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Assessing the Retrofit Potential of Building Control Systems

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ABSTRACT

It is well known that building control systems frequently under-perform, leading to wasted energy and poor space conditions for occupants. There are many reasons for this, including insufficient design or commissioning, deterioration of equipment over time, changes in building usage and poor maintenance. Therefore, building control systems are prime candidates for retrofits and upgrades. Such activities, though, can be very challenging in their own right. For example, information regarding the design intent and current control logic may be difficult or impossible to obtain due to lack of documentation, proprietary data and communication formats or unrecorded modifications. In addition, there is a great deal of variability in control system configuration and components, so each potential retrofit activity can become a time-consuming and expensive operation requiring a high level of expertise.

To reduce these barriers to implementing building control system retrofits, a method has been developed to assist in the identification and assessment of building control system operation and retrofit potential. The components of the method include a system identification process that categorizes the building by type and usage, then it produces an information model of the control system, which can be compared to other similar buildings by category. Control system requirements to meet two performance levels are provided, namely current best practice and high performance, along with suggested control technology packages to achieve the desired level of performance. This paper describes the method and demonstrates it via a case study.

1 INTRODUCTION

The building sector has increased its share of U.S. primary energy consumption, from 33.8% in 1980 to 39.9% in 2008 (DOE, 2011), while sick building syndrome (SBS) has become a greater concern, suggesting lower ventilation rates would increase the symptoms (Sundell et al., 2011). These increased rates have challenged our ability to reduce the building energy consumption without impacting indoor environmental quality (IEQ). Due to the building load varying with time, location and other factors, a more intelligent heating, ventilation, and air conditioning (HVAC) control system is necessary to maintain proper IEQ and continue saving energy. Managing the available resources can aid this goal if we create a HVAC control information database or model and apply it to investigate system design and retrofit opportunities. Researchers have put forth intense efforts in building information modeling (BIM), which aims to provide databases of specific building information including construction, life cycle analysis, operation monitoring, maintenance, and other modeling work (Eastman et al., 2008). Comparatively, there is an apparent lack of procedures and databases to implement building information for HVAC control strategies analysis, optimization, and retrofit design.

Therefore, the objective of this paper is to provide an overview of a conceptual design for a building control system information model (BCSIM), and the procedure for evaluation and retrofit design. It also includes a case study to briefly demonstrate the procedure. The outcome of the case study would include the deliverable retrofit package and contribute to BCSIM database with those specific case studies as demonstrations.

2 BUILDING CONTROL SYSTEM INFORMATION MODELING

The BCSIM model aims to profile building HVAC control system performance, retrofit designs, allowing comparisons. It is designed to establish a database by acquiring quantitative and qualitative information from existing buildings, HVAC systems, control systems, and monitoring parameters.

2.1 TYPICAL BUILDING CLASSIFICATION

The classification of building types varies with different industries and criteria. Based on the types of occupancy, the Uniform Building Code (UBC) and the International Building Code (IBC) categorized buildings into 10 groups, including assembly, business, educational, factory and industrial, high hazard, institutional, mercantile, residential, storage, and utility and miscellaneous (Geren, 2006). For commercial buildings, however, a principal activity based classification was defined in the Commercial Buildings Energy Consumption Survey (CBECS) conducted by U.S. Department of Energy, including 14 types of commercial buildings (CBECS, 2003).

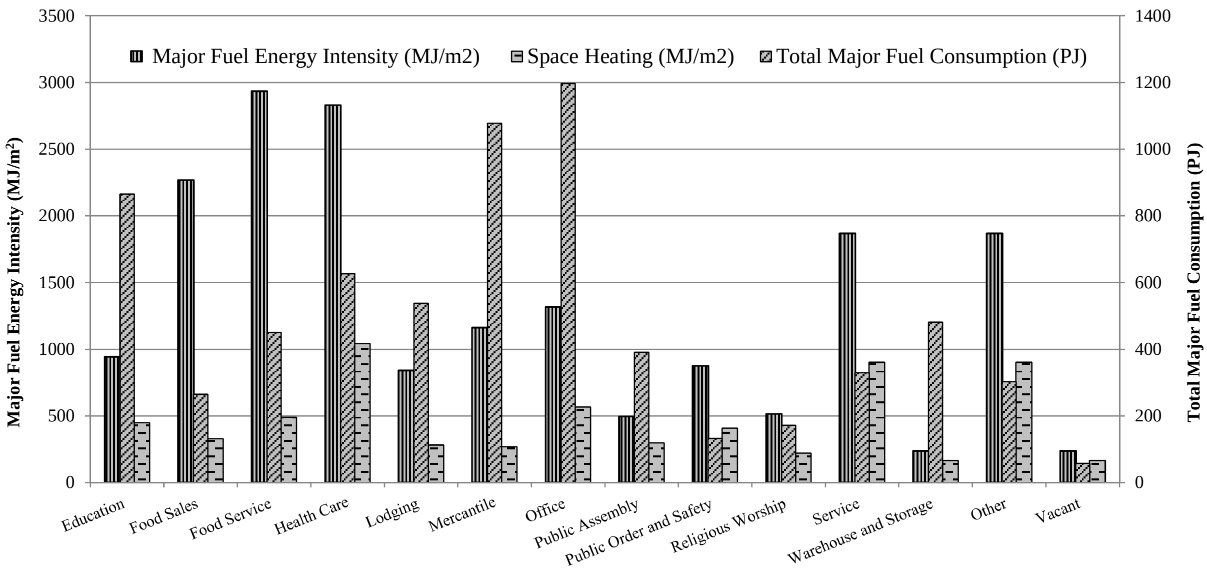

Figure 1 Energy consumption for each commercial building type based on CBECS data.

From **Figure 1**, the major fuel energy intensity of building profiles varies with building types. The food sales, food service, and health care buildings have the highest energy intensity. Office, education and mercantile buildings have the largest portion of total major fuel consumption, while their dominant energy consumptions are space heating and lighting. The energy consumption of space heating is also dominant for health care, other, public order and safety, public assembly, education, service, religious worship, warehouse and storage and vacant buildings, ranging from 163.5 MJ/m^2 to 901.7 MJ/m^2; for the food sale building, the refrigeration consumes about half of the energy, 1076.6 MJ/m^2; for the food service, the cooking is dominant, 721.1 MJ/m^2 (CBECS, 2003). Because of the variance in energy consumption profiles for different types of buildings, it would be necessary to include the building type as a primary factor to develop efficiency improvement strategies.

2.2 HVAC SYSTEM TYPE

The HVAC system type would be another important factor for BCSIM. There are different types of criteria for HVAC system classification. From the heating and cooling medium perspective, it can be mainly classified into all-air system, air-and-water system and all-water system (McQuiston et al., 2005). Based on the number of conditioning zones, it can be categorized as single or multiple zone system. For the all-air system, based on the duct work arrangement between the air handler and the conditioned space, it can be further divided into single zone system, reheat system, variable-volume system and dual duct system. Based on the volume change of supply air, it can include constant volume system and variable air volume (VAV) system. A more complete and reasonable baseline classification was given by ASHRAE (2010a). As shown in Table 1, this classification includes 10 types of HVAC systems, and each system has its own specifications in fan control, cooling, and heating types.

Table 1 Baseline HVAC system types based on ASHRAE (2010a) (except low-rise buildings).

System No. (Type)	Building types	**Fan Control**		**Cooling Type**		**Heating Type**			
		Constant volume	variable air volume (VAV)	Direct expansion	Chilled water	Hot-water fossil fuel boiler	Electric heat pump	Fossil fuel furnace	Electric resistance
1.PTAC (Packaged terminal air conditioner)	Residential	√		√		√			
2.PTHP (Packaged terminal heat pump)	Residential	√		√			√		
3.PSZ-AC (Packaged rooftop air conditioner)	Nonresidential and 3 Floors or Less and <2300 m^2	√		√				√	
4.PSZ-HP (Packaged rooftop heat pump)	Nonresidential and 3 Floors or Less and <2300 m^2	√		√			√		
5.Packaged VAV with Reheat (Packaged rooftop VAV with reheat)	Nonresidential and 4 or 5 Floors and <2300 m^2 or 5 Floors or Less and 2300 m^2 to 14,000 m^2		√	√		√			
6.Packaged VAV with PFP Boxes (Packaged rooftop VAV with parallel fan-powered boxes and reheat)	Nonresidential and 4 or 5 Floors and <2300 m^2 or 5 Floors or Less and 2300 m^2 to 14,000 m^2		√	√					√
7.VAV with Reheat (Packaged rooftop VAV with reheat)	Nonresidential and More than 5 Floors or >14,000 m^2		√		√	√			√
8.VAV with PFP Boxes (VAV with parallel fan-powered boxes and reheat)	Nonresidential and More than 5 Floors or >14,000 m^2		√		√				√
9. Heating and Ventilation (Warm air furnace, gas fired)	Heated Only Storage	√		None	None			√	
10. Heating and Ventilation (Warm air furnace, electric)	Heated Only Storage	√		None	None				√

2.3 CONTROL SYSTEM

Basically, a control system includes the control hardware, software and logic. In commercial buildings, the control system design is generally customized to meet specific HVAC requirements. Basic control hardware used in HVAC systems include analog electronic, and direct digital control (DDC) (ASHRAE, 2007). Basic control modes include two-position (or on-off control), floating control, and modulating control (or called analog control, e.g. proportional plus integral plus derivative (PID) control) (Haines and Hittle, 2006). Advanced control strategies include rule-based control, model-based predictive, fuzzy control, neural network control, agent-based intelligent control and self-adaptive control, which still requires more investigation about their pros and cons (Dounis and Caraiscos, 2009; Marik et al., 2011). The control sequences are summarized in **Table 2** based on control targets in typical HVAC systems, including zone air temperature, static pressure, humidity, supply fan, economizer, mixing unit, air flow rate, zone damper position, etc. Each control sequence might be operated with its own control strategy (e.g. PI control or agent-based control.), but the ultimate goal of a HVAC control system design/retrofit should focus on system-wide level integration and energy conservation.

To communicate between different sensors, actuators, controllers and sub-systems, appropriate control protocols are critical for the HVAC control system. Currently, the main control protocols include network standard and HVAC information protocols (Montgomery and McDowall, 2008). The network standard provides a framework for each controller to understand the meaning of the data being sent and how to request data from other controllers. Common standards include Ethernet, ARCNET, RS-485, and wireless. The HVAC information protocols provide standards to package and unpackage the information to be sent and how it is physically transmitted. BACnet - A Data Communication Protocol for Building Automation and Control Networks has been widely accepted and approved, and covered by Approved American National Standard (ANSI) /ASHRAE Standard 135-2010 (ASHRAE, 2010b). This standard includes a set of rules about controller hardware and software, communication for HVAC, lighting, smart elevators, utility metering, physical access controls (PACs), etc.

Table 2 Examples of control sequences for different control targets.

Control target	Key sensors	Measured variable	Set point	Controllable actuator	Examples of control sequence
Zone air temperature	Room thermostat / Discharge thermostat	T_z	$T_{z\text{-set}}$	Hot / chilled water return valves	• Room thermostat opens or closes the hot or chilled water return valves based on either heating or cooling requirement. • In large system, add a discharge thermostat to improve the system response speed.
Static pressure	Static pressure sensor	P_{sta}	$P_{sta\text{-set}}$	Return-relief fans / relief damper	• Require a controller to operate the relief damper independently to maintain $P_{sta\text{-set}}$. • In large system, to compensate the pressure drop in the return air duct, a relief fan (exhaust fan) can be used to maintain $P_{sta\text{-set}}$.
Humidity	Humidistat /Thermostat	φ, T_z	φ_{set}, $T_{z\text{-set}}$	Humidifier / cooling coil / reheating coil	• The conditioning airflow should pass through the cooling coil and then the heating coil. • If the system requires fixed low humidity limit, a humidifier can be added to maintain φ_{set}.
Supply fan	Fire safety switch /Smoke detector	Fire / smoke	No fire /smoke	Fire safety switch	• If fire or smoke appears in the building, the fire safety switch in old building, or smoke detector in new building will stop the fan.
Economizer	Outside / Zone thermostats	T_o, T_z	$T_{z\text{-set}}$, $T_{o\text{-set}}$	Outside / return / relief damper	• A mixed-air controller modulates the outside, return and relief damper based on T_o, T_z.
Mixing unit	Room thermostat	T_z	$T_{z\text{-set}}$	Hot /cold ducts dampers	• In one-motor mixing box control, the room thermostat controls the damper motor to provide either hot or cold air based on demand. • In two-motor system, the room thermostat controls the hot air damper. If the cooling valve is fully open but still a low total volume, a volume controller can override the room thermostat to partially open the hot air damper.
Air flow rate	Airflow rate sensor	Q	ΔP_c	Supply fan motor	• The airflow rate measurement is used to control the return fan motor speed to maintain a constant differential less than supply air flow rate.
Single-duct zone damper position	Zone thermostat	T_z	$T_{z\text{-set}}$,	Zone damperr	• Each zone thermostat modulates its zone damper to maintain $T_{z\text{-set}}$ based on different loads. • If T_z decreases, the zone damper will be modulate towards to minimum position. • A discharge temperature controller controls the supply air temperature.

2.4 INVENTORY OF CATEGORIZED MONITORING PARAMETERS

To acquire the real-time environmental information, the control system requires a reasonable inventory of field monitoring parameters as control inputs. Then, the controller compares those measurements with set points. If the difference is larger than the allowance range, then actuator would make adjustments to correct for the difference. Kusiak et al. (2010) had ranked the importance of series parameters for energy modeling for a multi-zone VAV system via statistical methods. However, there is still a lack of standards or models which can be used as references to determine which parameter should be measured. To provide a reasonable inventory, one possible solution is to simulate a system that has sensor data for every possible variable in the system. With this complete knowledge, the system could, in theory, decide the absolute best control strategy. Then this best-case scenario is compared to a more generic baseline, regarding economics of equipment costs, maintenance, worker comfort/productivity, and energy conservation.

Table 3 summarizes a list of possible monitoring variables mainly based on $HVACSIM^+$ (Clark, 1985). The original inputs of 26 types of component models are reorganized into 8 major subgroups of input signals: control signal, flow rate, heat flow, pressure, position, rotational speed, humidity ratio and temperature. Meanwhile, other parameters such as CO_2 concentration, solar normal flux, occupancy, internal load, room schedule, occupant activity, and light level are also included as supplemental parameters for the Type 5 room model. In this way, with the maximized monitoring parameter list, a reference guide can be developed to provide information for building HVAC control and monitoring variable selections.

Table 3 Summary of monitoring parameters mainly based on HVACSIM+ models.

Variables\Types	Type 1: Fan or Pump	Type 2: Conduit (duct or pipe)	Type 3: Inlet Conduit (duct or pipe)	Type 4: Flow merge	Type 5: Damper or Valve	Type 6: Flow split	Type 7: Temperature sensor	Type 8: PI controller	Type 9: Linear valve with pneumatic actuator	Type 10: Hot water to air heating coil (simple)	Type 11: Hot water to air heating coil (detailed)	Type 12: Cooling or dehumidifying coil	Type 13: Three-way valve with actuator	Type 14: Evaporative humidifier	Type 15: Room model	Type 16: Sticky P controller	Type 17: Mixing dampers and merge	Type 18: Plenum	Type 19: Flow balance control	Type 20: High light or low light controller	Type 21: "Grounded" water or air split	Type 22: Steam spray humidifier	Type 23: Steam nozzle	Type 24: Ideal gas nozzle	Type 25: Steam to air heat exchanger	Type 26: Control signal inverter
Control signal								√	√				√			√	√			√						√
Flow rate																										
air mass flow rate	√	√		√	√	√			√	√	√	√	√	√	√			√	√			√			√	
steam mass flow rate																						√				
water mass flow rate										√	√	√														
Heat flow															√											
Pressure																										
air pressure	√	√	√	√	√	√			√	√	√		√				√		√		√		√	√		
water pressure										√	√															
steam pressure																									√	
Position																										
actuator relative position					√				√				√													
Rotational speed																										
rotational speed	√																									
Humidity ratio																										
outlet air humidity ratio												√														
inlet air humidity ratio												√		√								√				
Temperature																										
ambient temperature		√	√																							
air temperature	√	√	√	√			√			√	√	√	√	√	√		√					√			√	
water temperature										√	√	√														
mass temperature															√											
stagnation temperature																							√	√		
steam temperature																						√			√	
Light Level*															√											
Occupancy*															√											
CO_2 Concentration*															√											
Solar Radiation*															√											

*parameters not listed in HVACSIM+ models

3 EVALUATION AND RETROFIT PROCESS

In order to deliver a reasonable retrofit package, the building profile of the study case is generated from BCSIM and then applied in the evaluation and retrofit process. It generally includes existing HVAC system evaluation, retrofit design, simulation and comparison analysis.

3.1 EVALUATION PROCESS

The objective of the evaluation process is to create a BCSIM profile for the evaluation object. As illustrated in Figure 2, a building profile is firstly built to identify its building type, HVAC type, building size, and HVAC components. Then, the monitored parameters in existing buildings are used as the baseline model. The inventory of maximized monitoring parameters (**Table 3**) is used to analyze the building profile of this study case to generate a reasonable maximized inventory. Meanwhile, the existing building HVAC system performance is evaluated from the aspects of energy consumption, indoor comfort, safety, and occupancy satisfaction. As a result, a performance score can be given for the baseline performance and an inventory of maximized potential monitoring parameter packages would become available.

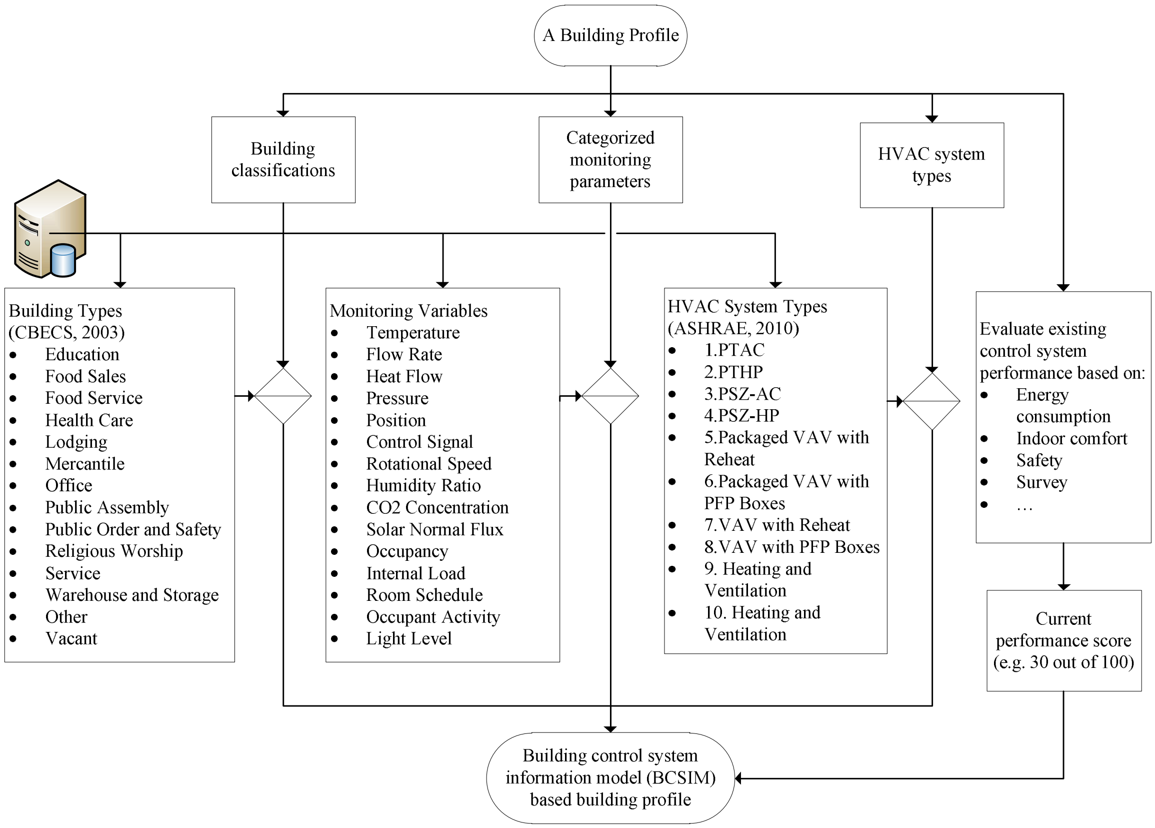

Figure 2 Flow chart of the HVAC system evaluation process.

3.2 RETROFIT DESIGN AND OPTIMIZATION

The purpose of retrofit design is to improve the building performance. However, it is a challenge to evaluate this improvement, due to the lack of available standards/criteria. Therefore, it becomes necessary to develop reasonable criteria to evaluate the retrofit design. First of all, based on the retrofit requirement, the retrofit would be separated into two types, best-practice and high performance. The best practice retrofit design would be defined as acceptable economic cost and high energy efficient improvement. This type might be widely applied in commercial retrofit designs and practices, and adapted by some governmental regulations and building industrial requirements. The high performance retrofit design would be defined as the highest energy efficiency performance, with a state-of-the-art energy efficiency profile and comfort index. This type might be mostly implemented by institution laboratories or high-technology facilities. Possible criteria for these two types of retrofit design are proposed in Table 4.

Another challenge is how to select a reasonable list of control and monitoring parameters. An optimization or selection methodology needs to be explored to generate the inventory of parameters for monitoring/ control. One possible suggestion is to maximize the potential parameters based on **Table 3**, and then use that maximized parameter inventory to build a virtual reference HVAC system with simulated operation results, which could serve as the high performance HVAC control system reference. Then, based on the specific requirements in this study case, some expensive retrofit options might be removed or advanced algorithms (e.g., genetic algorithm, neural network, etc.) can be used to optimize the parameter selections. These would require further exploration.

Table 4 Example of possible criteria for best-practice and high performance retrofit design.

Criteria	Baseline [a]	Best-practice		High performance	
		Value [b]	(Reduction)	Value [b]	(Reduction)
Total energy consumption (MJ/m^2.year)	1033.4	516.7	(-50%)	206.7	(-75%)
Peak-load (MJ/m^2)	Vary	Vary	(-50%)	Vary	(-75%)
Annual major fuel expenditures ($\$/m^2$)	16.6	8.3	(-50%)	4.2	(-75%)
Safety	N/A	High		Medium	
Initial investment ($\$/m^2$)	N/A	1000		2000	
Simple payback (year)	N/A	20		15	
Percentage of people dissatisfied (%)	N/A	20		15	
System response time (s)	N/A	60		30	

[a] Value based on the total major fuel energy intensity for all buildings (CBECS, 2003).
[b] Value based on approximate estimation.

The conceptual process of BCSIM retrofit design investigates a series of retrofit categories including HVAC system type, local weather profile, control type and sequence, data acquisition, etc. Based on suggestions by Haines and Hittle (2006) and Watts (2007), similarities exist among the retrofit options for different system types, such as to remodel the system to become a VAV system or to reset the mixed air controller. For single-zone system, adding reset to the mixed air controller based on zone load can save energy. The control sequence of cooling and heating valves needs to be improved to avoid overlap and the fan speed needs to be minimized to save energy. For multi-zone systems, adding a reset for mixed air controllers based on zone load can save energy; or alternatively, the heating coil control can be reset based on outdoor temperature. For reheat system, adding discriminator relay to reset the supply air temperature can minimize the energy use; replacing existing thermostats with dead-band thermostats can minimize the reheat demand. From the local weather prospective, it is recommended to add an economizer for hot dry, mixed-dry and marine climate, and cold and severe cold (and subarctic/arctic) climate; and to correct refrigerant charge for hot dry, mixed-dry and marine climate, and mixed-humid and hot humid climate. For control modes, it is recommended to replace the Proportional (P) controller with proportional plus integral (PI) controllers. Other options for retrofit design need further analysis. Then, the related hardware and software will be selected based on the selected retrofit options. However, those retrofit design lists are not completed and would still require more efforts to explore potential retrofit strategies with quantitative information.

3.3 SIMULATION/MONITORING RESULT COMPARISON

In order to evaluate if the retrofit design meets the requirements, two points of comparison need to be conducted; simulation based comparison and field measurement based comparison. The simulation will compare the existing HVAC control system performance with the retrofit design, from energy consumption, thermal comfort, safety, etc. If the simulation result does not meet the retrofit design requirements, then the designer should redo the retrofit design with some alternative options, until the design requirements are satisfied. Then, the retrofit design package will be delivered for installation and construction. After completion, field test and monitoring will be conducted to analyze the actual performance, and compare it with the simulation results. This comparison can thereby generate constructive suggestions for future study and enhance the original BCSIM database.

4 DEMONSTRATION WITH BUILDING 101

Building 101 is an office building located at the Navy Yard in Philadelphia. The HVAC system is single-duct and multi-zone type, with each air supply controlled by VAV unit. The heat equilibrium is achieved by adjusting the heating/cooling supply in response to the dynamic change of heat loss/gain. As shown in **Figure 3**, based on our conceptual evaluation, retrofit design, and simulation/monitoring processes, the existing Building 101 profile would be firstly processed by the BCSIM and generate the basic required information for later processes. Then, the retrofit design checklist for Building 101 could include, 1) add discriminator relays for reset of hot and cold plenum set points; 2) reset the mixed air controller based on cooling demand; or reset the heating coil controller based on the outdoor temperature; 3) use actuating vent registers; 4) replace the standard vents in each room with wireless controlled louvered vents; 5) replace existing thermostats with dead-band thermostats; 6) reset the mixed air temperature controller from the discriminator relay; 7) correct refrigerant charge; etc. Further analyses are required to evaluate other retrofit options and simulation results.

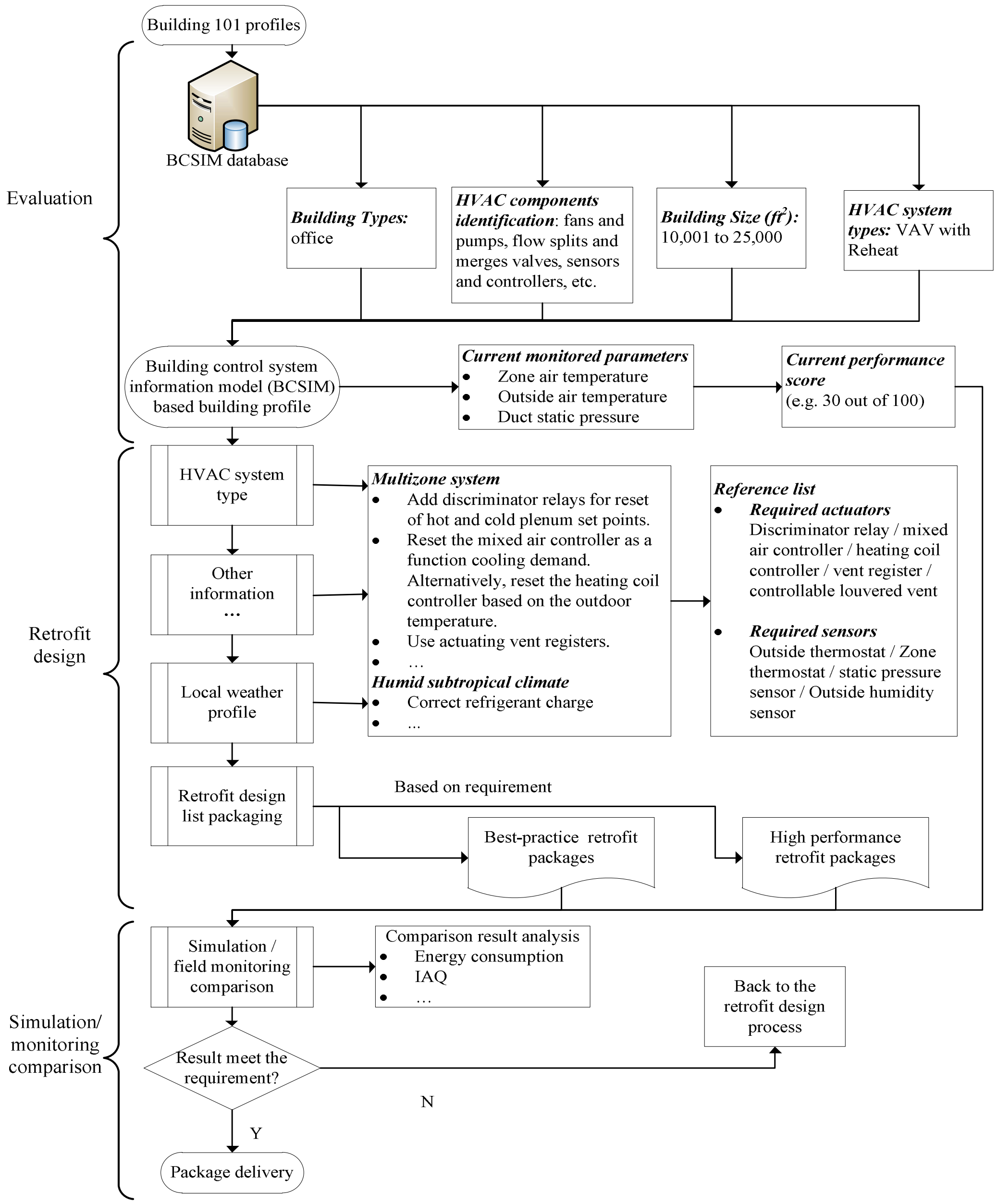

Figure 3 Example of conceptual HVAC system evaluation, retrofit design and comparison process.

5 CONCLUSIONS

This paper presented a conceptual structure of building control system information modeling and the process of utilizing the BCSIM for specific building HVAC system evaluation and retrofit design. There are different categories of resources available for building control system optimization and requires further efforts to explore different methods of how to manage the building profile into the BCSIM model. Meanwhile, researchers and the industry need to establish a fundamental method or standard to evaluate the performance of a control system, so that comparisons among different control strategies would become practicable. It would also require more efforts to investigate different methods for the systematic optimization, parameters selection, and retrofit design simulation and comparison. Future work would also need to focus on system-wide energy reduction and IEQ improvement.

NOMENCLATURE

T	temperature	(C°)	**Subscripts**	
P	static pressure	(Pa)	*z*	zone
φ	relative humidity	(%)	*set*	set point
Q	air flow rate	(m^3/s)	*o*	outside
			c	control

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