EXPERT SYSTEMS FOR THE CONCEPTUAL DESIGN OF AIR CONDITIONING SYSTEMS

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1. Introduction

An energy system for heating, ventilating and air-conditioning of buildings consists of one or more of the following subsystems: a heating subsystem for adding heat to a fluid; a cooling subsystem for removing heat from a fluid; a dehumidification/humidification subsystem for controlling humidity; a distribution subsystem to carry a fluid to the rooms that are to be heated or cooled, equipment for moving the fluid and a terminal subsystem for transferring heat between the fluid and the room. The design procedure for energy systems can be broken into the following stages (1):

1) Data gathering and discussions with building owner/architect;
2) Concept design i.e. configuring subsystems and components into a system;
3) Overall system layouts, sizing of major components and energy simulations;
4) Detailed design i.e. design of lighting, heating and other components;
5) Specifications and contract documents;
6) Drafting.

Computerised aids are extensively used in the design process e.g. ESP (2), BLAST, HCC, and Superduct (3). Typically these are used for simulation, component sizing, drafting and as word processing packages. However, at the predesign and concept design stages, where the most important decisions are made, little use is made of CAD.

The concept design stage involves the engineer in determining the outline form of the final system. The design engineer combines various types of equipment to form a system that provides specified indoor environmental conditions at minimum life cycle cost. There are many possible system configurations from the numerous system components available. Choice of components may be straightforward in small buildings with conceptually simple systems. However, in larger buildings and/or if serious attempts are made to recover heat or to use more than one heating/cooling source the systems can become very complex with many interacting subsystems and components.

Many feasible configurations are ignored by the design engineer because of lack of experience with particular systems and/or project time limits. In a growing international market for consulting engineering services (4), and with continuing technological developments, it becomes increasingly important to make well informed and speedy decisions. A computerised design aid with an easily expandable knowledge base, and capable of making expert design decisions would be an invaluable tool.

Developing CAD tools for this level of design is not easy. Decisions made at this level are not based on mathematical analyses of system layout but on knowledge, accumulated through experience, of descriptions and capabilities of various systems and components. Much of this knowledge is heuristic in nature, i.e. it is not based on any fundamental principle or algorithm, and is difficult to represent using contemporary symbolic and mathematical methods.

2. Method of Approach

Design, and in particular, conceptual design has been studied from the point of view of computer modelling (5, 6, 7, 8, 9). The approach to concept design used in this research is the optimal search of a problem or search space. The search space contains all potential solutions or configurations of an energy system and an *expert system* is used to search for an optimal design solution.

The roots of expert systems lie in the field of artificial intelligence (AI), which may be said to be the science that tries to create intelligent behaviour in computers. An expert system is a computer programme that performs a task normally done by an expert or a consultant and in so doing it uses captured, heuristic knowledge (10).

Expert Systems differ in important ways from conventional data processing systems in that they employ (1) Symbolic representation, (2) Symbolic inference and (3) Heuristic search. These features enable expert systems to represent, in a manageable way, the abstract knowledge, that is characteristic of conceptual design. This ability to make expert decisions distinguishes them from conventional computer programmes which manipulate numerical data. Advantages of using an expert system approach in design of energy systems include:

1) All feasible configurations are considered and evaluated;
2) Expert systems can be used as intelligent preprocessors and postprocessors to numerical or algorithmic routines which are used to evaluate developing system designs e.g. energy system simulation programmes or heat gain/heat loss routines;
3) The knowledge base can be modified or updated to consider changing trends or advances in new technology.

2.1. Knowledge for Design

Knowledge provides the means for achieving a high degree of problem solving ability and needs to be formally studied if one is to record it in a computerised knowledge base. In AI, a representation of knowledge is a combination of data structures and interpretative procedures that, if used in a certain way in a programme, will lead to knowledgeable behaviour (11). These characteristics facilitate the representation of experts' knowledge in computer programmes. Knowledge for the design problem can be classified according to function as follows (1):

1) Domain Knowledge - knowledge about subsystems and components e.g. boilers, VAV systems, heat pumps;
2) Constraint Knowledge - constraints imposed by building location, building specifications, and economic limits;
3) Procedural Knowledge - knowledge of how components can be selected and configured into a system and evaluated;
4) Analysis Algorithms - knowledge of how to quantitatively evaluate

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developing and final solutions e.g. use of simulation programmes;

5) Solution Knowledge - knowledge of the developing system as the design proceeds e.g. sketches of the concept design.

The representational characteristics of this knowledge are described in some detail in (12). The following sections describe how HVAC systems' components can be modelled in a hierarchical fashion.

2.1.1. HVAC Systems and Components - Domain Knowledge

Designers reduce the complexity of an air-conditioning system by partitioning it into subsystems and components. The entire system can then be understood in terms of its component pieces and their interrelationships. Figure 1 shows the partial hierarchical decomposition of the air-handling plant. This breakdown is based on Carrier (13). Each of these subcomponents are composed of many subtypes and subcomponents. In this way a tree like hierarchy can be derived.

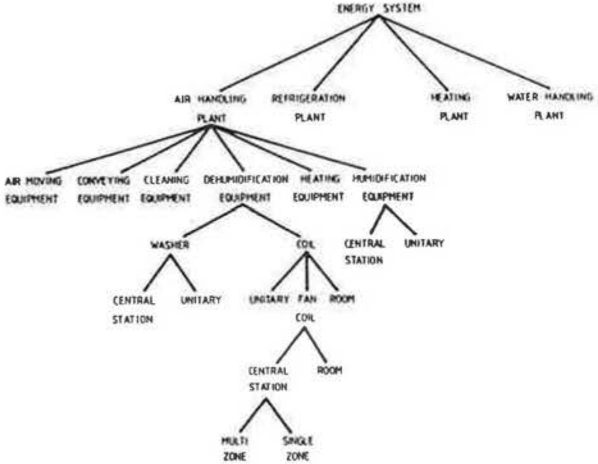

Figure 1 "Approximate" Hierarchy of Energy Systems - breakdown by component (Part only shown).

A true hierarchy, however, is only an approximation to a real system. A single component may perform more than one function. Heat pumps, for example, may heat or cool a space. Also, a single function may require more than one piece of equipment. Heating, for example, requires a terminal unit and a hot fluid, and also heating plant to heat the fluid. This introduces the concept of an *"approximate hierarchy"*.

Figure 2 shows a tree like classification of HVAC systems, with the full expansion of the air-water subtype. This tree is based on the classifications given in (14). Classification into a tree like hierarchy simplifies selection of a system, where a subtype shares many of its parent's general characteristics.

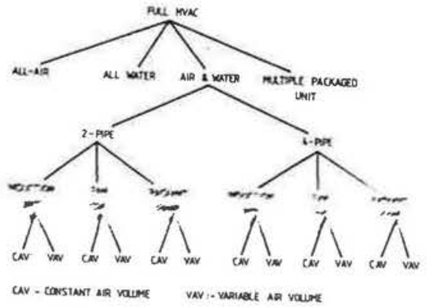

Figure 2 Classification of Energy System Types (Full HVAC only shown).

2.2. Constraints

Constraints describe the requirements that must be satisfied by the final system. These constraints may be project constraints or component configuration design knowledge expressed in the form of constraints. Constraints may be classified hierarchically as shown in Figure 3. Project constraints are specific to a given problem and are imposed by (i) Building specifications, (ii) Location and (iii) Budget restrictions. An example of a project constraint is given by the following:

If a room has a density of X people/m^2 and there is heavy smoking, then minimum ventilation requirements are Y air-changes/hour.

The density of people in the room is a constraint declared by virtue of the building function and layout; the amount of smoking is a factor depending on the function of the room. Combination of these two lower level constraints formulates a higher level constraint on the Building Energy System design.

Design knowledge such as the compatability of two components or their suitability for a given function can be expressed in the form of component configuration constraints.

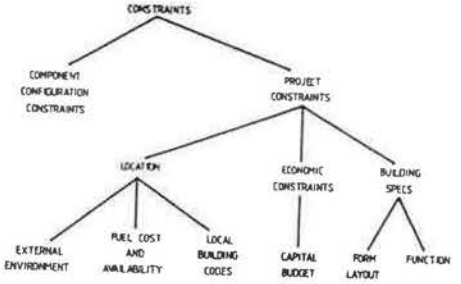

Figure 3 Hierarchy of Constraints.

2.3. Design of HVAC Systems - Procedural Knowledge

The view of a system in terms of subsystems corresponds to the view of the design procedure in terms of goals and subgoals. In some cases the goals and subgoals will be independant of each other. In general, however, the subgoals do interact (if only loosely) and this is handled by constraint propagation between the interacting subproblems. For example, consider the energy conversion plant of the Building Energy System shown in Figure 4. The system operates on the principle that the heat pump recovers heat from building zones which need cooling and dehumidification and supplies the energy to zones which simultaneously need heating. Conventional boilers and refrigeration units provide the extra heating and cooling that is needed at certain times of the year. In the design procedure, addition of heating and cooling plant to HVAC system may be treated as two separate subgoals if refrigeration units or boilers are used. However, these subgoals obviously interact when a heat pump is being selected. This is illustrated in Figure 5.

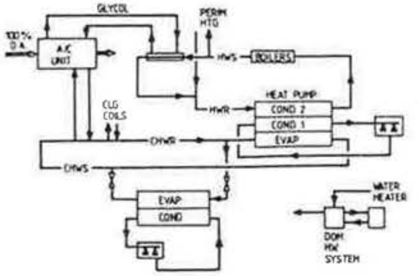

Figure 4 Block Schematic of a Typical Energy System.

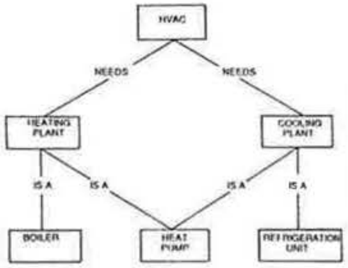

FIGURE 5 Illustration of Interacting Goals

A powerful tool to help in the selection of a system is a rating strategy which evaluates the comparative performance of various systems under given design specifications. Selection is usually a compromise between what is ideal and what is practicable for a given situation. A system under consideration has specific operating and maintenance costs and also has some characteristics and operation performance which differs from other systems. It is important, therefore, to compare the systems on a common basis. A useful rating strategy and one amenable to programming is that used by Dubin (15). A list of characteristics or "*items of consideration*" (IOC's) are considered for each system. The importance of each IOC for a given application is determined and assigned a number (*P* factor) from 1 to 10. Each energy system will differ in degree of performance for each IOC. A Weight Factor *(W)* on a scale from 1 to 10, with 10 being the most satisfactory, is assigned to each system for each IOC. A Relative Benefits Factor (RBF) may be defined as follows:

$$RBF(IOC) = P \times W \tag{1}$$

The total RBF of each system, for a given application, maybe evaluated:

$$Total\ RBF = \sum_{IOC=1}^{n} RBF(IOC) \tag{2}$$

The Cost Benefits Factor may then be calculated as follows:

$$CBF = Total\ RBF/(Total\ operating\ costs + Total\ owning\ costs) \tag{3}$$

The system with the highest RBF or the lowest CBF is the optimum system.

3. Functional Description of the Expert system

The preliminary design of energy systems has been successfully modelled using an expert system IDABES (Intelligent Design Assistant for Building Energy Systems) which is under development in the Mechanical Engineering Dept., University College Galway. The decision making and "*experts*" knowledge of IDABES is coded in OPS5, a general purpose AI programming language, while the analysis and graphical routines are written in FORTRAN.

3.1. Architecture of Expert System

The architecture of *IDABES* is similar to a pure Production Systems layout (16) with some additional components and is shown in Figure 6.

A Rule-Based Programme or Production System is a computer programme that explicitly incorporates production rules to represent knowledge. A production rule is a conditional statement composed of conditions and actions. It consists of an IF part and a THEN part; IF condition 1, condition 2, ... THEN action 1, action 2. An action typically modifies a data base or it may be some arbitrarily defined function.

The *user interface* is is a display manager and arranges input and output data in an easy to read manner.

The *control strategy* contains the procedures, implicit and explicit, that determine the overall order of problem solving activities. It acts upoun problem data and knowledge in the rule base to solve the design problem.

The *global data base* reflects the state of the developing solution. A description of the building, its characteristics and of the selected system are stored here during execution.

The *rule base* contains the production rules of the expert system and represent most of the design knowledge. The production rules are organised into modules which are responsible for the goal nature of the design.

Data base 1 contains knowledge of energy system characteristics represented in tabular and linked-data format (17). Various design procedures are also represented here.

Data base 2 contains weather data stored in conventional sequential data files.

The *analysis routines* which are called by the production rules, are used to calculate the thermal load and ventilation requirements of the building.

Figure 6 Architecture of Expert System.

3.2. Design Procedure

The design procedure as implemented is comprised of the following subgoals:

1) Formulation of building specifications - includes data gathering;
2) Determination of thermal characteristics of the building;
3) Determination of priority factors of the building and evaluateion of systems;
4) Selection of a basic system type;

A goal oriented approach to the solution is implemented by using rule modules. Each module is responsible for a specific goal or subgoal. Rules within a module are independent pieces of code and interact via the global data base, which is modified by the action of the rules. Typically there is a single rule in a module that is activated when the goal has been achieved or cannot be achieved given the current availability of information. The following is an example of such a rule.

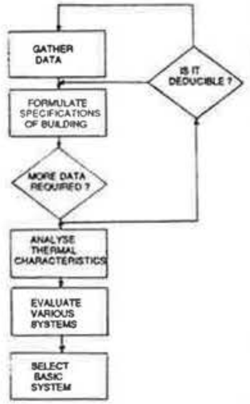

FIGURE 7 Flow Chart of Design Procedure.

IF Goal is Analyse Building Temperature
AND All relevant data has been formulated
THEN Modify Goal to check if sufficient areas of the building have been analysed.

If sufficient area has not been analysed in order to determine the buildings' overall characteristics the expert system will decide on a further relevant area, and will in turn reactivate the goal "*Get Room Data*" before any more analysis is performed.

The thermal characteristics of the building are analysed using FORTRAN-coded routines, based on CIBS guide. The input data for these is obtained and arranged by the production rules of the expert system. In this way the expert system behaves as a preprocessor of input data.

The goal "*Determination of Priority Factors*" of the building evaluates quantitatively the priorities for the building in terms of its air-conditioning requirements. The priority factors are determined using experts experiential knowledge coded in production rules. Each rule in this module contains a piece of knowledge about a particular factor influencing the selection of an HVAC system. Due to the independance of rules from each other a particular rule will be activated only if it is relevant; irrelevant rules will simply not be considered.

When this goal has been achieved the goal "*Selection of a Basic System Type*" begins. Selection of a system type is done using a combination of results of the thermal analysis and the priority factors as previously determined. The first step in the selection of a system is to select a basic system type from the three basic subtypes: Heating Only with Natural Ventilation; Heating Only with Mechanical Ventilation or Full HVAC. The expert system behaves as a postprocessor of output from the analysis routines and selects a basic system type. An example of a rule that is relevant to this part of the design is as follows:

IF Goal is Analyse thermal load
AND Perimeter does not require air conditioning
AND Perimeter does not require mechanical ventilation

THEN Select "*Heating Only with Natural Ventilation*" as the basic system type.

Selection of a subtype from lower in the hierarchy is done using the value of Total RBF as described in section . Data base 1 is searched using a beam search paradigm and the resulting system is output to the user via the interface. Figure 8 illustrates typical output of the system.

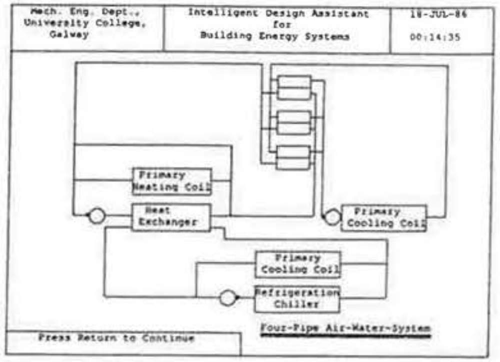

Figure 8 Example Output.

4. Conclusions

Expert systems have potential in the concept design stages of energy system design. They can successfully encapsulate the abstract and experiential knowledge, characteristic of this kind of design.

Evaluation of decisions or concepts is an essential part of any design and analysis programmes can and should be used for analysis of buildings and for evaluation of certainties in design decisions. An interesting feature of the use of expert systems at these early stages of the design, is that it now becomes more feasible to do analysis and simulations that were previously considered too time consuming. Expert systems can be used as preprocessors of data and postprocessors, where they analyse and make conclusions from output results.

Expert systems have the ability to evaluate all suitable systems for selection. This is time consuming and tedious if performed by hand and in fact, is rarely ever done.

Graphics, presently implemented in a simple way, is recognised as being of great importance to the future development of an expert system as this is the way engineers communicate their designs.

This research provides a basic framework for future developments in the area of computer aided conceptual design of HVAC systems. The preliminary stages of the design have been implemented for a limited group of systems. Future developments should consider: the selection and configuration of further subsystems and components lower in the hierarchical tree. This will require expanding the knowledge base with knowledge of HVAC subsystems and components to various levels of abstraction.

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