COMPUTER-AIDED DESIGN OF ENERGY-EFFICIENT HVAC SYSTEMS

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ABSTRACT

The developments in the computer-aided building design will enable designers to improve the energy performance in buildings, through a more appropriate design which will be better structured, will learn from previously accumulated knowledge (e.g., heuristics, databases), and will use new methods for the generation and evaluation of the design alternatives. A scenario is presented to emphasize the designer's expectations, and also the authors view on the development of this integrated computer-aided building design software, which will be used for the design of energy-efficient HVAC systems. Some areas of research, required for the development of this software, are proposed, and they are as follows: (1) the acquisition of the common experience, (2) the development of databases for energy performance of buildings (monitored and predicted), and for manufacturer's data, (3) the automatic generation of a set of new design alternatives, to refine the initial prototype, and (4) the implementation of the requirements from standards, norms or bylaws.

INTRODUCTION

In the industrialized countries about one third of the total energy consumption is used in buildings for lighting, cooling, heating, equipment, to control a comfortable indoor environment. There is still a large potential for improving the energy efficiency in buildings, the economically acceptable potential by using only the today's technologies being estimated at 15 up to 50%. The first step in improving the energy efficiency is the improvement of the building design process, and this can be done by using advanced tools such as Computer-Aided Building Design software.

The presently available software on market, fulfils only partially its objectives. This software consists of independent programs used to generate finished drawings (e.g., Auto CAD, Intergraph, Versacad), to size airduct and piping systems (e.g Varitrane Duct Design, Intergraph HVAC Design, AutoCAD AEC Mechanical, Duct LINK, Top Duct), or to estimate the energy consumption of a given building (e.g., BESA, Micro-DOE2, BLAST). Therefore, it may be more appropriate to talk about computer-aided drafting or computer-aided analysis as opposed to computer-aided design. The computer-aided design software should be viewed as an "intelligent assistant" during the design process, and should contain databases and application programs located around a "manager" (Zmeureanu and Fazio 1989). The central piece is the "manager", developed as an expert system, which helps the designer in the development of design alternatives, in the decision-making process, in verifying the proposed solutions against the standard prescriptions,and in the evaluation of all design alternatives. The "manager" controls the information transfer between different modules and activates each module in a rational sequence. Hence, it is developed as a combination of consultation and critiquing expert systems. In the first case, the "manager" engages a dialogue with the designer, which is asked to provide additional information, while in the second case the designer suggests a decision, and the system performs the review and evaluation, relative to the given requirements (Hägglund 1989).

So far most developments of the expert systems for the design of energy-efficient buildings were oriented for solving individual problems related to building envelope (Fazio and Gowri 1989, Fazio et al. 1989, Tham et al. 1990), building form, orientation and materials (Shaviv and Kalay 1990, Bharati 1990, Halleux 1989), passive solar design of houses (Dry and Givoni 1986), or design of HVAC systems (Fazio et al. 1989b, Camejo and Hittle 1989, Case et al. 1990, Björnsson et al. 1987). However, the complexity of the design process requires a more global approach, which also led other researchers to the idea of developing an integrated building design environment (Brambley et al. 1989).

DESIGN SCENARIO

To better understand what a designer expects from the computer-aided building design software, let us imagine that Mr. R has to design the HVAC system for an energy-efficient office building.

Step 1: He starts the process by using the data base of the building provided by the architect, which contains the graphical representation of the building, floor by floor, plus elevations, and the attributes of different components, such as thermal resistance of walls or shading coefficient of windows. Some other values are automatically calculated such as floor area per floor or net wall area. If the data base of building is not available, Mr. R uses the scanner to transfer the graphical information from drawings to the project data base, and then he adds all specifications.

Step 2: If the project is in the preliminary design stage, Mr. R looks in his data base for a similar project, in terms of factors such as building type (e.g. school, office or warehouse), location, total floor area and number of floors. If the data base contains the required information, then the available indices such as air flow rate per zone in L/s/(m^2 floor area), size of the cooling or heating plant in kW/(m^2 floor area) or the initial cost of the cooling or heating plant in $/kW are automatically used along with the actual data. Now Mr. R knows the initial cost and the break-down for each component (duct, piping, terminals, air-handling units and cooling/heating plants), the operating cost (demand, consumption and maintenance), the size of air handling units, the capacity of chiller and cooling tower, and many other information required for a preliminary estimation of the project.

If the database does not contain a similar project, or Mr. R does not want to use the information from the database, then the "manager" will transfer the request to the design module.

Step 3: The "manager" checks if the building envelope, as proposed by the architect, respects the requirements from standards (e.g., ASHRAE Standard 90.1-1989), codes (e.g., National Building Code), or laws (e.g., Regulation respecting energy conservation in new buildings - Quebec). For example, if the ASHRAE Standard is used, then Mr. R can use either the prescriptive criteria, presented as the Alternate Component Packages, or the performance criteria which are incorporated into the ENVSTD micro-computer program. In the first case, the maximum percentage of glazing is given in terms of climatic conditions, internal loads, shading coefficient and thermal transmittance of windows, and the maximum thermal transmittance of the exterior walls is given in terms of climatic conditions, wall heat capacity and insulation position. In the second case, the maximum annual heating and cooling load of the building are calculated in terms of transmission and solar heat gains through windows and walls, internal loads, wall heat capacity, and climatic conditions.

Step 4: Using a stylus and a digitizer table, Mr. R breaks the graphical representation of the entire floor into different thermal zones, and then ask the manager to use the database for assessing values to other factors such as ventilation rate (based on the number of people and the minimum requirements for outdoor air), infiltration rate or expected schedules of operation. For example, the number of people is calculated by multiplying the floor area with the recommended people density (e.g., 1 person per 20 m^2 for private offices). Then the minimum ventilation rate is calculated as:

$$\dot{m}_v = \max \{\dot{m}_{v1},\ \dot{m}_v\}_2$$

where

$$\dot{m}_{v1} = \text{number of people} \times \left(\frac{L/s}{\text{person}}\right)$$

$$\dot{m}_{v2} = \text{floor area} \times \left(\frac{L/s}{m^2\ \text{floor area}}\right)$$

Presently, the following values are used for the design of an air-conditioned office building in Montreal:

$$\frac{L/s}{\text{person}} = 3.5, \qquad \frac{L/s}{m^2\ \text{floor area}} = 0.5$$

The input data file for the energy analysis program is then automatically generated, and the "manager" asks the program to calculate, for each thermal zone, the supply rate and the peak heating/cooling load. These results are compared with the design recommendations for office buildings (e.g., supply air flow rate must be equal or greater than 4.5 ach or 45 L/s/person) and corrected if needed.

Step 5: The "manager" advises the designer on the appropriate type of HVAC system, and generates the initial design, which is called base model or prototype. The ASHRAE Standard 90.1 - 1989 "Energy efficient design of new buildings except new low-rise residential buildings" recommends the prototype HVAC systems in terms of building type and size, and provides a detailed description of the main design parameters. For example, the following three types of HVAC systems are recommended for office buildings:

a. Packaged rooftop single zone, one unit per zone, for small office buildings with total floor area smaller than 1,900 m^2.
b. Packaged rooftop VAV with perimeter reheat, for office buildings with total floor area greater than 2,000 m^2, and either smaller than 7,000 m^2 or having less than three floors.
c. Built-up central VAV with perimeter reheat, for office buildings greater than 3 floors or 7,000 m^2.

Step 6: The "manager" suggests the appropriate terminals of the HVAC system (e.g., diffusers), by taking into account the capacity of each unit, but also the architectural and acoustical requirements. This information, along with the total supply air volume for each zone, leads to the assessment of the total number of diffusers per zone, and their size. Then, a suggested location of all supply and return grilles appears on the layout of each floor, which is displayed on the workstation. For example, the rules used by the manager to locate the diffusers can be based on the following information provided by a manufacturer. A linear slot diffuser which has a nominal capacity of 50 cfm per foot of slot, and can have 1-4 slots and 1-2 ways of air supply, should be located in the centre of the room whenever possible, in such position that airflows from different diffusers do to converge at right angles. The minimum distance between diffusers and walls is chosen to reduce the impact between the air jet and the vertical elements, the final recommended velocity being 50-150 fpm. For colliding air jets the relative velocity at midway should not exceed 150 fpm. The distance between co-linear diffusers should not exceed 12-16 ft.

Mr. R can use the digitizer table and stylus to relocate some grilles, and then asks the "manager" to check if the minimum recommendations are fulfilled.

Step 7: Mr. R sketches the air duct and piping systems on each floor and connects the terminals, by using the digitizer table and stylus. Then, the "manager" is asked to check if the proposed sketch complies with the standards requirements (e.g., maximum length of the flexible duct is 14 ft). After all corrections are made, the "manager" activates the air duct and piping design program, and Mr. R obtains the complete design of his network, including the requirements for fans and pumps, and a complete list of materials.

Step 8: Based on the required capacity of the air handling unit, the climate conditions, the building type and size, and the available sources of energy, the "manager" suggests the configuration of this unit and the capacity of each component such as cooling coil, filter or fan. For example, the air handling unit for air-conditioning in summer in Montreal (Canada) is composed of mixing box, cooling coil, reheating coil (for constant volume system), and supply fan, while for Kathmandu (Nepal) it might require a washer spray on evaporative cooling mode (Fazio et al. 1989b).

In addition, the psychometric representation of the heat and mass transfer phenomena within the air handling unit are displayed on the workstation. If Mr. R. accepts the design solution, then the "manager" activates the selection module, which searches in the manufacturer's database for the required configuration. Some other parameters defining the performance of the components, such as pressure loss on the air side of cooling coils or through the air filter are extracted from the database. If the solution is not accepted, then Mr. R. proposes a new sequence of components, and the "manager" calculates the capacity of each component and displays the psychometric representation.

Step 9: The "manager" suggests a configuration of the central cooling and heating plant, if required. The values of some variables are evaluated, such as the water flow mass rate between different components (e.g., between cooling coils and chiller, or between chiller and cooling tower) or the requirements for pumps. Mr. R can agree with the suggested configuration, or can modify it. Finally, the equipment in the central plant is selected from the database. Some other parameters such as coefficient of performance, part-load efficiency (for chiller) or efficiency (for boiler) are also extracted.

Step 10: The "manager" completes the previously developed input data file with actual information regarding the secondary and primary HVAC systems, and then it activates again the energy analysis program. Several levels of results are obtained such as daily, monthly and annual energy performance (cost and consumption). The initial and life cycle costs under different assumptions are also calculated.

Step 11: The "manager" compares the simulated performance with the target values from the database, which are based either on monitored energy consumption in some energy-efficient buildings, or on predicted performance of previous projects. If a request is made, the "manager" automatically generates new design alternatives, to refine the previous prototype of the HVAC system, and the process will re-start from step 4.

Step 12: Once the final design alternative is obtained, the knowledge acquisition module is activated, and the main data are saved in the database.

AREAS OF RESEARCH

The development of such integrated computer aided building design package assumes research and development work, shared by professionals in different fields. For example, further developments such as parallel processing, data storage and retrieval, processor speed or monitor resolution will provide new capabilities for this integrated package. However, the central part of this package and the main area of interest for the authors are the "manager" and the database, which should incorporate the knowledge related to the design of energy-efficient buildings. Their development opens some interesting directions for research, and some of them are presented below.

A. Since there is a large number of people involved in the design of buildings, one can assume that the required knowledge is already available and can easily be implemented in an expert - system. This is not entirely true. Most designers have large experience, because of their day-to-day activity, in topics such as:

a. The right succession of operations in completing a design,
b. The range of values of different variables (e.g. cold deck temperature is between 13 and 18°C, or air supply per room corresponds to 4-8 ach),
c. The typical size and performance of some equipments from a few number of manufacturers (e.g. roof top units from the manufacturer Y can handle cooling capacities between 2 and 40 tons of refrigeration),
d) Most used requirements from standards and by-laws,
e) Problems experienced in the past due to the operation of a particular component.

As in many other fields, the knowledge is not well structured. Hence it is not a surprise that many designers may use different rules of thumb for the same design objective, which are obtained over several years of personal experience. For this reason, those designers will hardly accept the use of such integrated package, unless:

- a detailed documentation of the "manager" is available, explaining all steps and reasons for each decision, and
- the "manager" can easily be modified by the designer.

Therefore, instead of concentrating the efforts for the development of a working prototype, with the only purpose of displaying the concept, and leaving for later the opportunity for complete development, a more efficient alternative on long term is first to develop the complete documentation (procedures, heuristics, databases etc). A similar approach is used by the very popular adventurer books for the young generation "Choose your own adventures" or Dungeons and Dragons". The reader gets some particular capabilities and fictitious weapons, and faces different adventures. During the story, he has to decide which action to take among several which are proposed, for each difficult situation. Basically, each book is a literary description of a huge decision tree.

This research can take 2-3 years, and only after its completion the researcher has to look for the most appropriate hardware and software, for implementing his expert-system.

This approach has two main advantages:

- the structured knowledge and databases are entirely available to everyone for analysis and modification; the mechanism of decision-making process is fully understood, which increases the user's confidence in the final recommendations or conclusions;
- the design capabilities of the expert-system are not influenced by the hardware - software selected in the early development phase.

B. Even less experience is accumulated regarding the energy performance of the proposed design and that of a real building. The use of energy analysis programs in the design process is not a common practice, since they are mainly used in the research process and in the evaluation of the building retrofit. The databases relating the building design and its energy performance, based on projects carried out by different companies or on Post Occupancy Evaluations, are not presently available. Hence, the database should contain information such as:

- monitored energy performance of existing buildings, and main parameters describing their construction and operation;
- predicted energy performance, specifying the software used and the main input data;
- data from the Post-Occupancy Evaluation of the projects developed by the designer;
- date from manufacturer's catalogues;

This database will grow rapidly as soon as the integrated package is used by the designers, and will represent a key factor on the efficiency, and then on the penetration of this package into the design process. Therefore, the quality of information contained in the database is of a major concern. Once the general structure of the database is developed, the information can be implemented either by the designer through a manual procedure, or by transferring data from other databases, which may require some file processing, or by using the knowledge acquisition module, which will save the main data from a current project database. Hence, it is important to check all new data in a database, to find if some unusual values occur, and if they fit the pattern of the previous information. This verification can be done by using a data quality-control system, integrating a database and an expert system, which contains the constraints to be respected (Parsaye et al. 1990).

Usually a large database contains knowledge or qualitative description of a phenomenon or equipment, which is seldom noticed by the designer, unless an exhaustive analysis is carried out. The commercial discovery programs, called deductive or intelligent databases, can help designer to make discoveries automatically, that is to define rules and patters (Parsaye et al. 1990, Ketonen 1989, Lirov and Ravikumar 1989, Braune 1989). For example, the expert system STAREX (Simultaneous Test and Replace Circuit Pack Troubleshooting Expert Systems Prototyping and Implementation) has about 90% of its rules constructed artificially from sources other than human experts. As another example, the authors developed a database of the energy performance of office buildings in Montréal (Zmeureanu and Fazio 1990) using the dBase IV and found the following interesting conclusions, which can be translated into rules and implemented on the "manager":

- the monthly average electrical demand in buildings constructed immediately after the 1973 oil crisis reaches 80 W/m^2 floor area, due to a larger use of electricity as the main source of energy; this fact can be explained by the low cost, and continuous and safe supply of electricity in Quèbec;
- the cost of equivalent - kWh is higher in new buildings than in older ones, because the former use more electricity, and its cost includes consumption, demand and penalties for exceeding the subscribed demand;
- the distribution of energy consumption by source is as follows: electricity 68%, gas 15%, oil 15%, other 2%;
- the average cost of equivalent - kWh is as follows: electricity 4.15¢, gas 1.74¢, and oil 1.49¢.

C. An interesting area of research is the automatic generation of a set of new design alternatives, among which the designer can select the most appropriate one, in order to refine the previous prototype of the HVAC system. There is a large number of variables in the design of a building and HVAC system, and it is practically impossible to evaluate in a reasonable short time all design alternatives which can be developed. This generation process should on one side, mimic the behaviour of an expert in this field, and on the other side use techniques, which are not currently used in the conventional design process.

In the first case, the generation should be based on alternatives such as creativity, professional experience, full knowledge of the state-of-the-art technologies and procedures. For example, for selecting a packaged air-handling unit for a small building, the designer can choose among three main categories of equipment available on the market, that is roof top unit, split system and individual room unit, and his first decision will be influenced by his general knowledge about equipment, which can be presented as follows:

i. The roof top unit contains all components within the same unit (e.g., direct expansion cooling coil, direct-fired heater, refrigerant compressor, air cooled condenser, and supply fan), and can be used, for a single or multiple-zone building which has a cooling load of up to 100 tons of refrigeration.

ii. The split system has an indoor unit, which contains cooling coil, heating coil, supply fan and filter, and an outdoor unit, usually installed on the roof, which contains refrigerant compressor, air-cooled condenser, and condenser fan. This unit has a maximum cooling capacity of 15-20 tons of refrigeration.

iii. The individual room unit has a small cooling capacity, can be easily shut off if the space is not occupied, and the occupant of the room can select the operating mode (cooling or heating). The most used individual room units are the following:

- fan-coil unit, with a capacity between 47 and 470 L/s;
- unit ventilator, with a capacity between 470 and 940 L/s;
- water-to-air heat pumps, which has a central source of water at a temperature which allows each heat pump to provide either heating or cooling; the first cost is high, and the operating cost is low;
- self-contained heat pump or through-the-wall unit, which has the lowest first cost of any individual unit, and also the lowest operating cost.

In the second case, the use of computerized tools brings new procedures, some of them being theoretically known, but less or not at all currently used, because of the large computing time required.

One possible method to define those alternatives appropriate for the refinement of the initial prototype is the elimination parametrics technique (Ternoey et al. 1985), which analyses some extreme cases in which the effect of a specific parameter is eliminated. For example, the previous prototype is compared to one with no heat losses through the building envelope, or without air infiltration or lighting system, in order to evaluate the maximum variation of the energy performance. Therefore, the most appropriate design alternatives are those showing the largest variation. The authors applied this method to refine a prototype of a large energy-efficient office building, which was developed following the recommendations from the ASHRAE Standard 90.1-1989 (Zmeureanu and Fazio 1990b). They found that the energy cost of the prototype is dominated by the internal loads, and then any improvement in the building envelope can only have a marginal effect. If the designer's final objective is the reduction of the energy consumption, then the best approach is to increase the thermal insulation of the exterior envelope and reduce the air infiltration.

The "manager" should suggest a list of parameters to be eliminated, among which the designer will choose, and eventually introduce new ones. After the energy performance is evaluated for all extreme cases, corresponding to the selected parameters, the "manager" should display a list of recommended design alternatives, which are expected to have the largest positive effect on the energy performance of the building. To develop the rules for recommending the design alternatives, the evaluation of the energy performance of a large number of buildings should be carried out by the researcher using the energy analysis programs.

Once the initial prototype was refined using the most appropriate design alternatives, a further improvement can be obtained by using optimization methods. Hence, this approach has the advantage of reducing the number of design alternatives to be evaluated and therefore reducing the computing time.

D. The standards related to the design of an energy-efficient HVAC system can be classified as:

a. Prescriptive standards, which apply to individual components and define the limit of some particular parameters. It is important to notice that the use of the recommended values will not automatically lead to the optimum design in terms of energy use, but to an acceptable energy-efficient design. For example, the coefficient of performance of the chilled water equipment, water cooled, shall be greater than 4.6 (if capacity is greater than 300 tons of refrigeration), 3.7 (if it is between 150 and 300 tons), and 3.7 (if it is smaller than 150 tons).

b. Performance standards, which evaluate the whole energy performance, and provide energy targets for comparison purposes. For example, the Building Energy Performance Standard (BEPS) recommends that the design energy budget for a new large office building in New York, NY is 360 kWh/m^2/yr, while in San Diego, CA is 338 kWh/m^2/yr (Baird et al. 1984).

The requirements from standards, by-laws and regulations can be used as minimum reliable information for developing the initial prototype, and also to correct the design alternatives proposed by the user. Therefore, this subset of "manager" should be structured following the main steps of the design process, as performed by this integrated package, rather than to be developed as an all-purpose database. Several legal documents concern the design of an energy-efficient building with a comfortable indoor environment, and the developer should solve the conflicting situation between different requirements. A non-exhaustive list of legal documents which should be implemented for designing a commercial building in Montréal (Canada) is presented below:

- National Building Code, 1990.
- Regulation respecting energy conservation in new buildings, Québec 1988.
- ASHRAE Standard 90.1-1989. Energy Efficient Design of New Buildings except low-rise Residential Buildings.
- ASHRAE Standard 62-1989. Ventilation for Acceptable Indoor Air Quality.

- ASHRAE Standard 55-1981. Thermal Environmental Conditions for Human Occupancy.
- Reglement concernant la ventilation des bâtiments dans la ville de Montréal, No. 4936, 1975.
- Reglement sur la qualité du milieu de travail, Québec, 1982.
- Norme internationale ISO 7730, 1984. Ambiances thermiques modéreés. Détermination des indices PMV et PPD et spécification des conditions de confort termique.
- National Fire Protection Association. NFPA 90-1980.

E. Once the main characteristics of each component of the HVAC system (e.g., fan, diffuser or fan-coil unit) are defined, the "manager" should have access to a database, containing detailed information from different manufacturers. Usually the selection process involves additional calculations, following methods which are specific to each manufacturer, and some companies have already developed their own selections software. Some examples are presented below:

- LOGIC (Lennox Objective Guide to Installation Comparison) developed for LENNOX Industries Inc., Dallas, Texas (U.S.A.), 1990.
- PENN FANSIZER developed by Penn Ventilator Co., Inc. Philadelphia, PA (U.S.A.), 1989.
- QUICKFAN. Fan Selection Software developed by Bayley Fan Group, Lebanon, IN (U.S.A), 1989.
- Krueger Electronic Catalog. Product Performance Program and Krueger Application Programs developed by Krueger Manufacturing Co., Tucson, AZ (U.S.A.), 1989.
- DRI-CALC. Humidification Sizing and Selection Software developed by Dri-Steem Humidifier Company, Hopking, MN (U.S.A.), 1989.

However, the integration of these programs within the "manager" is not a trivial task, since these programs were developed independently, and have different structures. For some other manufacturers, the catalogues are the only source for developing the database.

If some components from different manufacturers fulfil the technical requirements (e.g., cooling and heating capacity, air flow rate, size), then for the final selection the "manager" should use some rule of thumb, based on several years of experience with these products. For example, the unitary air-conditioning units from manufacturer A are the best on the local market, or the airflow modulation equipment for the variable air volume system manufactured by B is less reliable than that coming from company C.

CONCLUSIONS

The use of expert systems for generation and control of the design process of energy-efficient HVAC systems will give a new dimension to this creative process, and will certainly improve the energy-efficiency in buildings. The integrated software proposed in this paper should be viewed as an old colleague, with a very large experience in the design and operation of HVAC systems, sitting next to the designer, and who accepts any number and type of questions. In the same time, he looks over the shoulder of the user and corrects any errors he can see on the drafting table.

The research required for this development will enable us to better structure the design knowledge in this particular field, to discover patterns in energy performance of buildings or equipments, and to develop methods for generating new design alternatives, with the purpose of improving the initial prototype.

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