Literature Review of Artificial Intelligence and Knowledge-Based Expert Systems in Buildings and HVAC&R System Design

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ABSTRACT

Building and HVAC&R design professionals are being required to evaluate numerous design alternatives and properly justify their final conceptual selection. This trend, coupled with the retirement of experienced designers, increasing complexity of energy price structure, and unwillingness of clients and building owners to commit additional funds to the design phase itself, can only be satisfied by approaching the conceptual design process in a more scientific, comprehensive, and rational manner as against the current empirical, and often ad hoc, approach. Knowledge-based expert systems (KBES) offer a promising solution to this problem of conceptual design. Numerous KBES studies are available in the ASHRAE and allied literature that relate to areas such as diagnostics, energy consumption analysis, maintenance, and operation. Relatively little exists in using knowledge-based systems for HVAC&R conceptual design. This paper consists essentially of two sections: a background on artificial intelligence (AI) methods and a literature review of KBES applied to engineering design. The purpose of this literature review is not to cover all areas where KBES can be applied but to focus on the specific area of conceptual design involving synthesis of HVAC&R components. A subsequent paper will present and illustrate a new methodology based on a combination of KBES and algorithmic tools that allows the rational conceptual design and selection of secondary and primary components of HVAC&R systems.

OBJECTIVE AND SCOPE

The *2000 ASHRAE Handbook—HVAC Systems and Equipment* (ASHRAE 2000) in its first page states that "Few projects allow detailed quantitative evaluation of all alternatives… common sense, historical data and subjective experience can be used to narrow choices to one or two potential systems." With the increasing complexity of energy price structure, energy standards, and the availability of an arsenal of systems and components, common sense and subjective experience are very often inadequate to generate proper design alternatives. In addition, clients and owners are increasingly requiring that a more comprehensive approach to HVAC&R system selection be adopted while being unwilling to commit more funds to the conceptual design process. The current availability of high speed/low cost computers, user-friendly building energy simulation programs, well-defined energy standards such as ANSI/ASHRAE/IESNA 90.1-2001 (ASHRAE 2001), and the advancement of artificial intelligence (AI) tools and methodologies allows the possibility of satisfying the current and the future needs for quick, reliable, and accurate generation and evaluation of HVAC&R system design alternatives during the conceptual design.

A certain number of AI papers applied to the HVAC&R field were published in the late 1980s and early 1990s (ASHRAE 1995). Most of these papers addressed the issues of diagnostics and proper operation of existing buildings and facilities. Relatively less focus was given to conceptual design as testified by the far fewer papers in this area. Subsequently, and in keeping with the general trend of the scientific and engineering community, the HVAC&R industry seemed to have lost interest in this approach. However, the enormous strides made by information technology in the past few years have led to a resurgence of interest in the use of AI in all disciplines of engineering. Knowledge-based expert systems (KBES) hold renewed promise both in terms of diagnostics and design integration, the latter being the primary focus of this paper.

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The traditional KBES approach involves using the knowledge engineer to interact with the domain expert in order to extract the knowledge and encode it into the KBES shell or program. This approach was found to be inefficient due to the lack of understanding of the domain by the knowledge engineer. With the availability of user-friendly KBES shells, the domain expert can easily be trained to utilize these shells and directly encode the knowledge, resulting in a more efficient process and a more reliable system. It will be noted that the knowledge does not necessarily involve direct human expertise; knowledge can be acquired from books, manuals, standards, case studies, etc.

This paper consists of essentially two sections: a background on artificial intelligence (AI) methods, and a literature review of KBES applied to engineering design. The background section covers definitions, different search methods, different methods to represent knowledge, a background of different types of associated tools, and an introduction to engineering design models. Although there is a large body of literature dealing with integration of AI methods and design in engineering domains such as civil engineering, computer engineering, and manufacturing, less exists in the area of HVAC&R system design. This lack of information in the HVAC&R domain forced us to explore other engineering domains that have similarities to the HVAC&R domain from the design approach standpoint. The second portion of this paper presents a detailed literature review, along with summary tables, organized in three sections: (1) AI and KBES applied to civil engineering design, (2) AI and KBES applied to energy systems design, and (3) AI and KBES applied to HVAC&R systems design.

BACKGROUND REVIEW OF AI METHODS

Definitions

It is appropriate to start by recalling some of the basic definitions of AI terms. Russell and Norvig (1995) propose grouping AI systems into four categories: (1) systems that think like humans (approach centered around humans), (2) systems that act like humans (approach centered around humans), (3) systems that think rationally (approach centered around rationality), and (4) systems that act rationally (approach centered around rationality). *Artificial intelligence is the enterprise of constructing a physical-symbol system (or an inorganic man-made artifact such as a computer) that can reliably pass the Turing test* (Ginsberg 1993). The Turing test is a behavioral test for intelligence (proposed by Alan Turing) that is based on whether or not the artifact (commonly, a computer) can be programmed well enough to have a five-minute conversation with an interrogator and have a 30% chance of fooling the interrogator. Trying to construct systems as defined above is too complex and can be considered a long-term goal. As a result, current AI researchers have tended to focus their efforts on the more limited problem of mimicking the human thinking process or activity. This effort comprises two main areas:

1. *Knowledge representation* is the study of finding the language in which knowledge can be encoded and used by a machine. Knowledge representation in AI is intended to reduce problems of intelligent action to a search problem (Ginsberg 1993). The integration of search and knowledge representation is considered to be the core of AI.
2. *Search* is a method of solving a problem by examining a large number of possibilities and identifying one (or a small number of) solution(s) during the search. In actual applications, the number of possibilities (or the search space) is extremely large, which makes the search intractable and computationally demanding. Methods such as heuristics search (wherein one uses existing knowledge) provide practical solutions to this problem.

We have used material from several sources (Liebowitz 1997; Dym 1994; Sriram 1997) to create Figure 1, which summarizes the various methods used in AI areas in the form of a flow chart. We note that there are eight different generic approaches: (1) problem solving and planning, (2) natural language and processing, (3) robotics, (4) knowledge-based systems (KBES), (5) computer vision, (6) learning, (7) genetic algorithms, and (8) neural networks. KBES engineering design is the primary focus of this review. This, in turn, has been applied in seven different areas, within which engineering/manufacturing is of direct relevance to us. Further, the applications area can be grouped in two categories: (a) formation problems that are concerned with design (Sriram 1997) and (b) derivation problems that are concerned with operation and maintenance. Finally, we divide the design category into "routine" and "innovative" (Dym 1994).

Search Methods

The search process is the final step to obtaining the solution to a problem. Search can be described diagrammatically as a tree (see Figure 2). The main objective is to find a path from the starting node (i) to the goal node (g) by searching the entire search space using a preselected search procedure. In order to save space, the computer does not store the entire search space. It starts from the initial node (i) and moves in the search space by producing new nodes at different levels represented by $d = 1,2,3$ and using these new nodes to continue the search until the goal node (g) is reached.

The most common search methods are *blind search* and *heuristic search*. The difference between the two methods is the fact that while heuristic search makes use of domain-specific knowledge (i.e., rules of thumb) to make the search more efficient, blind search does not exploit domain-specific information. How the next step in the search tree is selected by using blind search depends only on the current node's position, while heuristic search makes use of specific domain information in deciding on the next step to take.

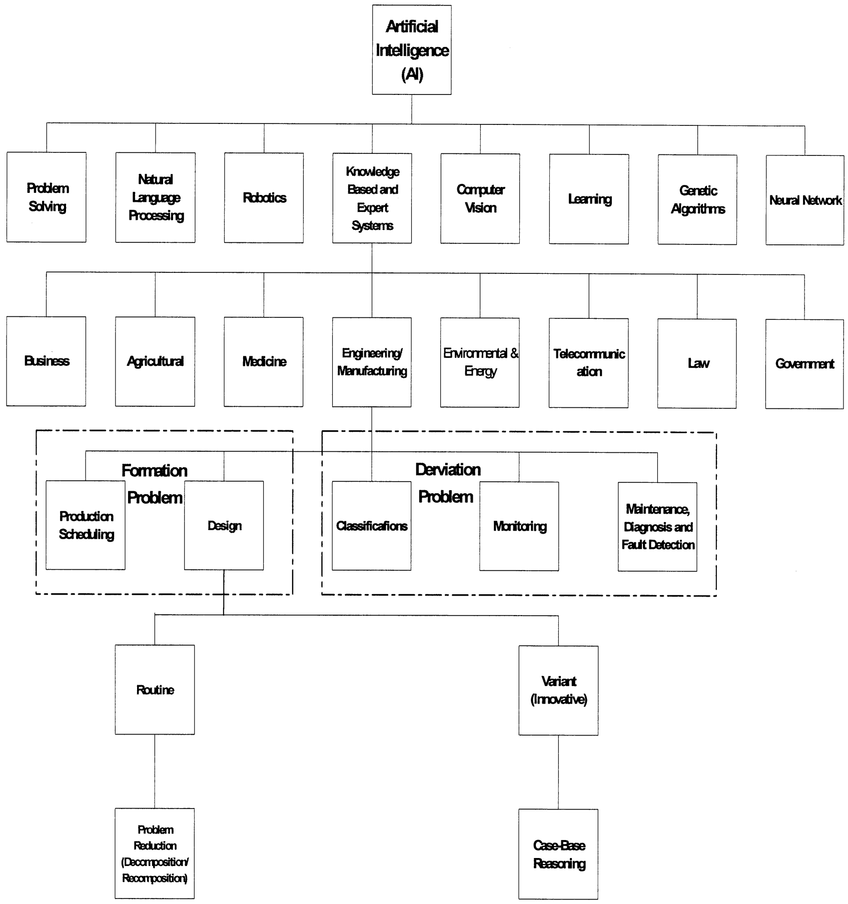

Figure 1 *Categories of AI applications (note that "Creative Design" is not shown.*

Blind (Uninformed) Search. The most common blind search techniques are: (1) depth-first search (DFS) and (2) breadth-first search (BFS). In DFS, the expansion is always to the depth of the search tree that results in a generation of nodes only one level below the current level. The search continues till no further nodes can be generated, at which instance the algorithm goes back to the parent node and explores new nodes. In BFS, the expansion is always breadthwise. The nodes are generated and tested for the entire width of the search space at each depth level before moving on to the next depth level.

The use of any method depends on the application and the depth of the search tree. The search is said to be efficient when a minimum number of possible nodes in the search tree are identified, with the number of nodes being dictated by the size of the computer memory and the computing time. DFS is efficient when more than one acceptable solution exists, and so the search can be terminated once the first solution is discovered. BFS is efficient when the search tree is very deep. Unconstrained DFS and BFS methods require massive computer resources and, in order to make the search feasible, a procedure that will constrain the size of the search tree is required.

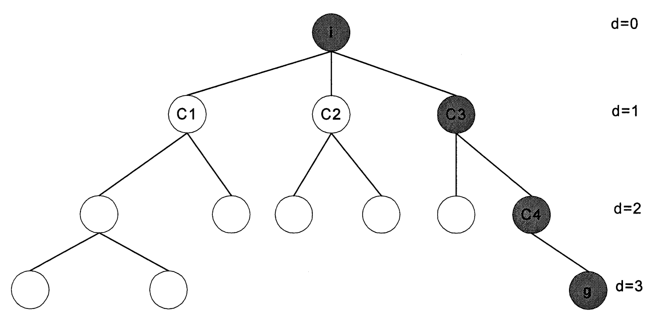

Figure 2 *Conceptualization of the search process.*

Heuristic (Informed) Search. The previous section presented search methods that systematically search for solutions by generating nodes (or states) and then testing them against a preset goal. Without a mechanism that reduces the search space, the search can be extremely large, which, in turn, will make the search inefficient, if not impossible. Heuristic search provides a solution to this problem. Heuristic search can be defined as a "guided" search toward the region where acceptable solutions exist by applying domain-specific knowledge. Heuristic search methods can be grouped as best first search (BFS), memory bound search, and iterative improvement algorithms. These methods can find solutions more efficiently and can also be used to solve optimization problems.

Knowledge Representation

As shown in the previous sections, the role of knowledge representation is to reduce or transform an intelligent action problem into a search problem. A typical computer sequence used to solve an intelligent action problem involves the following steps: (1) identifying and acquiring the knowledge required for the problem, (2) selection of the language that will be used to encode the knowledge, (3) using the language to represent the knowledge, and (4) implementation of the encoded knowledge to solve the problem (namely, the search process). Items 1-3 can be defined as the knowledge representation (and acquisition) stage. The most common methods for knowledge representation are production systems, semantic networks, and frames (Durkin 1994).

Production Systems. Production systems, which are one of the most popular knowledge representation methods, are built from a group of rules where every rule consists of an antecedent-consequents pair. The antecedents specify the set of conditions while the consequents specify a set of actions. A typical rule as applied to an air handler can be presented as follows:

IF the airflow of a system varies as a function of the space cooling sensible load,

AND the zone supply air temperature remains constant, (Note: the AND is normally heuristic)

THEN the air system is a variable air volume constant temperature system.

Semantic Network. A semantic network is made of sets of nodes that represent concepts, objects, events, and links that connect the nodes semantically. A semantic network in which the links are labeled is called an IS-A network. A semantic network provides the flexibility to add nodes and links whenever needed, while providing the property of "inheritance," which is the ability of each node to inherit the properties of its connected node. Figure 3 shows an example of a simple IS-A semantic network for an HVAC&R system as applied to a fan coil unit. The decomposition tree organizes the static knowledge in a hierarchical manner depicting how various components can be linked to form a specific system.

Frames. Frame-based knowledge representation is a natural continuation of the semantic network knowledge representation. The semantic network seems to have been superseded by the frame-based knowledge representation due to its richness, the more complex knowledge representation capability, and its conceptual similarity to object-oriented programming (OOP).

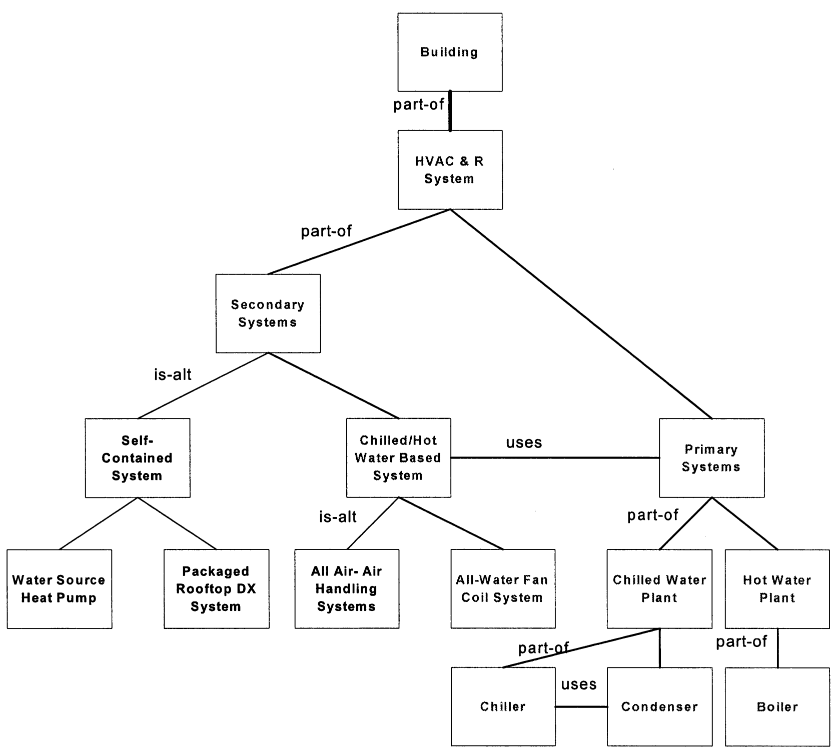

Figure 3 *Example of semantic network knowledge representation in HVAC&R design alternative involving a fan coil system.*

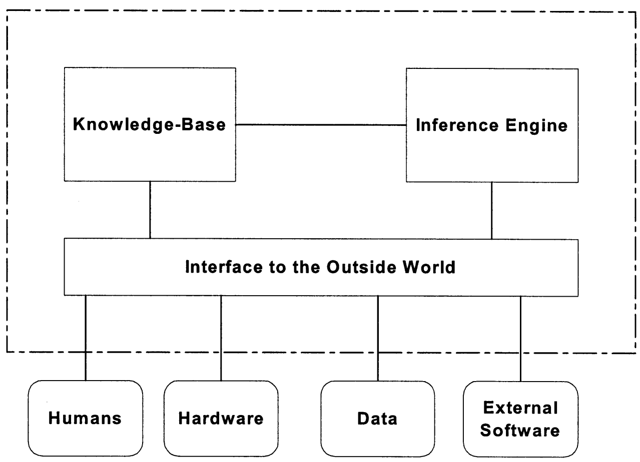

Figure 4 *Typical structure of a knowledge-based system.*

In frame-based knowledge representation, the knowledge is represented in data structures called *frames* (or *objects*), with every frame having a number of *attribute* descriptors called *slots*. Slots can be one of two types, *abstract* or *concrete*. A concrete slot contains a specific value; for example, in "plant cooling capacity" = 1,000 ton: The value 1,000 is associated with the slot of "cooling capacity" of the frame "chilled water plant."

An abstract slot may contain any possible value for the slot. For example, the slot "cooling capacity" can include a description of where to obtain the information (from other slots) or be used to activate an attached and dormant function or program (called *demons*) that will calculate the cooling capacity. The slots can be relational as well—this type of slot contains relational information between frames. For example, the frame "chilled water plant" can have a slot called "part-of," which can take the value of "primary system," which is the name of another frame. Relational slots provide a mechanism for defining a network of frames where the relational slots are the links as described in the section of semantic networks. Another advantage of this method is the hierarchical organization of the knowledge base that can be exploited by using inheritance as an inference mechanism. In order to develop knowledge-based systems for real life applications, a combination of several knowledge representation methods may be required, for example, production systems and frame-based methods.

Knowledge-Based Systems (KBS)

Background. Knowledge-based systems (KBS) are one area within the family of AI applications. KBS include expert systems (KBES) and other problem-solving methods where a knowledge base and search mechanisms are incorporated in order to perform tasks such as design synthesis and design evaluation. The main difference between KBS and conventional (procedural) programs lies in the structure. Conventional programs are characterized by intertwining the domain knowledge and the software that controls the application of the knowledge. In KBS, the knowledge base (or the encoded knowledge represented by one of the methods described earlier) is totally separated from the control process or inference (or search); this explicit separation of the knowledge from the control makes it easier for future addition of new knowledge. A typical KBS is shown in Figure 4.

KBES Description and Problem Types. A knowledge-based expert system (KBES) is a computer program designed to mimic a human expert in a particular specialized domain. Normally, the user will start a dialogue in which he or she describes the problem and the expert system provides solutions or recommendations by guiding the user through a series of questions. A typical KBES consists of a knowledge base, an inference engine, and an interface to the user. The development typically includes the following stages:

1. Problem statement and knowledge analysis.
2. Classification of the problem type (e.g., monitoring, diagnosis, planning, design, etc.) to derivation or formation problem.
3. Selection of problem-solving strategy (search centered, knowledge centered, and their subgroups such as goals and data or abstractions, etc.).
4. Selection of the knowledge type (heuristics, quantitative, etc.).
5. Selection of KBES tools for knowledge representation such as rule-based or object-oriented (traditional languages, single paradigms, hybrid paradigms, commercial shell).
6. Knowledge acquisition, representation, and encoding.
7. Prototype development.
8. Verification and validation.
9. Implementation and maintenance.

Sriram (1997) defines two distinct groups of problems solved by KBES.

1. **Derivation**—where the problem conditions are parts of the solution and the knowledge base is used to complete the solution. Diagnosis is a good example for this type of problem where the diagnostician relates symptoms to an appropriate fault, and the KBES provides a solution.
2. **Formation**—where the problem conditions are given in the form of properties that a solution (or solutions) must satisfy. The solution (or solutions) normally does not exist in the knowledge base; however, the solution (or solutions) can be generated by utilizing knowledge from the knowledge base. Design problems and design synthesis are classic examples of these types of problems.

KBES Applications. Typical Applications of KBES are: (1) control-governing systems to meet specifications; (2) design-configuration of components; (3) diagnosis- reasoning of system malfunction; (4) planning-selection of sequencing of activities; (5) scheduling-resource assignments; (6) selection-selection of best choice among several options; and (7) monitoring-comparison of observations to expectations (Liebowitz 1997).

Problem Solving (PS) Techniques. As described earlier, problem solving can be considered as a search for a solution by examining a large number of possibilities. Sriram (1997) classifies the problem-solving techniques as search-centered techniques and knowledge-centered techniques. Search methods covered previously were blind search and heuristic search. In addition, methods like genetic algorithms and simulated annealing belong to this group. Knowledge-centered methods include goals and data (forward-chaining, backward-chaining), abstractions (hierarchical refinement, heuristic-inc-gen-test), and others. Detailed descriptions of these methods can be found in Sriram (1997).

KBES Tools. A KBES tool can be written in traditional languages such as FORTRAN, C, LISP; single knowledge representation languages such as OPS5 (rule-based), PROLOG (logic-based), and SMALLTALK (frame-based); and hybrid knowledge representation languages that combines several knowledge representation languages in one framework such as KEE and KAPPA (rule-base, frame-base, and procedural). Using a language provides flexibility during the development. However, the disadvantage is that all the subsystems must be developed that includes the inference engine and the interface. Expert systems tools (or shells) are more popular for KBES development (45% of the market according to Liebowitz [1997]). A KBES shell is a program with an inference engine, interface facility, and empty knowledge base. The task of the developer is only to acquire the knowledge and to encode it using the knowledge representation system used by the shell.

The traditional KBES approach involves using the knowledge engineer to interact with the domain expert in order to extract the knowledge and encode it into the KBES shell or program. This approach was found to be inefficient due to the lack of understanding of the domain by the knowledge engineer. With the availability of user-friendly KBES shells, the domain expert can easily be trained to utilize these shells and directly encode the knowledge, resulting in a more efficient process and a more reliable system. It will be noted that the knowledge does not necessarily involve direct human expertise; knowledge can be acquired from books, manuals, standards, case studies, etc. KBES development techniques are well documented and can be found in such books as Liebowitz (1997) and Tzafestas (1993).

ENGINEERING DESIGN MODELS

Engineering design involves mapping of a specified function onto a description of a realizable physical structure (Tong and Sriram 1992). The desired function is what the artifact is designed to perform. The physical structure is a set of parts or subsystems combined together to perform the function. In order to have a feasible system, the physical structure must be capable of being assembled or fabricated.

One measure for classifying design tasks is the availability of methods and knowledge to perform the design tasks. From an AI standpoint, the design process can be characterized as a search through a space of alternative designs where synthesis tools help to generate new points in the design space and analysis tools are used to evaluate the alternatives for correctness and quality.

If the methods and the knowledge to generate and select the optimal solution exist, the design can be classified as a *routine* design. Here, we know in advance everything we need to complete the design (Dym 1994). "Everything "in this context means that (1) we have the domain knowledge, or that we know where to obtain the knowledge, (2) we understand the process, (3) we know how to decompose and recompose systems and subsystems, and (4) we have the tools and the knowledge to analyze the design alternatives. In the routine design, we can generate every node (or point) in the design space and we have the knowledge to control the search within the design space. Even though everything is known in advance, routine design still needs considerable amount of knowledge due to the interactions among goals and subsystems.

In *creative* design, we do not know everything in advance. Creative design typically leads to totally new products or inventions. This kind of design cannot utilize AI methods, where knowledge and knowledge representation are the key elements.

In *variant* design, we have the knowledge about the design domain, and we understand the sources of the design knowledge. However, we do not have full understanding of how to apply the knowledge, or we are missing key design knowledge elements (Tong and Sriram 1992). "Missing design knowledge" implies that we do not have the knowledge to directly generate new points in the design space or the knowledge to control the search. Case-base reasoning is normally used for this type of design problems.

AI IN ENGINEERING DESIGN

General

Numerous KBES studies are available in ASHRAE and allied literature that relate to areas such as diagnostics, energy consumption analysis, maintenance, and operation (ASHRAE 1995). As stated earlier, the purpose of this literature review is not to cover all areas where KBES can be applied but to focus on the specific area of conceptual design involving synthesis of HVAC&R components. Although there is a large body of literature in integration of AI methods and engineering design in engineering domains such as civil engineering, computer engineering, and manufacturing (for example, Giarratano and riley 1998; Hopgood 2000; Krishnamoorthy and Rajeev 1996; Maher 1987, 1990; Miller and Walker 1988; Sciubba and Melli 1998; Simon 1999), relatively little exists in the area of HVAC&R in general and HVAC&R systems design in particular. This lack of information and methodologies in the HVAC&R domain forced us to explore other engineering domains that have similarities to the HVAC&R domain from the design approach standpoint. The majority of work seems to have been done in the area of structural engineering. The literature review is organized in three sections: (1) AI and KBES applied to civil engineering design, (2) AI and KBES applied to energy system design, and (3) AI and KBES applied to HVAC&R system design. Every section includes a summary table of various papers identified in the literature with a short description and methods used in every paper.

Civil Engineering Design (see Table 1)

Integration of AI methods for design synthesis started in the mid-1980s, mainly for structural design. This section covers selected papers from the years 1988 to 2000, which are considered good examples. Fenves et al. (2000), in the framework of the project SEED-Config (SEED is **S**oftware **E**nvironment to support **E**arly phases in building **D**esign), present a design tool intended to assist structural engineers to rapidly synthesize design alternatives at the conceptual stage. SEED-Configurator is composed of four modules: (1) a design information repository, (2) a design knowledge manager, (3) a classification reference manager, and (4) a geometric modeler. The main concept of SEED is the hierarchichal representation of main systems, subsystems, and components as decomposition trees. The design information repository and the design knowledge manager provide an interface to the user and to the design knowledge representation, respectively. As mentioned earlier, the representation is hierarchichal with different depths (more general in the first module and more specific in the second). In order to utilize SEED, the designer has three design modes: selective, interactive, and automatic. The automatic mode, for example, automatically generates the design alternatives.

Stuurstraat and Tolman (1999) address the need for integration of multiple domain knowledge for design and the need for more sophisticated tools for the conceptual design. Danaher (1998) presents a utilization of a commercial expert system shell for preliminary structural design of multistory rectangular buildings. In addition, the author provides detailed information of how to select an expert system shell for KBES development. Frames and production systems (if-then rules) are used for knowledge representation; the structural system is represented in a hierarchical fashion starting from major systems and ending with materials and components. The process of design alternatives generation starts by inputting design information such as number of stories, number of bays, dimensional information, etc. After the input stage, the system generates feasible partial alternatives for every level, utilizing heuristic rules to eliminate infeasible solutions. The process continues to other subsystems and finally ends up as a combination of feasible partial solutions, which are now considered as the complete design alternative. In addition to heuristic rules, the program utilizes functions to perform rough calculations.

Sabouni and Al-Mourad (1997) present an expert system for preliminary design of tall buildings (TALLEX). The authors utilized a commercial KBES shell as the KBES engine, a combination of production rules and numerical procedures for calculations generating 16 solutions. These solutions are then graded based on results calculated in the evaluation procedure, with the evaluation engine using weight factors stipulated by the user. Moula et al. (1995) review a KBES that has been developed in the area of geotechnical engineering. The paper covers geotechnical KBES in the areas of site characterization, foundations, slopes, tunnels, soil improvement, geosynthetics, and groundwater. Harty and Danaher (1994) present a KBES (DOLMAN) for preliminary structural design of buildings. Conceptually, this KBES is similar to that proposed by Danaher (1998), which leads us to believe that the newer study is a successor to DOLMAN. DOLMAN provides, in addition, an evaluation or grading system based on cost and CAD interface to AutoCAD®.

Bedard and Ravi (1991) developed a knowledge-based system for architectural configuration of office buildings. The system generates space layout alternatives for multistory office buildings based on predefined constraints imposed by the owner or other restrictions such as building codes. In addition, the system takes into account other factors such as flexibility and functionality. The concept applied in this system is a sequenced "generate and test" procedure where the process starts with initial generation of alternatives or configurations using details concerning rentable space, number of floors, and the geometry of the building, which represents the first level in the hierarchy. The configurations are then tested against the constraint imposed by the owner and other constraints that are relevant to this level, resulting in reduction of the feasible alternative and keeping the alternatives that comply with the constraints at this level. The process continues for every level, finally resulting in a small number of alternatives. The evaluation tool ranks every alternative based on weight factors defined by the user. The system is a hybrid system using frames and rules and takes advantage of the combination of hierarchical knowledge structure for design objects as building configurations (frames) and inferential knowledge (production rules).

Haber and Karshenas (1990) address the importance of a more scientific approach for design alternatives generation during the conceptual design stage. The result was the development of CONCEPTUAL, an expert system for conceptual structural design. CONCEPTUAL utilizes the decomposition tree approach and the hierarchical knowledge representation, where every building system is located at a different level in the hierarchy tree. The recomposition is a guided (or heuristic) search for the least cost combination or path from the top of the tree to the bottom. The output lists the best (lowest cost) five alternatives. PROLOG is used to develop the KBES.

Rosenmann (1990) presents several expert systems for design analysis and evaluation utilizing BUILD Expert System shell written in PROLOG. The KBES used a shell for the development of PREDIKT, a system for preliminary design of kitchen; CODE, a system for compliance checking of design codes; and SOLAREXPERT, a system for evaluat-

TABLE 1
Summary of AI and KBES Applied to Civil Engineering Design

	Author	Paper Title	Domain Area	Use/Duty	Description	AI methods and Knowledge Representation	Name of AI/ KBES System
1	Fenves et al. (2000)	SEED-Config: A tool for conceptual structural design in collaborative building design environment	Structural	Conceptual Design and Synthesis	Developed to assist designers in rapidly synthesizing alternative structural designs	Hierarchal, case-based reasoning	SEED-Config
2	Stuustraat and Tolman (1999)	A product modeling to building knowledge integration	Buildings	Design Integration	Addresses the need for more scientific approach for conceptual design and integration of several knowledge domains	NA	NA
3	Danaher (1998)	Applying AI to preliminary design of buildings	Structural	Conceptual Design and Synthesis	Developed to assist designers in rapidly synthesizing alternative structural designs	Hierarchal frames and production rules using commercial shell Kappa-PC	NA
4	Sabouni and Al-Mourad (1997)	Quantitative knowledge-based approach for preliminary design of tall buildings	Structural	Conceptual Design	KBES program for preliminary structural design, the program generates 16 design alternatives based on IF-THEN rules and conventional calculations. The design alternatives evaluated by rate of acceptance ratio	KBES, rule-based using EXSYS commercial shell	TALLEX
5	Moule et al. (1995)	Knowledge-based systems in geotechnical engineering	Geotechnical	Design, selection, failure diagnosis	Covers variety of KBES developed for site characterization, foundations, slopes, tunnels, soil improvement, geosynthetics, and groundwater	NA	NA
6	Harty and Danaher (1994)	A knowledge-based approach to preliminary design of buildings	Structural	Conceptual Design	KBES program for preliminary structural design, generates design alternatives based on IF-THEN rules and conventional calculations. Design alternatives evaluated by rate of acceptance ratio	KBES, rule-based system.	DOLMAN
7	Bedard and Ravi (1991)	Knowledge-based approach to overall configuration of multistory office buildings	Architecture	Architectural layout	A KBES program designed to assist designers in architectural design of multistory office building, the program generates space layout alternatives based one predefined constraints. Design alternatives evaluated, ranked based on weight factor defined by user	KBES, hybrid system of frames and production rules.	NA
8	Haber and Karshenas (1990)	CONCEPTUAL: An Expert System for Conceptual Structural Design	Structural	Conceptual Design	An expert system for conceptual structural design utilizing hierarchical presentation of building systems and guided (heuristic) search for lowest cost combination.	KBES, hybrid system of frames and production rules; uses PROLOG	CONCEPT
9	Rossenman (1990)	Application of expert systems to building design analysis and evaluation	Design and Analysis	Code compliance, preliminary design and evaluation.	KBES developed based on existing shell for preliminary design of kitchen. Building code compliance and evaluation tool for passive solar system. Interface to CAD program and procedural programs.	KBES, hybrid system of frames and production rules; uses PROLOG and C	BUILD, PREDIKT,CODE, SOLAREXPERT
10	Adeli (1998)	An overview of expert systems in civil engineering (Chapter 5)	Structural, Construction management environment, geotechnical education	Structural analysis, design of bridge and roof trusses, construction management	Paper covers variety of KBES developed for several domains in civil engineering such as structural, management, water resources, geotechnical, and education.	KBES, hybrid system of frames and production rules; uses PASCAL PROLOG, C, FORTRAN	SACON, SSPG, BTEXPERT, RTEXPERT,
11	Maher et al. (1988)	Expert systems for structural design (Chapter 6)	Structural	Conceptual Design	Developed to assist designers in rapidly synthesizing and evaluating of alternative structural design	KBES, hybrid system of frames and production rules; uses PSRL, OPS5, LISP	HI-RISE

ing passive solar energy design. The BUILD system can represent knowledge as frames or as a production system with rules. Some systems have interface to CAD programs and procedural programs written in C.

A detailed overview of expert systems in the area of civil engineering can be found in Adeli (1988). The article presents various expert systems developed for different domains in the area of civil engineering, such as structural engineering, construction management, environmental engineering, geotechnical engineering, and civil engineering education. The systems presented demonstrate various knowledge representations, searches, optimization, and integration with procedural programs.

Maher et al. (1988) present one of the first expert systems developed for preliminary structural design of high-rise buildings (HI-RISE). HI-RISE is a KBES that configures and evaluates several structural design alternatives; the output is a set of feasible solutions and the relative cost of every alternative. The design knowledge of HI-RISE is process knowledge and structural knowledge, with hierarchical presentation and semantic networks used to represent the structural knowledge. HI-RISE utilizes frames (or schemas) that allow hierarchal representation of the solution tree; heuristics-based production rules guide the recomposition and eliminate infeasible solutions, and LISP functions are used to represent numerical calculations. As indicated earlier, HI-RISE is considered to be one of the pioneering approaches for integration of AI methods and engineering design.

Energy Systems Design (see Table 2)

HVAC&R systems can be considered to be a subset of thermal systems used to maintain acceptable indoor air quality and thermal comfort in buildings. As a result of limited information of implementation of AI methods to the design of HVAC&R systems, a literature review of thermal systems is presented in this section.

Melli and Sciubba (1997) and De Marco et al. (1993) present a prototype expert system for conceptual synthesis of thermal processes called COLOMBO. COLOMBO is capable of assisting the engineer in the generation of design alternatives by recomposing power plant configuration from a library of components such as compressor, steam turbine, steam generator, condenser, pumps, gas turbine, etc. The configurations are typical power cycles for power generation. In order to generate design solutions, the user specifies the electrical power capacity (the design goal) along with a procedure that works backwards. The procedure involves scanning a library of components and then connecting them such that they can satisfy the goal (required power level) specified by the user. The procedure follows the thermodynamic process sequence by starting from the electric generator, turbine, fuels availability, combustion chamber, compressor, etc. If-then rules are applied to constrain the number of solutions and to guide the assembling of systems. The procedure is written in SMALLTALK.

Mohiuddin et al. (1996) utilize a KBES shell (VIDHI) to develop an expert system for thermal design of natural and draft wet cooling towers (ESTOWER). The expert system utilizes rule-based knowledge representation and a backward-chaining inference engine, while several numerical calculation procedures are incorporated in the rule-based system. The selection and design of the cooling tower is done by asking the user a set of questions relating to the design parameters, such as ambient wet-bulb temperature or location, inlet water temperature, type of cooling tower (natural or draft), geometry, cooling tower media, etc.

Wang et al. (1995) present an intelligent system (IDIS-CDHEN) for conceptual design of a heat exchanger network (HEN). The system is an integration of various knowledge representations (frames, production rules, procedural knowledge) and forward-chaining inference.

Lo and Nashid (1993) demonstrate a KBES approach for optimal design of a distribution electrical power network. The KBES utilizes production rules to optimize (from first cost standpoint) physical layout (X and Y coordinates) of electrical power substations based on predicted load demand, and the most cost-effective routing of the feeder. The KBES integrates Prolog for the AI section and Turbo-C for the procedural calculations.

Kott et al. (1987) integrate a knowledge-based approach and second law analysis to automatically synthesize thermal energy systems. The automated design starts with the formulation of the problem, which are the input and output requirements, feasibility constraints, and penalty function (first cost, annual operating cost, and cost of constraints violation). The design space constitutes all possible solutions (feasible and infeasible). After establishing the design space, a guided search identifies the optimal solution that satisfies the input/output requirements, complies with the constraints, and minimizes the penalty function. The knowledge-based approach generates the solution space (or the design alternatives) and executes the search, which is a guided search based on heuristics. Analytical procedures, such as mass balance, first law, and second law, are used to verify the feasibility of the process. LISP has been used for writing the code.

HVAC&R Systems Design (see Table 3)

The domain of HVAC&R systems design is not as rich as the area of civil engineering in terms of implementation of AI methods for design. Personal discussions with researchers involved in developing KBES for HVAC&R system design revealed that the industry lost interest in this topic in the mid-1990s. In addition, the results of the literature research showed that the effort put into developing KBES for design was incomplete. The main effort was in building diagnostics and design integration and included other domains such as architecture, lighting, and structure. This section reviews the papers dealing with integration of AI methods to HVAC&R design.

An ongoing ASHRAE-funded research project is intended to demonstrate proof-of-concept in applying genet-

TABLE 2
Summary of AI and KBES applied to Energy Systems Design

	Author	Paper Title	Domain Area	Use/Duty	Description	AI methods and Knowledge Representation	Name of AI or KBES System
1	Melli and Sciubba (1997)	A prototype expert system for the conceptual synthesis of thermal processes	Power plant thermal systems synthesis	Conceptual design	KBES prototype for conceptual synthesis of thermal process mainly for power generation like Rankine and Brayton cycles. KBES recomposes systems based on matching the design goal to a set of interconnected components. Production rules used to guide the assembly and to restrict the number of generated solutions.	Production rules, frames	COLOMBO (uses SMALLTALK)
2	Mohiuddin et al. (1996)	ESTOWER: An expert system for the thermal design of wet cooling tower	Thermal equipment design	Cooling tower design	KBES prototype for thermal design of natural and forced draft cooling towers. KBES utilizes rule-based knowledge representation and backward chaining for inference.	Production rules	ESTOWER (uses VIDHI shell)
3	Wang et al. (1995)	An intelligent design environment for conceptual process design	Thermal process design	Conceptual design of heat exchanger network	KBES for the design of heat exchanger network (HEN). The KBES utilize rule base and frames for knowledge representation and forward chaining for inference. Procedural knowledge used for analysis.	Production rules, frames	IDIS-CDHEN
4	Lo and Nashid (1993)	Expert systems and their applications to power systems—Part 3:Examples and applications.	Electrical power	Layout and distribution transformers and substations	KBES for the layout design of electrical substations and feeder. KBES utilizes rule base for knowledge representation. Procedural program in turbo C used for analysis.	Production rules	Uses PROLOG
5	Kott et al. (1987)	Knowledge-based approach to automated design of thermal energy systems	Power plant thermal systems design and optimization	Power plant thermal systems design and optimization	KBES for the design synthesis of thermal process. KBES utilizes heuristics knowledge to develop design alternatives, guided search and procedural knowledge to verify assembly, and thermodynamics feasibility and optimization procedure.	Backward-chaining inference (described as goal driven search)	Uses LISP

TABLE 3
Summary of AI and KBES Applied to HVAC&R Systems Design

	Author	Paper Title	Use/Duty	Description	AI methods and Knowledge Representation	Name of System
1	Wright et al. (2001)	Building system design synthesis and optimization-interim report	Configuration, optimization of secondary HVAC systems	An AI based system for optimal configuration and selection of main components of basic secondary system using genetic algorithm. This project is in progress, scheduled for completion in the year 2002.	GA (genetic algorithm)	NA
2	Shams et al. (1994a)	Development of knowledge-based system for the selection of HVAC systems types for small buildings—Part 1	Selection of HVAC&R systems	A prototype KBES for selection of HVAC&R for small buildings up to 20,000 ft^2 using production rules and heuristic rules. This paper deals with the knowledge acquisition of the HVAC & R domain.	Production rules	NA
3	Shams et al. (1994b)	Development of knowledge-based system for the selection of HVAC systems types for small buildings—Part 2	Selection of HVAC&R systems	This is the second part of the previous paper and deals with the expert system development to encode the knowledge from part 1	Production rules	NA
4	Bajpai (1994)	An expert system approach to the design of automotive air-conditioning systems	Selection of HVAC&R system for cars and trucks	A KBES for design and evaluation of HVAC&R for cars and trucks utilizing procedural methods for analysis and rule-based system for evaluation and modifications.	Production rules using commercial shell (KEE)	NA
5	Robin et al. (1993)	Integration of expert knowledge and simulation tools for thermal design of buildings and energy systems	Selection of building envelop and HVAC&R systems	A KBES for selection and design of HVAC&R for buildings utilizing procedural methods for analysis and rule-based system for advice and suggestions	Production rules and frames using commercial shell (nexpert-object)	SETIS
6	Morel and Faist (1993)	Design tools for building thermal analysis: The significance of integration	General description of design tools	The paper presents several design tools such as TRNSYS and DOE-2.1 and KBES such as INTOX and RATES; the paper emphasis the need for integration of design tools for building thermal design	NA	NA
7	Pohl et al. (1990)	ICADS: an intelligent computer-aided design environment	Coordination of drafting and building disciplines	A demonstration of prototype CAD system for coordination among several building disciplines using public domain KBES	Production rules and frames using commercial shell (CLIPS)	NA
8	Case et al. (1990)	Multiple cooperating knowledge sources for the design of building energy systems	Coordination of drafting and bid specifications	A demonstration of prototype KBES for integration of drafting and specifications. A simple example for solar domestic hot water heating system used to demonstrate the concept.	Production rules and frames	NA
9	Cornick et al. (1990)	Incorporating building regulations into design systems: An object-oriented approach	Integration of building regulations to building design	The paper presents several topics associated with design models and using KBES for building code compliance. This article is not domain specific.	Production rules and frames	NA
10	Kulusjarvi (1990)	HVAC-engineering system description	Integration of AutoCAD and KBES for HVAC design	This paper demonstrates integration of AutoCAD as a drafting tool and SCEMA, a KBES for HVAC design assistance.	Production rules	SCEMA
11	Camejo and Hittle (1989)	An expert system for the design of heating, ventilating, and air-conditioning systems	Selection of HVAC&R systems	A prototype KBES for selection of HVAC&R systems using production rules and heuristic rules, utilizing commercial shell. KBES contains several knowledge bases for different functions such as systems, equipment, and controls. Rules of thumb and probabilities used for systems selections and applicability.	Production rules, using syntax that converts the rules to FORTRAN and EXSYS	NA
12	Doheny and Monaghan (1987)	IDABES: An expert system for the preliminary stages of conceptual design of building energy systems.	Selection of HVAC&R systems	KBES for the preliminary stage of building thermal systems design. KBES executes search in the design space using rule-based system. FORTRAN used for calculations.	Production rules using rule-based language (OPS5)	IDABES

ics algorithms for configuring and optimizing secondary HVAC&R systems (Wright et al. 2001). In addition, simple simulations to determine system performance are performed during a typical day in summer, winter, and an intermediate point.

Shames et al. (1994a, 1994b) demonstrated a KBES for selection of HVAC&R systems for small buildings. The papers, the outcome of ASHRAE RP-642 research project, consist of two parts: part 1 deals with the knowledge acquisition, and part 2 with the expert system shell used for the project. The development of this KBES followed the traditional KBES development of knowledge acquisition from domain experts and encoding the knowledge into a KBES shell. The KBES assists the engineer in the selection of the design concept based on site-specific information (in this case, for small office buildings up to 20,000 ft^2 and two climatic regions) such as building size, space availability, glazing, region, etc., and heuristic rules. The KBES displays solutions such as constant-volume, variable air volume, and water-source heat pump, etc. The solutions are then evaluated for energy consumption and first cost based on a database developed for various combinations of building size, amount of glazing, systems type, and energy for the two climatic areas. The knowledge representation is based on production rules with backward chaining inference. Overall, the procedure has been demonstrated on a relatively simple case study and, in that regard, it is also more like a proof-of-concept study.

Another study on KBES applied to HVAC&R application is due to Bajpai (1994). This paper deals with the design of air-conditioning systems for cars and trucks. The design tool comprises five stages. The first stage is the definition of the problem and the design parameters; the second stage, calculates the cooling load using a mathematical module. The calculated load is then used to determine the size of the system and the components. At this stage, the designer defines the size of the system and selects the components (compressor, evaporator, condenser, and expansion device). The selected components are then analyzed from the thermodynamic balance standpoint. The KBES is the last stage where the results from the thermodynamic analysis are evaluated and modified by using an expert knowledge base. The KBES used is a rule-based production system utilizing a commercial shell.

An attempt to integrate KBES and building energy simulation has been made by Robin et al. (1993). This paper presents a computer program (SETIS), which integrates KBES and algorithmic methods to assist the engineer in building thermal design (mainly envelope) and to select the HVAC system design principle. The program comprises five main modules: (1) the KBES module (knowledge-base and the inference engine), (2) the algorithmic module (procedural calculations tools), (3) database module (database of envelope components and HVAC systems), (4) control module (which manages the process of information transfer), and (5) user interface module.

The design process starts with the selection of: (1) location of building; (2) geometry, duty, and internal loads of the building; and (3) HVAC system principle (this is not the actual selection of the system). During the process, built-in defaults can be used if the information is nonexistent. After establishing the design parameters, the program utilizes classic calculation procedures based on ASHRAE methods and collected knowledge to analyze the thermal behavior of the building.

The HVAC system principle is selected based on ten weighting design criteria. They include thermal comfort, acoustics, first cost, energy cost, etc.; the selected alternative will be one with the highest weighting score. The program utilizes "object oriented" and rule-based methods to represent the knowledge.

Morel and Faist (1993) presented several design tools for building thermal systems; the main purpose of this paper is to summarize design tools; elaborate description of the systems is not presented. In addition to tools such as TRNSYS and DOE-2.1, KBES tools such as INTOX and RATES were also discussed. However, these tools were mainly for design integration with other domains. Phol et al. (1990) demonstrate a prototype of a computer-aided design (CAD) system with emphasis on coordination among several disciplines and computer-aided drawing.The KBES incorporates production rule systems with frame-based knowledge representation using a public domain KBES shell (CLIPS). Case et al. (1990) also present a KBES prototype with emphasis on integration of drafting, database, and bid specifications. An example of a residential solar domestic hot water system is presented to demonstrate the concept of integration, the production rule system, and frames used for knowledge representation. Cornick et al. (1990) describe how to incorporate building regulation into the design. Even though the paper does not specifically address the HVAC&R design aspects, it covers topics such as design models, object-oriented approach, and rule-based knowledge representation. Kulusjarvi (1990) integrates AutoCAD® and a KBES (SCEMA), which is an expert system using a decomposition tree for HVAC components and production rules. Camaejo and Hittle (1989) demonstrated a prototype expert system for HVAC systems design by using several knowledge bases, each for different function and different level in the design process. A knowledge base contains information such as system selection (for example, fan-coil or VAV) and another knowledge base is used for equipment selection that corresponds to the system selected in the previous stage. Finally, a third knowledge base selects the control systems (the article indicated that this knowledge was in development when the article was published) using a commercially available expert system based on rules for knowledge representation. Doheny and Monaghan (1987) present IDABES, which is a KBES for preliminary stages of conceptual design of building energy systems. The KBES executes a search in the design space, which includes all of the possible solutions using rule-based language (OPS5), along with analysis using FORTRAN code. A rating strategy tool used to rate the proposed systems, this procedure incorporates items for consideration (IOC), which has importance factor (P) and system selection grading by weighting factors (W) with all the P and W factors subjectively defined by the user. The value $P \times W$ is a value RBF, which represents the relative benefit factor. The final selection is based on the highest sum of all the IOC RBF or the lowest CBF, which is the total RBF, divided by the sum of the total operating cost and total owning cost. The paper recognized the limitations of late 1980s computing and AI tools and provides excellent recommendations for future development of AI tools for HVAC&R design.

SUMMARY

Numerous KBES studies are available in the ASHRAE and allied literature that relate to areas such as diagnostics, energy consumption analysis, maintenance, and operation. The purpose of this literature review was not to cover all areas where KBES can be applied but to focus on the specific area of conceptual design involving synthesis of HVAC&R components. KBES hold renewed promise in being able to provide a scientific, comprehensive, rational, and rapid means to identify feasible design alternatives to a stipulated building design problem. This paper consisted of essentially two sections: a background on AI methods and a literature review of KBES applied to engineering design. The background section covers definitions, different search methods, and different methods to represent knowledge, background of different types of associated tools, and an introduction to engineering design models. Although there is a large body of literature dealing with the integration of AI methods and design in engineering domains such as civil engineering, computer engineering, and manufacturing, relatively little exists in the area of HVAC&R systems design. This lack of information led us to explore other engineering domains that have similarities to the HVAC&R domain from the design approach standpoint. The second portion of this paper presents a detailed literature review, along with summary tables, organized in three sections: (1) AI and KBES applied to civil engineering design, (2) AI and KBES applied to energy systems design, and (3) AI and KBES applied to HVAC&R systems design. A subsequent paper will present and illustrate a new methodology based on a combination of KBES and algorithmic tools that allows the rational design selection of secondary and primary components of an HVAC&R system.

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