A KNOWLEDGE-BASED SYSTEM FOR ANALYSIS AND DESIGN OF PASSIVE SOLAR BUILDINGS

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A methodology for the development of a knowledge-based system (KBS) for design and analysis of passive solar buildings is presented. The KBS developed is part of a combined knowledge-based-algorithmic system which integrates various modules, including the energy analysis program BEEP, a database and a hypertext all running simultaneously in a flexible graphical user interface. The system supports a systematic, iterative procedure of design alternative generation and evaluation. Energy and comfort indices are employed in evaluating the various design alternatives. The program developed is intended primarily for the design of direct gain residential or office buildings. Two typical applications are presented for residential passive solar buildings.

INTRODUCTION

The design of a passive solar direct gain building involves synthesis and analysis and depends on both quantitative and qualitative knowledge. Quantitative knowledge may be derived from scientific theories or experiments, while qualitative knowledge is usually acquired through years of experience. Synthesis is the creative part of design. During synthesis the designer usually generates various design alternatives which are feasible solutions within design constraints. The performance of the product of synthesis must be verified using analysis. During analysis the various performance characteristics are calculated and tested against evaluation criteria which are set at the beginning of design. In such an iterative process of generating-testing various design options the designer eventually selects the most promising solution which is then further developed and finally implemented.

During the conceptual design stages, qualitative knowledge can be used since decisions concern the determination of the general layout of a building. However, later on during the preliminary and detailed design stages, decisions that are taken concern the type, location and size of the direct gain windows (defined as windows with high solar gains-generally near south-facing), the thermal storage mass amount and location as well as the optimum amount of insulation. In this case, qualitative knowledge is not adequate; quantitative knowledge and accurate analysis techniques are indispensable to carry out design. However, despite the need to use accurate means, especially during the preliminary design phases, designers often perform the design task intuitively, based on previous experience. They rarely conduct a detailed and accurate analysis to test the product of synthesis. This is mainly due to lack of user-friendly, easy to use analysis tools which can rapidly analyze and compare design alternatives without sacrificing accuracy.

The objective of the knowledge-based system approach described here, is to reduce these problems with a methodology and a computer program that can be used in both the creative and analytical aspects of the passive solar design process. A discussion on the design process is presented below with passive solar design issues, the main concepts of the methodology and its implementation issues. Two typical applications of the methodology are also presented.

Passive Solar Design Principles

A primary objective in the design of a passive solar building is to decide about the area and characteristics of the direct gain windows, and the thermal mass thickness, properties and its distribution in order to prevent frequent overheating while at the same time achieving high savings in energy consumption. Of course, as for all buildings, the amount of insulation is also an important parameter to be selected.

In order to meet these objectives the designer should perform many cycles of synthesis and analysis to investigate through different design alternatives the possibilities for an optimum building response under various weather conditions. This process requires a flexible, yet rigorous tool to perform the analysis part of design. For the synthetic part, since it is not suited to a pure algorithmic description, a Knowledge-Based System could incorporate sufficient information and qualitative knowledge to support the designer.

The most important performance indices involved in this process are the following:

- **The operative temperature (2) and its swing.** This is a representative room temperature that takes into account the radiant heat exchanges in a room as well as room air temperature. Its swing is approximately inversely proportional to the storage effectiveness of the thermal mass in a direct gain room.
- **The ΔTsolar** (1), is the net increase of the room mean temperature above ambient temperature due to solar gains, and can be used to determine the optimum amount of insulation, and window area and type. Alternatively, the auxiliary heating loads can also be computed on a clear winter day, until the desired energy savings are achieved. These indices show also how effectively the solar energy is used to heat the building.
- **The peak heating/cooling loads** calculation is an important requirement for the sizing of the heating/cooling equipment.
- **The mean radiant temperature (MRT)** along with other environmental and personal variables is necessary in determining the occupant thermal sensation

indices PMV and PPD (2) in the building.

KNOWLEDGE-BASED SYSTEM DEVELOPMENT METHODOLOGY

In passive solar and energy efficient building design, detailed conventional algorithmic programs have proved to be cumbersome in the iterative design process. This is mainly due to their inability to manipulate heuristic and qualitative knowledge. However, they are very versatile and effective in numerical data manipulation that characterizes analysis. On the other hand, KBS are not robust in numeric data manipulation, while they are very effective in declarative knowledge manipulation and handling of logical inferences and reasoning. Therefore, Knowledge-Based Expert Systems and traditional algorithmic programs could be combined in order to support good decisions throughout the whole building design process.

The KBS developed enables the use of both knowledge-based techniques and accurate analysis during the preliminary design stages, when decisions have considerable impact on the final design product and life-cycle of the building. Since the problem at hand deals with design, which is of the formation type, a hybrid object-oriented system supporting both frames and rules is considered more appropriate (4,5). The selected development tool LEVEL5 OBJECT™ met requirements concerning integration capabilities with other programs, ease to update, user interface characteristics and multiple inference strategies. The fact that LEVEL5 OBJECT™ runs under the multitasking operating environment of Microsoft Windows™, made it a perfect fit for the developed system because this facilitated the integration of the KBS with BEEP (6), which is the main algorithmic program used during design.

"PASSIVE SOLAR EXPERT" (PSE)

The program developed (PSE) includes several modules. Figure 1 illustrates the links of the KBS with the other modules. BEEP is the energy analysis module and its primary capabilities are the following (7):

- Distributed elements such as thermal storage mass are modelled as twoport network elements without the need for discretization.
- Room interior radiant heat exchanges (infrared) among the room interior surfaces are modelled in detail (separate from convection).
- A time-varying conductance such as that corresponding to a window with night insulation is modelled accurately.
- The solar radiation absorbed by each room interior surface is calculated. This is important in determining the effects of the thermal storage mass location and solar absorptance on direct gain room performance.
- The room mean radiant temperature and the operative temperature are determined accurately.
- On/off auxiliary heating is modelled by means of an iterative technique; proportional control being linear, is modelled directly.

At run-time BEEP is called from the KBS in order to perform analysis for a specific design alternative. Results obtained from BEEP needed by other modules are transferred through LEVEL5. The second algorithmic module of the system is used for the calculation of the comfort indices PMV and PPD which predict the thermal sensation of people in a zone based on Fanger's model. The ASHRAE ACCESS database (3) can also be accessed on-line by the designer in order to extract material properties and other required information. "Design Guidelines" is the hypertext module of the system and contains information about passive solar systems and design heuristics. The KBS controls and coordinates the other modules and is in continuous contact with the designer. Its knowledge base accommodates the design heuristics and information regarding the design process control and interface characteristics.

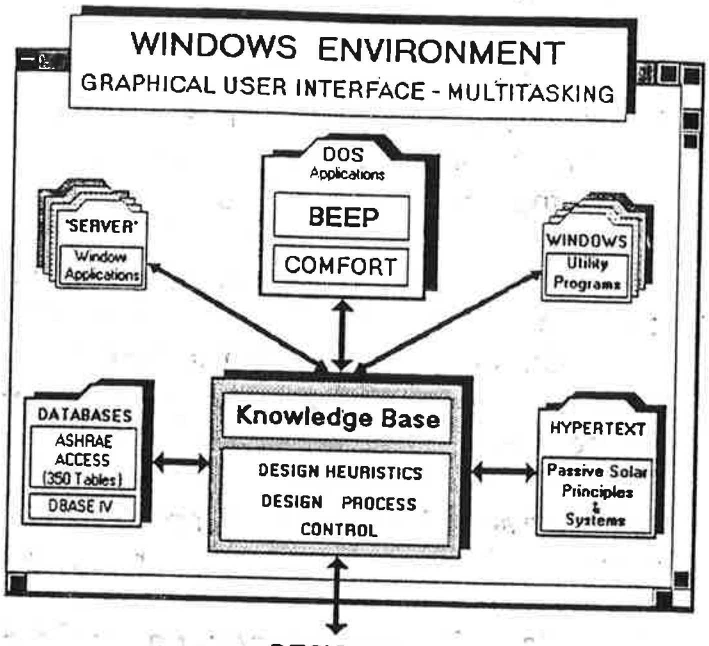

Fig.1 Architecture of Passive Solar Expert

The basis for the structure of all this information in LEVEL5 OBJECT expert system shell is the 'Class'. A Class is used to produce multiple instances of an object. 'Instances' encapsulate the structure of objects and hold actual values obtained during a session. Each Class has a name and properties that specify for example whether it inherits the characteristics of any other Class or Classes, if it is sourced from a database etc. The Class characteristics are represented by attributes which can be of different types (eg. string, numeric etc.). These attributes have their own 'procedures' and 'behaviour' in the form of Facets, Methods, Rules and Demons. Rules and methods (procedural attachments) represent the inferential knowledge. Backward chaining rules and forward chaining demons describe the operational logic and cause-and-effect relationships needed to make decisions and trigger certain actions during a session. Methods establish procedures for determining values. Various constraints are also incorporated in the KBS which specify acceptable values or range of values for important attributes (e.g. $-0.5=<PMV<=+0.5$).

DESIGN WITH "PASSIVE SOLAR EXPERT"

Passive Solar Expert supports an iterative system-user procedure of design alternative generation and evaluation. The main principle of its operation is the improvement in performance of successive design alternatives which consist of different building zone arrangements, building envelope component materials and properties, their dimensions and location in the zone. The generation of design alternatives is performed step-by-step, by generating-testing-improving an alternative; thus the designer experiences immediately the impacts of his decisions. The basic unit which is considered each time is the "zone" and is assumed to be isothermal for load calculations.

A design alternative for a zone is completed when three important cases have been considered:

Case 1. The zone performance is computed on a relatively clear winter day (KT=0.7) assuming no auxiliary heating/cooling so as to investigate the thermal storage effectiveness of the zone thermal mass distributed along the inner surfaces.

Case 2. The zone performance is determined on a relatively clear winter day with heating/cooling in order to check how effectively the solar energy is utilized within the zone.

Case 3. The zone performance is determined on a cold cloudy winter day (KT=0.2) with auxiliary heating/cooling in order to determine the size of equipment required under worst case conditions, and the relevant effect of thermal mass.

For each case the system displays graphically the portion of solar radiation that is absorbed by each room interior surface (fig.2). This information helps the designer to decide on the distribution of the thermal storage mass in the room interior. At the instance of constraint violation, for example if the PMV/PPD values exceed the allowable by ASHRAE range, the system informs the designer. Results for all the values of interest are accumulated by the system in a table along with important input variables and are shown to the designer with recommendations for possible improvements. Recommendations are based on evaluation of the different design options on a relative basis and using the heuristics. If the designer is not satisfied with the results, he can improve the zone performance by developing a new alternative. This can be repeated examining the performance of various design alternatives until the overall results are satisfactory.

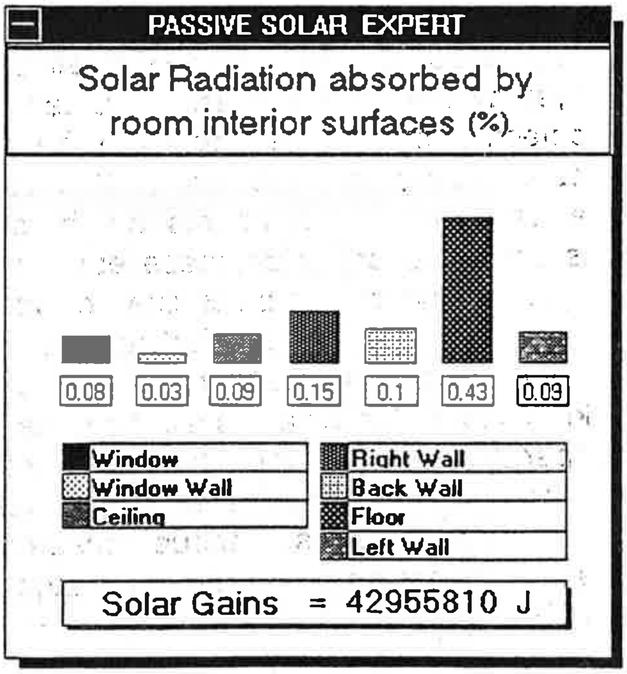

Fig.2 Dynamic display of solar radiation absorbed by each room interior surface for a particular design alternative

Case Studies

Two example case studies are described below for design in two different climatic regions in order to demonstrate the use of Passive Solar Expert.

The first example deals with a typical single-family residential building in the area of Montréal (latitude 45°). This is a wood frame building with brick on the exterior walls, and interior partitions of plasterboard on wood frame. Figure 3 presents results from five design alternatives for a south facing zone (6 x 7.5)m^2 in area, with a large direct gain window and two small windows on the west wall which do not have significant solar gains. The results represent the most important performance attributes discussed earlier. For the first three design alternatives (DA) there is no additional thermal storage mass in the zone. Consequently, high temperature swings occur in all the three alternatives for clear days. The first DA includes carpet on the floor (but no night insulation for the window). The 2nd alternative shows that when night insulation is used, there is a reduction in both auxiliary heating and peak load. This is due to better window performance and thus lower heat losses during the night. The third DA, demonstrates the contribution of a better insulated exterior wall to an improved performance of the envelope, causing another reduction in auxiliary heating and peak load. For this alternative auxiliary cooling is needed which indicates that overheating occurs due to the lack of sufficient thermal storage mass. Results from DA 4 show that thermal mass can significantly reduce the auxiliary heating load on clear days (KT=0.7). There is also reduction in the temperature swing for a clear day and reduction in peak load for both clear and cloudy days as compared with the previous alternatives. For the 5th DA, a relatively small reduction in window area causes a reduction of peak load and auxiliary heating load on a cold cloudy day, while there is a slight increase of their values on a clear day.

INPUT								OUTPUT									
DA #	KT	Set-back (°C)	INFL. ach	# Glaz.	Window area m^2	R of walls (RSI)	R of Shutters (RSI)	Peak Load (W)	Total Heat Load (MJ)	Toper (°C)		Solar Gain (MJ)	PMV		PPD	
										Min	Max		Min	Max	Min	Max
1	0.7		0.5	2	5.2	2.462	0			6.8	31.2	75.5	-6.7	1.8	100	69
	0.7	0						2254.2	96.7	18.3	28.7	75.5	-2.6	0.9	95	24
	0.2	0						2288.6	121.9	18.5	20.1	6.1	-2.5	-2	94	79
2	0.7		0.5	2	5.2	2.462	0.3			7	32.4	75.5	-6.7	2.2	100	87
	0.7	0						2089.7	89.3	18.5	28.9	75.5	-2.5	1	94	26
	0.2	0						2124.3	113.1	18.7	20.2	6.1	-2.5	-2	93	79
3	0.7		0.5	2	5.2	4.35	0.3			7.5	33.2	75.5	-6.5	2.5	100	94
	0.7	0						1985.3	83.5	18.6	29	75.5	-2.5	1	93	28
	0.2	0						2000.5	103.8	18.8	20.3	6.1	-2.4	-2	92	77
4	0.7		0.5	2	5.2	4.35	0.3			13.4	21.8	75.2	-4.4	-1.4	100	50
	0.7	0						1467.2	56	19.2	23.9	75.2	-2.3	-0.7	89	16
	0.2	0						1734.1	103.7	19.1	20	6.1	-2.3	-2	90	81
5	0.7		0.5	2	3.9	4.35	0.3			13.2	20.4	56.7	-4.5	-1.9	100	76
	0.7	0						1509.9	61.2	19.3	22.7	56.7	-2.2	-1.1	88	33
	0.2	0						1689.9	100.3	19.1	20	4.6	-2.3	-2	90	80

Fig.3 Residential building (latitude 45°). Summary results for five design alternatives.

The second example investigates the performance of a single-family dwelling in a temperate climate (latitude=35°), with hot summers and relatively cold winters. It is a concrete structure with brick exterior and interior walls of thickness 0.25m and 0.14m respectively. Results from a typical zone are shown in figure 4. The first design alternative considers exterior walls without any insulation, single glazing for the south facing direct gain glass sliding doors and carpet on floor (without extra thermal mass). The absence of significant thermal mass results in a high temperature swing and the single window pane and uninsulated exterior walls cause considerable heat losses which are reduced in design alternatives 2 and 3. Despite these reductions, in both design alternatives 1 and 2 there is indication of overheating which means that thermal mass must be used to store the excess energy for use at night. Design alternative #3 considers an increase in mass of 0.12m concrete on the floor, without carpet which otherwise acts as an insulating layer (1). The result is a reduction in operative temperature swing, auxiliary heating load and peak load for a clear day (KT=0.7). Night insulation also has a positive effect as shown in design alternative #4. It causes a reduction in the peak load and auxiliary heating load for both clear and cloudy days. Increase of the wall resistance in design alternative #5 contributes to a significant reduction in the peak load and auxiliary heating load for clear and cloudy days. Decrease of the window area in design alternative #6 results in a reduction of the peak heating load for KT=0.2, while there is an increase in the auxiliary heating load and peak load for KT=0.7.

INPUT								OUTPUT									
DA #	KT	Set-back (°C)	INFL ach	# Glaz.	Window area m^2	R of walls (RSI)	R of Shutters (RSI)	Peak Load (W)	Total Heat.Load (MJ)	Toper (°C) Min	Toper (°C) Max	Solar Gain (MJ)	PMV Min	PMV Max	PPD Min	PPD Max
1	0.7		0.5	1	4.2	0.5	0			5.8	33.1	75.6	-7	2.4	100	93
	0.7	0						1520.5	64.1	17.1	28.9	75.6	-2.9	1	99	26
	0.2	0						1652	90.7	17.1	19.3	8.7	-2.9	-2.2	98	87
2	0.7		0.5	2	4.2	0.5	0			6.1	32.6	63.5	-6.9	2.3	100	89
	0.7	0						1385	58.1	17.4	28.7	63.5	-2.8	0.9	98	24
	0.2	0						1516.2	83	17.4	19.4	7	-2.8	-2.2	98	87
3	0.7		0.5	2	4.2	0.5	0			9.8	21.8	63.5	-7.5	-2.4	100	91
	0.7	0						1291.3	52	17.7	23.6	63.5	-3.9	-1.6	99	58
	0.2	0						1526.4	93.6	17.3	18.9	7	-4.1	-3.5	100	99
4	0.7		0.5	2	4.2	0.5	0.3			9.7	22.2	63.5	-7.5	-2.2	100	86
	0.7	0						1248.5	50.1	17.9	24.1	63.5	-3.9	-1.4	99	47
	0.2	0						1486.1	92.2	17.4	18.9	7	-4	-3.5	100	99
5	0.7		0.5	2	4.2	2.2	0.3			18.9	23.1	63.5	-3.6	-1.8	99	70
	0.7	0						226.1	4.4	19.9	23.5	63.5	-3.2	-1.6	99	61
	0.2	0						758.4	51.4	18.8	19.3	7	-3.6	-3.4	99	99
6	0.7		0.5	2	3.36	2.2	0.3			17.6	21.1	50.8	-4.2	-2.7	100	97
	0.7	0						342.2	9.2	19.6	22.3	50.8	-3.2	-2.2	99	84
	0.2	0						745.4	51.3	18.8	19.3	5.6	-3.5	-3.4	99	99

Explain | Generate New Zone | Generate New Alternative | Quit

Fig. 4 Case study 2. Summary results for six design alternatives

CONCLUSIONS

The combination of qualitative and quantitative knowledge in a single, user-friendly system has been shown to be very useful for passive solar analysis and design. The system developed (PSE) can be used at the preliminary and detailed design stages and combines both heuristic and algorithmic techniques and knowledge. It supports an iterative, system-designer cooperative process of design alternative generation, testing and evaluation.

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