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Development and Implementation of HVAC-KBCD: A Knowledge-Based Expert System for Conceptual Design of HVAC&R Systems—Part 2: Application to Office Buildings

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ABSTRACT

A previous paper articulated the current problems faced by HVAC&R professionals involved in the conceptual design process and proposed a solution based on a knowledge-based expert system (KBES) approach, which can automatically synthesize all the feasible secondary and primary systems that can then be evaluated using currently available hourly building energy simulation programs. The previous paper described the general framework of such a KBES module called HVAC-KBCD. The module consists of (1) static knowledge (based on heuristics, design practice, and standards) containing assembly and application rules needed to prune or shrink the solution space of all feasible secondary and primary systems and (2) dynamic knowledge containing initiation and matching rules to provide a guided search and further shrink the solution space by imposing restrictions of how to combine secondary systems among themselves (since the building has several zones) and with primary systems. These capabilities, along with specially developed models for first and maintenance costs, have been programmed into a commercial KBES shell. This paper describes the type of knowledge specific to office buildings that needs to be coded into the HVAC-KBCD module and illustrates its capabilities when applied to a case study example. The case study serves to illustrate the relative ease and thoroughness with which this design assistant can generate and evaluate a large number of HVAC&R system design alternatives.

INTRODUCTION

Currently there are no mechanisms to automatically synthesize feasible secondary and primary HVAC&R systems that can then be exported and linked to corresponding models in an hour-by-hour building energy simulation program such as DOE-2 (Winklemann et al. 1993). As explained in the companion paper (Maor and Reddy 2004), the configurations have to be defined a-priori, resulting in a limited number of alternatives and limited system configurations. The current process limits the number of system types and configurations, thereby reducing the probability of an optimum solution. The proposed solution methodology is to automate the process of generating a set of feasible HVAC&R secondary and primary systems that can be evaluated using available, detailed simulation programs. Leveraging the computing speed available today, hundreds of combinations can be run in a reasonable time. After the simulation and the preliminary evaluation of such a large number of alternatives, the engineer selects the most promising alternatives (say, the top 10) that meet the engineer's criteria on which to perform more precise evaluations. This approach will benefit both experienced and novice professionals during the conceptual design stage, resulting in a more scientific and comprehensive evaluation and a better design solution. A comprehensive literature review of artificial intelligence and KBES in buildings and HVAC&R system design has been published in a previous paper (Maor and Reddy 2003).

The companion paper (Maor and Reddy 2004) describes the general framework of such a KBES called HVAC-KBCD (knowledge-based conceptual design) capable of automatically synthesizing the complete set of possible HVAC&R systems, which can then be analyzed using available building energy simulation programs such as DOE-2.1. This synthesis is done by first pruning or shrinking the solution space of the design alternatives by applying static expert knowledge (Level 1) and then by a guided search dominated by dynamic application knowledge (Level 2). Level 1 starts with a database of

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Table 1. Data for Office Building in U.S.*

	Number of Buildings (Thousands)	Percent of Total Number of Buildings	Total Floor Space (Million ft^2)	Percent from Total Floor Space Buildings
Total Office Buildings	705	100%	10,478	100%
1,001 - 5,000 ft^2	405	57.4%	1,084	10.3%
5,001 - 10,000 ft^2	131	18.6%	915	8.7%
10,001 - 25,000 ft^2	94	13.3%	1,580	15.1%
25,001 - 50,000 ft^2	35	5.0%	1,293	12.3%
50,001 - 100,000 ft^2	22	3.1%	1,542	14.7%
100,001 - 200,000 ft^2	10	1.4%	1,378	13.2%
200,001 - 500,00 ft^2	5	0.7%	1,525	14.6%
>500,000 ft^2	1	0.14%	1,161	11.1%

* From EIA (1995).

all feasible secondary systems (and another for all feasible primary systems) and uses assembly rules and application rules based on heuristic expert knowledge, design practice, and standards to generate the permissible design alternatives of secondary systems (and primary systems). Level 2 uses initiation rules along with matching rules to combine secondary systems among themselves (since the building has different zones) and with primary systems. These capabilities have been programmed into a commercial hybrid KBES shell along with procedural programming capabilities that have the ability to perform simple heuristic cooling and heating design load as well as first and maintenance cost calculations. ANSI/ASHRAE/IESNA Standard 90.1-2001 (ASHRAE 1999a, 1999b, 2001a) has been used to set the minimum allowed energy performance for equipment such as fans, chillers, boilers, etc. This paper illustrates and demonstrates the entire methodology described above to the conceptual design of an office building.

OFFICE BUILDINGS: BACKGROUND

Despite cyclical market fluctuations, office buildings are considered the most complex and competitive segments of real estate development. Over the years the office building market has proved itself resilient and efficient at meeting the needs of American business (Gause 1998). Survey data of 705,000 office buildings (EIA 1995) indicates that 89% of the office buildings in the U.S. have from 1,001 to 25,000 ft^2 gross area. Furthermore, office buildings ranging from 1,001 to 5,000 ft^2 represent 57% of the total number of office buildings. This high percentage may lead to a false impression that buildings in this size should be the primary focus of HVAC&R KBES development. Given the small size of these buildings, their typical hours of operation, and the availability of a variety of energy-efficient HVAC&R equipment (in many cases residential grade), the design is extremely simple. In many cases, the contractor is capable of designing and constructing the HVAC&R system. Since design of such buildings is relatively simple, the need for an intelligent tool to assist in HVAC&R design may be questioned. The answer to this question can be found in the U.S. Energy Information Administration survey (EIA 1995). If we look at floor space (see Table 1) of the surveyed buildings, we will find that buildings ranging from 1,001 to 25,000 ft^2 comprise only 34% of the total floor space. Buildings ranging from 25,001 to 200,000 ft^2 represent 40% of the total; buildings from 200,001 to 500,000 ft^2 comprise 15%, while buildings above 500,000 ft^2represent 11% of the total floor space.

From this information it is clear that KBES development should focus on office buildings above 25,000 ft^2. Designing such buildings requires much more HVAC&R knowledge, and the number of feasible design alternatives is much higher. In addition, the fact that large buildings are less forgiving of conceptual design errors than are small buildings emphasizes the value of a KBES design assistant. This fact leads us to concentrate on KBES for office buildings larger than 25,000 ft^2, which represent more than 50% of all office buildings. The HVAC&R system is one of the most costly items in an office building's construction; typically 15% of the total construction budget is dedicated to the HVAC&R system (Gause 1998). Further, as stated above, the HVAC&R design in such buildings is more complex and requires mature professionals with the ability and the knowledge to propose and analyze several promising design alternatives.

According to Gause (1998), an office building can be divided into the following categories:

a. **Class** is the most basic feature of office buildings. An office building's class represents the quality of the office building by taking into account variables such as age, location, building materials, building systems, amenities, lease rates, etc. Office buildings are of three classes: A, B, and C. Class A is generally the most desirable building, in the most desirable location, and offering first rate design, building systems, and amenities. Class B buildings are in good locations, have little chance of functional obsolescence, and have reasonable management. Class C buildings are typically older, have not been modernized, are often functionally obsolete, and may contain asbestos. These low standards make Class C buildings potential candidates for demolition or conversion to other uses.

b. **Location** of an office building is typically (i) downtown, (ii) suburban, or (iii) in a business/industrial park. Downtown buildings are usually high-rises, while suburban sites feature low to mid-rise buildings and business/industrial parks, one- to three-story buildings (Gause 1998).

c. **Size and Flexibility**: Office buildings are typically grouped into three categories: (i) high-rise (16 stories and above), (ii) mid-rise (four to 15 stories), and (iii) low-rise (one to three stories). Floorplate (floor space area) size typically ranges from 18,000 ft^2 to 30,000 ft^2 and averages from 20,000 to 25,000 ft^2. The size of a floorplate is driven by the optimal combination of core function areas such as stairs, mechanical rooms, elevators, etc., and rentable (or useable) office space. Smaller floorplates are typically inefficient from a space planning perspective due to the high percentage of total floor space utilized by core areas and, therefore, rendered unusable. Too large a floorplate may require structural and design measures such as additional stairways, elevators etc., which may increase the construction cost. As indicated earlier, 20,000 to 25,000 ft^2 is average for a cost-effective office floorplate. From a developer's standpoint, a rectangular floor configuration best meets the planning needs of a typical office. Rectangular arrangements work more efficiently than curved, diagonal, or irregular shapes (White 1993).

d. **Use and Ownership**: Office buildings can be single tenant or multi-tenant. A single-tenant building can be owned by the tenant or leased from a landlord. From an HVAC&R systems standpoint, a single tenant/owner is more cautious and considers issues such as life-cycle cost and energy conservation. In many cases the HVAC&R systems are not selected based on the lowest first cost but on life-cycle cost. In some cases, the developer may wish to select an HVAC&R system that allows individual tenants to pay directly for the energy they consume.

e. **Building Features and Amenities**: Examples of building features are typically parking, telecommunications, HVAC&R, energy management, restaurants, security, retail outlets, health club, etc.

Understanding these issues is critical to the successful development of KBES for HVAC&R design. For example, HVAC&R systems must meet stringent criteria, such as individual thermal control, noise, and flexibility, to be applied to Class A office buildings. HVAC systems such as single-zone constant volume, water-source heat pump, and packaged terminal air conditioner are a few examples of systems that are inapplicable to Class A buildings. On the other hand, variable air volume systems do meet these requirements. Such issues must be researched before any attempt is made to develop a KBES for HVAC&R design applicable to different building classes.

DEVELOPMENT CRITERIA AND LIMITATIONS OF PROPOSED KBES

In order to provide a useful intelligent tool that will assist the HVAC&R designer in proposing and evaluating design alternatives for office buildings, the following criteria were used to develop the KBES:

a. **Building Size**: The office building will range from 25,000 to 300,000 ft^2, which includes more than 50% of existing (and assumed future) office buildings categorized by area.

b. **Number of Floors**: The office building will be two stories and higher. One-story buildings are not included, since single-story buildings are less likely to measure 25,000 ft^2or more and generally employ rooftop packaged HVAC&R equipment, which is relatively easy to design. The KBES will provide solutions for perimeter zones and the two types of cores, with and without roof coupling.

c. **Solutions Format**: The synthesized solutions will be in a format identical to the terminology and input sequence required by the DOE-2.1 E building simulation program (Winklemann et al. 1993).

d. **Energy Standards**: The knowledge base of system and component specifications will comply with the minimum requirements of ASHRAE 90.1-1999 (ASHRAE/IESNA 1999a, 1999b, 2001). This feature will assist the designer in complying with local energy codes during the early stages of the design. Although the standard has not been adopted by many states, there is a trend in many jurisdictions to adopt this standard or at least use it as a reference.

e. **Owning Cost**: The KBES will be capable of calculating preliminary owning cost of secondary, primary, and domestic hot water (DHW) systems.

f. **Maintenance Cost**: The KBES will be capable of calculating preliminary maintenance cost of secondary, primary, and domestic hot water systems.

g. **KBES Shell**: The KBES will utilize a low-cost commercial KBES shell. The shell will be capable of supporting frame-based and rule-based knowledge representations and also procedural programming (Maor and Reddy 2004). The selected shell must be equipped with user-friendly graphical interface and the ability to export data to external programs such as spreadsheets, etc.

The HVAC-KBCD prototype thus developed has the following limitations:

1. **Total Cooling Capacity**: The maximum cooling capacity will be 1,000 tons. Since this research demonstrates the concept of KBES utilization for conceptual design, we felt that 1,000 tons would be adequate for office buildings up to a range of 300,000 ft^2. However, extending the cooling capacity to more than 1,000 tons is relatively simple.

2. **Perimeter Heating**: The KBES will not allow the use of zone reheat (ceiling or sidewall supply air) for locations where the number of heating degree-days (HDD) HDD(65°F) > 4,000. The KBES will default to perimeter

Table 2. List of Knowledge Forms for Office Building Operation

Form #	Form Code	Form Duty	Comments
1	KA-OFFICE-GENERAL-DATA	Summary of all office data	This form summarizes all the data needed for energy simulation.
2	KA-OFFICE-PEOPLE-SCH	People occupancy schedule	
3	KA-OFFICE-LIGHTING-SCH	Lighting schedule	
4	KA-OFFICE-EQUIPMENT-SCH	Office equipment schedule	
5	KA-OFFICE-INFIL-SCH	Infiltration schedule	This schedule is required to address infiltration when the building is not pressurized during unoccupied hours
6	KA-OFFICE-HEATING-SCH	Space heating temperature schedule	Typically used for night setback
7	KA-OFFICE-COOLING-SCH	Space cooling temperature schedule	Typically used for night setup
8	KA-OFFICE-DHW-SCH	Domestic hot water usage schedule	
9	KA-OFFICE-FAN-SCH	Fans operation schedule	To allow fan control during unoccupied hours
10	KA-OFFICE-OA-SCH	Outside air schedule	Outside air control during unoccupied hours

heating baseboards for all-air systems or systems such as free-standing fan coils, PTAC, WLHP, etc. For locations where HDD< 4,000, the KBES will not allow baseboard heating and will default to zone reheat (ceiling or sidewall supply air) for all-air systems. The purpose of this restriction is to provide a kind of "warning" to the user and attract attention to the consequences of compromising thermal comfort in cold climates.

3. **Winter Humidification**: A winter humidification option was considered in the early stages of the KBES development, mainly in order to address indoor air quality, thermal comfort, and the prevention of electrostatic discharge. After further investigation, we discovered that building owners are reluctant to install winter humidification systems due mainly to maintenance issues. Often special fabrics are utilized along with local humidification systems to minimize electrostatic discharge. Also, since the acceptable lower bound for relative humidity in office buildings is around 30% (ASHRAE 2000) and hours of occupancy are less then 4,500 hours/year, the energy usage of a winter humidifier is relatively low. For these reasons, winter humidification option has not been included in the KBES.

OFFICE BUILDINGS—KNOWLEDGE ACQUISITION AND REPRESENTATION

Since specific knowledge or data is required by the KBES, special forms (called "Knowledge Acquisition Form") have been developed to capture such knowledge (Maor 2002). These forms also provide a means to manage and update the relevant knowledge. These knowledge forms provide detailed information of component specifications, default values that are consistent with ASHRAE-90.1-1999, and the sources used. The types of knowledge needed for successful HVAC&R system synthesis are discussed below.

Table 3. List of HVAC-KBCD Secondary Systems

	System Description	System Code
1	Single-zone variable temperature	SZVT
2	Variable air volume	VAV
3	Two-pipe fan coil	TPFC
4	Four-pipe fan coil	FPFC
5	Packaged single zone	PSZ
6	Packaged variable air volume	PVAV
7	Water loop heat pump	WLHP
8	Packaged terminal air conditioner	PTAC

Building Operation

This knowledge can be considered as default data that can be used for office buildings without specific information, such as occupancy schedule, lighting schedules, typical cooling temperature schedules, etc. In addition, default information, such as lighting power density (LPD), equipment power density (EPD), occupancy density, etc., is also required for effective building energy simulation. A list of all the knowledge forms used for office building operation is shown in Table 2.

Secondary Systems—Application

Secondary systems used in office buildings are listed and described in Table 3 along with their acronyms.

Table 4. List of HVAC-KBCD Secondary System Knowledge Forms—Components

	Summary	Supply Fan	Cooling Coil	Heating Coil	Pre-Heat Coil	Humidifier	Return Fan	Econo-mizer	Zone Reheat	Baseboard Heat
SZVT	SZVT-SUM	SZVT-SF	SZVT-CC	SZVT-HC	SZVT-PHC	SZVT-HUM	SZVT-RF	SZVT-ECON	SZVT-ZRHT	SZVT-BASEBO
VAV	VAV-SUM	VAV-SF	VAV-CC	VAV-HC	VAV-PHC	VAV-HUM	VAV-RF	VAV-ECON	VAV-ZRHT	VAV-BASEBO
FPFC	FPFC-SUM	FPFC-SF	FPFC-CC	FPFC-HC	NA	NA	NA	NA	NA	NA
TPFC	TPFC-SUM	TPFC-SF	TPFC-CC	TPFC-HC	NA	NA	NA	NA	NA	NA
PSZ	PSZ-SUM	PSZ-SF	PSZ-CC	PSZ-HC	NA	PSZ-HUM	PSZ-RF	PSZ-ECON	PSZ-ZRHT	PSZ-BASEBO
PVAV	PVAV-SUM	PVAV-SF	PVAV-CC	PVAV-HC	NA	PVAV-HUM	PVAV-RF	PVAV-ECON	PVAV-ZRHT	PVAV-BASEBO
WLHP (see note)	WLHP-SUM	WLHP-SF	WLHP-CC	WLHP-HC	NA	NA	NA	NA	NA	NA
PTAC	PTAC-SUM	PTAC-SF	PTAC-CC	PTAC-HC	NA	NA	NA	NA	NA	NA
Total	8	8	8	8	2	4	4	4	4	4

Note: WLHP system has additional components as follows:
(1)Water Loop – WLHP-WL
(2)Heat pump tower -WLHP-HPCT
(3)Heat pump boiler - WLHP-HPBO
(4)Heat pump water pump -WLHP-PUMP

Secondary Systems—Configuration

The knowledge required to configure secondary and primary systems from basic components represents a major part of the knowledge obtained for the KBES. As indicated earlier, a special knowledge acquisition form was developed to capture this knowledge. In addition to the knowledge acquired vis-à-vis components, assembly and application rules are also required to configure systems from basic components. As indicated, these rules are used manually to synthesize secondary systems. Each and every knowledge form includes all the component data required to run the DOE-2.1 E building simulation program. As shown in Table 4, 54 knowledge forms have been developed to capture secondary system knowledge applicable for office buildings. Finally, assembly and application (of components) of rules are needed to synthesize and reduce the number of subsystems that will serve particular thermal zones. We have identified 36 rules for this task as shown Table 5.

After applying the configuration rules shown in Table 5 to generate feasible secondary systems from basic components, a sorting process is applied to separate secondary systems that can serve perimeter zones from secondary systems that can serve core zones without roof (core 1) and core zones with roof (core 2) (see Table 6).

The matching matrix approach has been utilized in numerous KBES. For example, Sciubba and Melli (1998) applied this approach to represent the structure of a gas-powered power plant consisting of "Brayton" cycle components and a heat recovery boiler. A similar approach has been used in this research to represent how perimeter systems can be connected to applicable core systems. Since secondary systems can be packaged or supported by primary systems, two matching matrices were developed, one for matching secondary systems with primary systems (Table 7) and another for matching packaged secondary systems among themselves.

A feasible configuration for a building secondary system must have a set of two "True" values (denoted by the numeral "1") one on each half of Table 7 to configure a feasible perimeter system along with corresponding core systems. These two tables have been encoded in the KBES shell in the form of rules.

Primary Systems—Application

The selection of appropriate primary systems is driven by the secondary systems. Primary systems are required when the secondary systems need chilled water and hot water. As noted above, the KBES distinguishes between secondary systems with primary systems and packaged secondary systems. It is important to note here that certain packaged secondary systems need hot water for heating, while the cooling system is a direct expansion (DX), self-contained system; therefore, a chilled water plant is not required. Matching primary systems to secondary systems is straightforward. If the cooling system is packaged and equipped with hot water zone reheat or hot water baseboard, a chilled water plant is not required, while a hot water boiler is needed.

The primary systems used in the HVAC-KBCD KBES are typically chilled water systems and hot water systems. The chillers included are both electric and gas driven. Electric chillers include water-cooled centrifugal chiller (with centrif-

Table 5. List of HVAC-KBCD Secondary System Knowledge Forms—Subsystem Configuration Rules

System	Form	Number of Assembly Rules	Number of Component Application Rules	Total Number of Rules
SZVT	SZVT-RULES	4	7	11
VAV	VAV-RULES	4	7	11
FPFC	FPFC-RULES	0	0	0
TPFC	TPFC-RULES	0	0	0
PSZ	PSZ-RULES	1	6	7
PVAV	PVAV-RULES	1	6	7
WLHP	WLHP-RULES	0	0	0
PTAC	PTAC-RULES	0	0	0
Total	8	10	26	36

Table 6. HVAC-KBCD Number of Configured Secondary Systems

System	Number of Perimeter Systems (P)	Number of Core Systems w/o Roof (C1)	Number of Core Systems w Roof (C2)
SZVT	6	2	3
VAV	6	2	3
FPFC	1	NA	NA
TPFC	1	NA	NA
PSZ	6	2	3
PVAV	6	2	3
WLHP	2	2	2
PTAC	3	NA	NA
Total	31	10	14

Table 7. HVAC-KBCD Matching Matrix of Secondary Systems w/Primary Systems

	SZVT C11	SZVT C12	VAV C11	VAV C12	SZVT C21	SZVT C22	SZVT C23	VAV C21	VAV C22	VAV C23
SZVTP1	1	0	0	0	1	1	0	0	0	0
SZVTP2	1	0	0	0	1	1	0	0	0	0
SZVTP3	1	0	0	0	1	1	0	0	0	0
SZVTP4	1	0	0	0	1	1	0	0	0	0
SZVTP5	0	1	0	0	0	0	1	0	0	0
SZVTP6	0	1	0	0	0	0	1	0	0	0
VAVP1	0	0	1	0	0	0	0	1	1	0
VAVP2	0	0	1	0	0	0	0	1	1	0
VAVP3	0	0	1	0	0	0	0	1	1	0
VAVP4	0	0	1	0	0	0	0	1	1	0
VAVP5	0	0	0	1	0	0	0	0	0	1
VAVP6	0	0	0	1	0	0	0	0	0	1
TPFCP1	0	1	0	1	0	0	1	0	0	1
FPFCP1	1	0	1	0	1	1	0	1	1	0

Table 8. HVAC-KBCD Matching Matrix of Secondary to Primary Systems

Secondary System	Chiller Plant	Boiler Plant
SZVT P 1	1	1
SZVT P 2	1	1
SZVT P 3	1	1
SZVT P 4	1	1
SZVT P 5	1	0
SZVT P 6	1	0
VAV P 1	1	1
VAV P 2	1	1
VAV P 3	1	1
VAV P 4	1	1
VAV P 5	1	0
VAV P 6	1	0
TPFC P 1	1	0
FPFC P 1	1	1
SZVT C1 1	1	1
SZVT C1 2	1	0
VAV C1 1	1	1
VAV C1 2	1	0
SZVT C2 1	1	1
SZVT C2 2	1	1
SZVT C2 3	1	0
VAV C2 1	1	1
VAV C2 2	1	1
VAV C2 3	1	0
PSZ P 1	0	1
PSZ P 2	0	0
PSZ P 3	0	1
PSZ P 4	0	0

Table 8. HVAC-KBCD Matching Matrix of Secondary to Primary Systems *(continued)*

Secondary System	Chiller Plant	Boiler Plant
PSZ P 5	0	0
PSZ P 6	0	0
PVAV P 1	0	1
PVAV P 2	0	0
PVAV P 3	0	1
PVAV P 4	0	0
PVAV P 5	0	0
PVAV P 6	0	0
WLHP P 1	0	0
WLHP P 2	0	0
PTAC P 1	0	1
PTAC P 2	0	0
PTAC P 3	0	0
PSZ C1 1	0	0
PSZ C1 2	0	0
PVAV C1 1	0	0
PVAV C1 2	0	0
WLHP C1 1	0	0
WLHP C1 2	0	0
PSZ C2 1	0	1
PSZ C2 2	0	0
PSZ C2 3	0	0
PVAV C2 1	0	1
PVAV C2 2	0	0
PVAV C2 3	0	0
WLHP C2 1	0	0
WLHP C2 2	0	0

ugal compressors), water-cooled rotary chillers (with screw compressors), air-cooled rotary chillers (with screw compressors), and gas-driven chillers (only gas-engine chillers have been included in this research). Originally, two types of thermally powered chillers were considered: water-cooled two-stage absorption chillers and water-cooled gas-driven engine chillers. After more rigorous evaluation of chillers applied to office buildings, we decided to eliminate the absorption chiller option in this study for the following reasons:

1. **Thermal Efficiency**: Two-stage absorption chillers are inferior to gas-engine-driven chillers from a thermal standpoint. Therefore, the annual energy consumption (and the operating cost) of gas-driven engine chillers will always be lower in case one wants to better manage the operating costs by adopting hybrid systems (gas and electric).
2. **Application**: Absorption chillers are more suitable for applications where waste heat is available as from an industrial process or cogeneration plant. This type of waste heat is not very common in commercial office buildings. For large facilities (with office buildings) where waste heat and district steam supply is available, the absorption chiller option can be considered.
3. **Cost**: Absorption chillers and gas-driven chillers are typically in the same price range, while both are considerably more expensive than all electric chillers (Means 2002a).
4. **Maintenance Cost**: Maintenance cost is the only criterion where absorption chillers are superior to other chillers. However, this item by itself is insufficient to justify absorption chillers in the majority of commercial office buildings.

The hot water boiler types included in this research are standard fuel (gas or oil) and electric boilers. Given the superior efficiency of hot water boilers versus steam boilers for space heating, steam boilers are not included in the KBES. In addition, hot water boilers are simpler to operate and maintain than steam boilers, resulting in lower operating and maintenance costs. The DHW (domestic hot water) systems included in this research are electric only, given the low usage of domestic hot water in office buildings and the simplicity and lower cost of electric heaters. As noted previously, a matching matrix approach is used to match secondary systems to primary systems, as shown in Table 8.

Primary Systems—Configuration

The knowledge pertinent to configuring primary systems deals with chilled water plants, hot water plants, and domestic hot water systems. Unlike the approach taken in the secondary systems, where we considered basic components such as fans, coils, economizers, etc., the chilled water plant and boiler plant configuration use packaged chiller and boilers as “basic components.” Typical chiller package include compressor(s), an evaporator, condenser, electrical, refrigeration piping, etc. Cooling towers or evaporator pumps, for example, are also considered basic components. A configured chiller system includes a packaged chiller, evaporator pump, condenser pump (for water-cooled systems), and cooling tower (for water-cooled systems).

As indicated in Maor and Reddy (2004), chiller plant configuration deals mainly with the synthesis of different configured chiller set modules (level 1 configuration) to form a whole chiller plant (level 2 configuration). Knowledge forms for chiller systems, boilers, and domestic hot water are shown in Tables 9, 10, and 11, respectively.

Owning and Maintenance Cost

Knowledge acquisition, representation, and calculation procedures and regression coefficients for owning and maintenance costs are based on published data (Means 2002a, 2002b) were covered in some detail in Maor and Reddy (2004) and in Maor (2002). Four knowledge forms have been developed to summarize all owning and maintenance costs related to each of the various secondary and primary systems (Maor 2002).

Heuristic Knowledge of HVAC&R Systems

The HVAC-KBCD module developed for office buildings employs specific heuristic knowledge, such as factors for thermal zoning area calculations, design cooling, and heating load calculations along with domestic hot water load calculations.

The thermal zoning for office buildings assumes rectangular geometry for a typical floor, where the perimeter zone is a strip 15 feet from the exterior wall (ASHRAE 1999b; Knebel 1983). In order to simplify the numerical calculation in the KBES, we developed a linear regression model that correlates the percentage of the perimeter zone area to the total floor. The percent of the perimeter area from the total floor depends on the total area of the floor and the ratio of the floor length to the floor width. In order to perform regression analysis for perimeter area percentage, five sizes of rectangular office floor areas consistent with typical office building design practices were selected (15,000, 20,000, 25,000, 30,000, and 35,000 ft^2). Further, the following length to width ratios, 1.0:1, 1.7:1, 2.5:1, and 3.0:1, were chosen. Calculations were performed in order to determine perimeter zone percentages. The results for every floor size revealed that for small floorplates (15,000 ft^2 or less), the ratio of perimeter to total floor area ranges from 49% to 55% (1:1 to 3.0:1 ratio, respectively). On the other hand, for large floorplates (35,000 ft^2) the ratio of perimeter to total floor area ranges from 32% to 36% (1:1 to 3.0:1 ratio, respectively). These findings allow us to assume that the ratio of perimeter area to total floor area is more sensitive to the total

Table 9. List of HVAC-KBCD Primary Systems, Chillers, Subsystems, Components, and Variables Knowledge Forms

Electric Chiller Type	Summary	Chiller Efficiency	Chiller Number	Chiller Size	Evaporator Pump	Condenser Pump	Performance Curves	Cooling Tower	Secondary Pump
Centrifugal	E-CENT-SUM	E-CENT-EFF	E-CENT-CH#	E-CENT-SIZE	E-CENT-EVAPP	E-CENT-CONDP	E-CENT-PERFC	E-CENT-COOLT	E-CENT-SECPUM
WC-Rotary	E-ROTWC-SUM	E-ROTWC-EFF	E-ROTWC-CH#	E-ROTWC-SIZE	E-ROTWC-EVAPP	E-ROTWC-CONDP	E-ROTWC-PERFC	E-ROTWC-COOLT	E-ROTWC-SECPUM
AC-Rotary	E-ROTAC-SUM	E-ROTAC-EFF	E-ROTAC-CH#	E-ROTAC-SIZE	E-ROTAC-EVAPP	NA	E-ROTAC-PERFC	NA	E-ROTAC-SECPUM
Thermal Chillers									
Absorption	T-ABS-SUM	T-ABS-EFF	T-ABS-CH#	T-ABS-SIZE	T-ABS-EVAPP	T-ABS-CONDP	T-ABS-PERFC	T-ABS-COOLT	T-ABS-SECPUM
Gas Engine	GD-ROTWC-SUM	GD-ROTWC-EFF	GD-ROTWC-CH#	GD-ROTWC-SIZE	GD-ROTWC-EVAPP	GD-ROTWC-CONDP	GD-ROTWC-PERFC	GD-ROTWC-COOLT	GD-ROTWC-SECPUM
Total	5	5	5	5	5	4	5	4	5

Table 10. List of HVAC-KBCD Primary Systems, Boiler Knowledge Forms—Components

	Summary	Boiler Size/Efficiency	Boiler Pump
Electric Boiler	E-BOILER-SUM	E-BOILER-SIZE	E-BOILER-PUMP
Fuel Boiler	F-BOILER-SUM	F-BOILER-SIZE	F-BOILER-PUMP
Total	2	2	2

Table 11. List of HVAC-KBCD Primary Systems, DHW Knowledge Forms—Components

	Summary
Electric Heater	ELE-DHW-SUM
Fuel Heater	FUEL-DHW-SUM
Total	2

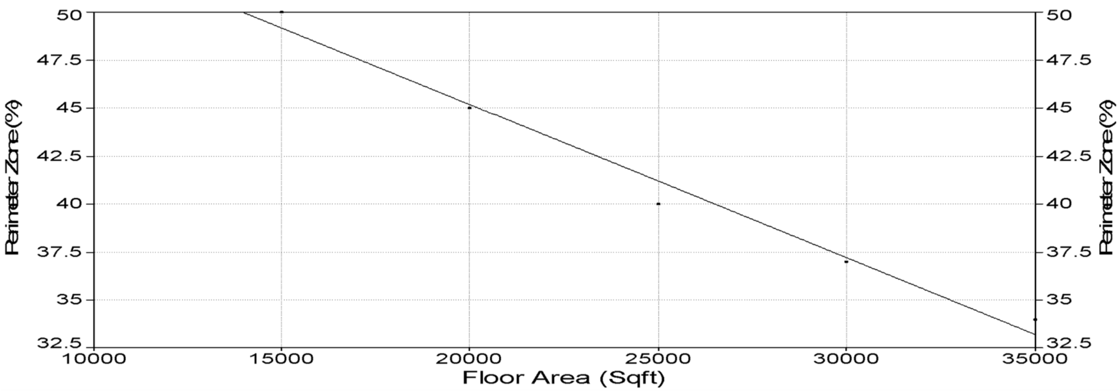

Figure 1 *HVAC-KBCD—Average perimeter zone percent area for typical office floor area.*

Table 12. HVAC-KBCD Perimeter Zone as Percent of Total Area for Typical Office Geometry

Length × Width 1.0: 1	Length × Width 1.7: 1	Length × Width 2.5: 1	Length × Width 3.0: 1	Average
48	50	51	53	50
42	44	47	50	45
38	39	42	44	40
35	36	38	40	37
32	33	35	36	34

floor area than to the length to width ratio (see Table 12). As a result, an average for every floorplate size has been used for the regression analysis (as shown in Figure 1).

The areas for perimeter zones and core zones can be calculated as follows:

Perimeter zones (ft^2):AP = (L * W) * {[61.2- (L * W)* 0.0008]/100}* N

Core zones w/o roof (ft^2): AC1= (L * W) * {[1-[(61.2- (L * W)* 0.0008)/100]}*(N-1)

Core zones w/ roof (ft^2): AC2= (L * W) * {[1-[(61.2- (L * W)* 0.0008)/100]}* 1

where N = number of floors, L = building length, and W = building width.

The total area of the building will be the sum of AP, AC1, and AC2. The design cooling and heating loads, airflow, and DHW factors for office buildings assumed in HVAC-KBDC are shown in Table 13.

Office Building KBES Initiation Rules

Initiation rules are in fact a set of site-specific constraints. Based on user responses to a set of questions or input data, the KBES initiates the process of system synthesis (see Figure 2). After responding to these questions, the first step is to select applicable secondary systems serving the perimeter zones. Next, matching rules identify all the secondary systems serving the cores that are compatible. After selecting all the secondary systems, the third step matches all the applicable secondary systems to applicable primary systems, based again

Table 13. HVAC-KBCD Office Building Cooling, Heating, Airflow, and DHW Factors

Cooling Load Factor (ft^2/ton)	**Value**
Perimeter (CLPF)	250
Core w/o Roof (CLC1F)	325
Core w Roof (CLC2F)	300
Heating Load Factor ((Btu/h) / ft^2)	**Value**
All office buildings (One value used for HLPF, HLC1F, HLC2F)	32.5
Air Flow Factor (CFM/ ft^2)	**Value**
Perimeter (AFPF)	1.5
Core w/o Roof (AFC1F)	1.0
Core w Roof (AFC2F)	1.2
Domestic Hot Water Factor ((Btu/h) / ft^2)	**Value**
All office buildings (DHWF)	2.5

Note:
(1) The values are averages for office buildings (from Bell 2000).
(2) The value for DHWF is calculated based on sizing data from a DHW vendor.
(3) The perimeter airflow factor is lower than the average (2.0). The lower airflow factor for perimeter zones reflects (i) the trend to minimize the envelope heat gains resulting from more stringent energy standards (ASHRAE-90.1 – 1999) and (ii) the lower heat gain in the north exposure. The value 1.5 CFM/ ft^2 shown for perimeter zones is the average of 2.0 CFM/ ft^2 (maximum) and 1.0 CFM/ ft^2 (minimum).

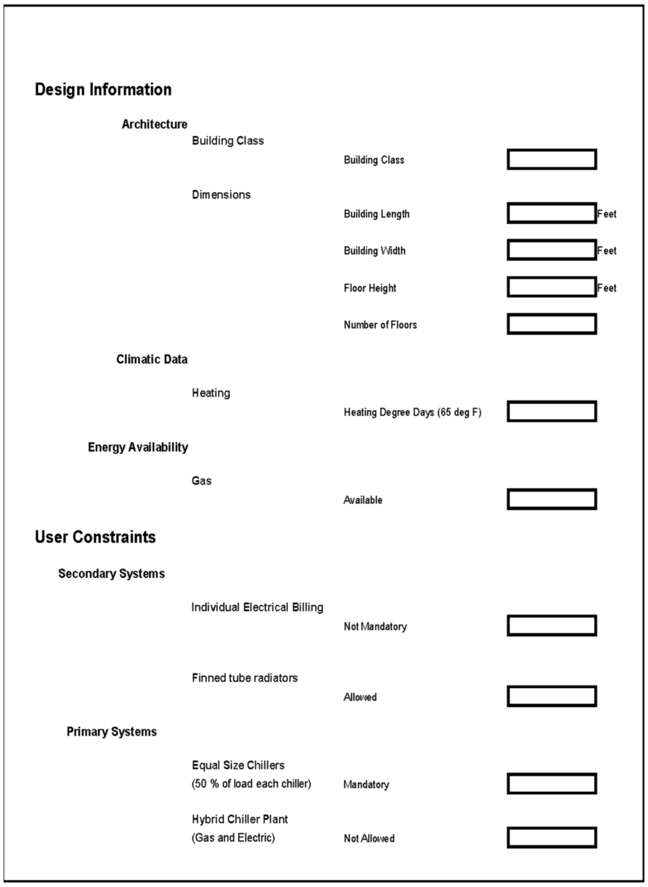

Figure 2 *HVAC-KBCD—initiation screen for office buildings.*

on site-specific constraints imposed to restrict the primary systems. The HVAC-KBCD module for office buildings include two set of rules. The first set includes six rules used for secondary perimeter system selection; the second set includes two rules used for chiller plant selection. These rules are summarized in Table 14.

As indicated earlier, initiation rules match the applicable perimeter secondary to the site constraint. These rules (as do the matching matrices described earlier) employ the same technique to encode the rules to the KBES. Two matching matrices have been developed, one for perimeter secondary systems with primary systems (Table 15) and another without primary systems (packaged). For example, if we have building class B, checking rule #1, Class_1 will yield “False.” This means that all the systems with “1” under the column “F” of the Rule Class 1 are applicable for this building. If the same building is, for example, an eight-story building, checking rule #2 will yield False; in that case, only systems with “1” in the column “F” under rule Floor_1 are applicable.

The *first rule* (Class_1 in Table 14) deals with office building class and has a major impact on the HVAC&R system synthesis. An office building class A requires maximum flexibility for future zoning changes, enhanced thermal zone control, more stringent acoustic requirements, etc. Typically, variable air volume (VAV) and packaged variable air volume (PVAV) can meet these requirements. Other secondary systems cannot meet all these requirements; therefore, only VAV and PVAV systems can be considered for class A office buildings. For class B office buildings, every system can be considered. If the user, while designing for class A, wants to explore systems that are not applicable for class A, he or she will be forced to input class B (even though the building is class A) in order to evaluate other systems. This approach is of educational value to inexperienced users.

The *second rule* (Floor_1) deals with the number of floors in the building. The number of floors has major importance when considering the building roof as a space for packaged rooftop HVAC&R equipment. Typically, packaged rooftop equipment can be considered for up to a five-story office building (Gause 1998). However, our professional experience indicates that some buildings with six stories have been equipped with rooftop equipment. Therefore, the maximum number of floors allowed for packaged secondary systems was assumed to be six instead of five. It is important to note that a WLHP secondary system is the only packaged system compatible with office buildings over six floors high.

The *third rule* (Climatic_1) deals with the climatic conditions of the building location as it applies to the selection of fin tube radiators or baseboards for perimeter zone heating. Typically, the decision to apply fin tube radiators or baseboard heaters depends on the heat loss from external walls or windows. If the heat loss exceeds 450 Btu/h per lineal foot of external wall or window, heat should be provided under the window or at the bottom of the wall (i.e., using radiators or baseboard heaters). If the heat loss is from 250 to 450 Btu/h per lineal foot, heat can be supplied under the window, at the bottom of the wall, by overhead diffusers located adjacent to the wall/window and discharging the air directly downward toward the window or the wall surface. If the heat loss is less than 250 Btu/h per lineal foot, heat can be supplied under the window, at the bottom of the wall, or by overhead diffusers located adjacent or slightly remote to the wall or window, discharging the air directly or indirectly downward toward the window or wall surface (Bell 2000).

The “border” between cold climate and mild climate zones is quantified by the number of HDD (65°F reference) of the building climatic location. The value used in the KBES is HDD = 4,000, which represents a lower bound requiring no more than 250 Btu/h heat loss per lineal foot in the perimeter envelope. In locations where HDD < 4,000, it will be difficult to justify (economically) radiators or baseboard heaters.

The *fourth rule* (Gas_1) deals with the availability of gas at the site for space heating and for gas-driven engine chiller. If gas is available, the KBES will consider all the heating systems that are powered by gas and electricity (electric heaters and electric hot water boilers).

Table 14. List of HVAC-KBCD Office Building Initiation Rules

Rule #	Rule Code	Condition to Test the Rule	TRUE	FALSE
1	Class_1	Building is class A	Building is Class A, Perimeter is VAV_P and PVAV_P only	Building is class B, allow for all perimeter subsystems
2	Floor_1	Number of Floors is <6	Number of Floors <6; use all perimeter secondary systems (with primary systems and packaged)	Floor >6. Use only secondary systems with primary systems and WLHP from packaged systems
3	Climatic_1	Heating degree-days <4,000	Heating degree <4000; perimeter systems will be without radiators	Heating degree >4000. Perimeter systems will be with radiators
4	Gas_1	Gas is available	Gas available; allow all combinations of chillers (hybrid systems), fuel boilers, and furnaces	Gas is not available; chiller plant will not have any absorption or gas engine chiller, fuel and gas heating. Only electric heating allowed.
5	Elec_Bill_1	Individual electricity billing is not mandatory	Yes, it is not mandatory; consider all secondary systems	No, it is not mandatory, Only WLHP allowed
6	Fin_tube_red 1	Finned tube radiators are not allowed	Yes, perimeter systems will be without radiators	No, perimeter systems will be with radiators
7	Chiller1	Need 50% of cooling capacity on each chiller	Apply only 50%, 50% cooling capacity in chiller plant	Apply 40%, 60%, and 50% cooling capacity in chiller plant
8	Chiller2	Allow hybrid chiller plant (gas and electric)	Apply both gas and electric chillers	Apply only electric chillers

Table 15. HVAC-KBCD Matching Matrix of Initiation Rules to Perimeter Secondary Systems w/ Primary Systems

Rules	Rule Class 1		Rule Floor 1		Rule Climatic 1		Rule Gas 1		Rule Elec Bill 1		Rule Fin Tube Red	
Rule Code	T	F	T	F	T	F	T	F	T	F	T	F
SZVT P 1	0	1	1	1	1	0	1	1	0	1	1	0
SZVT P 2	0	1	1	1	1	0	1	1	0	1	1	0
SZVT P 3	0	1	1	1	0	1	1	1	0	1	0	1
SZVT P 4	0	1	1	1	0	1	1	1	0	1	0	1
SZVT P 5	0	1	1	1	1	0	1	1	0	1	1	0
SZVT P 6	0	1	1	1	0	1	1	1	0	1	0	1
VAV P 1	1	1	1	1	1	0	1	1	0	1	1	0
VAV P 2	1	1	1	1	1	0	1	1	0	1	1	0
VAV P 3	1	1	1	1	0	1	1	1	0	1	0	1
VAV P 4	1	1	1	1	0	1	1	1	0	1	0	1
VAV P 5	1	1	1	1	1	0	1	1	0	1	1	0
VAV P 6	1	1	1	1	0	1	1	1	0	1	0	1
TPFC P 1	0	1	1	1	1	1	1	1	0	1	1	1
FPFC P 1	0	1	1	1	1	1	1	1	0	1	1	1

The *fifth rule* (Elec_Bill_1) allows the user to select systems that can charge electrical usage to the tenant directly. Even though several packaged rooftop units can be designed in a way that will allow individual billing, WLHP has been selected as the only system that will provide this capability due to its flexibility.

The *sixth rule* (Fin_tube_rad1) allows the user to be consistent with the third rule (Climatic_1) considering the utilization of radiators or baseboard heaters in cold climates. The sixth rule will not allow generation of solutions that are in conflict with the third rule. For example, if HDD > 4,000 and the user elects not to allow perimeter baseboard heaters, the KBES will not generate a solution. This feature will encourage the user to be more aware of the air diffusion system if he/she decides to use an overhead diffusion system for the perimeter zone. In order to override this restriction, the user must change the HDD to a value less than 4,000 (even though the local HDD may be greater than 4,000) and to disallow baseboard or radiators.

The *seventh rule* (Chiller_1) allows the user to specify two chillers of equal size (where each chiller provides 50% of the chiller plant capacity), or two chillers of unequal size. The selection can be 40% or 60% of the chiller plant total cooling capacity. This strategy allows the user to optimize chiller plant operation where the smaller chiller (the 40% chiller) will run more efficiently at low-load condition compared to a 50% chiller. The 60%/40% split is considered to yield (as closely as possible) equal systems, which is good design practice from both a hydraulic and system reliability standpoint.

The *eighth rule* (Chiller_2) allows the user to select only electric chillers or a hybrid chiller plant (electric and gas) as long as gas is available (rule 4). In some cases, the designer is reluctant to use gas-driven engine chillers due to reasons such as availability of service, professional preference, etc., even if gas is available at the site.

These rules have been found to be sufficient in order to initiate the process of synthesizing HVAC&R systems.

CASE STUDY

To illustrate the overall procedure of conceptual design using the HVAC-KBCD module, we will present a case study of an office building and test the efficacy of the prototype HVAC-KBCD by evaluating the ability of the KBES to generate a large number of feasible design alternatives in a form that can be transferred to the DOE-2.1 E building simulation program, while estimating the owning cost and maintenance cost. The reader can also refer to Maor (2002) for another case study involving testing the response of the KBES to various initiation rules and how these rules affect the number of the design alternatives generated.

Objectives

Since only minimal information about this building, located in Dallas, Texas, is available, assumptions (typical for office buildings in general) will be made in order to carry out the analysis. The process of evaluation will consist of generating design alternatives by the HVAC-KBCD along with owning and maintenance costs and then performing the energy building simulation on these alternatives to obtain estimates of the annual energy use and associated cost. LCC analysis can thus be performed.

Description of Building and Criteria

Building name:	Office Building 1
Location:	Dallas, Texas
Office building class:	A
Total area:	180,000 ft^2
Geometry:	Rectangular (200 ft × 100 ft)
Number of floors;	9
Typical floor height:	14 ft
Fenestration% of wall:	50%
Energy standard criteria:	ASHRAE-90.1-1999 envelope, HVAC&R, DHW, Lighting, Electrical

Electricity provider / rate: large commercial and industrial energy plan shown below:

Charge	Amount	
Demand Charge	For November-May $5.00 / kW	For June-October $5.00 / kW
Consumption Charge	For November-May $0.05 / kWh	For June-October $0.09 / kWh
Monthly Standing Charge	$100.00	

Gas:	Available at $0.31521/therm.
Heating degree-days:	2,259 (ASHRAE-90.1 –1999)

- Radiators or baseboard heaters are inadmissible (user constraint, due to moderate winter).
- No individual billing (developer constraint).
- Chiller plant will use two chillers of equal size (designer preference).
- Hybrid chiller plant (electric and gas) allowed (designer desires to explore this option).

The designer would like to evaluate the following alternatives:

1. Ten promising HVAC&R systems based on owning (first) cost sorted from the lowest to the highest.
2. Ten promising HVAC&R systems based on annual energy operating cost sorted from the lowest to the highest.
3. Ten promising HVAC&R systems based on life-cycle cost (LCC) where the LCC is determined assuming 10% interest rate and 20-year system life.

Results and Discussion

The HVAC-KBCD system (for system synthesis, owning and maintenance costs) and the DOE 2.1 E building simulation program (for annual energy cost analysis) generated 45 feasible HVAC&R systems for this office building. We would like to limit ourselves to the ten most promising configurations. The design alternatives can be sorted by the first cost, annual energy cost, or LCC. It was decided to use LCC, and the corresponding results are shown in Table 16.

From Table 16, we can identify solutions 28, 37, 19, 33, 34, 42, 43, 24, 25, and 32 as the design alternatives with the lowest first cost. All of these solutions utilize electric heat to heat the building. The main air-handling units for the VAV systems, in some cases, are equipped with hot water heating coils and heating plant equipped with gas-fired hot water boiler (BOP_FUEL). It is important to point out that the majority of the heating is done at the zone level. The heating in the air-handling unit is insignificant given that in this location (Dallas) the heating needs for outside air are extremely low. The chiller plant options selected (CHP 1, 17, 18, and 19) represent the lowest cost requirements. CHP 1 is a plant equipped with two water-cooled screw chillers; CHP 17 represents two water-cooled centrifugal chillers; CHP 18 represents two water-cooled chillers, the first screw and the second centrifugal; and CHP 19 is identical to CHP 18 but with the operating sequence reversed.

Table 16. Office Building 1—Results Sorted by Life-Cycle Cost

	Configurations - Codes									
	Secondary Systems			Primary Systems				Total Maint. Cost	Total Energy Cost	
Alt#	Perimeter 1-8	Core 1	Core 2	Chiller Plant	Boiler Plant	DHW	Total First Cost $	Annual $	Annual $	Life-Cycle Cost $
13	VAV_P1	VAV_C11	VAV_C22	CHP_10	BOP_FUEL	DHW_ELE	2,683,940	52,169	223,390	5,389,419
4	VAV_P1	VAV_C11	VAV_C21	CHP_10	BOP_FUEL	DHW_ELE	2,693,409	52,169	223,128	5,396,317
18	VAV_P1	VAV_C11	VAV_C22	CHP_21	BOP_FUEL	DHW_ELE	2,703,784	53,023	223,387	5,417,619
9	VAV_P1	VAV_C11	VAV_C21	CHP_21	BOP_FUEL	DHW_ELE	2,713,253	53,023	223,124	5,424,506
15	VAV_P1	VAV_C11	VAV_C22	CHP_18	BOP_FUEL	DHW_ELE	2,582,606	47,120	259,385	5,591,919
6	VAV_P1	VAV_C11	VAV_C21	CHP_18	BOP_FUEL	DHW_ELE	2,592,076	47,120	259,120	5,598,786
14	VAV_P1	VAV_C11	VAV_C22	CHP_17	BOP_FUEL	DHW_ELE	2,602,451	47,974	257,814	5,604,723
5	VAV_P1	VAV_C11	VAV_C21	CHP_17	BOP_FUEL	DHW_ELE	2,611,920	47,974	257,549	5,611,591
31	VAV_P2	VAV_C11	VAV_C22	CHP_10	BOP_FUEL	DHW_ELE	2,596,071	52,169	255,900	5,620,739
40	VAV_P5	VAV_C12	VAV_C23	CHP_10		DHW_ELE	2,596,071	52, 169	255,900	5,620,739
22	VAV_P2	VAV_C11	VAV_C21	CHP_10	BOP_FUEL	DHW_ELE	2,605,540	52,169	255,848	5,629,698
36	VAV_P2	VAV_C11	VAV_C22	CHP_21	BOP_FUEL	DHW_ELE	2,615,915	53,023	255,897	5,648,938
45	VAV_P5	VAV_C12	VAV_C23	CHP_21		DHW_ELE	2,615,915	53,023	255,897	5,648,938
27	VAV_P2	VAV_C11	VAV_C21	CHP_21	BOP_FUEL	DHW_ELE	2,625,385	53,023	255,845	5,657,897
10	VAV_P1	VAV_C11	VAV_C22	CHP_1	BOP_FUEL	DHW_ELE	2,562,762	46,266	269,713	5,665,091
1	VAV_P1	VAV_C11	VAV_C21	CHP_1	BOP_FUEL	DHW_ELE	2,572,232	46,266	269,448	5,671,959
16	VAV_P1	VAV_C11	VAV_C22	CHP_19	BOP_FUEL	DHW_ELE	2,582,606	47,120	269,377	,690,022
7	VAV_P1	VAV_C11	VAV_C21	CHP_19	BOP_FUEL	DHW_ELE	2,592,076	47,120	269,112	5,696,889
17	VAV_P1	VAV_C11	VAV_C22	CHP_20	BOP_FUEL	DHW_ELE	2,703,784	53,023	256,528	5,743,002
8	VAV_P1	VAV_C11	VAV_C21	CHP_20	BOP_FUEL	DHW_ELE	2,713,253	53,023	256,263	5,749,870
33	VAV_P2	VAV_C11	VAV_C22	CHP_18	BOP_FUEL	DHW_ELE	2,494,738	47,120	285,927	5,764,643
42	VAV_P5	VAV_C12	VAV_C23	CHP_18		DHW_ELE	2,494,738	47,120	285,927	5,764,643
24	VAV_P2	VAV_C11	VAV_C21	CHP_18	BOP_FUEL	DHW_ELE	2,504,207	47,120	286,256	5,777,343
32	VAV_P2	VAV_C11	VAV_C22	CHP_17	BOP_FUEL	DHW_ELE	2,514,582	47,974	284,481	5,778,675
41	VAV_P5	VAV_C12	VAV_C23	CHP_17		DHW_ELE	2,514,582	47,974	284,481	5,778,675
23	VAV_P2	VAV_C11	VAV_C21	CHP_17	BOP_FUEL	DHW_ELE	2,524,051	47,974	284,810	5,791,375
12	VAV_P1	VAV_C11	VAV_C22	CHP_9	BOP_FUEL	DHW_ELE	2,683,940	52,169	266,617	5,813,829
3	VAV_P1	VAV_C11	VAV_C21	CHP_9	BOP_FUEL	DHW_ELE	2,693,409	52,169	266,352	5,820,696
28	VAV_P2	VAV_C11	VAV_C22	CHP_1	BOP_FUEL	DHW_ELE	2,474,893	46,266	295,538	5,830,776

Table 16. Office Building 1—Results Sorted by Life-Cycle Cost *(continued)*

Alt#	Configurations - Codes						Total First Cost $	Total Maint. Cost Annual $	Total Energy Cost Annual $	Life-Cycle Cost $
	Secondary Systems			Primary Systems						
	Perimeter 1-8	Core 1	Core 2	Chiller Plant	Boiler Plant	DHW				
37	VAV_P5	VAV_C12	VAV_C23	CHP_1		DHW_ELE	2,474,893	46,266	295,538	5,830,766
19	VAV_P2	VAV_C11	VAV_C21	CHP_1	BOP_FUEL	DHW_ELE	2,484,363	46,266	295,867	5,843,476
34	VAV_P2	VAV_C11	VAV_C22	CHP_19	BOP_FUEL	DHW_ELE	2,494,738	47,120	295,190	5,855,589
43	VAV_P5	VAV_C12	VAV_C23	CHP_19		DHW_ELE	2,494,738	47,120	295,190	5,855,589
25	VAV_P2	VAV_C11	VAV_C21	CHP_19	BOP_FUEL	DHW_ELE	2,504,207	47,120	295,519	5,868,288
35	VAV_P2	VAV_C11	VAV_C22	CHP_20	BOP_FUEL	DHW_ELE	2,615,915	53,023	283,243	5,917,425
44	VAV_P5	VAV_C12	VAV_C23	CHP_20		DHW_ELE	2,615,915	53,023	283,243	5,917,425
26	VAV_P2	VAV_C11	VAV_C21	CHP_20	BOP_FUEL	DHW_ELE	2,625,385	53,023	283,409	5,928,524
30	VAV_P2	VAV_C11	VAV_C22	CHP_9	BOP_FUEL	DHW_ELE	2,596,071	52,169	292,617	5,981,232
39	VAV_P5	VAV_C12	VAV_C23	CHP_9		DHW_ELE	2,596,071	52,169	292,617	5,981,232
21	VAV_P2	VAV_C11	VAV_C21	CHP_9	BOP_FUEL	DHW_ELE	2,605,540	52,169	292,783	5,992,331
11	VAV_P1	VAV_C11	VAV_C22	CHP_2	BOP_FUEL	DHW_ELE	2,713,764	43,632	296,445	6,052,691
2	VAV_P1	VAV_C11	VAV_C21	CHP_2	BOP_FUEL	DHW_ELE	2,723,233	43,632	296,180	6,059,559
29	VAV_P2	VAV_C11	VAV_C22	CHP_2	BOP_FUEL	DHW_ELE	2,625,895	43,632	320,230	6,198,347
38	VAV_P5	VAV_C12	VAV_C23	CHP_2		DHW_ELE	2,625,895	43,632	320,230	6,198,347
20	VAV_P2	VAV_C11	VAV_C21	CHP_2	BOP_FUEL	DHW_ELE	2,635,365	43,632	320,559	6,211,047

Solutions 9, 4, 18, 13, 27, 22, 36, 45, 31, and 40 are the design alternatives with the lowest annual energy cost. The lowest energy cost solution is a gas-driven chiller and gas zone heating (in place of electricity, which was shown previously to be the lowest first cost solution). The availability of cheap natural gas and a constant electrical demand charge (regardless of the time of day and season) make the gas-cooling option the most energy cost-effective system for this building. All the ten solutions with the lowest energy cost utilize a hybrid chiller plant, where the gas-driven chiller is always the lead chiller and the electric chiller is the second. The second electric chiller can be a water-cooled centrifugal chiller or screw (CHP 21 and CHP 10, respectively). The solutions with CHP 21 have a low operating cost since the centrifugal chiller is more efficient. However, the difference is insignificant (less then $5), demonstrating that the gas-driven chiller does the majority of cooling. The all-electric chiller plant, shown as solution number 5 with CHP 17, demonstrates that for all-electric chiller plants, two centrifugal chillers are the most energy cost-effective.

LCC analysis incorporates first cost as well as annual energy and maintenance costs into one value representing the owning and operating cost for the system's lifetime. LCC analysis demonstrates that from the ten selected systems, six systems (13, 4, 18, 9, 31, and 40) utilize a hybrid chiller plant and four systems utilize all-electric chiller plants (15, 6, 14, 5). Most of the systems (the first eight systems) utilize natural gas for heating and only the last two systems use electricity for heating. Another interesting finding is that the most cost-effective solution from an LCC standpoint utilizes a hybrid chiller plant, gas heating (with hot water) for the perimeter zones, air-handling units, and electric zone reheat for the core in the upper floor. Figure 3 demonstrates how LCC, first, and annual energy costs vary among the 45 design configurations.

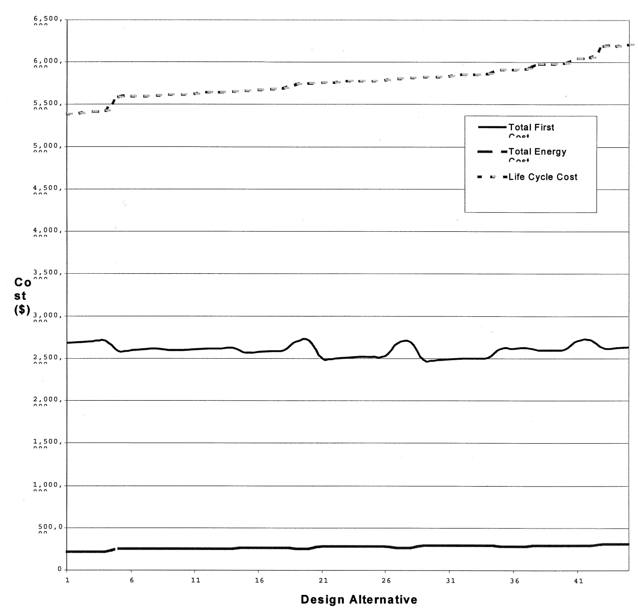

Figure 3 *Office Building 1—life-cycle, first, and energy costs—all 45 solutions.*

SUMMARY

The companion paper (Maor and Reddy 2004) addressed the HVAC&R conceptual design problem (or the selection of the HVAC&R design concept) and the limitations of current conceptual design procedures. It focused on the elicitation and development of methodologies and knowledge to be incorporated and represented in a KBES. In parallel with knowledge elicitation and generation, a commercial KBES shell was selected as the HVAC-KBCD prototype. This software was used to demonstrate the efficacy of the methods developed.

This paper is the demonstration of the concepts and methodologies described previously using the prototype KBES. One case study involving the conceptual design of an office building was selected for the demonstration. It served to demonstrate how the KBES can be employed as a design assistant to generate and evaluate a large number of design alternatives to select promising HVAC&R systems. The HVAC-KBCD can be easily expanded to handle other building applications, such as schools, hotels, retail stores, etc. The ultimate goal is to provide the building designer a tool whereby, upon simply specifying certain initiation data, the KBES automatically synthesizes and evaluates the feasible solutions by sorting them according to a pre-specified criterion (such as LCC). As in the office building application, every other application has its own characteristics in terms of architecture, operating schedules, typical cooling and heating loads, applicable HVAC&R systems, etc. All these characteristics can be explored and incorporated into the HVAC-KBCD, resulting in new sets of applicable HVAC&R systems and application-specific heuristics.

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