Proceedings of BS2013:
13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26-28

SIMULATION-BASED RECEDING-HORIZON SUPERVISORY CONTROL OF HVAC SYSTEM

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ABSTRACT

Optimizing the operations of a HVAC system in response to the dynamic loads and varying weather conditions throughout a year can result in substantial energy savings. However, the problems related to HVAC system optimization are always discrete, non-linear and highly constrained. So, a simulation-based optimization approach for a HVAC system is proposed. To minimize the energy consumption while maintaining the corresponding indoor thermal comfort, a model is developed using TRNSYS to simulate an office building and its HVAC system and using MATLAB genetic algorithm toolbox to solve the optimization problem and search for optimal control settings in a receding-horizon manner. The controllable input variables include supply air temperature and chilled water temperature. The results show that 24.1% energy use can be saved by optimizing the operation of the HVAC system.

INTRODUCTION

With the increasing concern about building energy consumption, there is a growing interest in the development of technologies for low energy buildings. Chinese academics estimate that the buildings sector actually accounts for 23% of total energy and will exceed 30% by 2010(Fridley G.David et al., 2007). Therefore, it is urgent to significantly reduce the energy use of HVAC system because of long lifespan of buildings. Optimal control of HVAC system aims at providing the desired indoor comfort and environment with least energy cost，which can be achieved by using two-level control structure. Low-level local control of a single set point is handled by an actuator. For example, the supply air temperature from a coiling coil is controlled by adjusting the opening of a valve that provides chilled water to the coil. Supervisory control is high-level control that aims at seeking the minimum energy input or operating cost to provide the satisfied indoor comfort and healthy environment, taking into account the ever-changing indoor and outdoor conditions as well as characteristics of HVAC system (S.Wang et al., 2008). Modern Buildings equipped with energy building automation systems (BAS) and building management control systems (EMCSs) allow optimizing the supervisory control for HVAC system to optimize set points and operation modes while providing the desired indoor environment quality at minimum energy cost.

Nowadays, there are a wide range of available building performance simulation softwares such as TRNSYS, ESP-r, EnergyPlus, and DOE2 applied in the design and optimization of building and HVAC system. But the capability of these state-of-the-art building performance simulation tools to simulate different-level controllers is different from each other. Some tools offer pre-defined control strategies (e.g. eQuest, DOE2), some offer flexibility in specifying local controllers (e.g. TRNSYS), and some offer flexibility in specifying only supervisory controllers (e.g. EnergyPlus). The domain-independent environments, such as MATLAB, are efficient tools for designing and testing of controllers in a simulation setting, but lack the model of all other physical phenomena in buildings(Marija Trcka et al., 2010). There is also no single building performance simulation tool that offers sufficient capabilities and flexibilities to handle both the all kinds of local controllers and advanced supervisory controllers. This problem can be alleviated by co-simulation. Co-simulation presents a particular case of simulation scenario where at least two simulators solve coupled systems of differential-algebraic equations and exchange data that couples these equations during the time integration (Marija Trcka et al., 2009). Co-simulation (data and process model co-operation) is one of the four level of shared development in building performance simulation software described by Jan Hensen (Jan Hensen et al., 2004).

Over the last decades, model predictive control (MPC) has been extensively and successfully applied in many fields, such as in chemical and mechanical engineering (S.JoeQin et al., 2003).

Model predictive control or receding horizon control (RHC) is an advanced control strategy which uses a model of the plant (building or system) to predict its future behaviours as well as the system response to the changes of control settings so as to optimize an objective function in a receding-horizon manner. The fundamental idea of model predictive control is to solve an optimal control problem in a receding-horizon manner: at any time step, the optimization problem is solved only for a short time horizon from the current state, then the first control action in the solution sequence is applied, and the procedure is repeated at the next time step. The most attractive features of MPC control approaches include the possibility to explicitly specify the desired cost of energy as a performance measure and to incorporate constraints on control and state variables in a systematic way(Pengfei Li et al., 2012).

In the majority of the previous studies, MPC is applied to some special system type and performed through simulations, such as determining the optimal start time for heating system(M.Kummert et al., 2005) and minimizing energy cost through thermal storage(G.Henze et al., 2005). There are also a number of researchers have focused on non-predictive model-based control(Nabil Nassif et al., 2005; ShengWei Wang et al., 2000).

Recently, some researchers turn to pay attention to build MPC framework in HVAC field. Two studies among of them should be received much attention. Brian Coffey et al. presented a flexible software framework for model predictive control using GenOpt, along with a modified genetic algorithm developed for use within it and applies it to a case study of demand response by zone temperature ramping in an office space(Brian Coffey et al., 2010). Jingran Ma et al. studied building energy demand reduction via model predictive control. The author employed BCVTB (Building Control Virtual Test Bed) software as middleware to link EnergyPlus and Matlab and the real-time data exchange between the two programs. A multi-zone commercial building equipped with VAV cooling system built in EnergyPlus, while system indentification is performed in Matlab to abtain zone temperature and power models, which are used in the MPC framework(Jingran Ma et al., 2012).

The main reason for MPC in building still being rarely used are the difficulties /cost of obtaining a model of an (individual) building that can be used in the MPC controller and the fact that energy costs played a minor role in the past(Frauke Oldewurtel et al., 2012). A model can be either a "physical model", or "non-physical model". In non-physical model approaches, self-learning algorithm, reinforced learning or neural networks are some of the methodologies. Clarke summarized the differences between model-based approach and the non-physical approaches mentioned above and compared their advantages and disadvantages of each other (Clarke J A, 2001). Learning algorithms can initially take days to predict the correct optimum start time and have difficulty dealing with unusual conditions such as long shut down periods, exceptional weather conditions and changes in building operation. Even the best trained self-learning controller cannot extrapolate beyond its range of experience. They have no underlying physical model of the system and process being controlled. The controlled entity is essentially a non-physical 'black-box model'. There are inherent limitations in the black box approach to control as the controller has no knowledge of the cause and effect relationships between the elements of the controlled system and external excitations such as climate and occupant interaction. Besides, development of model-based control is more desirable when the building is not built yet and no data can be obtained.

The aim of the presented work is to develop a platform for simulation-based supervisory control and optimization of HVAC system in a small-sized office building. TRNSYS16.1 software is employed to model the building and HVAC system, while the GA (Genetic Algorithm) procedures, implemented on MATLAB 2006a, is employed to solve the minimization problem of energy use. A TRNSYS component called Type155, combining TNSYS and MATLAB for co-simulation, acts as a supervisory controller to specify the PID controller settings at each time step. Two simulation cases are studied to evaluate receding-horzion supervisory control of a small-sized office buidling.

PROBLEM FORMULATION

A generic MPC framework is given by the following finite horizon optimization problem:

$$J(x) = \min_{u} \sum_{k=t}^{t+N-1} l(x_k, u_k), \qquad \text{Cost function (1)}$$

Subject to:

$x_{k+1} = f(x_k, u_k)$, k=t,…,t+N-1, Dynamics (2)

$x_k \epsilon$ X, k=t,…,t+N-1, Constraints (3)

$u_k \epsilon$ U, k=t,…,t+N-1, Constraints (4)

x_t=x(t), Current state (5)

Where N is the prediction horizon, x_k and u_k are the constraint sets respectively for states x_k and inputs u_k at time step k=t. The current state of the plant is used as the initial state and the dynamic system should be modelled to such a sufficient precision that a good control performance can be achieved.

For different types of HVAC systems, equipment characteristics, weather condition, occupancy schedule and utility rate structure, the optimal supervisory control problems are often significantly different. In this paper, we consider the optimal supervisory control problem for a typical HVAC system with the objective function being the total energy use of the HVAC system. The optimization problem is formed through the determination of the problem variables, the constraints and the objective functions. We select AHU supply air temperature and chilled water temperature as the problem variables. Both of the two variables affect the airside and waterside of HVAC system energy consumption. The constraints result from restriction on the operation of the HVAC system, which cover the lower and upper limits of variables.

The set points of the supervisory control strategy are optimized in order to minimize energy use, which including chiller, pumps, fans, and cooling tower power. The objective function is

$$fval=P_{fan}+P_{pump}+P_{chiller}+P_{coolingtower} \quad (6)$$

METHODOLOGY

In our study, an implementation of the simulation-based MPC of building and HVAC system has been investigated for supervisory control. An advantage of simulation-based approach is the rigorousness of the model built inside the simulator, which allows for higher accuracy of the computation of objective function (Truong X.Nghiem et al., 2011). Such an optimization process consists of two parts: a simulator (TRNSYS) to compute the objective function J and an optimization algorithm (Genetic Algorithm).

TRNSYS (TRaNsientSYstem Simulation program) is a complete and extensible simulation environment for the transient simulation of systems. It contains many components, which is so-called Types, such as multi-zone buildings components Type56. TRNSYS is well suited for dynamic simulation of HVAC equipment and system. However, TRNSYS is limited in its ability to model some types of controllers, especially advanced controllers such as receding-horizon supervisory control. MATLAB has powerful capabilities of numeric calculation and kinds of tools, such as the GADS (Genetic Algorithm and Direct Search) tool. The co-simulation platform coupling TRNSYS and MATLAB via Type155 is developed to simulate the HVAC system and optimize its operation.

GA-based optimization process

Genetic Algorithm is a adaptive search heuristic that mimics the process of natural evolution. In this study, the GA is employed as the optimization method to search the optimal values of the controller settings that minimize the fitness function (objetive function) value. The GA starts with random set points which are within their allowed ranges given by the constrained condition. At the computation of each generation, each set points (values of two control variables: supply air temperature and chilled water temperature) are given to the wrapping function to compute the fitness function value and predict the responses of the system during a prediction period. Then, GA generates the next generation by selection, crossover and mutation according to the fitness of parents and its rules. Through generations of computation, GA can find the optimal solution and deliver it to the TRNSYS controllers via Type 155.

The TRNSYS component Type155 implements a link with MATLAB. The connection uses the MATLAB engine, which is launched as a separate process. The FORTRAN routine TRNSYS communicates with the MATLAB engine through a COM (Component Object Model) interface. Figure1 illustrates the optimization process of supervisory control.

The supervisory controller (Type155) is turned on, when the both two conditions are satisfied. The first one is the time is falling the worktime period (8:00~18:00) and the other one is that optimization interval is 30 minutes, which means the supervisory controller is turned on every thirty minutes. At each optimization time interval (i.e., 30minutes), the GA-based optimization process seeks to find the optimal values and then send them to the TRNSYS building and HVAC system model, where the fitness function value are obtained through simulation and returned back to the genetic algorithm program for the next time calculation.

Wrapping TRNSYS into MATLAB function

The model developed within the Simulation Studio environment is saved in ASCII text format within in a .DCK file, which stores the information of Types and connections between them. The .DCK file can be executed by TRNEXE, an algebraic and differential equation solver which iteratively computes the system state at each time step. Figure2 shows a method of how to wrap TRNSYS and GA into a MATLAB function. GA can be easily called using ga function whin the m-file.

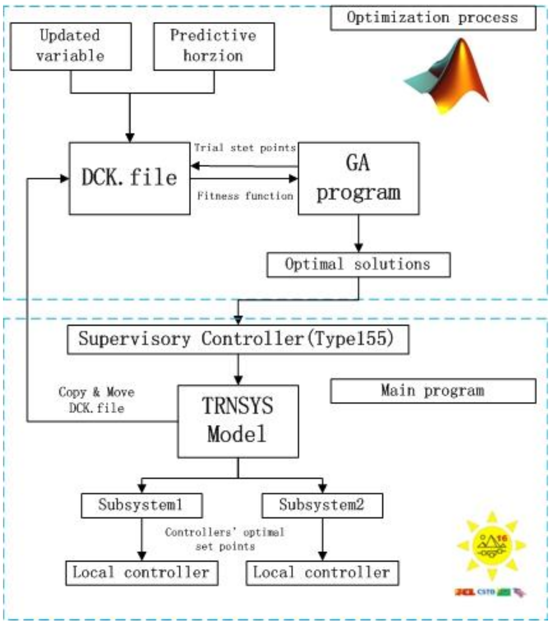


Figure 1 Optimization process

In the first step, the overall system model should be created within the TRNSYS Studio and the proper text format output files are also defined, which can be easily loaded and read by MATLAB. Then, the .DCK file is copied and moved for the first time in the m-file of Type 155 so as to modify the predictive time horizon and not alter the original file. The simulation information of trnStartTime and trnStoptime should be modified according to the current predictive horizon according to the trnTime, which is the current simulation time of TRNSYS. Next, in the wrapping function m-file, modeller should copy and move the DCK file again to update the DCK file by searching and replacing the relevant sections of the current .DCK file. The updated .DCK file is then executed by TRNEXE using the dos () or ! command in MATLAB. Results file can be loaded and read by textread command. Finally, the modeller then obtains the current fitness value of the fitness function for the current generation. GA will research the new optimal values until the terminal condition is satisfied. The number of the maximum generation is 100. Wrapping the execution of TRNSYS into a MATLAB function provides the capability to evaluate thousands of candidate solutions with no quickly and easily (Marcus Jones, 2010).

SIMULATION STUDIES

Building detail and the design parameters

A small-sized office building of 476.4 sq.m with two floors located in Eco-Tech Park on Jiading Campus of Tongji University is selected to research the HVAC system and its control system. The indoor temperature and relative humidity (RH) set point is 24℃/60% in summer and 20℃/45% in winter. Figure 3 shows the floor plan. Each floor is divided into four air-conditioned area and one non air-conditioned area. Zone1-5 and Zone2-5 (2nd floor) are non air-conditioned areas, the rest are air-conditioned areas.

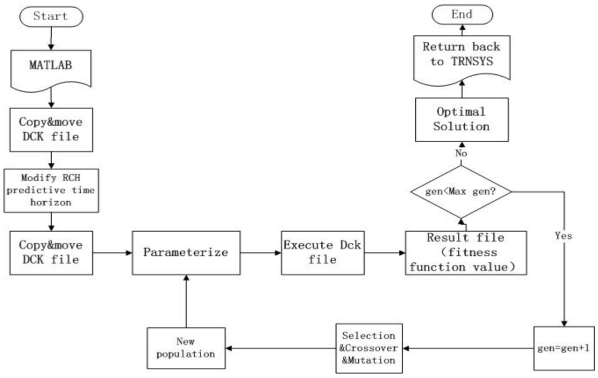


Figure 2 Wrapping TRNSYS and GA

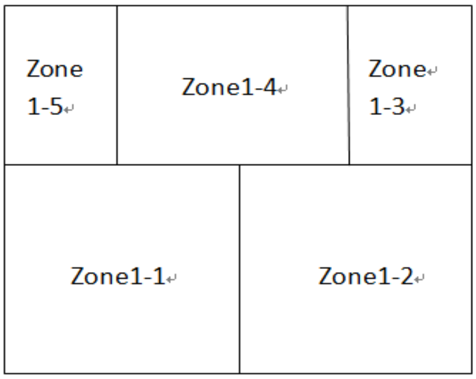


Figure 3 Plan of the office building

The heat transfer features of the building envelope and the internal loads, such as occupancy density, lighting power density (LPD), equipment power density (EPD), as well as the operating schedule are listed in Table 1 and Table 2.

Table 1 Heat transfer parameters of building envelope components

	EX-WALL	ROOF	WINDOW
U-Value(W/m^2.K)	3.49	0.8	2.83

Table 2 Internal loads and operating schedule

OCCUPANCY (M^2/PERSON)	LPD (W/M^2)	EPD (W/M^2)	SCHEDULE
4	13	20	8:00-18:00

HVAC system

The office building employs a chiller and a boiler as the cooling /heating source respectively and a VAV system as the HVAC system. There are 4 VAV boxes on each floor and one air handling unit (AHU). The outdoor air mixes with return air and the mixed air is further handled by AHU and then supplied to VAV terminals. Figure 4 shows the airside system of the HVAC system.

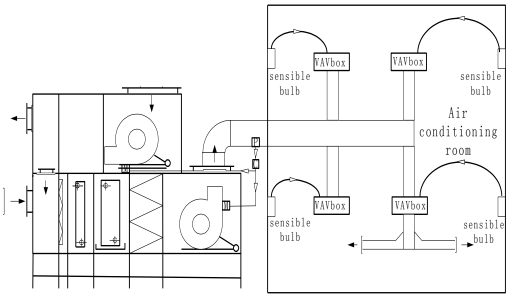


Figure 4 Airside system

Modeling

The control strategies implemented on the office building for performance determination and assessment include air loop control strategies and water loop control strategies. The supply fans in AHU (Air Handling Unit) are VFD (variable-frequency drive) fans, which are controlled by pressure without reset. 'Bypass Fraction Method' is selected as the coil model (Type753d) in TRNSYS, and the coil outlet supply air temperature is stabilized with PID controller by moderating the water flow rate. The supply air temperature is specified by supervisory controller. The outdoor air ratio of AHU is set to be 0.3. The indoor air temperature is maintained at the set point by moderating the supply airflow rate with PID controller. Chilled water pump is variable speed pump and cooling water pump is constant speed, which are turned on and off sync with the chiller (Type666). The time step of simulation in TRNSYS is 0.1h (i.e., 6 minutes).

Simulation results and analysis

In order to evaluate the simulation-based RCH supervisory control using GA optimization method (OptimalStrategy), an other control strategy is studied (Baseline Strategy). The baseline control strategy is a conventional control strategy. The set points of supply air temperature and chilled water temperature are set to be constant.

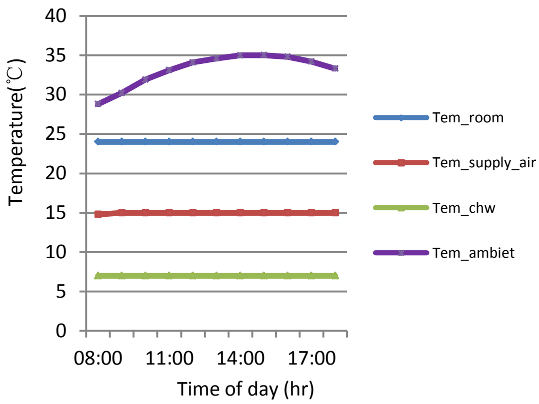


Figure 5 Baseline case temperature curves

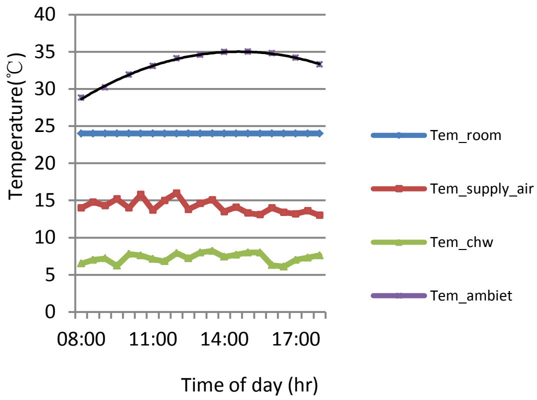


Figure 6 Optimal case temperature curves

Figure 5 and Figure 6 show that the indoor air temperature curves can be well controlled at the set point 24 ℃ during the working hours from 08:00 to 18:00 on a typical cooling condition day. The values of supply air temperature and chilled water temperature are controlled at 15℃ and 7℃ respectively for the baseline control strategy, while the values of the optimal control strategy are optimized at each optimization interval (i.e., 30 minutes).

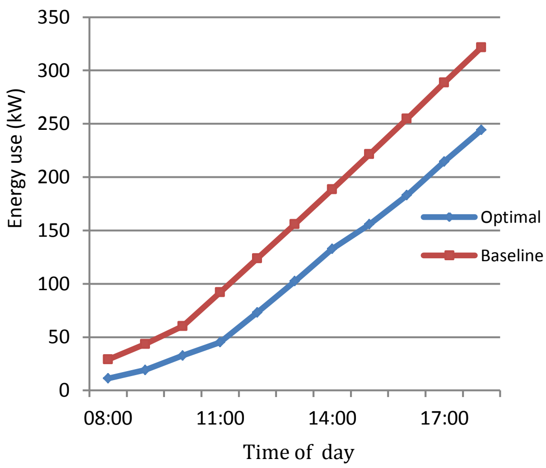
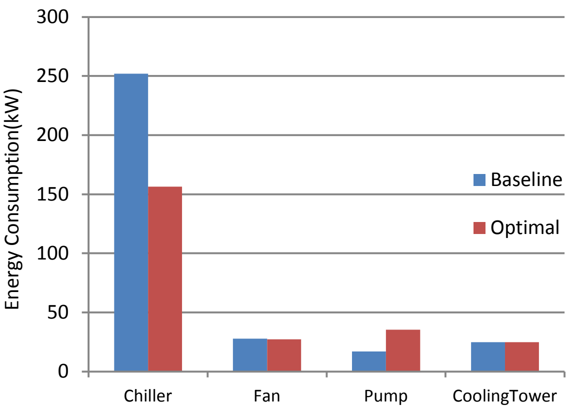


Figure 7 Total energy consumption curves

Figure 7 illustrates the total energy consumption curve of HVAC system under the two control strategies. Optimal strategy reduced total HVAC energy use by 24.1% compared to the baseline strategy. Figure 8 shows the energy use of chiller, fans, pump, and cooling tower on a typical cooling condition day. In this case, chiller accounts for the main energy use of HVAC system. Much energy can be saved by optimizing the chilled water temperature.

Figure 8 Energy use of HVAC system



CONCLUSION

The main task of this paper is to propose a receding horizon supervisory control strategy for minimizing HVAC energy use by coupling TRNSYS and MATLAB via Type155. Co-simulation technique can take advantage of each tool. It was shown by simulation that RHC brings substantial cost savings by specifying both the supply air temperature and chilled water temperature at each optimization interval.

The main disadvantage of the simulation-based optimization method is its slow run-time, which is largely due to the complexity of the model and the simulation time step considering the local controllers such as PID controllers. Some measures should be taken to address this problem in the future work, such as turn to the creation of Matlab lookup tables off-line by simulating the modeled components over their range of expected input conditions and then using these lookup tables as the 'model' in the on-line optimization or using System Identification Toolbox of Matlab to identify mathmatical models. Besides, for real application, the uncertainty analysis of model pridictive control due to the weather and occupancy predictions will be maded in the future. This control stratgy will also be implentmented on the real building and the measured data will be abtained to calibrate the model and verify the proposed supervisory control strategy.

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