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Development of an energy evaluation methodology to make multiple predictions of the HVAC&R system energy demand for office buildings

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ABSTRACT

HVAC&R systems are the most energy consuming building services, representing approximately half of the final energy use in the building sector. Despite their significant energy use, there is a lack of a consistent and homogeneous framework to efficiently guide research, mainly due to the complexity and variety of HVAC&R systems, but also to insufficient rigor in their energy analysis. Quantifying the energy consumption characteristics of HVAC&R system is complicated, because the energy savings provided by this system depend on various factors. This research evaluates energy consumption characteristics of HVAC&R systems, with the aim of establishing a common idea for the analysis of building energy efficiency. The objective of this study is to develop an energy evaluation methodology and a simple simulation program that may be used by engineers and designers to assess the effectiveness and economic benefits of HVAC&R systems. Our approach deals with the concept of HVAC&R system energy use aggregation levels that are composed of subsystems. To carry out a techno-economical estimation of HVAC&R systems considering different types of subsystems, the matrix combination analyzed, and a total of 960 HVAC&R systems can be implemented for a large-scale office building. The methodology of energy analysis that was carried out in this study highlights how to plan and design toward utilizing the most effective HVAC&R systems.

1. Introduction

During the last decade, the rapid growth of energy consumption and CO_2 emissions in the built environment has made energy efficiency and savings strategies a priority objective for energy policies in most countries developing new building regulations and certification schemes targeting performance requirements [1]. Major developed countries proposed cutting the region's greenhouse-gas emissions by 20–30% by 2020, accelerating its efforts to fight climate change. Although processes for establishing laws to achieve that goal, and of reaching social consensus differ from county to county, there is an across-the-board acknowledgment that cutting greenhouse gas emissions is not an option, but a necessity. In addition, low and zero energy policies aimed at curtailing building energy consumption are being developed as medium and long-term objectives. In that respect, HVAC&R (heating, ventilation, air-conditioning and refrigeration) systems in buildings are a very important energy consumption factor, the importance of which continues to increase, in relation to building energy use. The patterns of energy consumption in developed countries show that the building sector accounts for 30–40% of the overall national energy consumption, including those of the industrial and transportation sectors [2]. Representing approximately 50% of building energy use, HVAC&R systems are estimated to consume 20% of all sectors' aggregate energy consumption [3]. In order to achieve energy efficiency in buildings, the energy optimization of HVAC&R systems is particularly important [4]. The HVAC&R systems of contemporary buildings require superior energy performance to attain better energy efficiency, and maintain a pleasant environment, given the same level of operating costs and environmental impact [5]. The selection of HVAC&R systems has a great influence on the lifecycle cost of a building. The energy performance of HVAC&R systems is affected by their subsystem combinations and operating conditions, and at the same time sensitivity to a building's heating and cooling energy needs. Researchers and engineers involved in the field have been making continuing efforts to find an "optimal" system providing the best performance [6]. Therefore, it is important to explore and assess energy flow as a concept of energy use

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Nomenclature

C	energy consumption (kWh)
Q	thermal demand (kWh)
L	energy losses (kWh)
AHU	air handling unit
HX	heat exchanger
CAV	constant air volume
VAV	variable air volume
UFAD	under floor air distribution
FCU	fan coil unit
DOAS	dedicated outdoor air system
PAC	packaged air conditioning
EHP	electrical heat pump
FTU	fan terminal unit (electrical)
FPU	fan powered unit (hydraulic)
LTAD	low temperature air distribution
CHP	combined heat and power
HW	hot water
CHW	chilled water
CW	condenser water
H/C	heating and cooling
COP	coefficient of performance

Subscripts and superscripts

HG	heating generation
CG	cooling generation
PRI	primary
WT	water transport
MOT	motor
TR	transmission
AT	air transport
VEN	ventilation

aggregation levels [7] that take into account all air-conditioning, plant and transport subsystems of a HVAC&R system. This view, which may sound elementary, has not been studied sufficiently, or consistently, on a global scale. The primary objective of this study is to analyze the matrix combinations of air-conditioning, plant and transport systems, each a subsystem, and examine the energy consumption characteristics of various HVAC&R systems, comprising the combination of subsystems. The analyzed work in this paper is to carry out a techno-economical estimation of HVAC&R systems considering different types of subsystems under Korean climatic conditions. Furthermore, the method of analysis that was carried out in this study highlights how to plan and design toward utilizing the most effective HVAC&R systems. As a preliminary step, the study requires developments of HVAC&R system combination and energy evaluation methods. Based on this procedure, an easy to use simulation program was developed. It can analyze and select nearly all types of HVAC&R system combinations. And it helps in understanding the building energy demands in the early stage of building design. The energy efficiency of HAVC&R systems, which account for approximately 50% of building energy use, can be implemented through the following 3 steps: optimal system design; using high-efficiency equipment; and optimal control systems (Fig. 1). Based on the HVAC&R system energy use aggregation levels; air-conditioning, plant and transport subsystems, This study applies optimization alternatives to predict the HVAC&R design featuring minimal energy use, and investigate the change and sensitivity of energy consumption, depending on the variation of each subsystem. Energy consumption assessment was conducted on large office buildings. The research procedure and methodologies were as follows: First, this study examines the

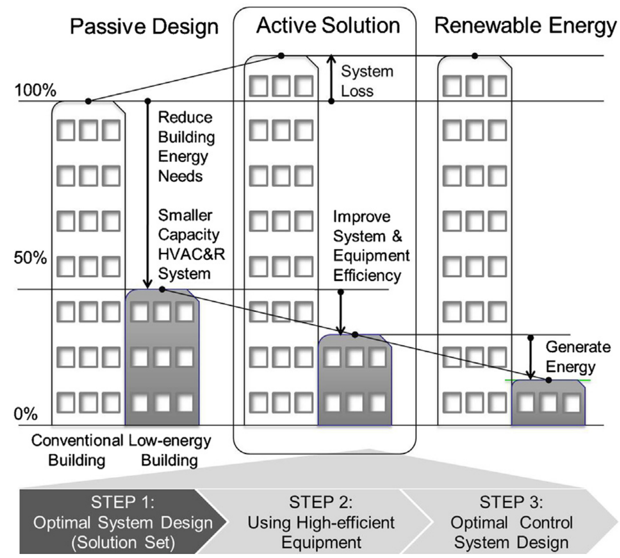


Fig. 1. Goal of building energy efficiency for HVAC&R system.

energy flow of each air-conditioning, plant and transport systems, which are component subsystems of a HVAC&R system, and the HVAC&R system energy use aggregation levels that are applicable. It then goes on to analyze all the possible combinations, and to propose an effective method of evaluating the energy demand of various HVAC&R systems. The matrix combination analyzed, and a total of HVAC&R systems can be implemented for office buildings. The methodology for energy estimation and prediction of HVAC&R systems was developed. Then, the study selects a baseline building model and HVAC&R system, to be used as the criteria of analysis and estimation methods, in order to identify the energy consumption characteristics of various HVAC&R systems. By using the evaluation methodology, we analyzed the changes and sensitivity of the total energy demand, in accordance with the modification of each subsystem: air-conditioning, plant and transport systems. Lastly, this study applies optimization alternatives to predict the HVAC&R design featuring minimal energy use.

2. HVAC&R system structure and description

2.1. HVAC&R system aggregation levels of energy use

HVAC&R system is a critical activity in terms of optimizing the control settings to reduce the energy consumption, improving the system efficiency, and preserving the thermal comfort for the occupants. Providing comfort to building occupants is the main goal of the designers of HVAC systems, but defining and qualifying thermal comfort service is a complex subject. It could be defined as the state of mind which expresses satisfaction with the surrounding environment (ASHRAE 55 [8]). Global energy consumption of an HVAC&R system may be obtained by the summation of the energy use of all its energy consuming devices. However, between global and equipment levels, two additional aggregation levels can be distinguished: subsystems and services [7] (Fig. 2). Perez-Lombard et al. [9] identified four main subsystems (cool generation, heat generation, water transport and air transport) and three kinds of energy flows (thermal demands, consumptions and losses) for the energy analysis of HVAC&R systems (Fig. 3). Thermal demands quantify heat transfers: at conditioned spaces, to ventilation air flow, at coils or by primary equipment for cool and heat generation. Consumptions refer to energy end use of conversion devices, mainly thermal generators and fluid movers. Energy losses are due to wasted energy or equipment inefficiencies. Basic energy

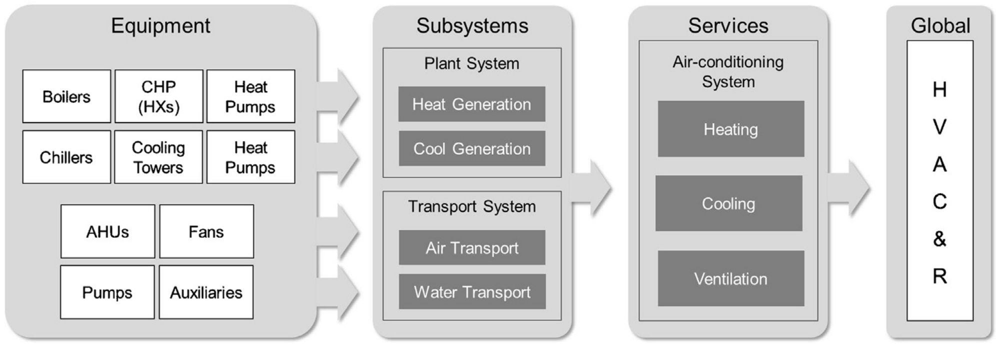


Fig. 2. HVAC&R systems energy use aggregation levels [9].

conservation equations in each of these subsystems are written in terms of final energy, making use of thermal loads (Q), energy losses (L), energy consumptions (C). Plant system consists of set of equipment responsible for the cool and heat generation. The heat extraction from the cold source requires the consumption of a given amount of energy. The energy rejected to the environment is positive and higher than the absolute value of heat extraction from the cold source:

$$C_{CG} = Q_{CG} + L_{CG} \quad (1)$$

Heat generators use a given amount of energy with the aim of adding heat to water or air. The energy balance in heat generation system is then:

$$C_{HG} = Q_{HG} + L_{HG} \quad (2)$$

The water transport system is made up of hydraulic equipment intended to drive the primary fluid, usually water, from the plant system to the water coils of the air-conditioning system. Heat added or extracted by plant systems to primary fluid is usually referred to as primary load (positive and negative for heat and cool generation, respectively). Thus the balance equation for the transport system is:

$$Q_{PRI} = Q_{COIL} + L_{WT} - C_{WT} \quad (3)$$

There are two kinds of water transport losses that in the water distribution network and by inefficiencies in the pumping equipment. The difference between water transport electric consumption and pump losses is thermally degraded in the fluid and can be referred to as pump heat:

$$Q_{WT} = C_{WT} + L_{PUMP} = C_{WT} - (L_{MOT} + L_{TR}) \quad (4)$$

An air-conditioning system is responsible for air distribution throughout the building. The only energy use involved is that of fans. If fan motor is placed in the air stream, all the consumed energy is thermally degraded and can be called fan heat:

$$Q_{AT} = C_{AT} \quad (5)$$

Losses have either a thermal character or are caused by air leaks or infiltrations. From the mass and energy balances in this subsystem the following equations can be derived:

$$Q_{COIL} = Q_{SP} + Q_{VEN} - Q_{AT} + L_{AT} \quad (6)$$

Global energy consumption of an HVAC&R system may be obtained by the summation of the energy use of all its energy consuming devices:

$$C_{HVAC\&R} = C_{HG} + C_{CG} + C_{WT} + C_{AT} \quad (7)$$

It is also common practice to consider another aggregation level for HVAC&R systems, related to the services provided, typically heating, cooling and ventilation.

2.2. Characterizing the energy performance of HVAC&R systems

A HVAC&R system is a complex, nonlinear, discrete system containing numerous variables and constraints. Therefore, the modeling and optimization of a HVAC&R system is a challenge for traditional mathematical models [10] and simulation approaches [11]. There was the gap in holistic studies on HVAC&R system performance characterization [9,12]. The energy use of the various air-conditioning, plant and transport systems has been separately assessed, but comprehensive studies, which purport to examine the systems as a unified subsystem in consideration of their mutual effects, have only been attempted sporadically [13]. Despite many studies with narrow scopes which examined individual and limited topics such as the optimization of HVAC&R control systems and the simulation, integration of some HVAC&R systems' elements only [14–16]. Due to the undefined range of energy analysis, and the complexity and diversity of HVAC&R systems, there is, on the whole, a lack of related research, and of systematic processes to inform energy policy. The US Department of Energy [17–19] has published three part studies on the energy consumption characteristic of commercial building HVAC&R systems in the US, with each part covering heat source, heat distribution and ventilation equipment, and energy saving options, respectively. Their vast body of studies was largely on each component of air-conditioning, plant and transport systems. In their study, Cho et al. [20] analyzed the energy consumption of each air-conditioning system type, in terms

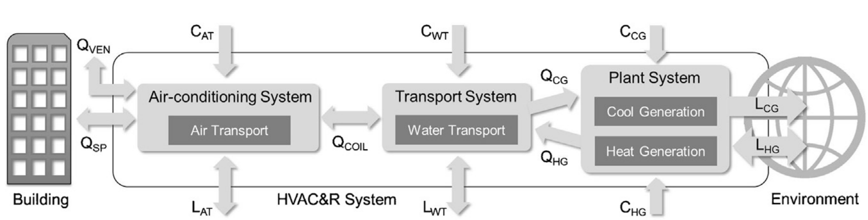


Fig. 3. Energy subsystems in HVAC&R systems [9].

of building energy needs, outdoor air supply system and transport energy. The limitation of this study is that the researchers grouped a plant system and energy source into one system, for their analysis. Consequently, this deficiency has been coarsely overcome by assuming a typical HVAC&R system for each building category. To improve this deficiency, simultaneous dynamic simulation of a typical office building and HVAC&R systems were adapted to analysis the energy performance of different parts of HVAC&R systems by Shahrestani et al. [21]. Andrew Kusiak et al. [22] suggested several data-mining algorithms which are applied to build the predictive models. A multi-objective computation algorithm was proposed for generating optimal HVAC&R system. Perez-Lombard et al. [9] applied the previous sequence for the construction of HVAC&R systems energy efficiency indicators to provide a general classification of such indices at four levels: global, service, subsystem and equipment. A subsystems approach was introduced for the energy analysis of HVAC&R systems based on generation efficiency, transport specific consumption and the demand ratio, a new measure of HVAC&R system thermal energy efficiency. Perez-Lombard et al. [7] also presented a case study to illustrate the application of the proposed energy efficiency indicators (EEI) to HVAC&R systems and to demonstrate the main advantages of the subsystems approach. On the other hand, Wemhoff and Frank [23] focused on a simple predictive code that calculates the energy use and outcome of an HVAC&R design for a user-specified system under steady loading. However, a comprehensive analysis of the energy consumption characteristics of HVAC&R systems as one set that links subsystems has yet to follow. Therefore, the aim of this study is to overcome this deficiency through an investigation of the performance of a variety of HVAC&R systems within an evaluation methodology and robust framework based on dynamic simulation of a prototypical office building. In performance evaluation methodologies of HVAC&R systems, several major criteria are considered within the scope of work in this research. These criteria include energy consumption, energy cost, capital cost. In the following sections, a prototypical office building and HVAC&R systems that are investigated in this research are described in detail.

3. Methodologies

3.1. Matrix analysis for subsystem combinations

The HVAC&R system is composed of an air-conditioning system, a plant system and a transport system. As shown in Fig. 4, the HVAC&R system, like the three-axis coordinates, can be viewed as a unified system, based on the combinations of each subsystem. The air-conditioning system is generally classified by heating and cooling system for interior and perimeter zones, and by the method for supplying outdoor fresh air to room. Heating and cooling methods are broken down into all-air, air-water, and all-water systems. Systems for perimeter and interior zones are determined in view of the characteristics of each method. Outdoor fresh air handling includes a system that functions as both a DOAS, and an air-conditioning system for heating and cooling. The plant system that supplies the heat needed in the air-conditioning system is broadly divided into cooling and heating sources. The transport system combinations can be put together based on the temperature differences of the primary fluid (chilled water), and the heat source supply method, in a central pumping system. First, to develop an energy demand evaluation procedure and program for all types of HVAC&R system combinations of office buildings, the HVAC&R system combinations have to be organized. Therefore a combination of air-conditioning, plant, and transport systems has to be constructed, and analyzed as a matrix system for the feasibility of each combined system. In practice, it is possible to utilize combinations of more than two systems in a same subsystem (plant system). In this study, however, the composition of each subsystem is established, with a single system as the base. The matrix combinations of air-conditioning systems indicate that interior zone systems, when conjoined with CAV and VAV systems, can be integrated with most perimeter zone systems. On the other hand, it is indispensable to combine a LTAD system and FPU, in order to raise the supplied air temperature that is low initially. UFAD system, albeit possibly combined with a variety of perimeter zone systems, is generally a method of regulating indoor air pressure, with an AHU for UFAD system. Separate DOAS, which can be planned for all air-conditioning systems, such as CAV, VAV, and LTAD system, were excluded, since they were deemed impractical, in light of initial outlay and maintenance costs. UFAD system can also be combined with DOAS and FTU. A radiant cooling/heating system and a chilled beam system can, in general, be combined with DOAS. In the case of medium and large office buildings, it is desirable to couple DOAS with FCU, and EHP. The matrix combinations of a plant system are made in such a way as to avoid overlapping investments in equipment. An absorption chiller is integrated with a steam boiler or CHP, since it requires a plant system generating high temperature heat source. A centrifugal chiller, an ice thermal storage system, and a water thermal storage system, all of which do not limit the heat generation system type to a great extent, can be conjoined with a steam boiler, a hot water boiler and a district heating system. A district heating system is grouped together with a district cooling system and a hot water driven absorption chiller. Generating both chilled and hot water, an absorption chiller/heater and a geothermal heat pump system are employed for both cooling and heating. The matrix combinations of transport systems are split into chilled water temperature difference, and pumping system zoning. Unlike air-conditioning systems or plant systems, there is no limitation to their possible combinations. A review of HVAC&R system matrix combinations identifies 16 air-conditioning, 15 plant, and 4 transport subsystem combinations for office buildings [24] (Fig. 5).

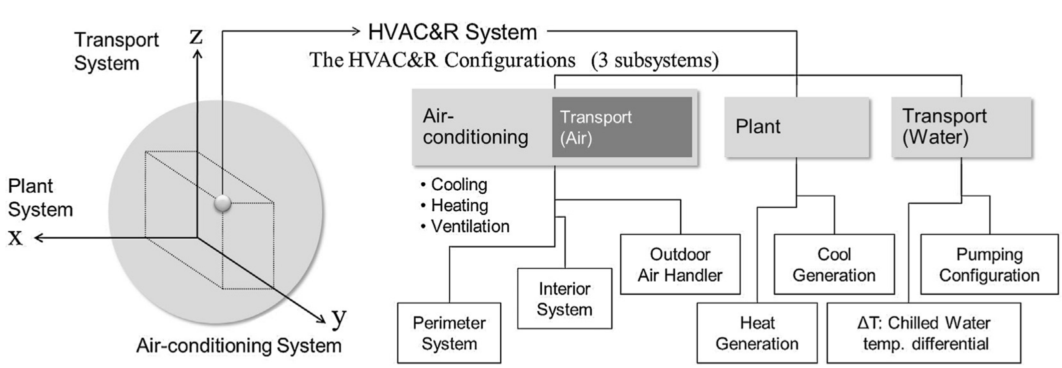


Fig. 4. The concept and composition of the HVAC&R system.

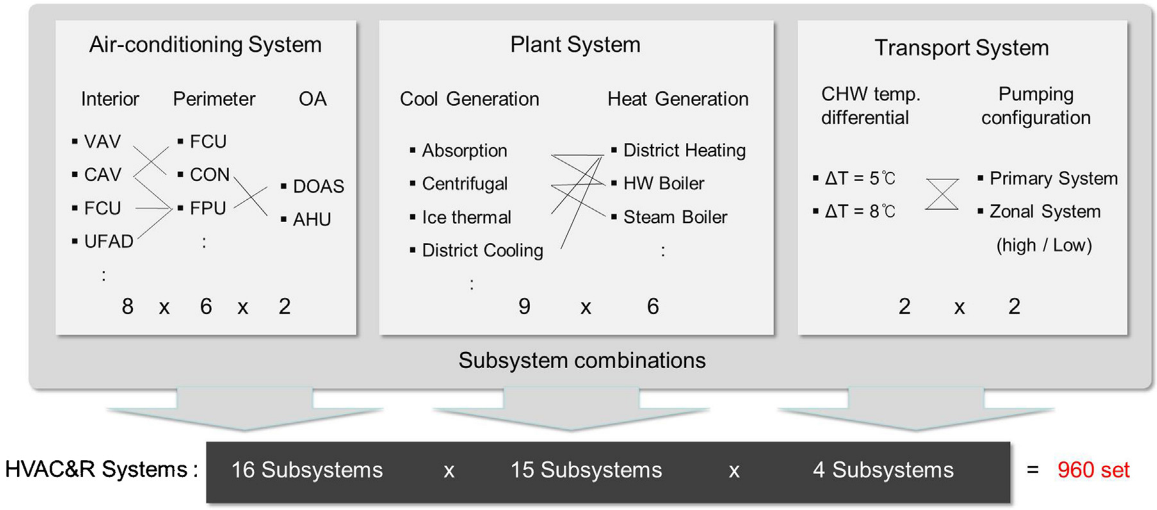


Fig. 5. Combination of all possible HVAC&R set configurations.

The composition of air-conditioning and plant systems is universally applicable, due to the feasibility of each subsystem combination. Table 1 lists the possible combination of the HVAC&R system, and a total of 960 combinations of each component subsystem (16 air-conditioning × 15 plant × 4 transport systems) can be produced.

3.2. Energy evaluation methodology

3.2.1. Baseline HVAC&R system

It is important to choose, among other things, a system to be used as the criteria of comparison, in order to efficiently analyze the energy consumption characteristics of HVAC&R systems. The baseline HVAC&R system is selected on the basis of the case studies of the designs of 74 large-scale office buildings [24], and the statistics published by the US DOE [17–19,25], in order to secure the validity of the baseline selection. The baseline HVAC&R system (VAV system with convector, direct fired absorption chiller/heater and primary pump system, chilled water temperature differential $\Delta T = 5\,^{\circ}\mathrm{C}$) consists of the systems generally applied to large-scale office buildings, as can be seen in Table 1. The air-conditioning and transport systems used both within and outside Korea are nearly identical, while the plant systems in Korea differ from those overseas, due to the nation's regulations, codes and standards.

3.2.2. Estimation for basic HVAC&R system energy use

Fig. 6 shows an evaluation method for estimating the energy demand of the 33 basic HVAC&R systems. Since an exponential number of models are bound to derive from the modification and combination of the subsystems, the widely applicable basic HVAC&R system, selected in the above, is used for comparative evaluation. In other words, the energy demand of the air-conditioning system, made to vary, is assessed, while the plant and transport systems are set up as the baseline subsystem (direct fired absorption chiller/heater and primary pump system, chilled water temperature differential $\Delta T = 5\,^{\circ}\mathrm{C}$). In the same method, the energy demand estimates of the plant system can be made with the air-conditioning and transport systems as the baseline subsystem (VAV system with convector and primary pump system, chilled water temperature differential $\Delta T = 5\,^{\circ}\mathrm{C}$), while the transport energy use can be estimated, establishing the other two systems as the baseline subsystem (VAV system with convector and direct fired absorption chiller/heater). To remove the building heating and cooling load, steady state peak load is used for sizing

Table 1
HVAC&R system matrix combinations for office buildings.

A: Air-conditioning system (total 16 subsystems)			
Subsystem #	Interior	Perimeter	Outside air
A01	CAV	←	←
A02	VAV	←	←
A03	UFAD	←	←
A04	FCU	←	DOAS
A05	Radiant C/H	←	DOAS
A06	Chilled beam	←	DOAS
A07	PAC(EHP)	←	DOAS
A08	CAV	FCU	←
A09	VAV	FCU	←
A10	CAV	Convector	←
A11	***VAV***	***Convector***	←
A12	UFAD	FTU	DOAS
A13	VAV	FPU	←
A14	LTAD	FPU	←
A15	CAV	PAC(EHP)	←
A16	VAV	PAC(EHP)	←

P: Plant system (total 15 subsystems)		
Subsystem	Heating plant	Cooling plant
P01	***Direct-fired absorption chiller/heater***	
P02	Absorption chiller	Steam boiler
P03	Centrifugal chiller	Steam boiler
P04	Ice thermal storage	Steam boiler
P05	Water thermal storage	Steam boiler
P06	Centrifugal chiller	HW boiler
P07	Ice thermal storage	HW boiler
P08	Water thermal storage	HW boiler
P09	Centrifugal chiller	District heating
P10	Ice thermal storage	District heating
P11	Water thermal storage	District heating
P12	District cooling	District heating
P13	HW driven absorption	District heating
P14	Geothermal heat pump system	
P15	CHP system with HW driven absorption	

T: Transport system (total 4 subsystems)		
Subsystem	Pump system zoning	CHW temp. differential
T01	***Primary pump system***	$\boldsymbol{\Delta T = 5\,^{\circ}C}$
T04	Primary pump system	$\Delta T = 8\,^{\circ}\mathrm{C}$
T04	Zonal pump system	$\Delta T = 5\,^{\circ}\mathrm{C}$
T04	Zonal pump system	$\Delta T = 8\,^{\circ}\mathrm{C}$
	Baseline HVAC&R system	

A11 – P01 – T01: Baseline HVAC&R system.

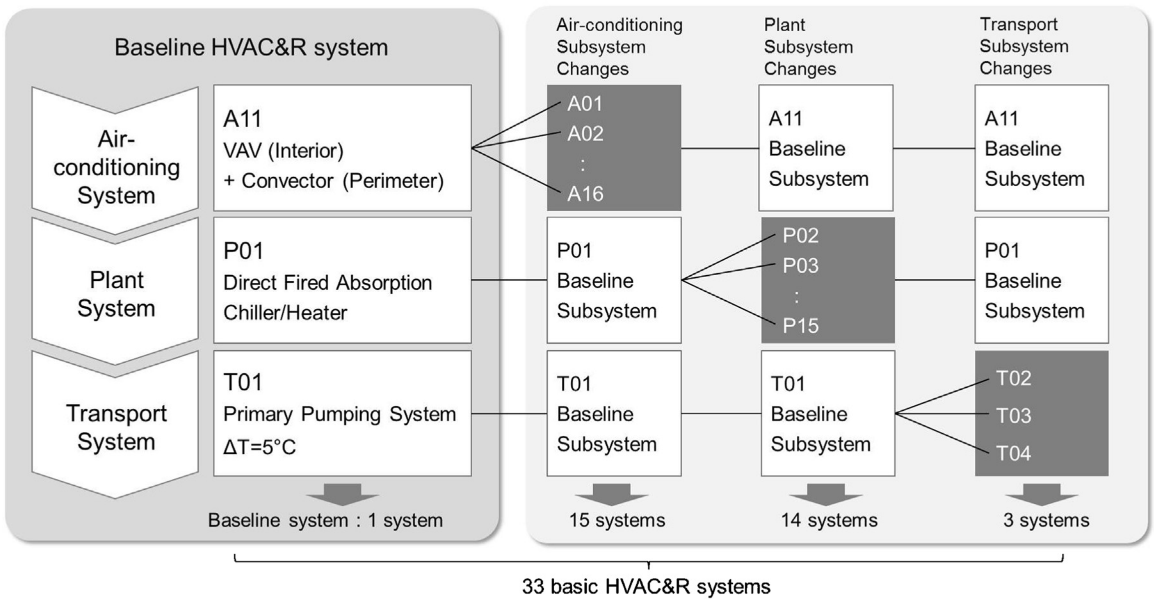


Fig. 6. A method for estimating the energy demand of basic HVAC&R systems.

the HVAC&R equipment; also, basic equipment control sequences, such as multiple unit control, minimum equipment operating condition, economizer, and inverter control, are used. The selected equipment is used to remove the building load for each hour, and the energy used in the equipment is then summed. The HVAC&R system energy consumption calculation process consists of 6 steps, which are energy input, building load calculation, energy consumption, energy cost, and primary energy conversion. Fig. 7 shows the HVAC&R system energy demand estimation steps. Based on this process, the HVAC&R system energy evaluation method is proposed.

3.2.3. *Prediction for extended HVAC&R system energy use*

Once the analysis of the 33 basic HVAC&R systems, combined by system type, is completed, the energy demand of all 960 extended HVAC&R systems can be predicted (Fig. 8). The energy use of the extended HVAC&R systems, as shown in Fig. 9, can be extrapolated from the energy use ratios of the three systems varying with each subsystem, compared to the 33 basic HVAC&R systems. To make such an analysis possible, it is more necessary than ever to make detailed classifications of energy demand by subsystem, and to compute energy consumption after converting a variety of energy types – such as electricity, gas, and district heat – into the

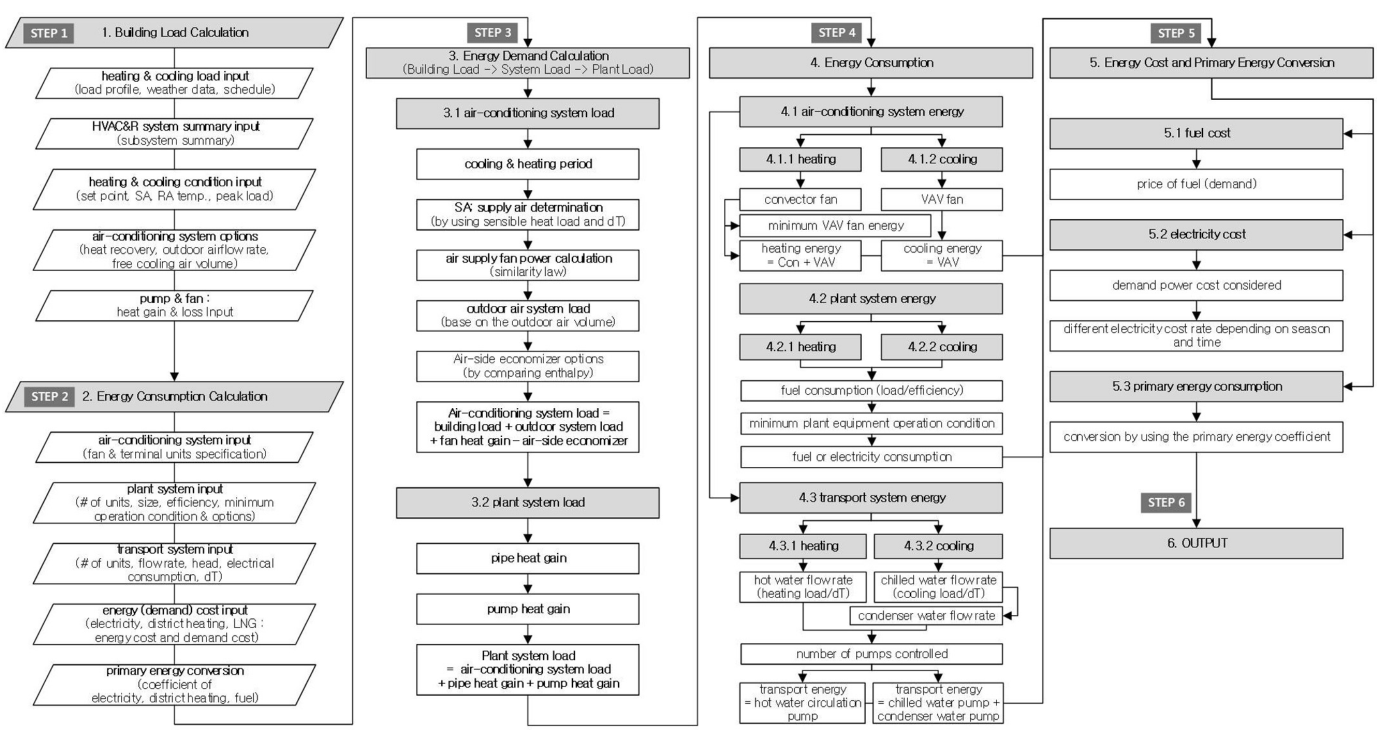


Fig. 7. A flow chart of the HVAC&R system energy calculation steps.

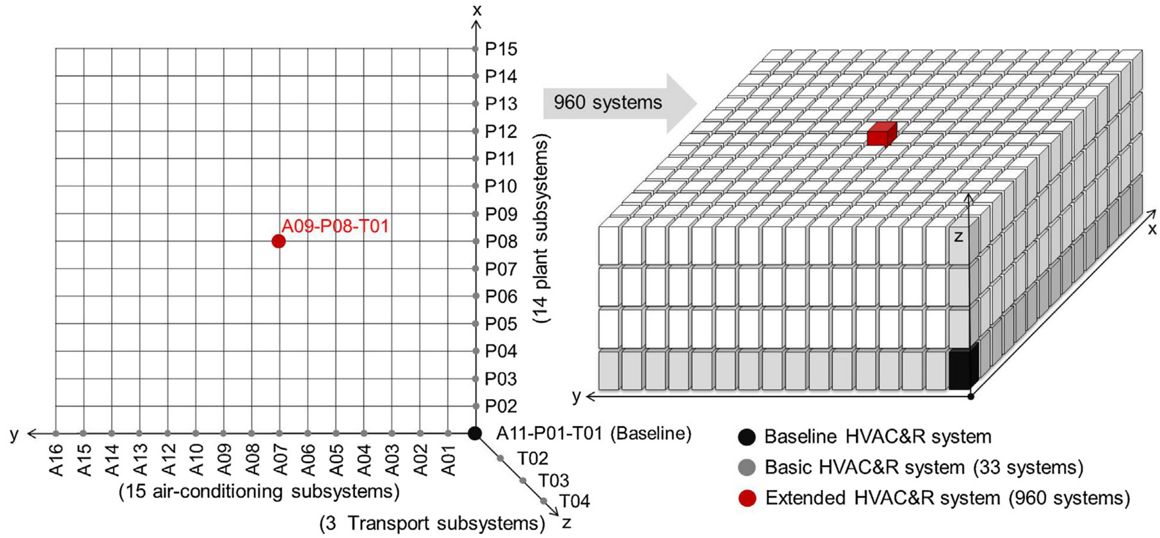


Fig. 8. A concept of predicting energy use for 960 HVAC&R systems.

primary energy. On the other hand, energy costs, differing from energy source, should be analyzed calculating end use energy, and at the same time, the computation of energy demand should be distinguished by subsystem, to enable estimations of the energy performance of the extended HVC&R systems that are composed of different combinations. As stated previously, 16 air-conditioning, 15 plant and 4 transport systems were analyzed. By composing these subsystem arithmetically 960 (=16 × 16 × 4) of extended HVAC&R systems could be developed, which was difficult to evaluate case by case. For this reason, we developed an effective method

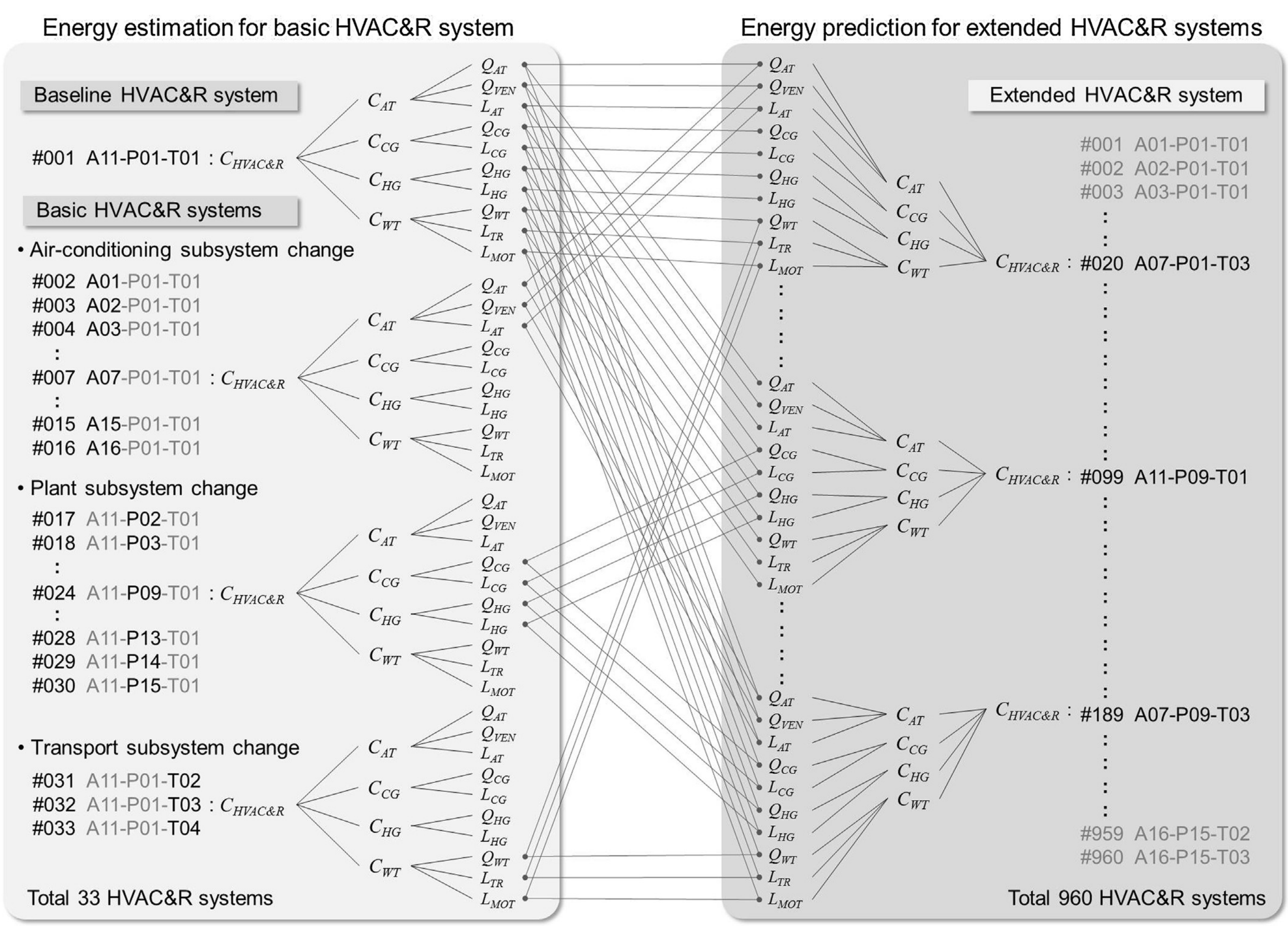


Fig. 9. A method for predicting the energy demand of extended HVAC&R systems.

Table 2
Energy performance of baseline HVAC&R system.

Items	Sub Items	Primary energy [kWh/yr]	Energy cost [US $/yr]
C_{AT}	AHU (cooling) fan	1,003,000	27,000
	AHU (heating) fan	1,215,000	34,000
	DOAS fan	–	–
	Terminal unit fan	169,000	5000
C_{HG}	Heating plant input	2,066,000	109,000
C_{CG}	Cooling plant input	3,191,000	168,000
C_{WT}	Chilled water pump	661,000	19,000
	Condenser water pump	1,353,000	39,000
	Hot water pump	482,000	13,000
	Braine pump	–	–
Demand charge	Electricity (normal)	–	67,000
	Electricity (night)	–	–
	District heating	–	–
	LNG	–	–
Total		10,140,000	477,000

to evaluate the extended systems, which is based on the idea that each subsystem is independent to the other subsystems. First, a detailed energy analysis of each subsystem was executed, and the outputs were collected for the subsystems as Table 2. The contents of the outputs are arranged so the outputs can be independent to each other even when the sub system changes. For example the heating and cooling plant system are separated so the energy consumption and cost can be estimated for the extended systems. Also, the base cost rate, air-conditioning, plant and transport systems are separately calculated. A 3-step process to analyze 960 extended HVAC&R systems had been developed. The energy consumption and energy cost for the extended systems are similar, in this section the process for predicting energy consumption is described.

Step1. Calculating individual primary energy weighting coefficients for air-conditioning and transport systems.
Step2. Calculating combined primary energy weighting coefficients of air-conditioning and transport systems.
Step3. Applying the combined primary weighting energy coefficients to the 15 basic plant subsystems to predict the extended HVAC&R systems.

To calculate the primary energy weighting coefficient at step1, the energy consumption when the air-conditioning system changes are compared to the baseline system which is composed of P01 and T01. The same weighting coefficient is processed for the transport system, when the baseline system is fixed to P01 and A11. For step2, the combined primary energy weighting coefficient of air-conditioning systems and transport systems are calculated. As shown in Table 3, the final combined weighting coefficient can be summarize in to 4 tables, which are T01-(A01–A16), T02-(A01–A16), T03-(A01–A16), and T04-(A01–A16). At step 3, the combined weighting coefficient is applied to the primary energy consumption of the 15 types of basic HVAC&R systems. An example of primary energy consumption for air-conditioning systems is presented in Table 4. As a result, the primary energy consumption and the energy cost of 960 HVAC&R systems can be predicted.

3.3. Development of a HVAC&R system energy evaluation program

Fig. 10 shows the basic structure and process of a HVAC&R system energy evaluation tool (HEET). The hourly building cooling and heating load profile for a typical floor of the building is input with four perimeter zones (north, east, west, south), and one interior zone. Therefore, any type of commercial dynamic energy simulation program, such as TRNSYS, energy plus, ESP-r, etc., can be used to run the HEET, if the 8760 h building energy demand profile for the typical floor is input. First, the building energy demand profile and

Table 3
An example of primary energy weighting coefficient for air-conditioning systems.

T: transport system	P: plant system	Items	A: Air-conditioning system (Primary energy weighting coefficient)				
#01	#01		#11	#01	#02∼14	#15	#16
Baseline	Baseline	AHU fan (cooling)	1.0000	0.9234	–	0.9234	0.9234
		AHU fan (heating)	1.0000	2.2087	–	2.2087	1.0000
		Terminal fan	1.0000	0.0000	–	1.2239	1.2239
		Heating plant	1.0000	1.0000	–	0.8624	0.8624
		Cooling plant	1.0000	1.1343	–	1.0336	0.9023
		Chilled water pump	1.0000	1.1024	–	0.7990	0.7369
		Condenser water pump	1.0000	1.1024	–	0.7990	0.7369
		Hot water pump	1.0000	1.0036	–	0.6430	0.6430
		Braine pump	1.0000	1.0000	–	1.0000	1.0000
		Co-generation heat	1.0000	1.0000	–	1.0000	1.0000
		Co-generation electricity	1.0000	1.0000	–	1.0000	1.0000

Table 4
An example of primary energy consumption for air-conditioning systems.

T: transport system	P: plant system	Items	A: Air-conditioning system (Primary energy consumption [MWh])				
#01	#02		#11	#01	#02∼14	#15	#16
		AHU fan (cooling)	1003	927	–	927	927
		AHU fan (heating)	1215	2683	–	2683	1215
		Terminal fan	169	–	–	206	206
		Heating plant	2066	2066	–	1781	1781
		Cooling plant	3191	3619	–	3298	2879
		Chilled water pump	414	457	–	331	305
		Condenser water pump	1351	1489	–	1080	996
		Hot water pump	305	306	–	196	196
		Braine pump	–	–	–	–	–
		Co-generation heat	–	–	–	–	–
		Co-generation electricity	–	–	–	–	–

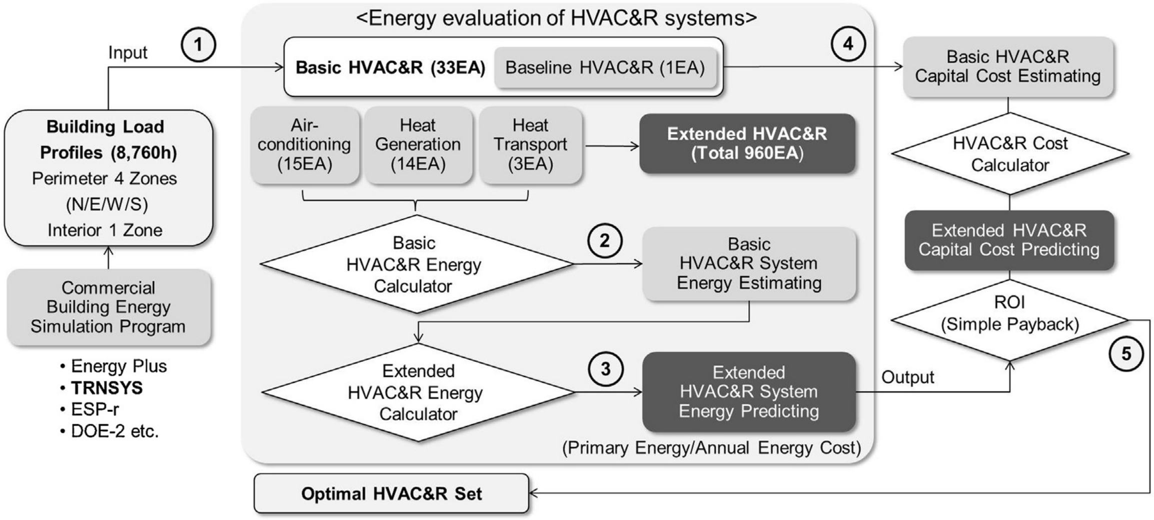


Fig. 10. A schematic flow chart of the major energy evaluation steps at the HEET.

the weather data is used to analyze the baseline system, which is the basis to evaluate every combined system. Second, the input is used for energy estimation of the 33 basic HVAC&R systems that include the baseline system. Each (air-conditioning, plant, transport) subsystem's energy consumption ratio of basic system to baseline system is calculated for every combined system. Third, as the air-conditioning, plant and transport system combination changes, the previously calculated ratio is used to predict the end use energy, and primary energy use of the extended HVAC&R system. Forth, the initial construction cost procedure is done similarly to the energy estimation procedure. The capital cost is calculated for baseline and basic HVAC&R system, which consists of typical floor, mechanical room, and riser construction cost. The construction cost is then used to predict 960 combinations of HVAC&R system initial construction cost. Finally, the energy cost and initial construction cost are used for economic assessment. As shown in Fig. 11, the HEET input is classified as mandatory input, and detail input. Mandatory inputs are essential input, which need to be properly input, for the building to be evaluated. The detailed input is specific information of air-conditioning, plant and transport system. Default values can be used by general users; by contrast, expert users can update the detailed input, such as COP, equipment efficiency, energy cost, and operation conditions. The initial construction cost for 960 combinations of HVAC&R system can be predicted, based on the number of floors, peak cooling and heating load. The first step calculation computes the 33 basic HVAC&R system energy consumption, and the energy cost is calculated. The second step calculation predicts the energy consumption, energy cost, and initial construction cost, for 960 combinations of the HVAC&R system. Finally, the economic assessment is executed by energy cost and initial construction cost. In the basic system estimation, monthly end use energy, primary energy, and annual primary energy are shown in graphs and numerical values. For the 960 extended HVAC&R systems, by selecting a specific air-conditioning, plant and transport system,

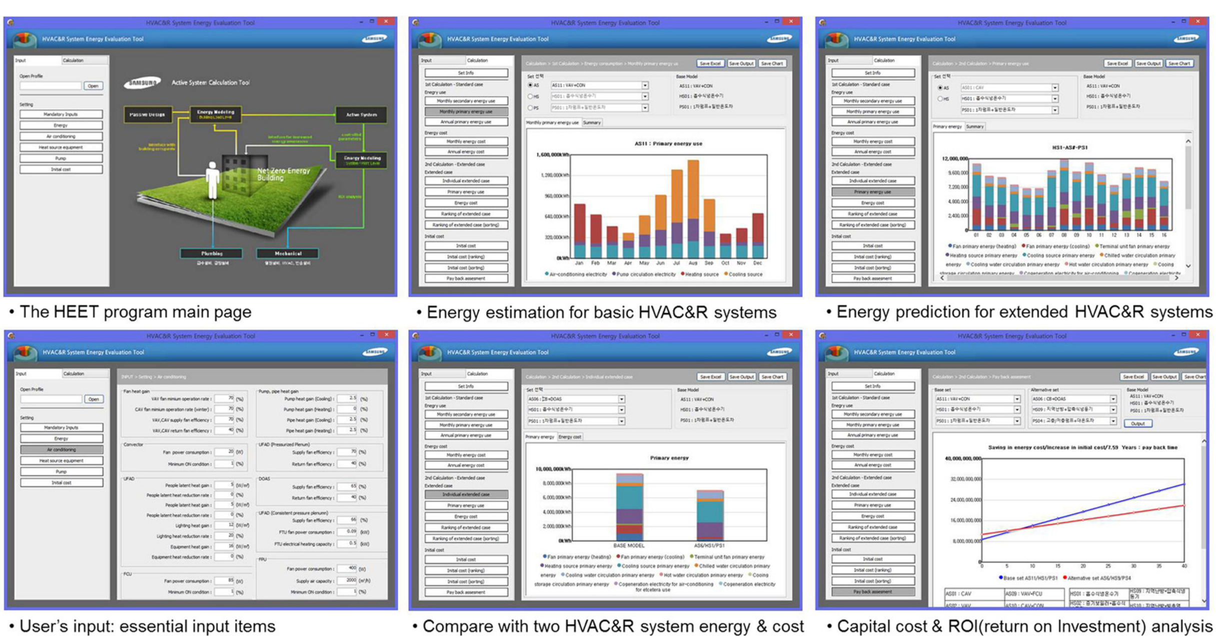


Fig. 11. The HEET (HVAC&R energy evaluation tool) program overview.

it can be compared with another system. Also the energy cost can be output in monthly and annual sum, and can be selected and compared with another system. The extended HVAC&R systems can be sorted, to identify the lowest primary energy consumption system. For economic assessment, the energy cost and initial construction cost is compared, to find the payback period.

4. Simulation results and case study

4.1. The energy evaluation program verification

To prove the correctness of the calculations and methodologies, the HEET program was verified by comparing with TRNSYS. TRNSYS is a building simulation program (BSP) which has capabilities to analyze complex HVAC&R system. First, the building energy demand (heating and cooling load) was simulated by TRNSYS, and used for the initial cooling and heating load profile for analyzing the HVAC&R system.

4.1.1. Building descriptions

In this study a prototypical office building has been selected to form a basis for the performance evaluation of a variety of HVAC&R systems. Building A is selected as the baseline building model, after case studies on gross floor areas, number of floors, and base case floor of buildings are carried out. The building has 30 floors with a typical floor area of 1500 m^2 and, its core located on the center, is modeled by distinguishing the 4 sides of the model into the perimeter and interior zones. Perimeter depth (distance from windows) is considered less than 5 m. In general, the core-to-gross floor ratios of office buildings are approximately 22% [26], side and center cores being the types frequently used. With regard to energy efficiency, core types, a variable affecting window-to-wall ratios (WWR) per direction can be modified, in accordance with length to width ratios. An isometric model and typical plan of the case study office building is shown in Fig. 12. The major boundary conditions are listed in Table 5. To achieve an acceptable indoor air quality level, the ventilation rate is set to 10 (L/s person) [27]. With regard to the occupancy pattern, the building is in use only during weekdays between 8 am and 6 pm. Indoor design temperature is set to 23 °C in cooling mode and 22 °C during heating mode. It should be noted that considering a variety of profiles for internal energy loads and delighting control along with different forms of possible shadings is not within the scope of this research. The prototypical building is created in TRNSYS and simulated using the Seoul weather data file.

Table 5
Building energy modeling boundary conditions.

Typical floor plan	Area	1444 m^2	GFA: 60,000 m^2
	Shape	Square	In middle floor
	Aspect	1:1	Total 30 floors
Elevation/section	Height	3.9 m	Floor height
	Plenum	1.0 m	–
	WWR	40%	ASHRAE 90.1
U-value (W/m^2 K)	Ex-wall	0.365	ASHRAE 90.1 (metal-framing; curtain wall)
	Roof	0.273	
	Slab	0.214	
	Window	2.84	
SHGC	Window	0.4	ASHRAE 90.1
Airtight	Infiltration	0.3	(ACH)
Internal heat gain (W/m^2)	Occupancy	0.1	# of people/m^2
	OA/plug	16	–
	Lighting	12	ASHRAE 90.1
Primary energy conversion factor			
LNG	1.1	Electricity	2.75
District cooling	0.614	District heating	0.934

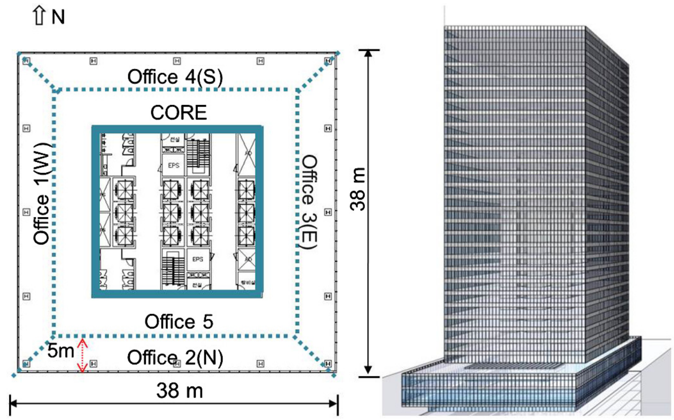


Fig. 12. An isometric model and typical plan of the case study.

Table 6
The HEET program verification with comparing three systems.

HVAC&R system	Air-conditioning	Plant	Transport
Set #1 (baseline)	A11	P01	T01
Set #2	A11	P06	T01
Set #3	A06	P09	T01

A06: chilled beam system with DOAS.
A11: VAV system with convector.
P01: direct-fired absorption chiller and heater.
P06: centrifugal chiller and hot water boiler.
P09: centrifugal chiller and district heating.
T01: primary pump system and CW temperature differential: $\Delta T = 5\,^{\circ}$C.

4.1.2. Simulation results

For verification, three HVAC&R systems were compared, and the systems are composed as in Table 6. HVAC&R system #1 (baseline system) is composed with the air-conditioning system as a VAV system with convector and plant system as absorption chiller/heater. System #2 is analyzed with a heat plant as centrifugal chiller and hot water boiler. System #3 is composed with chilled beam with DOAS for air-conditioning, and centrifugal chiller and hot water boiler for heat plant. Fig. 13 is the TRNSYS modeling of HVAC&R system #1. The major difference of TRNSYS and the HEET is the supply air volume calculation process. The HEET calculates the supply air volume of an air-conditioning system by the sensible heat load of the building at each hour; in contrast, TRNSYS decides the supply air volume based on the return temperature of the conditioned zone. For this reason, some difference occurred in the supply/return fan

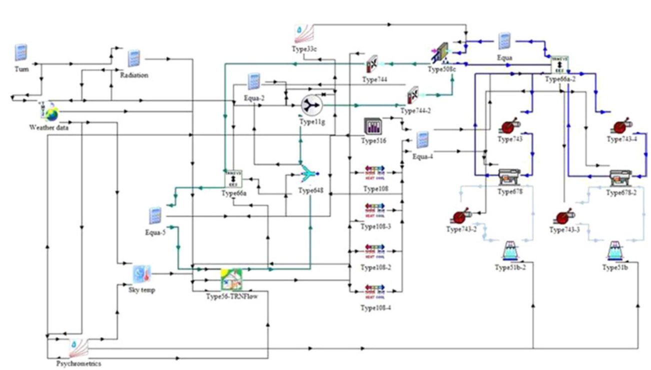


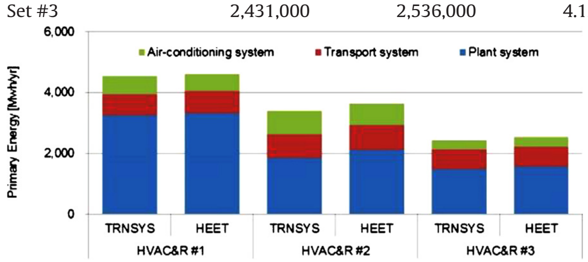
Fig. 13. TRNSYS model components and connections of set #1.

Table 7
Primary energy consumption comparison for set #1.

HVAC&R set #1	Primary energy demand (kWh/yr)		Difference
	TRNSYS	HEET	
AHU's fan (VAV system)	519,000	466,000	−11.40%
Convector fan	85,000	87,000	1.95%
Absorption chiller/heater	3,254,000	3,328,000	2.23%
Chilled/hot water pump	292,000	304,000	4.04%
Condenser water pump	392,000	427,000	8.20%
Total	4,540,000	4,610,000	1.52%

Table 8
Comparison of annual energy demand of set #1–3.

HVAC&R set	Primary energy demand (kWh/yr)		Difference
	TRNSYS	HEET	
Set #1 (baseline)	4,540,000	4,610,000	1.52%
Set #2	3,401,000	3,642,000	6.60%
Set #3	2,431,000	2,536,000	4.12%



electric consumption, which also resulted in errors in the heat plant energy and pump electricity consumption. As shown in Table 7, the annual primary energy consumption was much the same, except the supply/return fan energy use, which showed 10% difference. Also, the total primary energy consumption difference for HVAC&R system #1 was 1.5%, the difference for system #2 was 6.6%, and the difference for system #3 was 4.1% (Table 8). Finally, based on the same building heating and cooling load profile, the energy consumptions of three HVAC&R systems were compared. Also, there were minor differences in each component, and the total energy consumption pattern was similar, within a 7% range of error.

4.2. Case study: HCAC&R system energy consumption characteristics

4.2.1. HVAC&R subsystem impact assessment for energy performance

In order to analyze the air-conditioning system energy consumption, a direct-fired absorption chiller/heater is chosen for the plant system, and a primary pump system and chilled water temperature differential $\Delta T = 5\,^{\circ}$C for the transport system. The electricity consumptions of the AHU's supply/return fan, the DOAS's supply/exhaust fan, and the perimeter cooling/heating units' fan are computed, given each air-conditioning system. Fig. 14(a) shows the results of the primary energy consumption by each air-conditioning system. The VAV system with convector, the baseline system in this study, is already known as a considerable energy conservation system. Among the alternatives, the radiant cooling/heating system with DOAS, and the chilled beam system with DOAS figure as the most energy efficient, lowering energy demand by approximately 20%. The second best energy conservation system is the UFDA system with FTU and DOAS, an excellent system that can achieve approximately 16% of energy use reduction. Operated at a constant airflow rate throughout the year, the CAV system consumes more energy than the VAV system. The reason is that the fan power, proportional to the cube of air volume, uses a lot of energy when the former system runs all the year round, with the air volume set on the basis of the cooling peak load. The CAV system with FCU requires huge fan power, thereby increasing approximately 34% in energy use. All-water systems, such as the FCU system with DOAS, radiant cooling/healing system with DOAS, and chilled beam system with DOAS, consume a relatively small amount of energy, since the fans run only on the minimum outdoor airflow rate. However, the EHP system tends to consume a considerable amount of primary energy, due to the system's nature of increasing the fan power of indoor air, and using electricity. The UFAD with FTU and DOAS makes a variety of energy savings possible, as it does not require large ductwork, and the fan's static pressure loss is small. Although it is powered by electricity, the FTU is found to more than economize for the fan power of the air-conditioning system. Moreover, further energy savings can be expected, since there is no need for air-conditioning for the vertical height standing more than 1.8 m, thanks to the occupied zone air-conditioning. The LTAD system with FTU, albeit causing air volume to diminish by air-side large temperature differences, tends to consume large amounts of fan power, because it is a CAV system. Nevertheless, as a large chilled water temperature differential system, it may offer a benefit of pump power energy savings. For the plant system energy consumption analysis, a VAV system with convector was set as the air-conditioning system, and a primary pump system and chilled water temperature differential $\Delta T = 5\,^{\circ}$C as the transport system. Fig. 14(b) presents the results of the primary energy demand by plant system. As for a heat generation system, the district heating system is regarded as less primary energy consumption than heating plant systems using LNG, due to the differences in the primary energy conversion factor of energy sources. The energy efficiency of each cool generation system depends prominently on the equipment efficiency and pump power of the chilled/condenser water circulation pump. As the baseline system, the absorption chiller/heater system consumes the most primary energy, due to its low equipment efficiency, and great demand for chilled/condenser water, and to its heating plant equipment being less efficient than that of the district heating system. When it comes to a general system composition, the geothermal heat pump system, compared with the baseline system, can accomplish approximately 22% of energy efficiency. Although it has a high level of heating efficiency, it performs less efficiently in cooling, than the centrifugal chiller. In consideration of the characteristically large cooling load of office buildings, therefore, the district heating and centrifugal chiller system is assessed to be the most energy efficient, shaving off approximately 33% of energy demand. Despite the low efficiency of their chiller, the combined heat and power (CHP) system and other similar systems, which operate an absorption chiller with recycled waste heat, offer a great degree of energy saving effects, in that they are capable of continuously utilizing generated power and waste heat. Their energy saving effects amount to approximately 51%. However, it is necessary to always carefully consider energy and initial capital cost. Finally, for the transport system analysis, a VAV system with convector is used as the air-conditioning, and an absorption chiller/heater system as the plant system. The flow rate and head of the pump vary with transport system combinations. The energy use of pump power is studied, with the best performing in-line pump set as the criteria. Fig. 14(c) shows primary energy consumption by transport system type. The entire power of the primary pump system diminishes, although its single zoning and low-rise/high-rise zoning maintain an identical circulation flow rate, as the low-rise section pump gets its flow rate, and circulation flow rate is decreasing. The application of the chilled water temperature difference causes water circulation to subside, thereby simultaneously reducing pump size and power. Approximately 4% of energy demand reduction can be

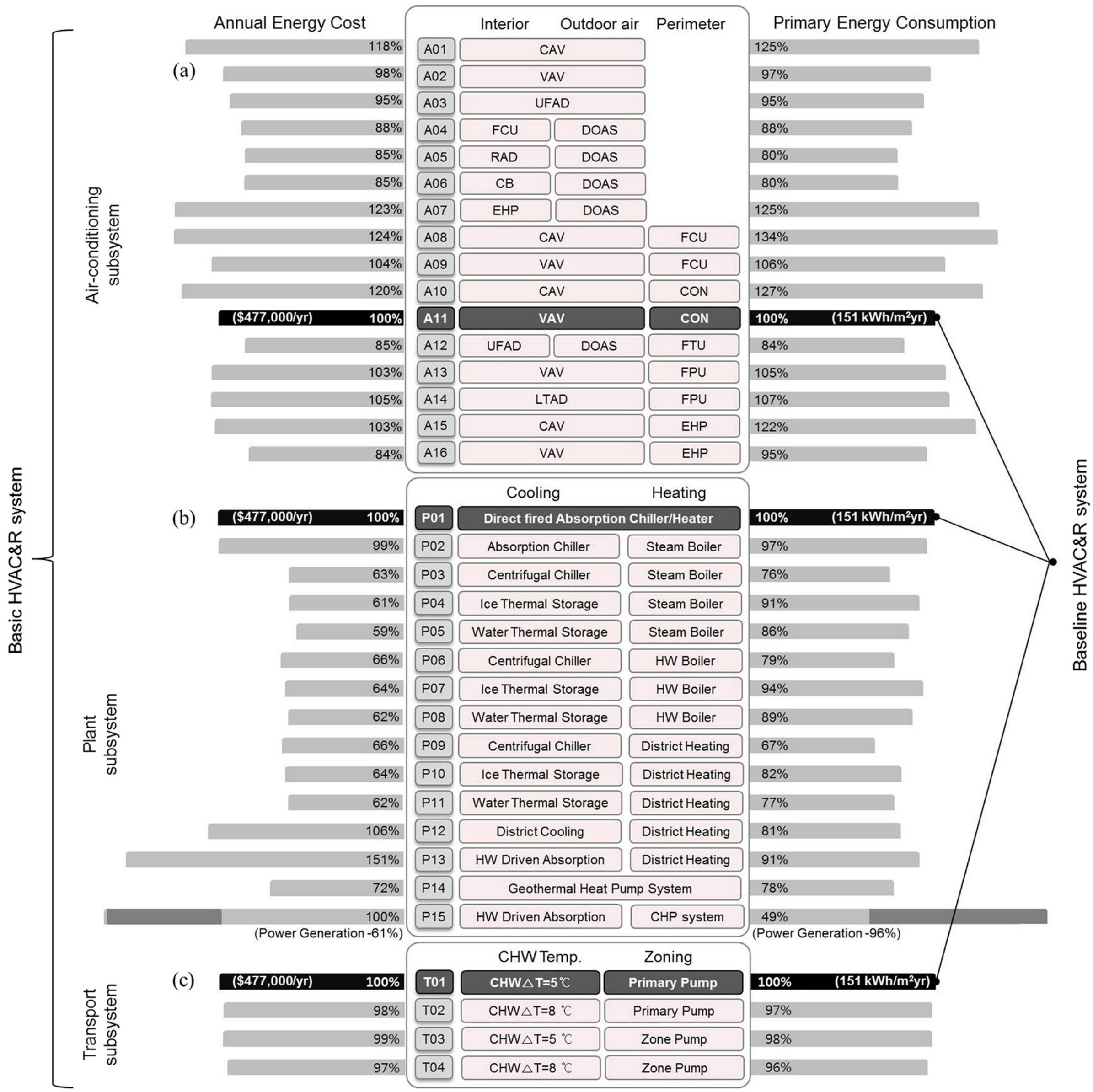


Fig. 14. Subsystem impact assessment for energy performance of HVAC&R systems; (a) air-conditioning systems, (b) plant systems and (c) transport systems.

attained, when the low-rise/high-rise pump zoning and the large temperature differential chilled water system are integrated into the baseline system.

4.2.2. Energy performance optimization of the HVAC&R system

The preceding sections analyze the energy consumption characteristics and sensitivity of the modulation of each HVAC&R component system, and identify the systems with high energy efficiency. Fig. 15 presents a graph analyzing the primary energy demand, annual energy cost and capital cost of the HVAC&R systems, made up of energy efficient air-conditioning, plant and transport systems. The baseline system is outperformed in energy savings by HVAC&R systems that consist of a chilled beam system with DOAS or a UFAD system with FTU and DOAS for the air-conditioning system, a centrifugal chiller and district heating system, or a CHP with absorption chiller for the plant system, and a high-rise/low-rise pump zoning and large temperature differential chilled water system for the transport system. Energy efficient HVAC&R systems curtail primary energy consumption by approximately 20–77%. However, it is found that the primary energy use does not decrease in proportion to annual energy cost. In other words, the cost of different energy sources does not appear to change in the same pattern as primary energy demand. Additional studies therefore should be done on the issue. It is possible to further improve energy efficiency, by analyzing the energy use structures of the alternative HVAC&R systems that achieve energy optimization. The next step, once the composition and combination of systems achieve energy optimization, is to enable additional energy efficiency, by introducing high efficiency equipment. Therefore, knowledge of the energy consumption characteristics and structure of each HVAC&R system makes it possible to assess the priorities of locations in which high efficiency equipment should be applied. For example, the application of high efficiency equipment should be considered in a chiller and a cooling tower for the plant system with high energy consumption of heating and cooling; in a pump for the transport system; and in a ventilation fan for the air-conditioning system. After the selection of a chiller with high COP, the radiant cooling/heating system is shown to work better with a high efficiency pump installed in the transport system, while the UFAD system benefits from a high efficiency ventilation fan in the transport

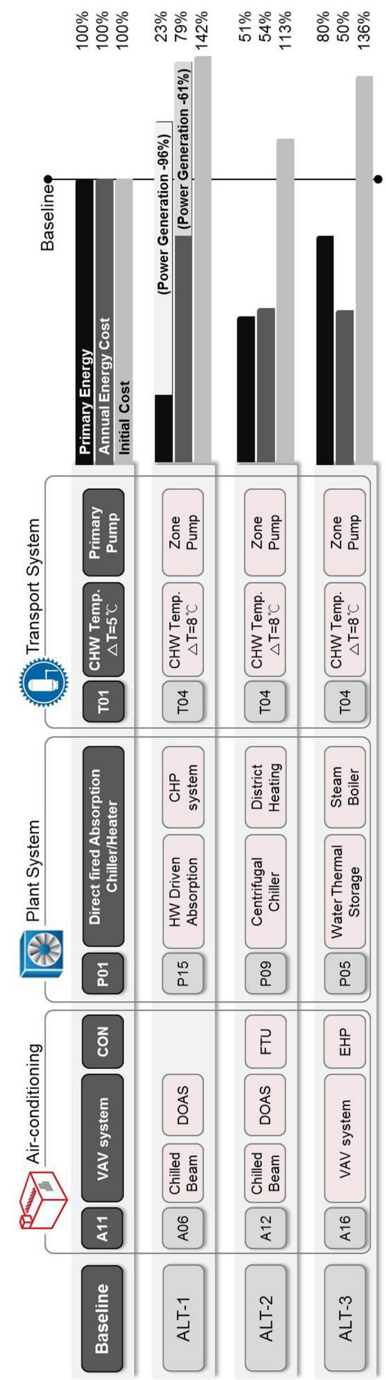


Fig. 15. Optimal energy performance of HVAC&R systems.

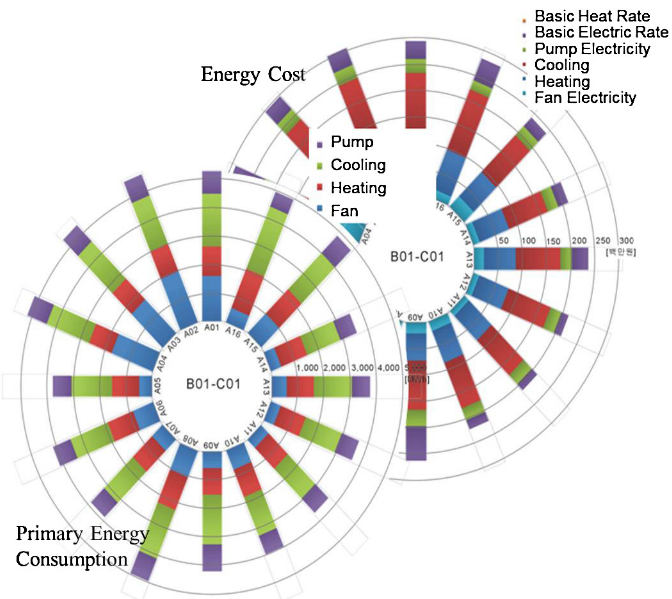


Fig. 16. An example of an energy performance map for HVAC&R systems.

system. It is possible to ultimately complete an energy map (akin to a genome map) that will reflect the energy use characteristics of the 960 HVAC&R systems. An example energy performance map shown in Fig. 16 presents the information unique to the primary energy demand, and annual energy cost of each HVAC&R system. Such information explains the itemized energy demand of each system, and helps to identify components that account for high energy use and cost, and to make decisions on which subsystem has priority, in the application of high efficiency equipment.

5. Conclusions

At the early stage of planning building HVAC&R systems, it is both difficult and important to evaluate the energy demand of HVAC&R systems emanating from a variety of system component combinations. In order to make such evaluations, this study first analyzed the energy flow of each subsystem (air-conditioning, plant, and transport systems) of the HVAC&R system, and established the concept and composition of the HVAC&R systems that were applicable. Simultaneous dynamic simulation of a typical office building and HVAC&R systems are adapted to analysis the energy performance of different parts of HVAC&R systems. Finally, the results of this study on the performance evaluation of 960 HVAC&R systems can be used as a complementary part of the existing building energy benchmarks in order to enhance the performance characterization assessment of a variety of HVAC&R systems. This is especially applicable to the decision making involved in HVAC&R system selection carried out in the early stages of a project design process. The following is a summary of the study results:

(1) Each subsystem, the air-conditioning, plant, and transport systems, of the HVAC&R system is derived with the aid of matrix combinations. In theory, the possible HVAC&R systems, made up of combinations of each subsystem, come to 960 in total for office buildings.
(2) 33 basic HVAC&R systems were analyzed. Based on this analysis, the method for predicting the energy demand of the 960 extended HVAC&R systems is suggested.
(3) An HVAC&R system energy analysis program was developed based on the procedure purposed in this study. The energy consumption difference between the HEET and the commonly used energy simulation TRNSYS was under 7%.
(4) According to the results of the air-conditioning system sensitivity analysis, the chilled beam system with DOAS is the most energy efficient, reducing energy use by approximately 20%, compared with the VAV system with convector as the baseline system. The UFAD system with FTU and DOAS offers approximately 16% of energy savings.
(5) As for the general plant system, the district heating system and centrifugal chiller, the most energy efficient system, can reduce energy demand by approximately 33%, compared with the direct-fired absorption chiller/heater as the baseline system.
(6) If the energy consumption characteristics and structure of each HVAC&R system are understood, it is possible to determine which system requires the application of high efficiency equipment. After the selection of the chiller with high COP, the radiant cooling/heating system runs more efficiently, when the efficiency of the pump in the transport improves, and the application of the high efficiency ventilation fan gives an edge to the UFAD system. Eventually, it is possible to generate an energy map indicating the energy use characteristics of the 960 HVAC&R systems. Such information delineates the itemized energy consumption of each HVAC&R system, and thus helps prioritize energy efficiency, based on the system type. Since it sheds light on the itemized energy consumption of each system.

This study recommends the optimal system only in terms of energy. Due to the fact that operating costs do not vary proportionally with energy source, there should be comprehensive follow-up studies that take economic efficiency into account. Understanding the energy consumption characteristics of the HVAC&R system is crucial, for energy efficiency in buildings. Therefore the developed HVAC&R energy evaluation program will be useful for decision making at the early stage of building design. The urgent tasks crucial to improving the energy efficiency of buildings involve understanding the energy characteristics of air-conditioning, plant and transport systems by component system type, and determining the composition of the HVAC&R system that warrants energy optimization. Information on the energy use characteristics of the HVAC&R system leads to strategizing energy efficiency.

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