the lower layer operation), we exploit the proposed modelling approach to find the optimal working points of the HVAC equipment, to autotune a set of feedback control strategies, and to develop appropriate benchmarking criteria. Extensive simulations demonstrate the effectiveness of the proposed methodology, which can lead to improvements in occupants' thermal comfort while at the same time consistently attaining energy savings.

The rest of the paper is organized as follows: Section 2 describes the modelling of the HVAC equipment. Partial differential equations are derived, which are then spatially discretized in Section 3 so as to obtain a control oriented modelling of the HVAC system. Section 4 illustrates the functioning of the model, while Section 5 presents the proposed methods for parameter identification and controller synthesis. Section 6 verifies the effectiveness of the methods via simulation and Section 7 concludes the paper.

2. Modelling the HVAC components

This section presents the heat and mass transfer equations governing a complete HVAC system consisting of condensing boilers, radiators, air handling units (with heating and cooling coils), heat pumps, chillers, fans, pumps, pipes, ducts and thermal zones. Interaction between components are also modelled, e.g. the heating coil is connected to a (condensing) boiler, while the cooling coil to a chiller. The boiler heats supply water, which is circulated throughout the system and aids in warming the zone through the radiator and also by interacting with the air through the heating coil in the AHU. A heat pump is finally connected to the floor heating system of the house. Lumped capacitance models are chosen for radiator, boiler, pipes, ducts and heating coil, resulting in partial differential equations which are spatially discretized so as to come up with control-oriented models. Fig. 1 shows a possible integration of all the components into a building: where a thermal zone is heated by floor heating connected to a heat pump, a boiler which is connected to both a radiator and an air handling unit. The air handling unit uses a heating coil (connected to the boiler) and a cooling coil (connected to a chiller) to warm or cool the air. Pumps and fans are used to put water and air

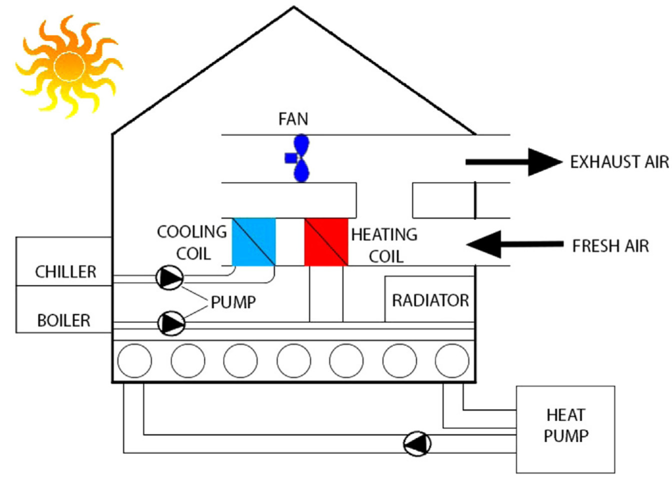

Fig. 1. Overview of the main components of the HVAC system.

in motion. Fig. 1 is just a possible example of HVAC configuration. The user can add and remove HVAC components depending on the building to be modelled. Additional thermal zones and floors can also been added.

2.1. Radiator

A simplifying assumption is made in the model of the radiator [12], assuming the same temperature for radiator surface as the water temperature inside the radiator. By this assumption, the heat from the radiator is transferred to the ambient only by convection. The indoor air in the zone acts as an ambient for the radiator. The evolution of radiator temperature T_{rad} in [°C] is as follows:

$$\frac{\partial T_{rad}}{\partial t} = \frac{w_{rad_{sw}}}{\rho_w A_{rad}} \frac{\partial T_{rad}}{\partial l} - \frac{K_{rad}}{C_w \rho_w V_{rad}} (T_{rad} - T_z), \tag{1}$$

where the first term represents heat exchange inside the radiator and the second term represents the heat exchange with the indoor air temperature T_z in [°C] of the zone. In (1) C_w is the thermal capacitance of water in [kJ/kg°C], $w_{rad_{sw}}$ is the mass flow rate of supply water into the radiator in [kg/s], K_{rad} is the heat transfer coefficient in [kW/°C], ρ_w is the water density in [kg/m^3], A_{rad} is the surface area of the radiator in [m^2] and V_{rad} is the volume of the radiator in [m^3]. The heat transfer coefficient K_{rad} is described as:

$$K_{rad} = h_{rad} A_{rad}, \tag{2}$$

where h_{rad} is the convection heat transfer coefficient of the radiator in [kW/m^2 °C]. The power transferred, Q_{rad} in [kW] by the radiator to the zone is given by the following equation:

$$Q_{rad} = K_{rad}(T_{rad} - T_z). \tag{3}$$

2.2. Condensing boiler

In most countries, it is now a requirement of the building regulations that newly installed gas-fired boilers should be condensing with a seasonal efficiency of 85% or more [25]. Since the exit flue gas temperature of a conventional gas fired boiler is usually high and a great amount of heat energy is lost to the environment, condensing boilers aim at recovering both sensible heat and latent heat by adding a condensing heat exchanger. The evolution of water temperature inside the boiler T_b in [°C] is as follows: