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A Knowledge-Based System for Energy-Efficient Building Design

Qun Gu

A Thesis

at the

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ABSTRACT

A Knowledge-Based System
for Energy-Efficient Building Design

Qun Gu

Energy-efficient building design is challenging because it requires from the designers an ability to apply energy-efficient techniques to the design process in the consideration of both artistic and technical aspects of the building. Building designers are constantly facing the problem on how to choose energy conservation options and how to implement them. This is especially true at the preliminary design stage when many important design decisions that significant affectly the energy performance are made.

The Model National Energy Code of Canada for Buildings [MNECCB 1995] provides the guidelines for the energy-efficient building design. Knowledge-Based Systems are well suited for the computerization of the Code requirements. By linking to simulation models representing the real world environment, the KBS approach can potentially support most aspects of compliance checking provided in the energy Code.

The objective of this research is to develop a systematic and integrated methodology to assemble a computer-based system that will perform as a design assistant. It will help architects and building designers at the preliminary design stage to compare current designs to the MNECCB in areas of the building envelope and lighting.

A suitable methodology is proposed as an integrated system that combines knowledge base, database and correlation model into a CAD environment. The knowledge base contains the design requirements given in the Code. Databases store design building data and reference building data. The correlation model is based on the trade-off compliance path provided in the Code in which a simplified correlation method is used to reduce the amount of input.

A three-step procedure to interpret Code text into knowledge base is developed through the analysis of the Code requirements. The data required to perform the Code checking are examined and the different methods to collect these data are studied. A visual user-interface system in a CAD environment is proved to be desirable and a method to directly collecting design building data from the working drawing is presented. Finally, a research prototype named Building Energy Code Advisor (BECA) is implemented and presented.

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LIST OF PARAMETERS AND ACRONYMS

γ	parameter used in determining GIF
δ_0 , δ_1 ,δ_2 , δ_3	parameters used in determining GIF
a_0	intercept for the base cooling load
a_1	variation of cooling load with respect to solar parameter
a_2	variation of cooling load with respect to internal load parameter
a_3	variation of cooling load with thermal transmittance
A_0, A_1.	climate correlation coefficients
A_c	centre-of-glass area [m^2]
A_d	divider area [m^2]
A_{de}	divider edge area [m^2]
A_e	edge-of-glass area [m^2]
A_f	floor area of the exterior zone, typically of 4.5m deep [m^2]
A_{fm}	frame area [m^2]
A_g	total glass area, [m^2]
A_o	opaque wall area [m^2]
A_t	gross wall area (A_w+A_o) [m^2]
A_w	window wall area including frame [m^2]
b_0	constant representing infiltration and ventilation losses
b_1	slope of the variation of annual heat loss with respect to U
B_0, B_1	climate correlation coefficients
C	annual cooling load
C_0, C_1. C_2, C_3. C_4, C_5.C_6	climate correlation coefficients
C_O	base cooling load [MJ /m^2 yr]
ΔC_O	correction for envelope losses / gains [MJ /m^2 yr]
CDD50	cooling degree days base 50°F (10°C)
CDD65	cooling degree-days at 65 ° F (18° C)
C_{min}	minimum cooling load for the particular climatic location and the choice of system modeled [MJ /m^2 yr]
E_0, E_1. E_2, E_3. E_4, E_5	climate correlation coefficients

FC	ratio between the wall area of zone under consideration and the total wall area of all zones
FWR	fenestration-to-wall area ratio
G_1, G_2, G_3, G_4, G_5	climate correlation coefficients
GIF	Solar Gain and Internal Gain Interaction Factor
HDD50	heating degree days base 50°F (10°C)
I	design heat gain from lights, people, and equipment [W/m^2 floor area]
IGRF	Internal Gain Reduction Factor
j	north, south, east, west, (northeast, northwest, southeast and southwest by interpolation)
k_1, k_2	climate factors used in annual heating load
L	annual heat loss [MJ /m^2 yr]
$L_0, L_1, L_2, L_3, L_4, L_5$	climate correlation coefficients
L_v	annual heating loss minus solar heat gains
L_w	annual heating loss minus internal heat gains
LAT	latitude in minutes
Q	annual heating load [MJ /m^2 yr]
$S_0, S_1, S_2, S_3, S_4, S_5, S_6$	climate correlation coefficients
SC_w	window shading coefficient
SHGC	solar heat gain coefficient
SHGCr	solar heat gain coefficient of a reference glass (single-pane, double strength, clear glass)
$SHGC_w$	solar heat gain coefficient of complete window product
$SHGC_g$	solar heat gain coefficient of glazing
$SHGC_{fm}$	solar heat gain coefficient of frame
$SHGC_d$	solar heat gain coefficient of dividers
SGRF	Solar Gain Reduction Factor
$T_0, T_1, T_2, T_3, T_4, T_5$	climate correlation coefficients
U	heat loss parameter [W/(m^{2}K)]
U_c	calculated centre-of-glass U-value [W/(m$^{2\circ}$K)]

U_e	calculated edge-of-glass U-value [W/(m$^{2\circ}$K)]
U_{fm}	calculated frame U-value [W/(m$^{2\circ}$K)]
U_d	calculated divider U-value [W/(m$^{2\circ}$K)]
U_{de}	calculated divider edge U-value [W/(m$^{2\circ}$K)]
U_{ow}	area-average U-value of opaque walls [W/(m^{2}K)]
U_o	opaque wall U-factor [W/m^{2}K]
U_w	window U-factor, including frame [W/m^{2}K]
V	solar heat gain parameter
VS	annual average daily incident solar energy on facade under consideration
VS_j	vertical solar on orientation j [W/m^2]
W	internal heat gain parameter [W/m^2]
x	parameter used in determining SGRF
X_1, X_2, X_3, X_4, X_5	climate correlation coefficients
y	parameter used in determining IGRF

Chapter 1

Introduction

1.1 General

Design standards play an important role in building engineering in that they are used to ensure the safety and functionality of buildings. Codes are developed from the experience of many past projects. Designers have to deal with a large amount of design standards in each building project. That is a complex, tedious and laborious task. The effective use of each design standards requires a good understanding of the terminology, the intentions and the approach followed by the Code. Different specifications apply to different categories of designers, and it is very common for a designer to use more than one Code in a single project, as he/she has to know the impact of his/her decisions on other design specialties and jurisdictions. Sometimes a designer may lack experience in the Code that he/she is using. So there will be difficulties associated with understanding and correctly applying the requirements of the new energy Code for buildings in Canada.

Traditionally energy issues were of concern to the HVAC engineers only. It is now clearly established that architectural design can have a significant influence on the energy consumption of new buildings. The new Model National Energy Code of Canada for Buildings [MNECCB 1995] is used not only by HVAC engineers, but also by all building designers. The Code has chapters dedicated to envelope and lighting design, which are of prime concern to the architect. The design criteria provided in this Code are as important as the criteria provided in National Building Code of Canada [NBCC 1995] although they are based on energy considerations. It is not easy for architects to understand all the technical terms, different compliance checking methods and their applicable conditions.

Rapidly developing computer techniques can provide a powerful tool to solve this problem. As almost all architectural firms use computers to complete designs and drawings, it is possible to provide a computer-based tool that specializes in energy Code processing in addition to integration with their existing CAD system. This can serve as a Code checking tool as well as a learning tool for the new MNECCB.

1.2 Energy-Efficient Building Design

Energy-efficient buildings are the results of not only a responsible attitude toward energy but also the designer's ability to apply energy-efficient techniques into the design process. Building designers are constantly facing the problem of how to choose energy conservation options and how to implement them. Annual energy usage in today's buildings represents more than one-third of the annual energy use in U.S. [Knight 1980] and a big portion in Canada as well. Much of this energy is wasted because of poor building design.

Energy-efficient building design is challenging because the artistic aspects of building design and the technical aspects must be considered together. The design procedure for energy-efficient buildings is essentially the same as for all other buildings except for the need of taking into consideration the energy-efficient design criteria. The amount of energy used in a building is a direct result of the climate, building shape, size and its envelope characteristics. Because of the large amount of variables affecting the climate and the building itself, it is very difficult and time consuming to predict building energy performance. Very often designers ignore the complexities of energy considerations in the early design stages and concentrate on other aspects instead. By the time they want to evaluate the building energy performance, the design has progressed so far in detail that it is too late to make fundamental changes.

In the conceptual design stage, the architect would study the requirements of clients and take major decisions regarding the building type, form, structure type, etc. The definition of major envelope assemblies would be made in the preliminary design stage. At this stage with only the development of floor layouts and elevations, the composition of exterior walls, roof, the location and approximate dimensions of openings can be determined. Building design is now sufficiently detailed to be examined from a technical standpoint, yet flexible enough to take changes without bringing too much trouble to both architects and engineers. Thus many important design decisions that significantly affect energy performance are made at this stage.

Although there are rules of thumb about energy-efficient building design that most architects are aware of, they lack in general more advanced technical knowledge on this issue and often give up energy considerations to other considerations such as aesthetic or cost when there is a conflict. The new MNECCB could thus guide designers under these circumstances and give them a systematic approach to account for building design energy issues.

The requirements contained in the Codes are largely in the form of statements and rules. Misinterpreting or overlooking provisions of the Code would lead to design problems. Knowledge-Based Systems (KBS) are well suited for the computerization of Code requirements expressed as rule sets. By linking to simulation models representing the real world environment, the KBS approach can potentially support most aspects of compliance checking provided in the energy Code.

1.3 Scope and Objectives

The objective of this research is to develop a systematic and integrated methodology to assemble a computer-based system that will perform as a design assistant. It will help architects of the preliminary design team to compare current designs to the MNECCB. By providing the Code text and technical advice to the user, it could also perform as a learning tool for the study of the MNECCB. The proposed system focuses on building envelope and lighting design because these tasks represent some of the main aspects that architects deal with at the preliminary design phase.

Following review of the relevant literature, a suitable methodology is proposed as an integrated system that combines knowledge base, database and correlation model into a

CAD environment. The knowledge base contains the design requirements given in the Code. Databases store design building data and reference building data. The correlation model is based on the trade-off compliance path provided in the Code in which a simplified correlation method is used to simplify input.

Through the analysis of Code requirements, a procedure to interpret and insert Code text into a knowledge base is presented: (i) Code text analysis, i.e., determine the descriptive statements and logical relations, (ii) use the statements and logical relations to build decision diagrams, and (iii) encode the decision diagrams into the knowledge base by means of object-oriented approach, which entails defining descriptive statements as classes and attributes and using logical relations to define rules to control the values of classes and attributes.

A visual user interface in a CAD environment is considered to maximize the advantages of incorporating the entire system in the design working drawing environment. Different types of design data and methods for collecting them are examined. A method that collects design building data directly from the working drawings is presented.

A research prototype named Building Energy Code Advisor (BECA) is finally implemented and presented in an attempt to demonstrate the feasibility and practicality of the proposed methodology. The architecture of the computer-aided design system consists of a pre-processor, the main module of MNECCB and a post-processor. Two case studies are also described to validate the accuracy of BECA.

Chapter 2

Literature Review

2.1 Introduction

The building Code checking process is an essential part of building design. It is a process that requires broad knowledge of the Codes, awareness of their continuous changes, good understanding of the design process, and a skillful person [Delis and Delis, 1995]. Numerous research efforts are devoted to develop computer programs to help designers.

This chapter provides some background materials in this research area. The Model National Energy Code of Canada for Buildings [MNECCB 1995] and ASHRAE/IES 90.1-1989 [ASHRAE 1989] are briefly described. Some previous works done in the field of automatic Code checking and energy performance evaluation are studied. Specific considerations concerning Code checking and energy-efficient evaluation are examined in the following sections to address the nature of energy Code and its usage in the design process.

2.2 Overview of MNECCB

Every country has its own Codes concerning the design, construction and safety requirements of buildings. But only few of them include the considerations of the energy issues. Energy is used in a building for heating, cooling, lighting and other services. It has been estimated that without reducing occupant comfort, approximately 40 percent of the energy used in buildings can be saved with the application of existing technologies [ASHRAE 1989]. ASHRAE/ICE 90.1-1989 [1989] is a widely accepted standard about energy-efficient building design. The approach and spirit used in the development of this ASHRAE Standard are also used in the development of new Model National Energy Code of Canada for Buildings [MNECCB 1995]. The study of strategies in the design of energy-efficient buildings, contained in the ASHRAE Standard will be helpful to better understand the MNECCB.

2.2.1. ASHRAE/IES 90.1-1989 (1989)

The ASHRAE Standard recommends several strategies for the design of building envelope and lighting systems. These strategies are generally accepted as guidelines for the design of energy-efficient buildings.

1. Consider design efficiency from the initiation of the design process. Building attributes such as building function, form, orientation, window/wall ratio, and HVAC system types shall be taken into considerations early in the design process because each of them has major energy implications.

2. Address the building energy requirements in the following sequence: try to minimize the energy requirements defined by the function of a building, minimize building

thermal loads, improve the efficiency of distribution and conversion systems and integrate building subsystems into an efficient whole.

3. Building thermal loads result from sources external and internal to the building. External loads are due to the difference between indoor and outdoor temperature, humidity, wind effects, etc. Internal loads come from the activities conducted within the building, the heat and moisture produced by the occupants, lights, and equipment. Improving energy efficiency in a building depends on how to take advantage of these loads and therefore minimizing the overall energy consumption. A well-designed building envelope system is very helpful to achieve this goal.

4. Lighting is a major energy end use in commercial buildings and a major contributor to internal loads. It increases the cooling loads in the summer and decreases the heating loads in the winter. A well-designed lighting system also contributes to the energy-efficient building design.

ASHRAE has one standard for low-rise residential buildings [ASHRAE STANDARD 90.2-1993 1993] and another one for all new buildings except low-rise residential buildings [ASHRAE/IES 1989]. In addition to the basic requirements that all building design shall respect, the ASHRAE Standard of 1989 provides two methods for verifying compliance: (i) the Prescriptive System/ Component Method and (ii) the Building Energy Cost Budget Method (Figure 2-1). The prescriptive method is generally used for conventional designs. The system performance criteria are available in these sections of the standard dedicated to lighting and envelope, and are useful when innovative design or more flexibility in the design is desired. The Building Energy Cost Budget Method should be used when the most innovative design concepts are being considered or the proposed design fails to meet either prescriptive or system performance method.

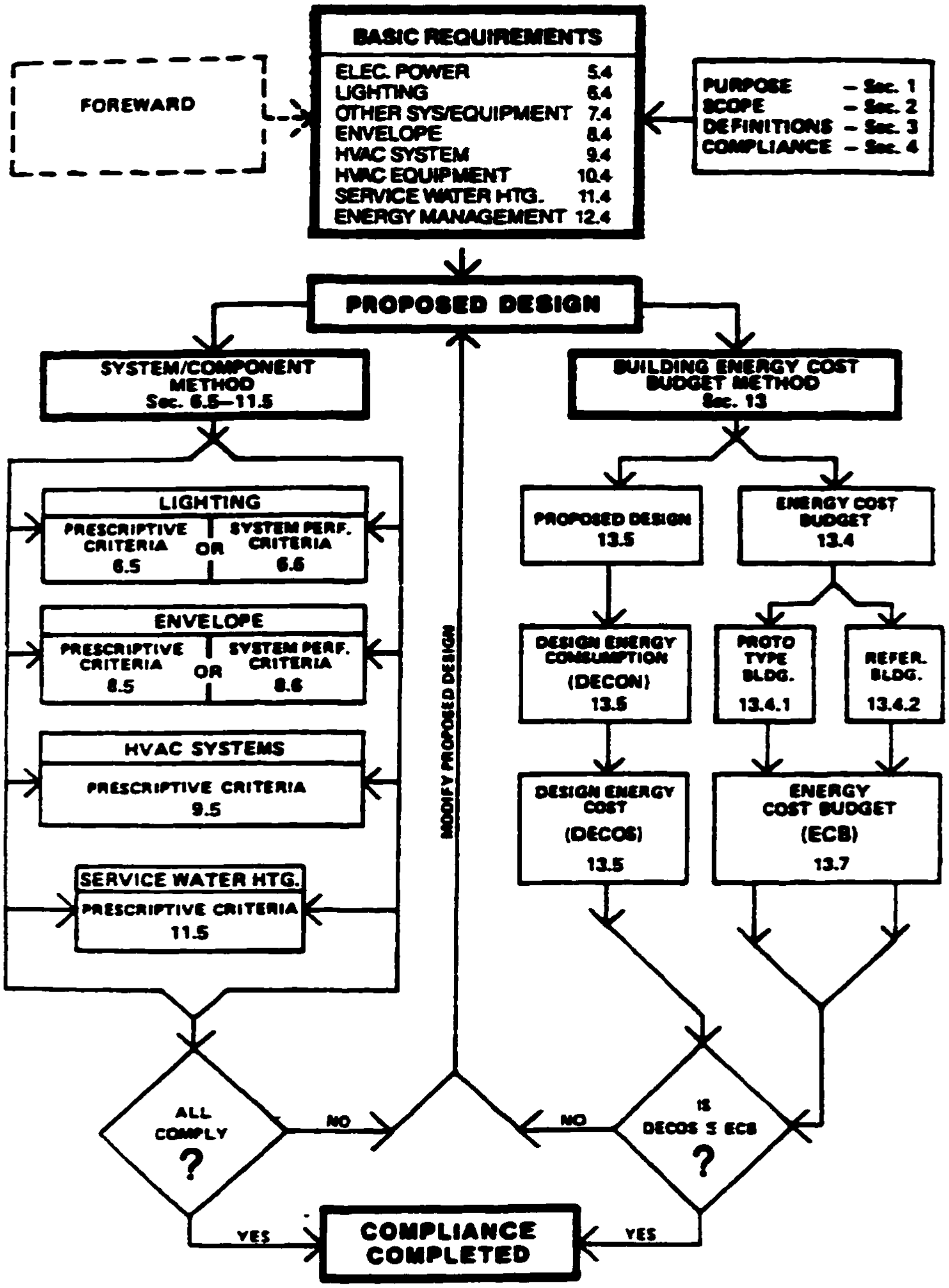


Figure 2-1: Alternative Methods of Achieving Compliance in ASHRAE Standard [ASHRAE 1989]

2.2.2. Model National Energy Code of Canada for Buildings (1995)

Following the format of ASHRAE Standard 90.1-1989, the MNECCB is comprised of two separate documents: one for houses and one for all buildings except houses. The research presented in this thesis deals with the Code for all buildings except houses. The checking paths provided in the Code are shown in Figure 2-2.

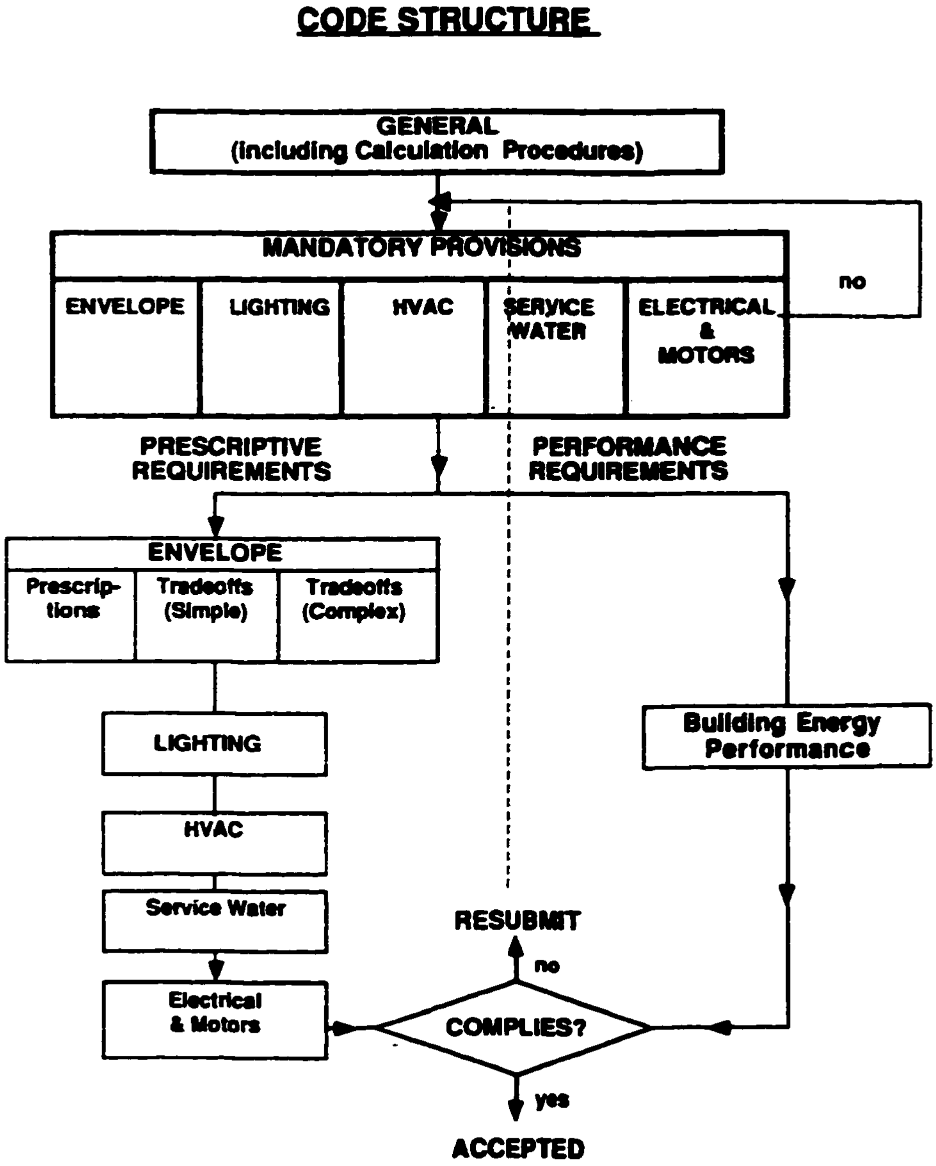


Figure 2-2: Compliance Paths in MNECCB [1995]

The Code includes different categories of requirements as in the ASHRAE Standard. Some are mandatory requirements applied to all buildings in all circumstances. The prescriptive requirements are used in the Prescriptive Compliance Path. When some of the building envelope characteristics are below the prescriptive requirements while others perform above, the designer can use the trade-off Compliance Path to verify whether the proposed envelope performs better than the envelope designed according to the prescriptive requirements.

The Building Energy Performance Path is an alternative to the prescriptive path. It takes every aspect of a building design into consideration. These aspects include: envelope, lighting system, HVAC system, service water heating system and electrical power. It evaluates the energy performance of the entire building. Although some aspects of the building design may not respect the prescriptive requirements, the proposed design is accepted if its expected energy consumption does not exceed that of a building designed according to prescriptive requirements. This path is not used in this research project because the focus is only on design of the envelope and lighting.

The MNECCB also includes regionally sensitive requirements and computer-based performance assessment. Regionally sensitive requirements are based on detailed cost/benefit analyses taking into account regional variations in climate, energy costs and construction costs. Computer programs are suitable to the Performance Compliance Path and the Trade off Compliance Path which involve series of judgements and calculations.

2.2.3. Structure of the MNECCB

There are eight sections and five appendices in the Code, namely: Part 1. Scope and Definitions, Part 2. General Requirements, Part 3. Building Envelope, Part 4. Lighting, Part 5. Heating, Ventilating and Air-conditioning Systems, Part 6. Service Water Heating Systems, Part 7. Electrical Power, and Part 8. Building Energy Performance Compliance.

The research project includes the content of Parts 1, 2, 3 and 4 and Appendices A and B. The explanations of technical terms in Part 1 are encoded as hotlinks and the users can view them with the mouse as explained in Section 6.2. General design requirements (Part 2) as well as design requirements for building envelope (Part 3) and lighting (Part 4) constitute the essential parts of the knowledge base used for Code checking.

Appendix A contains a set of tables that show the prescriptive requirements concerning the thermal characteristics of building enclosure (e.g. walls above ground, windows, roofs). Appendix B contains a set of tables providing the thermal characteristics of common building assemblies, such as exterior walls, windows and doors, which are used as recommended values.

2.3. Automatic Building Code Checking Approaches

To date many previous works have focused on the development of systems for computer-based standards processing. Such systems are able to present a standard and evaluate the intrinsic properties of the Code. Prototype of systems for different standards and Codes, from structural design Code to fire protection Code and the National Building Code of Canada [NBCC 1995], have been developed by Kumar et al. [1995], Nguyen et al. [1996], Delis and Delis [1995], and Vanier et al.[1998]. Different approaches including hypertext systems, knowledge-base systems and Code modeling language are presented in the following sections (2.3.1 to 2.3.3)

2.3.1. Hypertext Approach

An hypertext system is created of electronic pieces of text that are inter-linked instead of being bounded by the sequential structure of printed words [Kumar et al. 1995]. It can represent standards information and usually has a user-friendly interface that allows the users to browse easily through the information or viewing only the part of concern. Cross references are incorporated as "hotspots" that can be located by simply clicking on the references.

A system for the Norwegian building regulations [Mitusch 1988] was developed in two stages: (i) the development of a working knowledge base, and (ii) the transfer of this knowledge base into a hypertext environment. Another prototype system named HASES [Nguyen et al. 1996] has also used hypertext representations to browse through the fire protection regulations included in the National Building Code of Canada [NBCC 1995]. Although a complete report is generated, explanation facilities are lacking in the hypertext implementation.

Kumar et al. [1995] overcame this drawback by including in the computer-based system additional information to the Code. Figure 2-3 shows their proposed methodology. Explanation is added as additional information that demonstrates the theory behind the provision and to help clarifying ambiguous provisions.

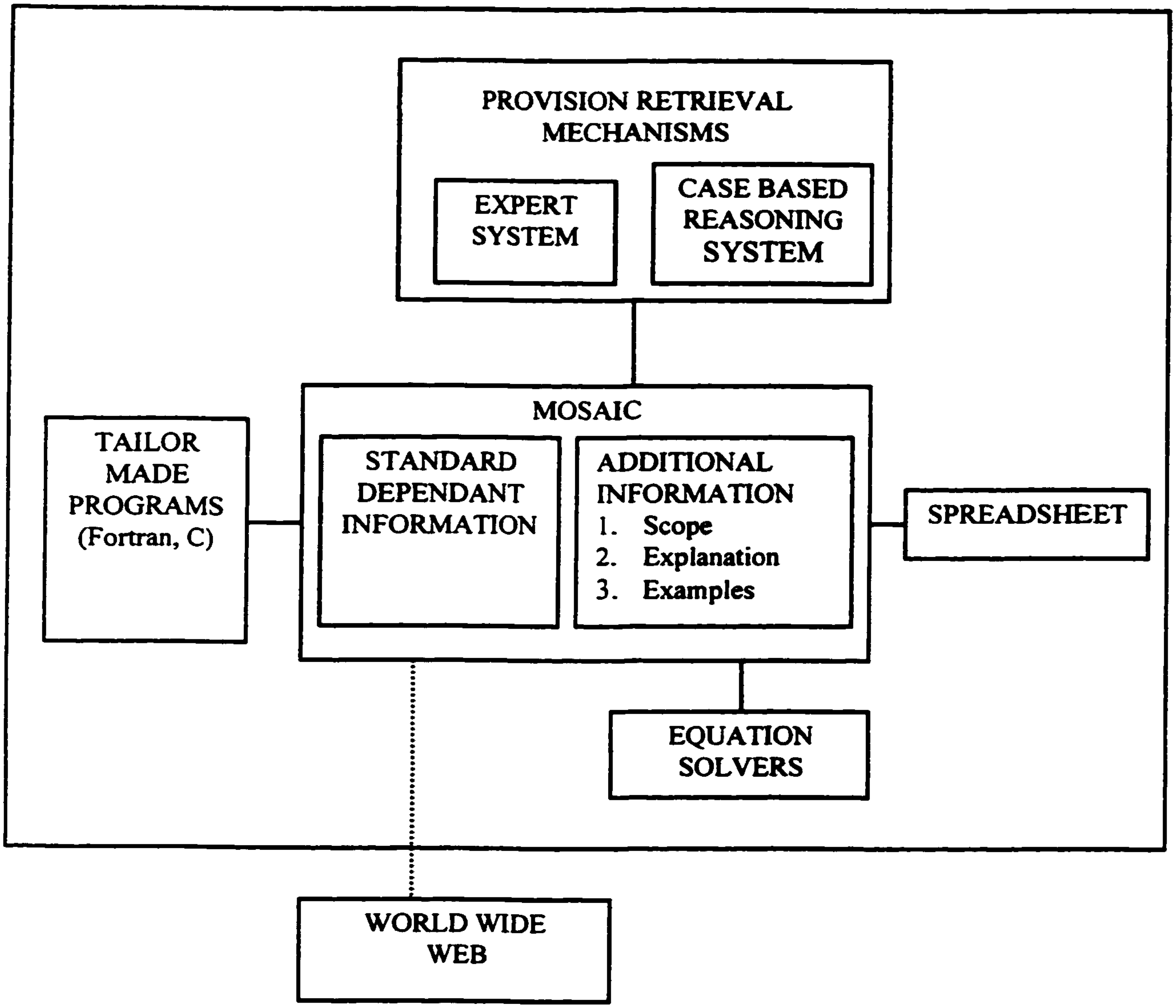


Figure 2-3: A Schematic Diagram of the Hypertext Approach of Kumar et al. [1995]

2.3.2. Knowledge-Based System Approach

Knowledge-Based Systems (KBS) remains one of the most widely used approaches for automatic Code checking. Many prototype systems have been reported to use this approach in verifying the compliance of building design with NBCC [Vanier et al. 1994], fire Code [Delis and Delis 1995, Nguyen et al. 1996] or structure Code [Kumar 1995].

The Fire-Code Analyzer (FCA) prototype [Delis and Delis 1995] is such a system that consists of a rule-based system, a frame-based system and a set of geometric algorithms. A knowledge base and a rule interpreter constitute the rule-based system. Rules represent paragraphs in the fire protection Code. Rules consist of an antecedent part 'IF' and a consequent part 'THEN'. If the antecedent is satisfied, the consequent is satisfied as well. As an example, the following statement concerns the protection of vertical openings:

> The fire resistance rating of enclosures in health care occupancies protected throughout by an approved automatic sprinkler system may be reduced to 1 hour in buildings up to, and including, three stories in height.

The rewriting of the Code text in the format of IF...Then... rule is like:

```
IF      building occupancy is health care      AND
        building is sprinkler protected        AND
        building height is 3 stories and less
THEN    fire resistance rating of enclosure may be reduced to 1 hour
```

This paragraph is translated into the following computer language, which is a part of the Code representation in the rule-based system:

```
(IF (AND (THE SPRINKLER-PRESENCE OF A BUILDING IS YES)
              (?SPACE IS IN  CLASS VERTICAL –OPENINGS)
              (THE SUPERSPACE OF ?SPACE IS ?ZONE)
              (?ZONE IS IN CLASS FIRE-ZONES)
              (LISP(<(THE STORIES-ABOVE-GRADE OF BUILDING) 4)))
(THEN    (A REQUIRED-ENCLOSURE-RATING OF ? SPACE IS 1)))
```

The rule interpreter matches the antecedent component to the facts contained in the frame-based system. Frame is a knowledge representation structure, which is composed a set of descriptive components to describe the objects or concepts that are associated with the frame. The frame-based system is used to represent the architectural features of a building. Each frame of the system clearly represents a feature and its properties (e.g. FRAME door has the following properties rating, swings_into, travel_dis_to_exit, etc). A set of frames constitutes a complex model (i.e. a building). Frames are organized hierarchically by two types of links: member links (i.e., "part-of" relationship) and subclass links (i.e., "is-a" relationship).

A geometric algorithm is developed in this system to illustrate the implicit information stored in the frame system regarding the various features of the building. Numerous algorithms like visibility, corridor sides, network of corridor nodes, travel distance, and exit signs algorithms are specifically developed to handle the numerical procedures contained in the fire Code requirements.

The input to the system consists of all information regarding the various parts of a building such as the number of stories, door dimensions, fire rating values, etc. The geometric algorithm performs the necessary calculations and stores the results in new frames. Then the rule-based system is activated to apply rules on the new data and a LISP procedure collects all error messages and prints them in a report.

Nguyen et al. [1996] use a knowledge base to control the checking process of the fire and safety requirements in NBCC [1995]. Decision diagram trees are used to determine the logical relationships between design data and Code requirements.

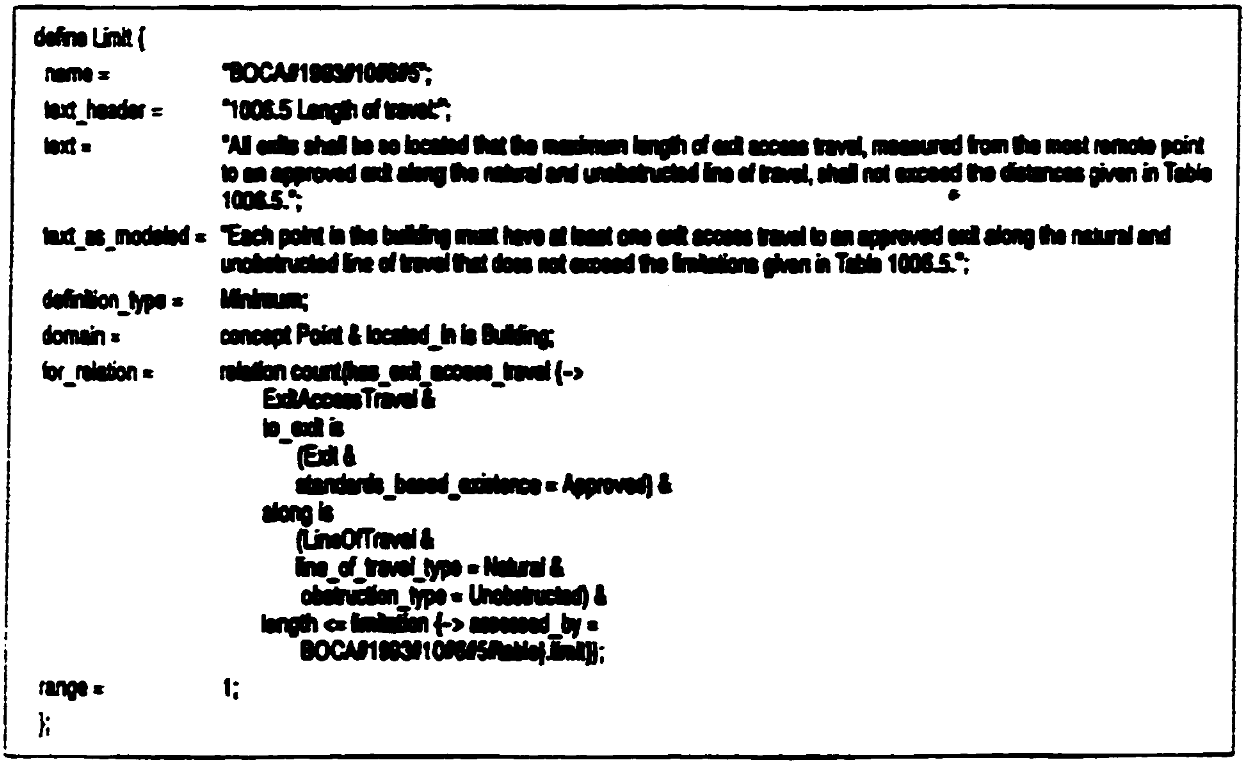
A computerized version of the Australian Building Code presents the information from the Code in a knowledge base [Sharpe 1991, Blackmore et al. 1994]. The user can access the Code provisions by locating the desired category of building and then review the information by answering TRUE/FALSE to some questions in order to identify the applicable conditions.

KBS systems are not only widely used for Code checking, but also in all aspects of building design. Building envelope design for example, is one of the areas that the KBS can be applied to [Fazio et al. 1989, Tham et al. 1990, Hubler and Steinmann 1995, Cornick et al. 1990]. It is also a tool commonly used in the building energy performance evaluation [Hitchcock 1991, Shaviv et al. 1996, Case et al. 1990, Cornick et al. 1990. Carroll and Hitchcock 1991].

2.3.3 Modeling Language and Framework Approach

Due to the dynamic nature of the standards and Codes, some recent works suggest the use of standard language for processing the knowledge that is explicitly presented in design standards [Kiliccote and Garrett 1998, Kiliccote and Garrett 1996, Garrett et al. 1995]. The elements involved in the checking procedure are separated into: (i) design systems, (ii) standards and (iii) standards processors. A distributed framework was developed in which different models of standards and other knowledge required to process these standards are defined as different modules. A communication language is used to communicate between them and with the users.

The language is composed of three sub-types of languages with different functions: (i) the description language (which is used in describing the knowledge stored in the module, e.g., to define that there is a module that can compute the maximum allowable height of a building), (ii) the standard modeling language (which is designed to allow users to describe the design information, ask for evaluation and request to do compliance checking), and (iii) the standard usage language (which is used to describe the design requirements). An example of standards usage language is shown in Figure 2-4. However, this communication language is far from mature and is still under development. It is currently used only to define textual provisions and tables in the Code.



```
define Limit {
 name =              "BOCA#1993/1006#5";
 text_header =       "1006.5 Length of travel:";
 text =              "All exits shall be so located that the maximum length of exit access travel, measured from the most remote point
                     to an approved exit along the natural and unobstructed line of travel, shall not exceed the distances given in Table
                     1006.5.";
 text_as_modeled =   "Each point in the building must have at least one exit access travel to an approved exit along the natural and
                     unobstructed line of travel that does not exceed the limitations given in Table 1006.5.";
 definition_type =   Minimum;
 domain =            concept Point & located_in is Building;
 for_relation =      relation count(has_exit_access_travel {->
                          ExitAccessTravel &
                          to_exit is
                             (Exit &
                             standards_based_existence = Approved) &
                          along is
                             (LineOfTravel &
                             line_of_travel_type = Natural &
                              obstruction_type = Unobstructed) &
                          length <= limitation {-> assessed_by =
                              BOCA#1993#1006#5#table}.limit});
 range =             1;
};
```

Figure 2-4: An Example of Standards Usage Language. [Kiliccote and Garrett 1998]

2.4. Building Energy Performance Evaluation

2.4.1. Procedural Method

Many of the early-developed simulation systems use this method. Soebarto and Degelman [1995] presented a simulation model that uses hourly energy calculations driven by an hourly weather data generator. It can perform the monthly energy loads calculations, utility bill predictions, peak load analysis, demand charge evaluations, life-cycle cost analysis, and some other energy-related analyses.

Load calculations, system simulations, and energy use estimations are performed simultaneously each hour in this energy simulation system. The heat transfer calculations in walls and roofs are performed using a one-dimensional transient model, which takes into account factors such as sol-air temperature, time lag and decrement factor. This method needs a lot of detailed data: the air temperature of every hour in a day, the thermal characteristics of each component of walls and roofs, the thickness of each layer of the wall or roof and the construction. Although the system tries to minimize the input by using a large set of default values, it is still tedious and practically difficult to use in the early design stage.

Another example of this kind of simulation model named ENERGY is using a similar simulation method as above. It is developed to solve one-dimensional heat-transfer equations through all exterior walls, taking into account the thermal mass of each external wall and internal partitions [Shaviv and Shaviv 1978]. Kim and Degelman [1998] also developed a hour-by-hour simulation model in which they tried to minimize the number of inputs by using substructure modules such as weather information, building description, etc. Again the number of design parameters is very large. Figure 2-5 shows as an example a set of type-dependent variables which is used to generate building descriptions.

No.	Description	Unit
1	Building type	
2	Building cost	$\$/m^2$ ($\$/ft^2$)
3	Occupancy	day/week
	Holidays	day/yr
5	Lighting types	1. Fluorescent
		2. Incandescent
		3. High pressure sodium
		4. Low pressure sodium
		5. Halogen
		6. Mercury
6	Lighting cost	$\$/m^2$ ($\$/ft^2$)
7	Infiltration	air change/hour
8	Building mass	kg/m^2 (lb/ft^2)
9	People density	m^2/person (ft^2/person)
10	Domestic hot water usage	l/person day (gal/person day)
11	Ventilation	m^3/min person (ft^3/m/person)
12	Light intensity	W/m^2 (W/ft^2)
13	HVAC types	1. Variable air volume
		2. Double duct
		3. Multizone
		4. Fan coil units
		5. Roof top units
		6. DX residential
		7. DX res. heat pump
		8. DX window unit
14	Heating fuel	1. Gas
		2. Elec. resistance
		3. Heat pump
15	Wall ID	In accordance with the manual
16	Roof ID	In accordance with the manual
17	Slab ID	In accordance with the manual
18	Window ID	In accordance with the manual
19	Window/Wall ratio	
20	Fan static pressure	cm H_2O (in H_2O)
21	Cooling SEER	Btu/W h
22	Heating COP	
23	Natural ventilation	(m^3/min)/m^2 (ft^3 m/ft^2)
24	Surface ref.	Consult manual
25	Building life	year
26	Mechanical system life	year
27	Solar system life	year
28	Discount rate	
29	Building escalation rate	
30	Electricity cost	$\$$/W h
31	Electricity escalation rate	
32	Gas cost	$\$$/ton
33	Gas escalation rate	
34	Water cost	$\$$/ton
34	Water escalation rate	
36	Demand charge	1. Yes
		2. No

Figure 2-5: A Set of Variables Used to Generate Building Descriptions [Kim and Degelman1998]

2.4.2. Object-Oriented Approach

From the study of automatic Code checking systems, the knowledge-based systems are found to be widely used at academic level. Virtually the majority of prototype knowledge-based systems use object-oriented programming techniques. Something is an object if it has a name, properties associated with it and messages that it can understand. Typically, when an object receives a message, the message either causes the object to take some action or to change one of its properties. In programming, object-oriented languages provide a way of encapsulating properties and messages into a single concept, which is often called class. Properties and messages are sometimes called members. Properties of class are sometimes called data members because they hold information. The messages a class of objects can handle are sometimes called methods or member functions [Cohoon, J.P. and Davidson, J.W. 1998].

This technique supports reuse and rapid prototyping for large-scale software development. The ability of a class to inherit properties and member function from an ancestor class (which is often referred to as inheritance) supports the principle of reuse. It has been a helpful tool in many building design applications [Ford et al. 1994, Heck and Wassermann 1995, Moni and White 1996].

For instance, a knowledge-aided design system named KADE [Mayer et al. 1991], which provides recommendations, evaluations and suggestions on energy-efficient building design during the conceptualization phase of the design process, uses the object-oriented developing approach. It uses a composite object system to represent the building information and incorporate the evaluation process. For example, on the class "building", the data members are the location (i.e. city), plan, etc, the method is "annual-energy-consumption".

Carroll and Hitchcock [1991] developed a estimation model for energy savings due to building retrofit; they use an interactive interface, a numerical module that produces intermediate results in the overall process of analysis, and a production rule system to generate prototypical building, based on information such as building type, age or location. Malkawi [1995] developed a system that incorporated simulation and reasoning. It was proved that the systems using this approach are easy to generate, manage and modify.

2.4.3. Intelligent Energy Analysis CAD Systems

In conventional design systems, graphical information is entered into a geometric system, while the non-graphical data such as the technical attributes are represented separately. So the analysis of the design model would be either visually, displaying drawings on the screen or by means of text software, which shows the technical information [Cornick et al. 1991]. Koegel [1987] gives an example of the structure of a typical conventional CAD system (Figure 2-6).

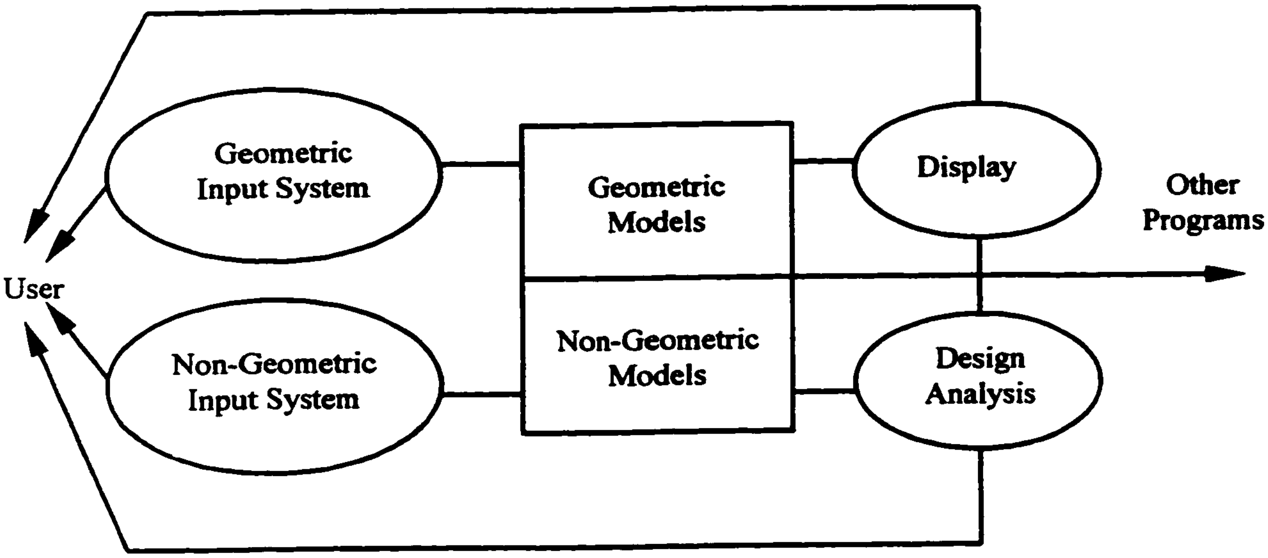


Figure 2-6: A Conventional CAD System [Koegel 1987]

Intelligent CAD systems facilitate the design process by incorporating designer knowledge into the system. This type of CAD system should be able to accept specific knowledge, to manipulate numeric data and to provide additional interface to transfer them. It should be able to organize within a general framework and to integrate geometric building information, technical information (e.g. material properties, building areas), and administrative requirements (standards, evaluations, etc). Figure 2-7 shows a model of intelligent CAD system.

Drawings are usually the physical medium used to communicate in the building design process. Building designers are more familiar with design drawings than sophisticated energy analysis software. Intelligent CAD systems support development of the design and integration of energy evaluation within the CAD environment.

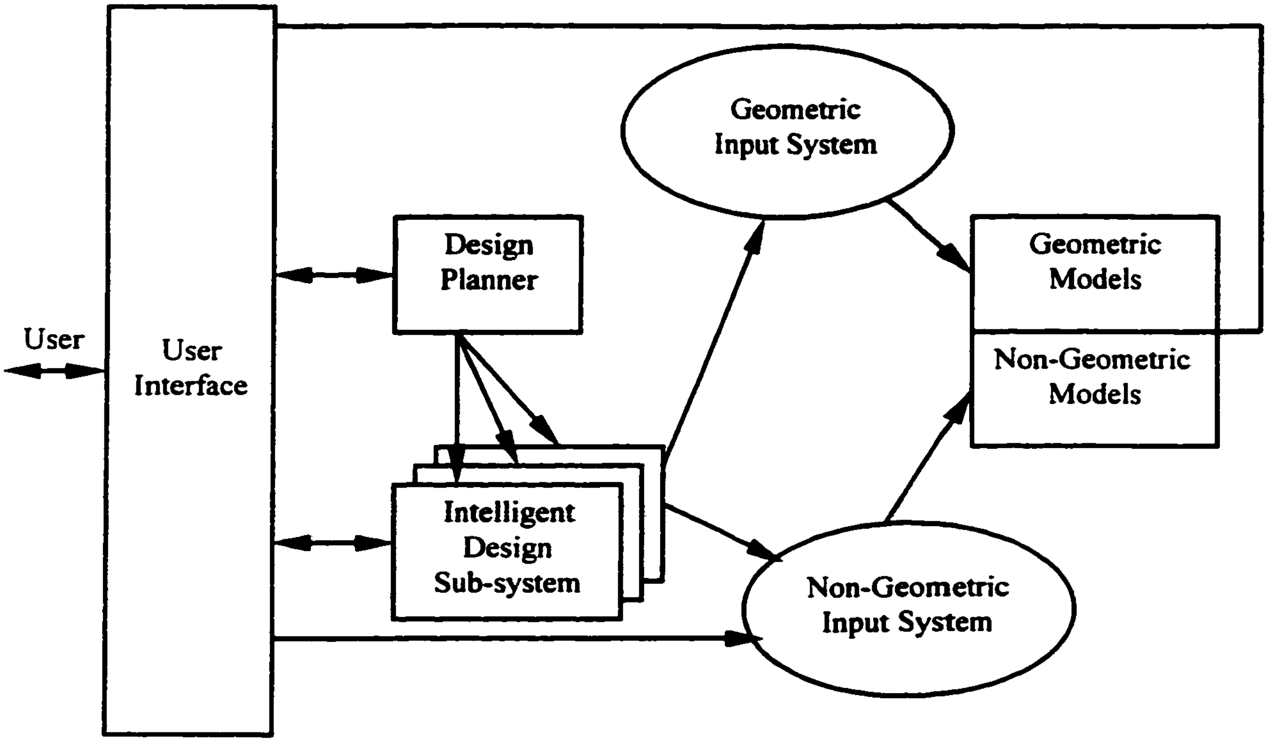


Figure 2-7: An Intelligent CAD System [Koegel 1987]

Brown [1990] described a computer tool for preliminary building energy design and analysis, developed at the University of Oregon. The system evaluates the architectural design in terms of its energy performance. The program is incorporated inside the CAD environment and does energy analysis along with the development of architectural design. Figure 2-8 shows an example of how the program works. The drawing icons for north, south, east and west elevations are part of the program interface and they are on the building plan and elevations. The south elevation icon has been opened to reveal the three element folders: walls, windows and roofs. The window folder is opened for two existing window specifications already created by the designer. Figure 2-9 shows an interface with window specifications.

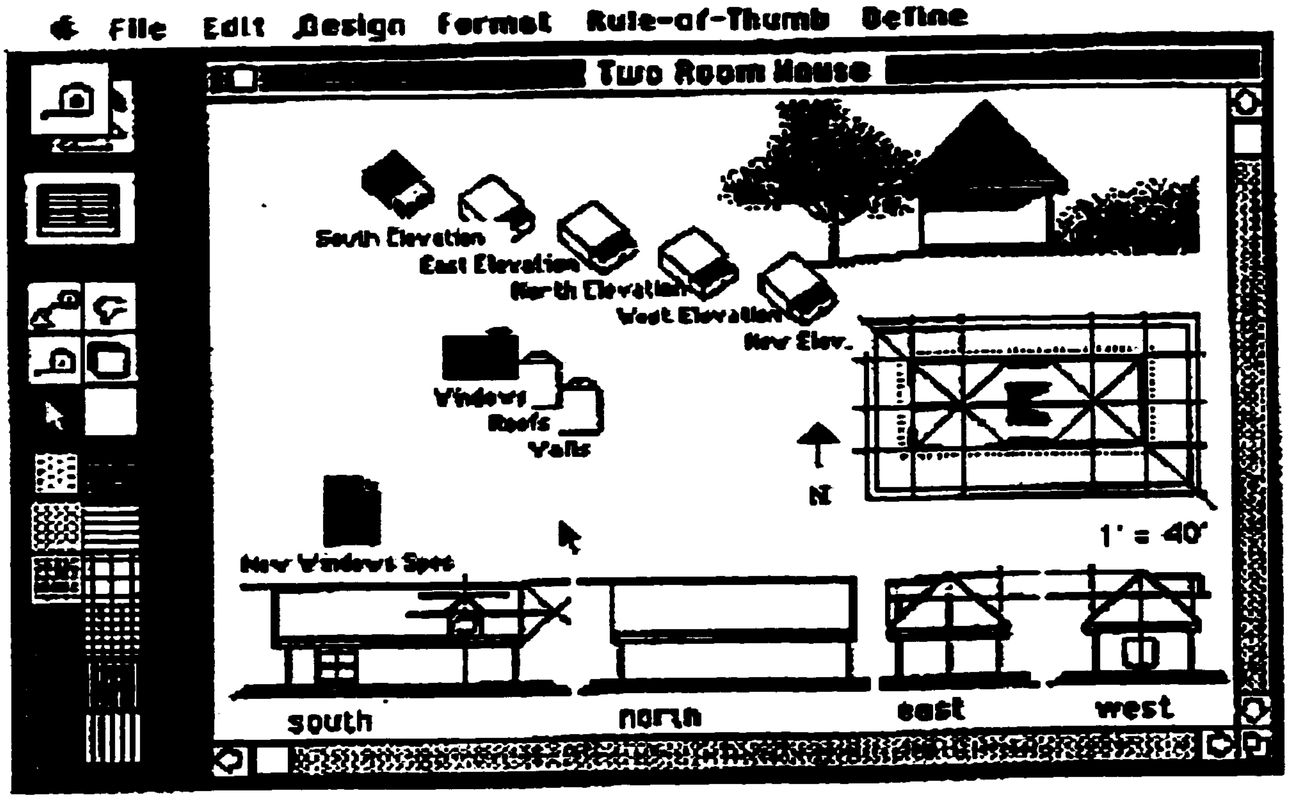


Figure 2-8: An Example of the Interface of an Intelligent CAD System [Brown 1990]

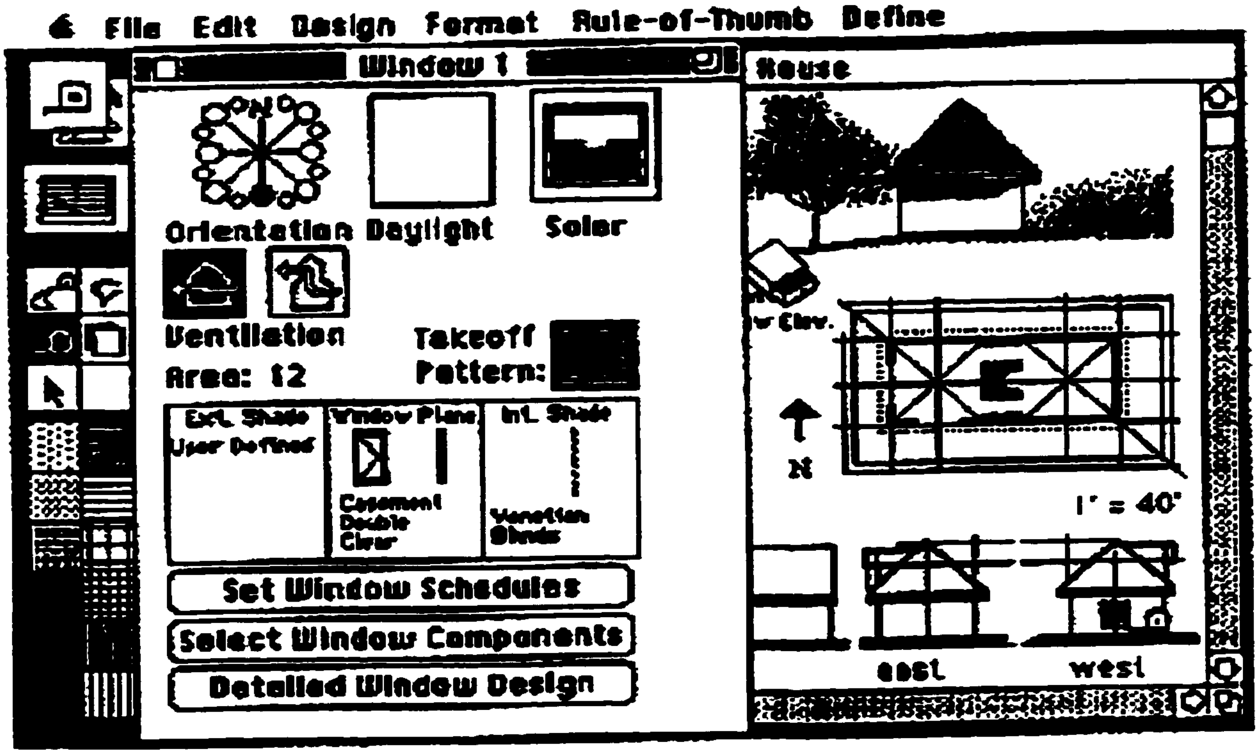


Figure 2-9: Interface for Window Description [Brown 1990]

As it is shown in the above two figures, the link to energy analysis program only appears as icons and does not dominate the design process. The icons that represent different aspects of energy considerations are available around the working drawing and there is no specific order in using them. Unlike most energy software in which designers must describe the building in numeric form such as R-value, the input required has two focus:

- Locations and dimensional data, such as areas and lengths, are "taken off" directly from the screen using graphic tools;
- The designer chooses certain materials, such as brick, instead of specify its physical properties.

This approach enables the designers to get an energy evaluation of a proposed design without giving detailed, numeric descriptions; at this stage, the information available to designers is more of a qualitative type. The major advantage of intelligent CAD systems is user-friendliness. This is the current trend in the development of all commercial software.

2.5. Special Considerations

2.5.1. Characteristics of Computer-Aided Building Checking System

Building Codes are difficult to use during the design stage [Kumar et al. 1995]. The large amount of information included in Codes requires considerable time and effort to get familiar with. The expression of provisions, accompanied with exceptions and cross references, are sometimes confusing for the users who have constantly to refer to different parts of the Code.

Building designers often have to deal with more than one Code, such as national Codes, provincial Codes and city by-laws. They have to use different Codes when they are working in different geographic regions. Moreover, MNECCB is a new model Code that supplements the NBCC in the building design process. Many building Codes are updated periodically and the frequent revision of Codes makes the efficient use of them even more difficult.

Because of the complex nature of the Code, the computer-aided approach is advantageous and can help the user in several aspects [Kiliccote 1995, Delis and Delis 1995]:

- The computer-based Code can free designers from the tedious process of manually checking designs, therefore allowing them to concentrate on other design aspects.
- The computer-aided approach is convenient in the comparison of different alternatives and can lead to a better design with maximum efficiency.
- The capability of incorporating many aspects of consideration and calculations in the system would ensure that the checking is done more completely and consistently.
- Expert knowledge in how to apply Code requirements in specific cases can also be formulated, incorporated and highlighted in a reviewing protocol format.

- The fast processing speed of computers in performing calculations and comparisons can shorten the duration of Code compliance checking in the design process and speed up the production of individual designs.

To achieve the objectives mentioned above, an automated system can now be developed with the following characteristics:

- A user-friendly interface is needed to ask questions, and to provide statements and choices according to the Code.
- The steps followed by the computer-based system must be kept to the minimum and be very clear. An instruction should be given whenever confusion could occur about how to progress to the next step.
- The system must lead to correct conclusions, provide reliable advice on how to improve the design and present results to users.
- It should provide easy access to the relevant Code text.

Many different organizations such as AIA (American Institute of Architects) or BOCA (Building Official and Code Administrators) suggest step by step procedures for applying building standards in the design process. Through the study of these recommended procedures and how a designer may use the Code, the use of design standards can be decomposed into the following steps [Choi and Garrett 1996]:

1. The first step is to classify the building or portions of building according to the classifications used in a design standard. A room in the floor layout can be classified as a staircase or a vestibule according to the applicable Code. In the energy Code, it is the building envelope components that should be identified, whether it is an opaque building assembly or not, whether it is in contact with the ground or not.

2. Then the designers have to make decisions on some building properties. Such a design decision may be the assignment of values to attributes of a building envelope assembly or the dimensions of a window.

3. Finally, the requirement specified in a provision is applied. In the case of energy Code, this may be a comparison of building area to the area specified in the Code, or a comparison of overall heat transmittance between the design and the Code requirements.

2.5.2. Related Parameters in Energy Performance Analysis

Traditional methods simulate the energy consumption of a building using building thermal characteristics in more or less ideal physical conditions [Olfsson et al. 1998]. This approach requires the use of a large number of parameters, many of them being impossible to acquire until the end point of design. Under practical design conditions, designers often have to make decisions based on limited information. However, designer makes the major decisions that affect the energy performance while the building design is still under development. Following a detailed study of the parameters related to energy-efficient building design, Shaviv et al. [1996] suggest that various energy-related design parameters should be considered differently according to the different design stages (Figure 2-10). For instance, window type is first selected at the preliminary design stage and finally corrected, if necessary, at the detailed design stage. In addition, these parameters are abstracted and classified into three different categories and need to be treated differently in the development of an energy performance evaluation system:

(i) If a design parameter has a weak effect on the energy performance and has no impact on other design parameters, then a default value can be specified.

(ii) If a design parameter has a strong influence on the energy performance, but it is insensitive to other design parameters, then a recommended value is to be given.

(iii) If a design parameter, with a strong influence on the energy performance, is also sensitive to other design parameters, then a series of simulations need to be initiated to determine the recommended values.

To assist the building designers in the preliminary design process, an energy performance evaluation system shall be able to distinguish different kind of design parameters and provide designers with both reasonable default values and accurate simulation results.

DESIGN PHASE	a.	b.	c.	d.	e.
TOTAL FLOOR AREA	o		+	+	
VOLUME OF BUILDING		o	+	+	
NO. OF EXTERNAL WALLS			o	+	
AZIMUTH OF REFERENCE WALL			o	+	
AREA OF INTERNAL MASS				o	+
HEAT CAPACITY OF FINTERNAL MASS					o
INITIAL TEMP. DISTRIBUTION		o			
HEAT GAINS: CONSTANT	o				
HEAT GAINS: SCHEDULE	o				
HEATER: SCHEDULE; TEMP.SET		o			+
COOLER: SCHEDULE; TEMP.SET		o			+
VENT: TYPE , SCHEDULE, ACH: DAY;NIGHT		o			+
WALL NO.1					
NUMBER OF LAYERS				o	+
MATERIALS				o	+
.....					
.....					
WALL-AZIMUTH, INCLINATION			o	+	
ARE OF WALL			o	+	
WALL: ALBEDO, EMISSIVITY					o
WALL-SC-SUMMER, WINTER				o	+
NO. OF WINDOW AND SOLR ELEMENTS			o	+	
WINDOW: AREA			o	+	
WINDOW: TYPE				o	+
WINDOW:SC-SUMMER,WINTER		o			+
UWINDOW: DAY, NIGHT				o	+
UWINDOW: SCHEDULE		o			+

Figure 2-10: Design Parameters for Different Design Phase [Shaviv et al. 1996]
(a) briefing (b) pre-conceptual (c) conceptual (d) preliminary (e) detailed design
(o) first considered (+) reconsidered

Having considered the characteristics of a computer-aided building checking system and the features of different energy-related parameters, a suitable methodology can now be proposed to develop a computer-based design system for energy-efficient buildings that takes these characteristics and features into consideration.

Chapter 3

Code Compliance Checking

3.1 Proposed Methodology

Based on the characteristics of computer-aided Code checking and building energy performance evaluation processes, the following considerations are presented concerning the proposed methodology:

- Energy-related requirements such as those from the MNECCB are both qualitative (e.g. continuity of insulation) and quantitative (e.g. heat transmittance of a building envelope assembly). The necessary checking paths provided in MNECCB include both descriptive requirements and trade-off calculations. Hence it is impossible to use only heuristic rules, or procedural simulation models, to obtain a satisfactory solution.

- MNECCB deals with a large number of data. Because the new energy Code is consistent with NBCC and other existing building Codes (e.g. CAN/CSA-A440 A440.2-M1991 [1991], CAN/CGSB-82.1-M89 [1989]), some common data such as climate data or requirements for window airleakage rate can be shared.

- The energy Code shall be applied as early as possible in the design process. Now, when most of the design drawings are developed by computer, it is more convenient for the user to access the Code from the CAD system. As the architects may change their designs very frequently, it is also a faster approach to check the compliance with the Code requirements.

This chapter presents the concept of a knowledge-based system that incorporates database, knowledge base, and correlation model within a CAD environment (Figure3-1). The integration of several techniques would eliminate some of the drawbacks of the traditional systems (Chapter 2) used so far for Code checking and for energy evaluation.

The proposed system has the following main features:

1. It is an integration of knowledge base, database and correlation model based on the knowledge-based system framework. The development of knowledge base is through the analysis and interpretation of the MNECCB text.
2. It is an intelligent CAD system which can facilitate the design process by incorporating designer's knowledge and expertise into the CAD environment.
3. Decision diagrams are used in the Code compliance checking procedure to help making design decisions.
4. Technical advice is provided if the design fails to comply with the Code requirements.
5. The object-oriented approach is used to develop the prototype system.

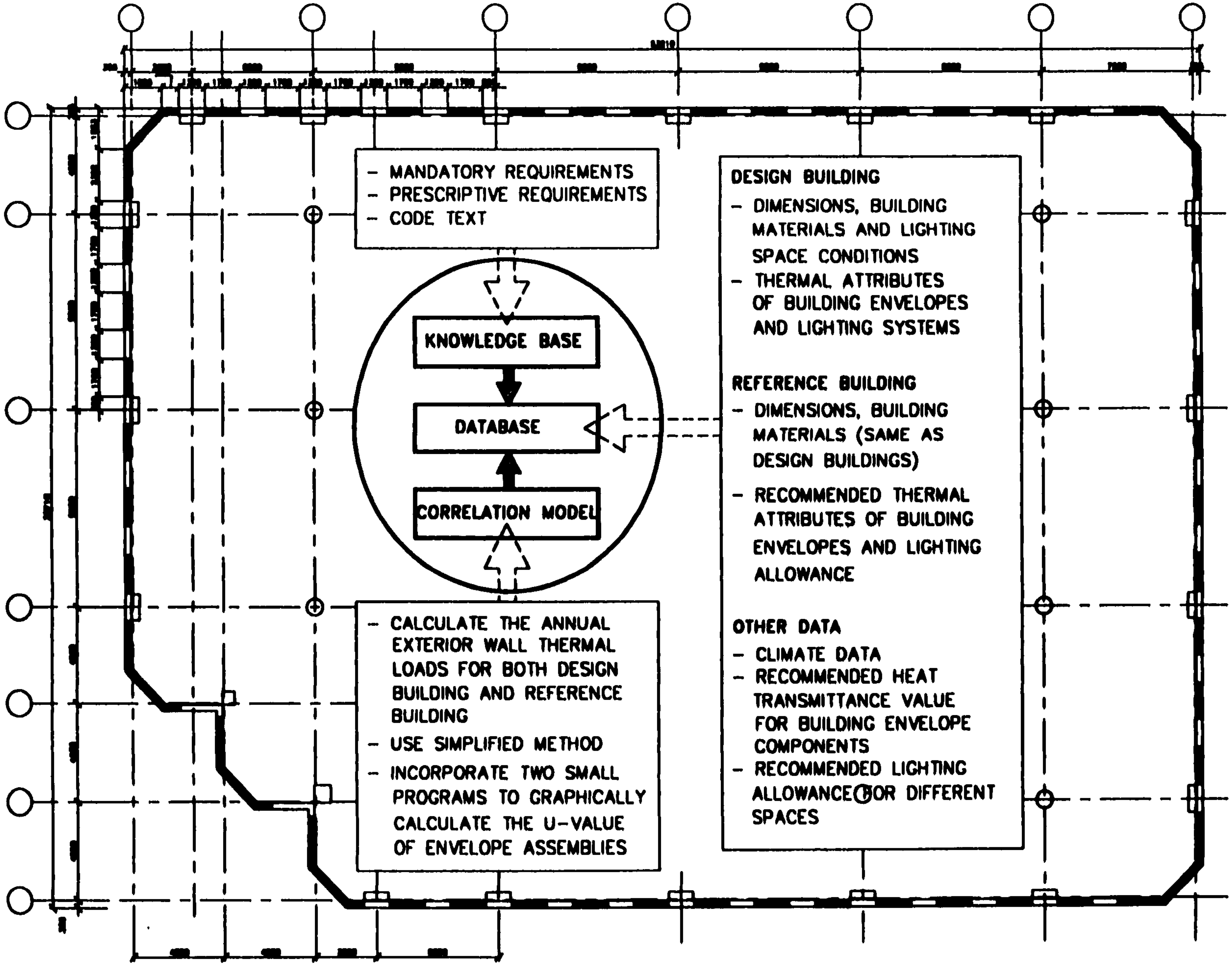


Figure 3-1: Proposed Methodology: integration of database, knowledge base and correlation model within a CAD environment.

3.2. Knowledge-Based System for Electronic Energy Code

The literature survey found substantial research and development activities related to the application of knowledge-based systems (KBS) in both Code checking area and energy-performance evaluation. We can see several reasons why knowledge-based systems are used:

- Codes contain regulations to judge a design is good or not. This decision-making mechanism is similar to that in the KBS, which uses heuristics to make decisions. This characteristic of the KBS makes them suitable in computer-aided Code checking area.

- Unlike many conventional energy evaluation systems that usually use procedural simulation approach, the KBS needs less input, less calculation and can still get results with acceptable accuracy. It is appropriate at the early design stage since results can be obtained much faster than using procedural simulation approach.

- KBS separates the knowledge from the control process. Instead of mixing the knowledge within the control of the knowledge, it stores pieces of knowledge in the knowledge base, and uses different rules to control them. The change on a specific piece of knowledge does not affect the rules that control it. Similarly, the changing of rules will not affect the knowledge representation as long as the rules still deal with the same parameters. This is an important advantage offered by heuristic models where changes may occur very frequently.

- Due to its heuristic nature, the KBS can track the knowledge used to generate the solution and explain how the conclusion is derived. This is used to provide advice on how to improve the design and to better understand Code requirements.

3.3. Integration of Different Modules

The functional integration of the three modules, knowledge base, database and correlation-based model, is a critical feature of the proposed methodology. The functions performed by each module are described in this section. The integration is based on rational relations between these different functions.

The database can automatically generate two sets of data at the beginning of Code compliance procedure. One set of data, called Design Building, contains information about the proposed building to be designed. It consists of the dimensional information, the materials used in the building envelope and their thermal characteristics, and the lighting conditions in the building. The other set of data, called Reference Building, contains information necessary to develop a reference building according to the Code. It has the same dimensional information as the design building. It uses prescriptive values for thermal properties of the exterior envelope (e.g. the recommended U-value for a metal stud wall) and light allowance, as provided in the energy Code. The database also stores many other necessary data such as climate data or recommended thermal characteristics for various building envelope assemblies.

The knowledge base stores the mandatory requirements and prescriptive requirements contained in the Code. All the proposed designs are checked for compliance with the mandatory requirements (e.g. the continuity of the insulation). Moreover, if the user chooses to use the prescriptive compliance path after satisfying the mandatory provisions (see Figure 2-2), the knowledge base is used to compare the design building with the prescriptive requirements. The knowledge base also stores the Code text and makes it accessible at any time to the user. Hypertext techniques are used to display the Code text and the explanation of technical terms, and can connect to the referred sections when there is a cross reference.

The correlation model allows evaluating the annual building thermal loads for both the design building and the reference building, as requested by the trade-off path approach. An acceptable design must have the annual thermal loads less than that of its reference building. A simplified calculation procedure is used for the following reasons:

(a) many parameters are not available at the early design stage, and therefore only the most significant ones should be used; and

(b) a time-consuming and detailed energy analysis is not necessary, nor meaningful, at this early design stage.

This integrated model is built in a CAD environment. A graphic design data collection technique is therefore used, which is able to collect design data directly from working drawings and to minimize the effort requested from the user. As architects usually communicate with pictures and drawings, they will appreciate this approach and therefore use the system more frequently at this early stage of building design.

3.4. Development of the Knowledge Base

The knowledge base incorporates statements and rules that constitute the prescriptive compliance checking procedure (Figure 2-2). The development of the knowledge base is performed in three steps:

(a) elements of knowledge and relations between them are extracted from the Code text;

(b) decision diagrams are developed;

(c) decision diagrams are integrated into the prototype system

3.4.1. Code Analysis

The energy Code defines the technical requirements of various components that comprise a building to ensure energy-efficiency of the resulting building. The technical requirements fall into one of the two categories: (1) mandatory requirements and (2) prescriptive requirements. They are in the form of descriptive text and tables. Compliance with these requirements ensures that significant design aspects and details are not overlooked. If a designer follows those requirements, his new building will have acceptable energy efficiency, but it will not be the most energy-efficient building. It is usually called the "worst design allowed by the Code". In order to achieve a better design, some minimum prescriptions should be exceeded in the proposed design.

An example of mandatory requirements of floors in contact with ground is given in

Part 3. Building Envelope,

Section 3.2 Mandatory Provisions,

Sub-section 3.2.3. Building Assemblies in contact with Ground,

Clause 3.2.3.2. Floors:

> Floors required to be insulated shall have insulation placed:
>
> (a) on their top surface for a distance not less than 1 m from their perimeter, or
>
> (b) vertically around their perimeters and horizontally under their bottom surface so as to form a thermal break from the foundation and such that the total extent of the insulation, measured vertically and horizontally, is not less than 1m,

An example of prescriptive requirements is given in Clause 3.3.2.3. Floors:

> The effective added thermal resistance of floors on ground that are less than 0.6 m below grade and of all floors incorporating heating equipment shall be not less than that shown in Table 3.3.2.A. of Appendix A for the region considered and for principal heating energy source for the building.

For the "Performance Compliance Path" and "Trade-off Compliance Path" in Figure 2-2, the Code does not prescribe minimum requirements for the design. The compliance is based on the performance level: the new building must not consume more energy than the one which complies with the prescriptive requirements. In the "Trade-Off Compliance Path", the performance is evaluated in terms of the annual thermal loads of exterior envelope of the building. This approach is followed in the present research. When the "Performance Compliance Path" is applied, the entire energy performance of the building is estimated with consideration of all sub-systems such as building envelope, lighting and HVAC systems, as well as service water systems.

3.4.2. Decision Diagram

Decision diagrams are used to incorporate the Code text into knowledge base and set up rules to make design decisions according to MNECCB (Appendix A). The design of a floor is shown as an example. Several design parameters related to floors are mentioned in the MNECCB:

a) location of building;
b) energy source;
c) location of the floor: above ground or in-contact with the ground;
d) type of construction;
e) continuity of insulation
f) insulation at top surface of the floor, or

g) insulation vertical around the perimeters and horizontally under the bottom surface
h) overall heat transmittance of the floor assembly.

The first four parameters are selected as the reference parameters, from which appropriate rules are developed. The corresponding Code requirements are extracted from Code text, according to these four reference parameters, and are represented by a decision diagram as shown in Figure 3-2.

A decision diagram consists of two basic elements: descriptive statements and logic relations. Descriptive statements are Code requirements about a specific aspect of building design. Logic relations are the relationships between the descriptive statements and are determined from the expressions written in the Code that indicate obligation, permissions or options.

The different Code provisions for a certain floor design aspect are presented within the rectangular frames in Figure 3-2. Statements are phrased exactly as in the Code to avoid misunderstanding. According to his design, the user responds by "Yes", "No", or "N/A" to the descriptive statements. The arrows that connect these requirements are the logic relations. Logical relations lead to a "Pass" or "Fail" result. "Pass" confirms the building design as proposed by the designer complies with the MNECCB. "Fail" indicates failure of the building design with respect to the same Code.

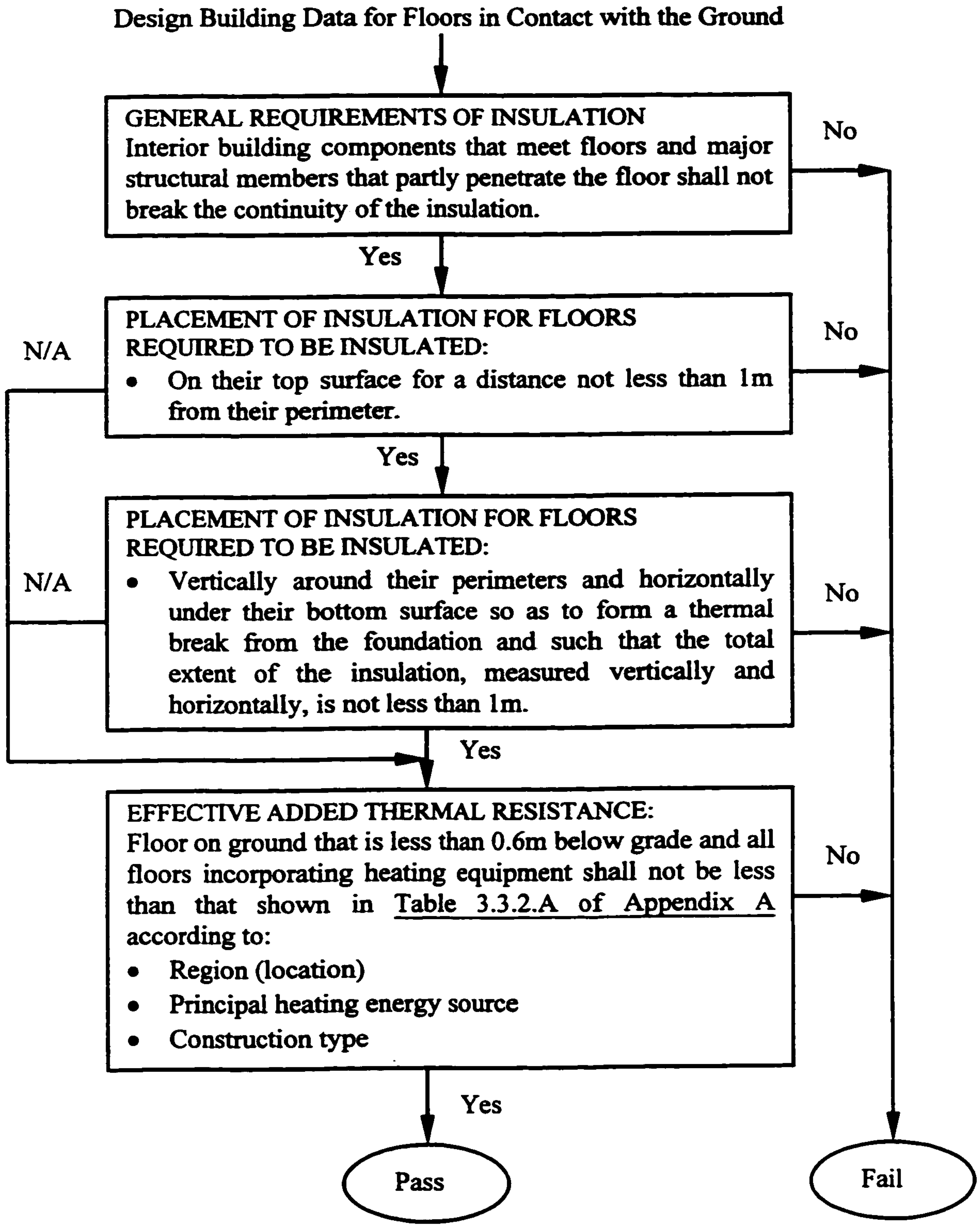


Figure 3-2: Decision Diagram for the Design of a Floor in Contact with the Ground

3.4.3. Encoding: Object-Oriented Approach

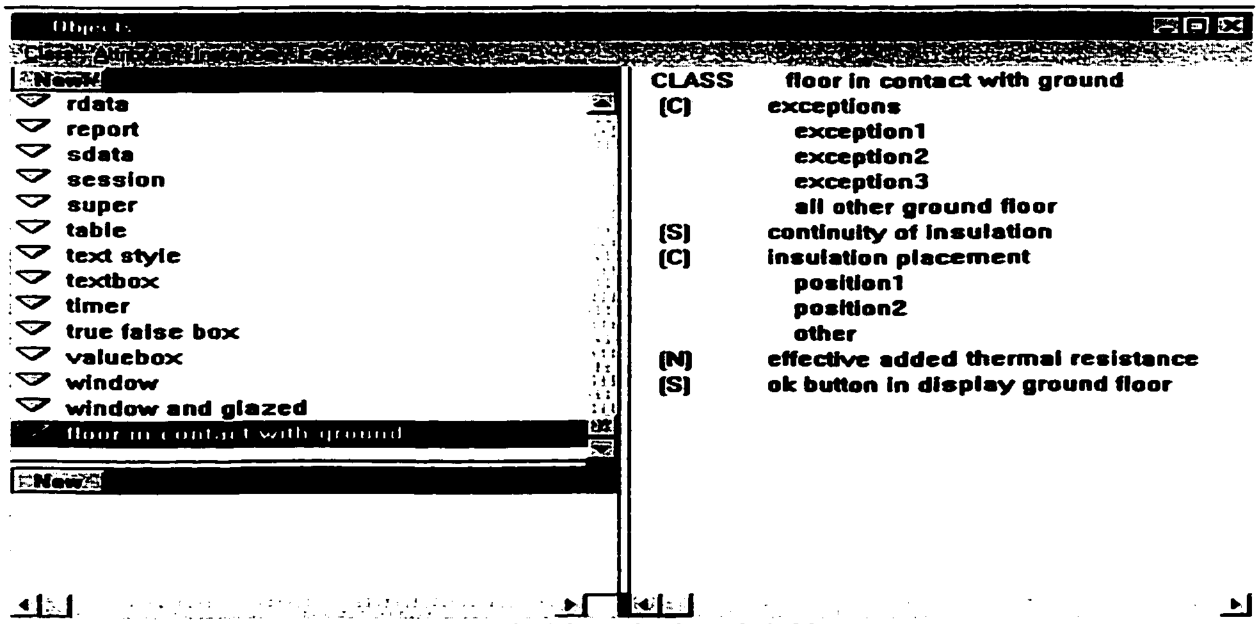
The final step in developing the knowledge base is to encode the decision diagrams into the prototype system. The object-oriented technique is used because it fits well the requirements of presenting Code knowledge in a knowledge base.

The different types of building envelope assemblies such as windows, walls or floors are defined as different basic classes. Through study of the Code, there are eight basic building components:

- Windows and other glazed areas
- Walls above ground level
- Walls below ground level
- Floors above ground level
- Floors in contact with the ground
- Roofs
- Exterior doors
- Exterior and interior lighting systems

The different parameters of a specific building component are defined as attributes of a basic class. As different object-oriented language use different names, in Level 5 Object [1994], a knowledge-based system shell, data members of a class are called attributes. For example, in the case of the "floor in contact with the ground" class, presented in Figure 3-2, there are three aspects to consider in the design: (i) general requirements of insulation, (ii) placement of insulation (horizontal or vertical) (iii) effective added thermal resistance (which means the overall thermal resistance of a building assembly in contact with the ground, excluding the thermal resistance of air films, adjacent ground and concrete, masonry structure or treated wood sheathing).

Figure 3-3 shows how the class and the attributes are defined in Level 5 Object. The left part shows the classes that are used in the knowledge base. The right part of the figure shows the definition of the class "floor in contact with ground". All the attributes begin with a definition [C], [S] or [N]: [C] represents a compound attribute, [S] represents a simple attribute, and [N] shows a numerical attribute. The first attribute "exceptions" showing the inapplicable conditions under new energy Code and should be excluded from checking, the following three attributes are the three design considerations presented in the decision diagram (Figure 3-2). The last attribute is used solely for the dialogue box in the prototype system.



```
rdata
report
sdata
session
super
table
text style
textbox
timer
true false box
valuebox
window
window and glazed
floor in contact with ground
```

```
CLASS   floor in contact with ground
[C]     exceptions
           exception1
           exception2
           exception3
           all other ground floor
[S]     continuity of insulation
[C]     insulation placement
           position1
           position2
           other
[N]     effective added thermal resistance
[S]     ok button in display ground floor
```

Figure 3-3 : Class and Attributes Definitions in Level 5 Object

The values of these attributes are either YES, NO or N/A or a numerical value. They are provided by the user. Rules are used to control relationships between the values of these attributes.

Rules are expressed as a two-part IF... THEN... relationship. The first part is a test condition, which is the premise or antecedent. If the test is satisfied (through a true match with this antecedent), then the second part, which is called action or consequent, is executed.

Rules are executed in one of two ways: data driven or goal driven. If the number of input data is limited and a large number of possible conclusions could be reached, then rules are better executed in data driven fashion (which is also called forward-chaining). In this case, rules with input data as antecedents are first applied to infer intermediate facts and successively other rules until ultimately a solution or sets of solutions is reached. Alternatively, if the number of possible conclusions is limited, it is more efficient to use goal driven reasoning, also commonly called backward-chaining. This method assumes first a goal state as true and reasons backwards to known data or facts input data that support it. Backward-chaining is used in the control strategies implemented in this prototype. An example of rules for the design of a floor in contact with the ground written in Level 5 Object syntax is shown below:

```
RULE  placement of insulation
IF    the insulation IS placed on top surface of the floors not less than 1m from perimeter
OR    the insulation IS placed vertically around floor perimeters and horizontally under
          floor bottom surface not less than 1m
THEN  the placement of insulation IS ok
```

```
RULE  design of floor in contact with ground
IF    the continuity of insulation IS maintained
AND   the placement of insulation IS ok
AND   the effective added thermal resistance >= minimum R-value in the Code
THEN  design of floor in contact with ground IS pass.
```

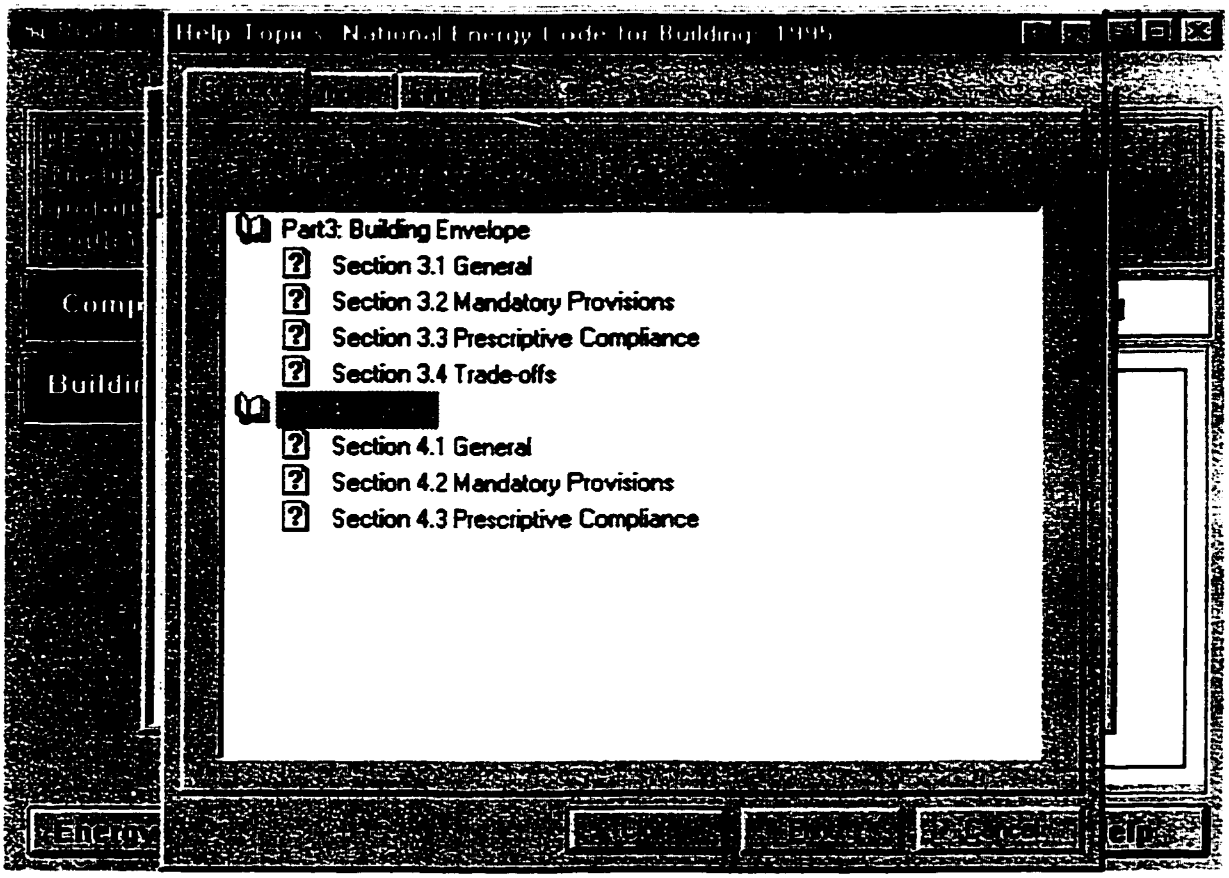
The object-oriented approach views the world in a different way than conventional procedural programs. It views the world as a set of objects (which are defined as classes), each of the object is described by a set of attributes and there is a set of rules to control the relationships between the objects. The knowledge is incorporated into knowledge base as attributes and rules that control the relations between attributes. The use of the object-oriented approach in the development of the knowledge base leads to a significant advantage: it is easy to make modifications and to expand the existing program, because the modification of the objects and modification of the rules are completely separated. If a new requirement is needed, the modification requires only adding a new rule. If a new type of building component is needed, a new class is added. Similarly, the expansion of added. Similarly, the expansion of the knowledge base can be accomplished by adding more rules without disturbing existing rules and classes.

3.4.4 Decision Making and Reasoning

There are several functions under the control of the knowledge base: (i) perform compliance checking, (ii) give technical advice to improve the design in case it does not pass the compliance check, and (iii) provide easy access to related Code text. The first two functions are derived from the use of the decision diagrams.

As the decision diagrams are used in developing the rules in the knowledge base, a result for compliance checking is always reached. When the result is "No", which means the design fails to comply with the MNECCB, it is possible to retrieve the considerations that are not respected using the decision diagrams, and to provide as a technical advice. The backward-chaining technique is used for the retrieval process, detects every possible parameter and finds out the fact that leads to failure.

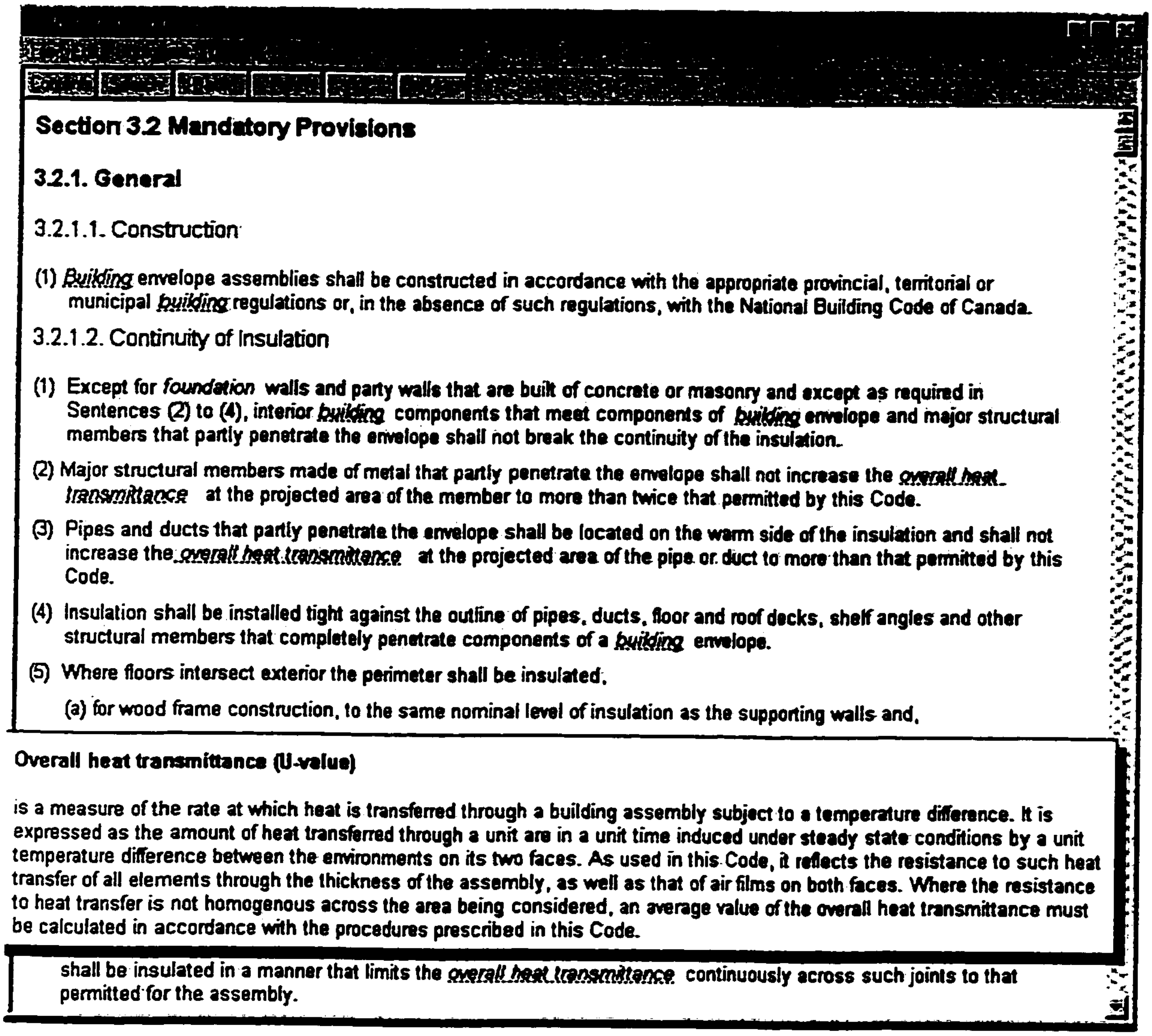
The hypertext technique is used in presenting the Code text. User interface, Code text storage and browsing method follow the format of a Windows [Microsoft Corporation 1995] program help file as shown in Figures 3-4 and 3-5. Technical terms can be explained right where these are encountered. Whenever another section of the Code is mentioned, the user can jump to that part by clicking on the underlined text. As other help files use the Window environment, searching functions such as search by the content of the book, index search and find are also supported.



Part3: Building Envelope
- Section 3.1 General
- Section 3.2 Mandatory Provisions
- Section 3.3 Prescriptive Compliance
- Section 3.4 Trade-offs

[illegible]
- Section 4.1 General
- Section 4.2 Mandatory Provisions
- Section 4.3 Prescriptive Compliance

Figure 3-4: Code Text Presentation with Contents, Index and Word Searching



Section 3.2 Mandatory Provisions

3.2.1. General

3.2.1.1. Construction

(1) *Building* envelope assemblies shall be constructed in accordance with the appropriate provincial, territorial or municipal *building* regulations or, in the absence of such regulations, with the National Building Code of Canada.

3.2.1.2. Continuity of Insulation

(1) Except for *foundation* walls and party walls that are built of concrete or masonry and except as required in Sentences (2) to (4), interior *building* components that meet components of *building* envelope and major structural members that partly penetrate the envelope shall not break the continuity of the insulation.

(2) Major structural members made of metal that partly penetrate the envelope shall not increase the *overall heat transmittance* at the projected area of the member to more than twice that permitted by this Code.

(3) Pipes and ducts that partly penetrate the envelope shall be located on the warm side of the insulation and shall not increase the *overall heat transmittance* at the projected area of the pipe or duct to more than that permitted by this Code.

(4) Insulation shall be installed tight against the outline of pipes, ducts, floor and roof decks, shelf angles and other structural members that completely penetrate components of a *building* envelope.

(5) Where floors intersect exterior the perimeter shall be insulated;

(a) for wood frame construction, to the same nominal level of insulation as the supporting walls and,

Overall heat transmittance (U-value)

is a measure of the rate at which heat is transferred through a building assembly subject to a temperature difference. It is expressed as the amount of heat transferred through a unit are in a unit time induced under steady state conditions by a unit temperature difference between the environments on its two faces. As used in this Code, it reflects the resistance to such heat transfer of all elements through the thickness of the assembly, as well as that of air films on both faces. Where the resistance to heat transfer is not homogenous across the area being considered, an average value of the overall heat transmittance must be calculated in accordance with the procedures prescribed in this Code.

shall be insulated in a manner that limits the *overall heat transmittance* continuously across such joints to that permitted for the assembly.

Figure 3-5: Code Text Presentation with the "Pop up" Explanation of Technical Term

Chapter 4

Correlation-Based Model

4.1 Introduction

Energy simulation plays an important role in two compliance paths recommended by the new energy Code [MNECCB 1995]: (i) the computer-aided trade-off path and (ii) the building energy performance path (Figure 2-2). Only the trade-off approach is used in this project. For the purpose of assisting building designers to make design decisions in the preliminary stage, evaluating the sensitivity of envelope design changes rather than try to provide an accurate evaluation of building energy consumption is more helpful. Hence, a correlation-based model is sufficient to provide a quick and simple way to represent the possible effect of changes of the envelope thermal characteristics. In this project, the correlation model is built on the basis of correlations developed by Cornick and Sander [1995].

In the ASHRAE Standard [1989], some correlations are presented to evaluate the system performance criteria in the building envelope design. These correlations allow to evaluate the annual heating and cooling loads of the entire envelope based on the following information: thermal transmittance, solar gains, internal gains and mass, and physical components of the envelope. The correlations are developed to model the complex relationships between the building envelope characteristics, the climate and the annual heating and cooling loads for a specific building design.

The annual thermal loads of the whole building are obtained by adding up loads for all exterior walls and windows. Three categories of data are used: climate data, building data and coefficients for each of the orientation. Examples of climate data are: CDD50 (cooling degree days base 50°F), HDD50 (heating degree days base 50°F), VS (annual average daily incident solar energy on facade under consideration). Example of building data are: FC (ratio between the wall area of zone under consideration and the total wall area of all zones), U_{ow} (area-average U-value of opaque walls), and FWR (fenestration-to-wall area ratio).

The ASHRAE correlation model is implemented into a computer software named ENVSTD [Crawley et al. 1990] which can be used by building designers to evaluate the relative impact of various envelope design options. It also shows the thermal impact of combination of envelope characteristics and helps designers to realize the design flexibility allowed within the limits of the design criteria.

However, due to the differences between ASHRAE/IES 90.1-1989 [1989] and MNECCB [1995], as well as the difference between the climates and construction types, it is necessary to develop simple and rational equations that are in accordance with the MNECCB. An energy database was developed based on this consideration [Cornick and Sander, 1995]. It contains monthly and annual values for both peak demand and energy consumption due to heating, cooling and fans, with respect to the orientation of walls and windows. The values in this energy database were generated by using the DOE-2.1E

[1992] energy analysis software, to perform hourly simulations for 25 locations throughout Canada.

Based on this energy database for Canada, Cornick and Sander [1995] developed a simplified energy model which can be used to estimate the change in energy consumption associated with a change in thermal characteristics of the exterior envelope. It predicts the heating and cooling loads as a function of orientation, climate, internal loads and wall/window characteristics. As the energy database was developed under limited locations, the authors extended this method to other locations by introducing a coefficient of correction for other climatic conditions. This simplified correlation-based model was not intended to estimate the absolute energy consumption of a building but to compare the energy impact of variation in thermal characteristics of exterior envelope. It is used in this prototype to provide a quick and relatively accurate tool for the evaluation of the envelope performance within the trade-off path of the MNECCB.

As explained in the Section 3.3, the database automatically generate two sets of data (Design Building data and Reference Building data) at the beginning of Code compliance procedure. In these two sets of data, some are the same (e.g. building envelope component dimensions), some are different (thermal characteristics of these envelope components). How many data and what kinds of data are needed in the prototype correlation-based model are determined by the three basic parameters and correlations described in the following sections. How to determine the appropriate thermal characteristics for the Reference Building data is based on the MNECCB. The sources of other data such as climate data are also explained.

4.2 Essential Data Used in Correlations

The background introduction explained why the correlations developed by Cornick and Sander [1995] was chosen as the main framework of our correlation-based model presented here. The appropriate data used in the Canadian Code and construction are selected and implemented in the model. This is explained along with the introduction of the main correlations.

4.2.1 Basic Parameters

There are three basic parameters used in the correlations developed by Cornick and Sander [1995]; namely: heat loss parameter U, solar heat gain parameter V and internal heat gain parameter W. As the base case model used in the development of the correlations has four exterior zones facing the cardinal orientations, the three parameters determined from following equations 4.1, 4.2 and 4.3 are for one of the four orientations (i.e. north, south, east and west). They vary depending on location, function and occupancy of the building, on dimensions of the building envelope components and their thermal characteristics.

$U = [A_o U_o + A_w U_w]/A_t$ [W/(m^{2}K)] Heat loss parameter (4.1)

$V = A_w SC_w/A_t$ [dimensionless] Solar heat gain parameter (4.2)

$W = I\,A_f/A_t$ [W/m^2] Internal heat gain parameter (4.3)

where:

A_o: opaque wall area [m^2]

A_w: window wall area including frame [m^2]

A_t: gross wall area (A_w+A_o) [m^2]

A_f: floor area of the exterior zone, typically of 4.5m deep [m^2]

U_o: opaque wall U-factor [W/m^{2}K]

U_w: window U-factor, including frame [W/m^{2}K]

SC_w: window shading coefficient [dimensionless]

I: design heat gain from lights, people, and equipment [W/m^2 floor area]

4.2.2 Data Used in Basic Parameters

From the study of equations 4.1, 4.2 and 4.3, three kinds of data that are necessary in the execution of the correlation-based model are classified. Some of them are obtained by user inputs or working drawings and actually they are first stored in the database as design building data. Some of them are acquired from the built-in database which is developed under the new energy Code requirements.

1. General building information: decided by building location, type, building area, etc. It is determined either by searching the built-in databases (when running a reference building calculation) or user input / program calculation (when running a design building calculation).

2. Specific building information on the area of different kind of walls, fenestration, floors of the design building: A_o, A_w, A_t and A_f can be either directly gathered from the working drawings or from user input.

3. Specific building information on thermal characteristics of these envelope components: U_g, U_w and SC_w are either from built-in databases (when running a reference building calculation) or user input / program calculation (when running a design building calculation).

Since "user input" is a general way of obtaining the data used in the basic parameters, only how to determine the appropriate database based on Code and how they are calculated by the small programs embedded in the correlation-based model are explained. There are still parameters on the area of some building envelope component, such as the centre-of-glass area, edge-of-glass area, or frame area of a window, etc, that are obtained either from working drawing, user input or assumed by the program.

Equation 4.1: heat loss

1. Overall heat transmittance of windows and sliding glass doors [U_w]:

    1.a).For windows and sliding glass doors within the scope of CAN/CSA A440.2-M1991 "Energy Performance Evaluation of Windows and Sliding Glass Doors" [1991] (fixed and operable windows covered by CSA standard CAN/CSA-A440-M90 "Windows" [1990], and sliding glass doors covered by CGSB standard CAN/CGSB-82.1-M89 [1989] "Sliding Doors" that are factory-assembled and intended for vertical installation in buildings).

$$U_w = (U_c A_c + U_e A_e + U_{fm} A_{fm} + U_d A_d + U_{de} A_{de})/ A_w$$

(4.4 [CAN/CSA A440.2-M1991 1991])

Where:

U_c: calculated centre-of-glass U-value $[W/(m^{2\circ}K)]$

U_e: calculated edge-of-glass U-value $[W/(m^{2\circ}K)]$

U_{fm}: calculated frame U-value $[W/(m^{2\circ}K)]$

U_d: calculated divider U-value $[W/(m^{2\circ}K)]$

U_{de}: calculated divider edge U-value $[W/(m^{2\circ}K)]$

A_c: centre-of-glass area $[m^2]$

A_e: edge-of-glass area $[m^2]$

A_{fm}: frame area $[m^2]$

A_d: divider area $[m^2]$

A_{de}: divider edge area $[m^2]$

1.b). For other forms of fenestration and sliding glass doors, the corresponding U-value can be obtained as follows:

(i) selected from Appendix B of MNECCB, or

(ii) selected from Table 5 of ASHRAE Handbook of Fundamentals [1993]

1.c). If the user chooses to use the VISION program [1992], the U-value of glazing is calculated and then the overall U-value of the window (including the frame) is obtained by the Equation 4.4.

2. Overall heat transmittance of opaque walls (U_o) can be obtained as follows:

2.a. Selected from Appendix B of MNECCB,

2.b. Calculated according to the procedure described in Appendix C of MNECCB, or

2.c. Calculated using the CONDENSE program [1993].

Equation 4.2: solar heat gain

1. Shading coefficient (SC_w) of windows:

The SC_w is calculated as the ratio of solar heat gain coefficient (SHGC) for the fenestration and SHGCr of a reference glass (single-pane, double strength, clear glass); for standard summer conditions, SHGCr is equal to 0.87 for normal incidence. Table 11 in ASHRAE Handbook of Fundamentals [1993] gives values for frequently used fenestration types.

1.a). Solar heat gain coefficient ($SHGC_w$) of windows and sliding glass doors within the scope of CAN/CSA A440.2 M1991 [1991] "Energy Performance Evaluation of Windows and Sliding Glass Doors" is calculated as follows:

$$SHGC_w = (SHGC_g A_g + SHGC_{fm} A_{fm} + SHGC_d A_d)/A_w \qquad (4.5)$$

where:

$SHGC_w$: solar heat gain coefficient of complete window product

$SHGC_g$: solar heat gain coefficient of glazing

$SHGC_{fm}$: solar heat gain coefficient of frame

$SHGC_d$: solar heat gain coefficient of dividers

A_g: total glass area, [m^2]

A_w: complete window area, based on outside dimensions of frame [m^2]

A_{fm}: frame area [m^2]

A_d: divider area [m^2]

1.b). In case of other fenestration and sliding glass doors, the solar heat gain coefficient can be

(i) selected from Appendix B of MNECCB [1995], or

(ii) calculated using the VISION program [1992].

Equation 4.3: internal heat gain

1. Internal load density I can be obtained from Chapter 5 of the MNECCB [1995].

4.3 Correlations

4.3.1 Basic Correlations

There are two basic correlations which are originally designed to be used in the Ottawa region, one calculates annual heating load (Q) and the other annual cooling load (C). Special climate correction coefficients are applied when using them in other Canadian regions other than Ottawa. Coefficients other than basic parameters U, V and W are shown in Tables 1 & 2 in Appendix B of the thesis and are interpolation from the initial set of data from Cornick and Sander [1995]. The following equations in Section 4.3 are also taken from the same reference.

These correlations were tested by Cornick and Sander. For both annual heating system loads and cooling loads, the predictions from the correlations are within 10% of the DOE-2.1E simulation results. The results for locations other than Ottawa are also tested and they agree with the system loads obtained by DOE-2.1E [1992] within 10% as well.

Annual heating load

Annual heating load (Q) is determined by using factors to account for solar heat gain and internal heat gains to modify the annual heat loss [Sander et al.1994]:

$$Q = L \cdot SGRF \cdot IGRF \cdot GIF \qquad [MJ/m^2\,yr] \tag{4.6}$$

where:

1. L is the annual heat loss given by:

   $$L = b_0 + b_1 U \qquad [MJ/m^2\,yr] \tag{4.7}$$

   U: heat loss parameter $[W/m^2K]$

   b_0: constant representing infiltration and ventilation losses;

   b_1 : slope of the variation of annual heat loss with respect to U;

2. SGRF is Solar Gain Reduction Factor given as:

   $$SGRF = L_v / L \tag{4.8}$$

   $$= 1 / (1 + \alpha_1 x + \alpha_2 x^2 + \alpha_3 x^3) \tag{4.9}$$

   L_v = annual heating loss minus solar heat gains

   $$x = V/L \tag{4.10}$$

3. IGRF is Internal Gain Reduction Factor given as:

   $$IGRF = L_w / L \tag{4.11}$$

$$= \exp (1 + \beta_1 y + \beta_2 y^2 + \beta_3 y^3) \tag{4.12}$$

L_w = annual heating loss minus internal heat gains

$$y = W/L \tag{4.13}$$

4. GIF is Solar Gain and Internal Gain Interaction Factor given as:

$$GIF = \exp (\delta_0 + \delta_1 \gamma + \delta_2 \gamma^2 + \delta_3 \gamma^3) \tag{4.14}$$

$$\gamma = (L - Q) / ((L - L_v) + (L - L_w)) \tag{4.15}$$

$$= (1 - SGRF \;\; IGRF) / ((1 - SGRF) + (1 - IGRF)) \tag{4.16}$$

$$\delta_0 + \delta_1 + \delta_2 + \delta_3 = 0 \tag{4.17}$$

Annual cooling load

The annual cooling load (C) is derived in a similar way to that used in heating load equation. Cooling load is primarily related to internal heat gain and solar heat gain rather than the envelope heat loss. Detailed descriptions are available in Sander et al. [1994]. Basically there are two terms in the equation: C_0 and ΔC_0. The first term C_0, called base cooling load, is calculated from the internal gain and solar gain parameters V and W, and it corresponds to the operation of fans and the minimum ventilation requirements. The second term ΔC_0 is a correction for the heat transfer through the envelope.

$$C = C_O + \Delta C_O \qquad [MJ /m^2 \, yr] \tag{4.18}$$

Where:

C_O is Base cooling load,

$$C_O = \max (C_{min} , a_0 + a_1 V + a_2 W) \qquad [MJ /m^2 \, yr] \tag{4.19}$$

C_{min}: minimum cooling load for the particular climatic location and the choice of system modeled

a_0: intercept for the base cooling load,

a_1: variation of cooling load with respect to solar parameter,

a_2: variation of cooling load with respect to internal load parameter.

ΔC_O is the correction for envelope losses / gains,

$$\Delta C_O = a_3U\ (\ 1 - C_{min}\ /\ C_O\ ) \qquad [\mathrm{MJ\ /m^2\ yr}] \qquad (4.20)$$

a_3: variation of cooling load with thermal transmittance.

4.3.2 Climate Correlation Coefficients

For the purpose of applying equations 4.6 and 4.18 at cities other than Ottawa, (i) climatic coefficients, (ii) climate data such as heating degree days, cooling degree days and vertical solar radiation and (iii) location data such as latitude are used:

1. Climatic coefficients used in the heating load equation:

$$b_{0\ canada} = A_0 + A_1 HDD65 \qquad (4.21)$$

$$b_{1\ canada} = B_0 + B_1 HDD65 \qquad (4.22)$$

$SGRF_{canada} = k_1 SGRF$ k_1 is a climate factor. (4.23)

$$k_1 = C_0 + C_1 LAT + C_2 CDD50 + C_3 VS_j CDD50 + C_4 VS_j + C_5 CDD50CDD65 + C_6 HDD65 \qquad (4.24)$$

$$\alpha_{1canada} = k_1\ \alpha_1, \qquad (4.25)$$

$$\alpha_{2\ canada} = k_1^{\ 2}\ \alpha_2, \qquad (4.26)$$

$$\alpha_{3\,canada} = k_1^{\,3}\,\alpha_3, \qquad (4.27)$$

$$IGRF_{canada} = k_2 IGRF \qquad k_2 \text{ is a climate factor.} \qquad (4.28)$$

$$k_2 = S_0 + S_1 CDD50 + S_2 VS_{ew} + S_3 LAT \qquad (4.29)$$

$$\beta_{1\,canada} = k_2\,\beta_1, \qquad (4.30)$$

$$\beta_{2\,canada} = k_2^{\,2}\,\beta_2, \qquad (4.31)$$

$$\beta_{3\,canada} = k_2^{\,3}\,\beta_3, \qquad (4.32)$$

The annual heating load is determined as the rewritten form of equation 4.6:

$$Q_{canada} = L_{canada} \bullet SGRF_{canada} \bullet IGRF_{canada} \bullet GIF_{canada} \qquad (4.33)$$

1. Climatic coefficients used in the cooling load equation:

$$a_0 = E_0 + E_1 CDD65 + E_2 VS_j + E_3 CDD50 + E_4 VS_j CDD50 + E_5\,(VS_j CDD50)^{1/2} \qquad (4.34)$$

$$a_1 = L_0 + L_1 CDD50 + L_2\,(CDD50)_{1/2} + L_3 HDD65 + L_4 VS_j + L_5 VS_j CDD50 \qquad (4.35)$$

$$a_2 = G_1 CDD50 + G_2 CDD65 + G_3 CDD50CDD65 + G_4\,(CDD50CDD65)^{1/2} \qquad (4.36)$$

$$a_3 = T_0 + T_1 LAT + T_2 LAT^2 + T_3 CDD50 + T_4\,(CDD50)^{1/2} + T_5 HDD65 \qquad (4.37)$$

$$C_{min} = X_1 CDD50 + X_2 CDD50^2 + X_3 CDD65 + X_4 CDD50CDD65 + X_5\,(CDD50CDD65)^{1/2} \qquad (4.38)$$

E, L, G, T and X are climate correlation coefficients.

CDD50: cooling degree-days at 50 ° F (10° C),

CDD65: cooling degree-days at 65 ° F (18° C),

HDD65: heating degree-days at 65 ° F (18° C) (Appendix C in NBCC),

LAT: latitude in minutes

VS_j: vertical solar on orientation j [W/m^2] (Table 20-26 in ASHARE Handbook of Fundamental, Chapter 27.20-27.26).

j: north, south, east, west, (northeast, northwest, southeast and southwest by interpolation)

4.4 Development of the Correlation-Based Model

Several improvements are made on the basis of Cornick and Sander [1995] correlation model after the implementation of correlation equation, the building of related code database and the acquisition of necessary design data and calculation programs.

The correlations are based on a base model with four exterior zones facing the cardinal orientation which can only represents walls facing exactly north, south, east, west. They give the results of energy load per m^2 of each segment of the wall. In the real design practice, it is rare that a building shape is very regular that it only has walls facing the above four directions. Very often the facades of a building do not face exactly north or south because of the restrictions from street directions.

To make it more applicable, the prototype presented here interpolates the initial four sets of data into eight sets (north, south, east, west, northeast, northwest, southeast and southwest). A special program is developed in the graphical user interface to determine which orientation a piece of wall in the working drawing is facing (see Section 4.2).

In the prototype correlation-based model, instead of evaluating individual pieces of walls on different orientation, an entire building is considered. The energy consumption on individual exterior walls (with different orientations and /or different thermal characteristics) is added up to form a whole building. In this way, the trade-off method (see section 2.2) could be implemented through the design of the entire building. The trade-off is no longer limited to the wall and window area ratio on one part of the exterior wall or the changing of U-values of wall or windows in this part. It can be applied between different parts of exterior walls that constitute the building and a lot more design choices are now possible. For example, decrease window area on one side of wall while increase window area on another side of wall might still be a good design strategy to save energy usage.

The prototype correlation-based model consists of three parts. The first part is a data reading engine that reads data from the Design Building data and Reference Building data. The second part is the calculation module which utilizes the correlations to give the energy loads for both Design Building and Reference Building.

The third part is the alternative generation engine that can compare the calculation results of Design Building and Reference Building and generate the alternative building data. If the energy load of Design Building is less than the Reference Building, the results are sent to the database and saved in Design Building data and Reference Building data respectively. If the Design Building has a higher energy load than the Reference Building, it means that the design is not in accordance with the energy Code requirements under trade-off path.

To generate alternative design options, first the thermal characteristics of the inputs are compared with the data in the reference design. Then the envelope component which the biggest variations is selected. The dimension and thermal characteristics of this piece of envelope are changed first (the thermal characteristic may take the value from reference building, the dimension value may increase or decrease depending on the first run of the calculation). The calculation procedure is executed to test whether this change is efficient or not. If it is not, the next piece of the envelope component is evaluated and this procedure is repeated several times until an acceptable resolution is reached. Finally, the alternative values and the final result are saved in the database as the checking result and advice.

Chapter 5

Data Collection for the Design Building

5.1 User Interface Characteristics

5.1.1 Graphical User Interface

Most conventional energy evaluation software developed in DOS or Windows environment use an interface that asks the user to input many energy-related parameters. The basic input data includes: total floor area, building volume, number of different exterior walls, heat capacity of this mass, number of layers for each exterior wall, thickness and thermal properties of each layer for each wall, window type, window and wall areas and U-value. This list can be very long. Besides having a tedious input procedure, this kind of software also requires the user to perform extra calculations before inputting some values such as areas or heat transmittance values.

Conventional energy evaluation systems use text format to represent the proposed design, which is totally different from the approach normally used by architects. Architects prefer drawings to present a design issue since much design information is incorporated in the drawings. If an energy performance evaluation system adopted the graphical form in presenting design, it would be easier for an architect to understand and use it.

Another reason for adopting a graphical user interface is to save time and make data input operations simple. With conventional energy evaluation systems, the user has to enter manually all the necessary design information. Even when working drawings are produced by computers in a CAD environment, designers still have to quit the CAD program and run another software to input those data manually. This procedure is time-consuming and bound to create errors.

5.1.2 Characteristics of a Desirable User Interface

A user interface that can collect design data directly from working drawings and help building designers visualize numerical values can thus overcome the drawbacks of conventional systems and make the best use of an energy analysis tool. Specifically such a user interface should:

- be developed primarily with graphic elements and be easy to understand, in other words, be user-friendly;
- collect design data directly from the working drawings in order to minimize work during the input process;
- help identify shapes and orientations of a building directly from the drawing; these are generally difficult to describe in words, especially when the shape is very complex;
- gather information regarding the height, length and area of building spaces, as well as exterior envelope components. This information is relatively easy to obtain, because it is already incorporated in the drawings;

- help the user to calculate the heat transmittance of building envelope assemblies such as walls and windows. These parameters are essential for the calculation of energy performance at an early design stage. However, their evaluation is difficult by the majority of architects.

The prototype presented here incorporates a graphical user interface that tries to meet the above criteria by classifying the useful data and developing different strategies to collect and present them.

5.2 Types of Energy-Related Design Data

From the analysis of the input data required for the Code compliance checking with respect to mandatory and prescriptive requirements, the energy-related design data can be classified in five categories:

1. General building information: information that is not graphically shown on the working drawings e.g., building location, building type, energy source of a building.
2. Descriptive requirements from the Code, which are generally not part of working drawings.
3. Dimensions and areas for windows, floors, spaces and different types of enclosure, all of which are embedded in drawings, while some may necessitate extra calculations (e.g. areas).
4. Building shape, wall and window orientations that are indicated in the working drawings

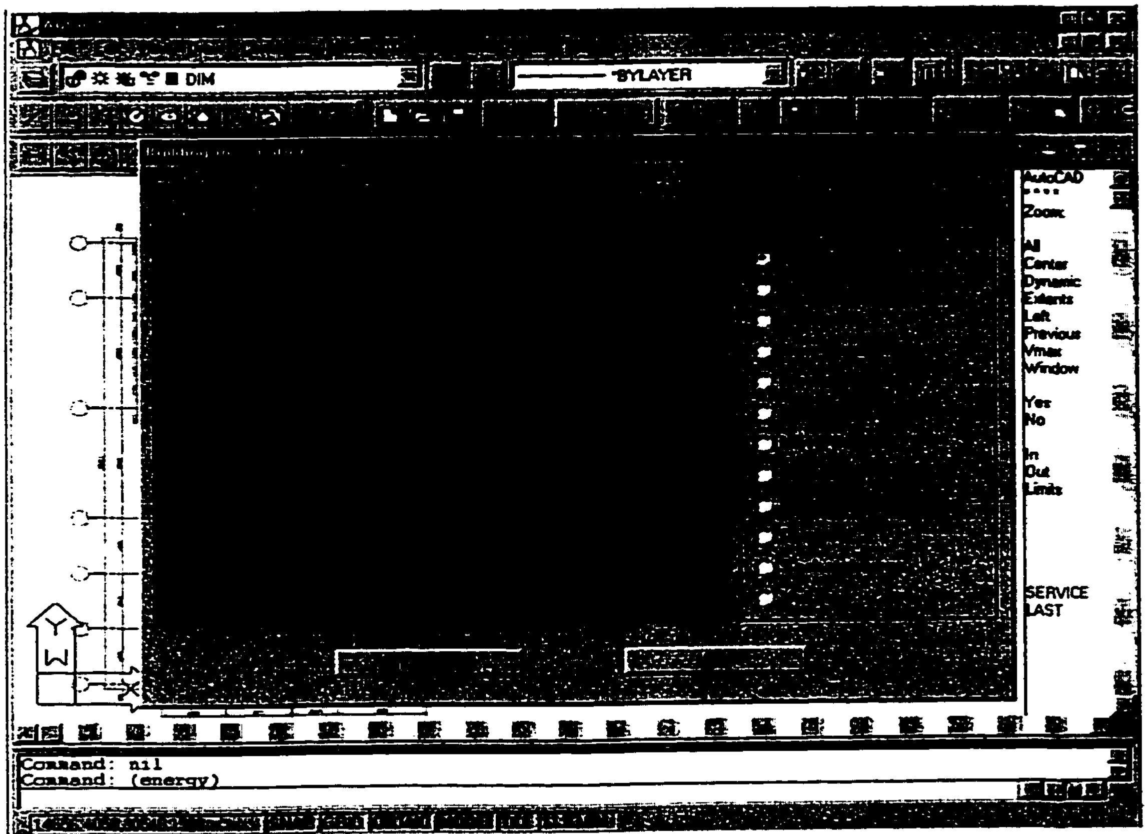
5. Numerical values that cannot be obtained directly from working drawings such as heat transmittance of exterior walls, roofs, floors and windows.

The following sections give in detail how these five categories of input data are collected, either directly from the working drawings or manually inputted by the user.

5.2.1 General Building Information

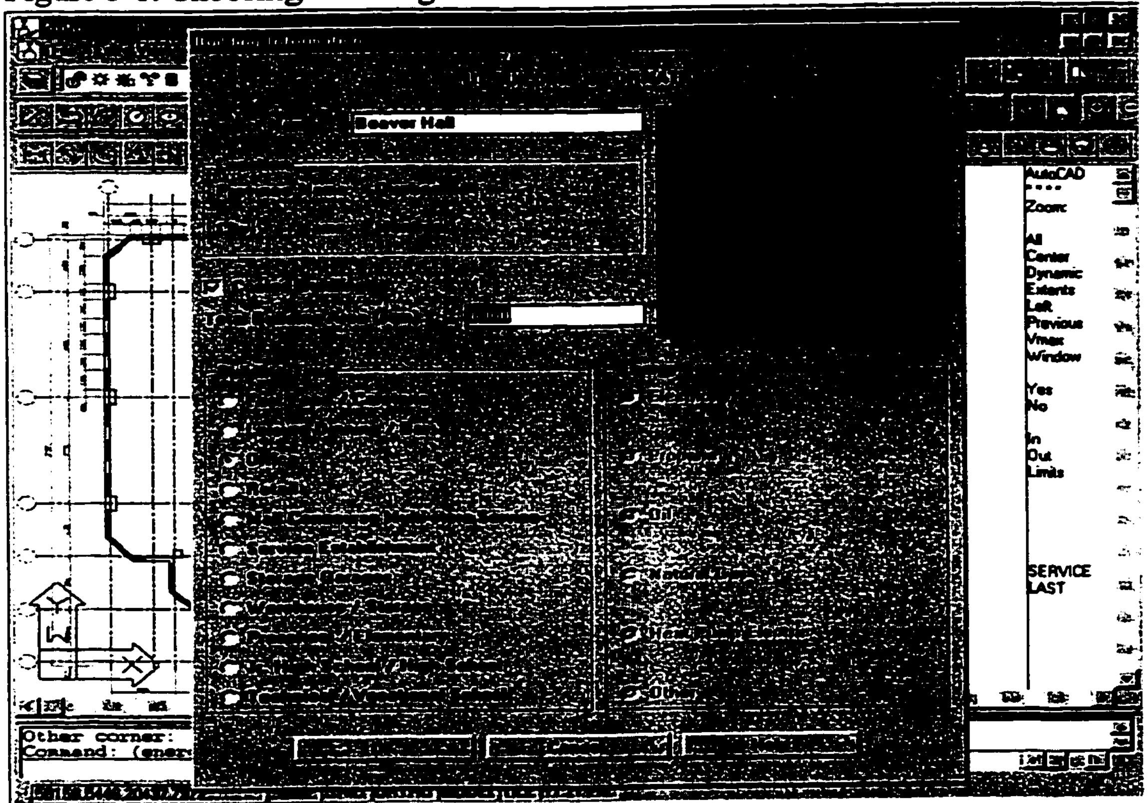
Data of the first category can only be collected directly from the user. Figure 5-1 shows the graphical user interface developed to input building location. Instead of having a list of 12 provinces and territories, a map of Canada is used. The user can either click on the map or choose a province location from the list. A dialog box with a list of cities then pops up from which the user chooses a city location. The map of that province is shown on the next dialog box to remind the user (Figure 5-2). Once a city is selected, the corresponding climatic data and climatic correction coefficients are loaded automatically from the database

In the case of general design data, we try to limit the number of data. Some options are given to the user regarding what kind of data the system is asking for. In developing the user interface, radio buttons, check boxes and lists are preferred because they provide clear choices to the user, unlike edit boxes (sometimes called blank boxes), which are kept to a minimum because they do not give enough indication on the expected answer. (Figure 5-2).



```
Command: nil
Command: (energy)
```

Figure 5-1: Choosing Building Location



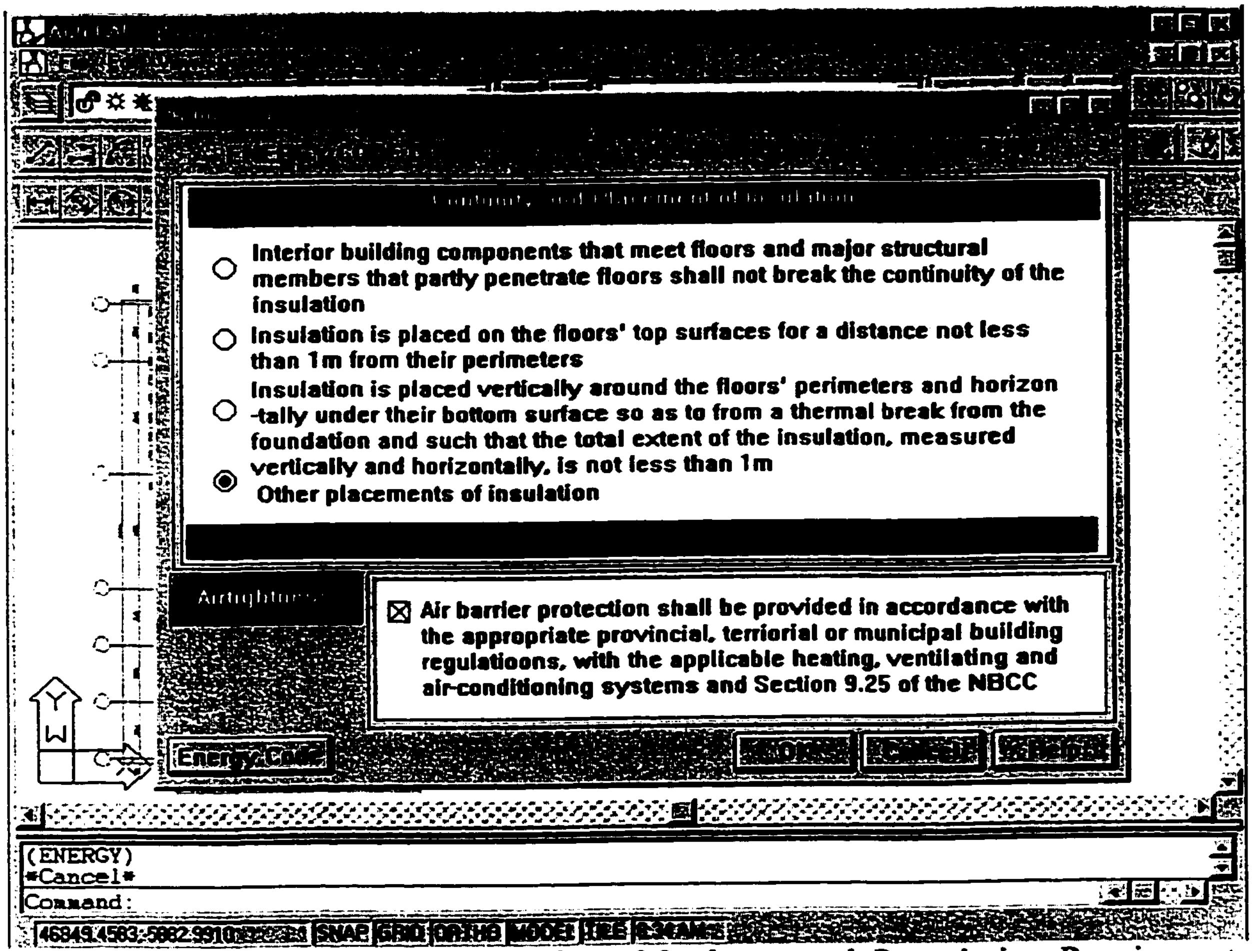
Beaver Hall

```
Other corner:
Command: (ener
```

Figure 5-2: Input of General Building Information

5.2.2 Descriptive Requirements

The rules used in the development of non-graphic data collection apply here: i.e. limit the range of input data and always give options to the user. The information is decomposed and presented as different possible conditions from which the user can choose which one applies best to his/her own design (Figure 5-3). Some of the mandatory and prescriptive requirements in the Code that cannot be paraphrased into options stay as descriptive statements to which users can assign a "YES" or "No" answer (Figure 5-4). More examples of such user interface to input design data concerning Code requirements are provided in Appendix C.



○ Interior building components that meet floors and major structural members that partly penetrate floors shall not break the continuity of the insulation

○ Insulation is placed on the floors' top surfaces for a distance not less than 1m from their perimeters

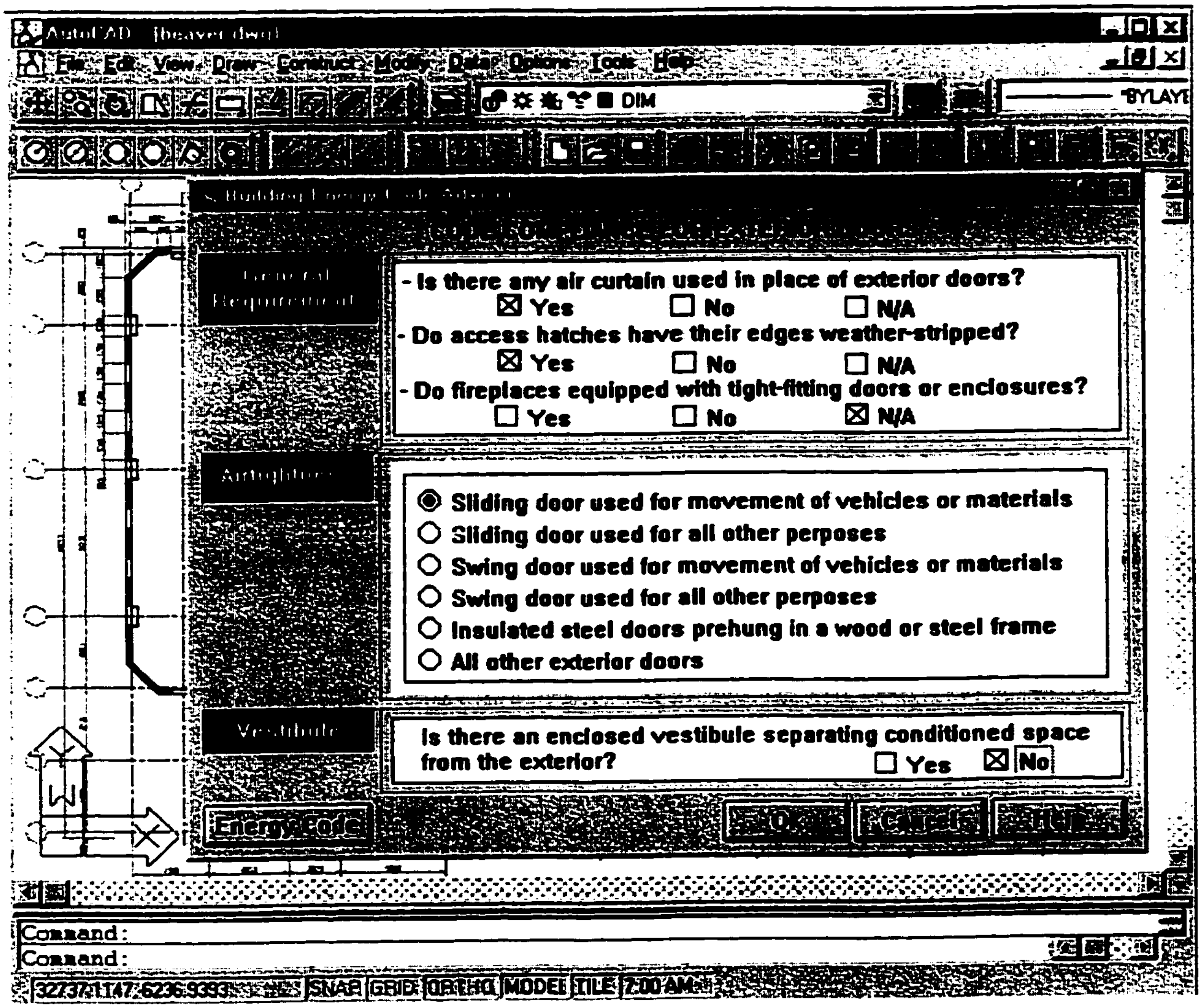
○ Insulation is placed vertically around the floors' perimeters and horizon -tally under their bottom surface so as to from a thermal break from the foundation and such that the total extent of the insulation, measured vertically and horizontally, is not less than 1m

● Other placements of insulation

☒ Air barrier protection shall be provided in accordance with the appropriate provincial, terriorial or municipal building regulatioons, with the applicable heating, ventilating and air-conditioning systems and Section 9.25 of the NBCC

```
(ENERGY)
*Cancel*
Command:
```

Figure 5-3: Collecting Design Data from Mandatory and Prescriptive Requirements Regarding Floors in Contact with Ground



- Is there any air curtain used in place of exterior doors?
  ☒ Yes ☐ No ☐ N/A
- Do access hatches have their edges weather-stripped?
  ☒ Yes ☐ No ☐ N/A
- Do fireplaces equipped with tight-fitting doors or enclosures?
  ☐ Yes ☐ No ☒ N/A

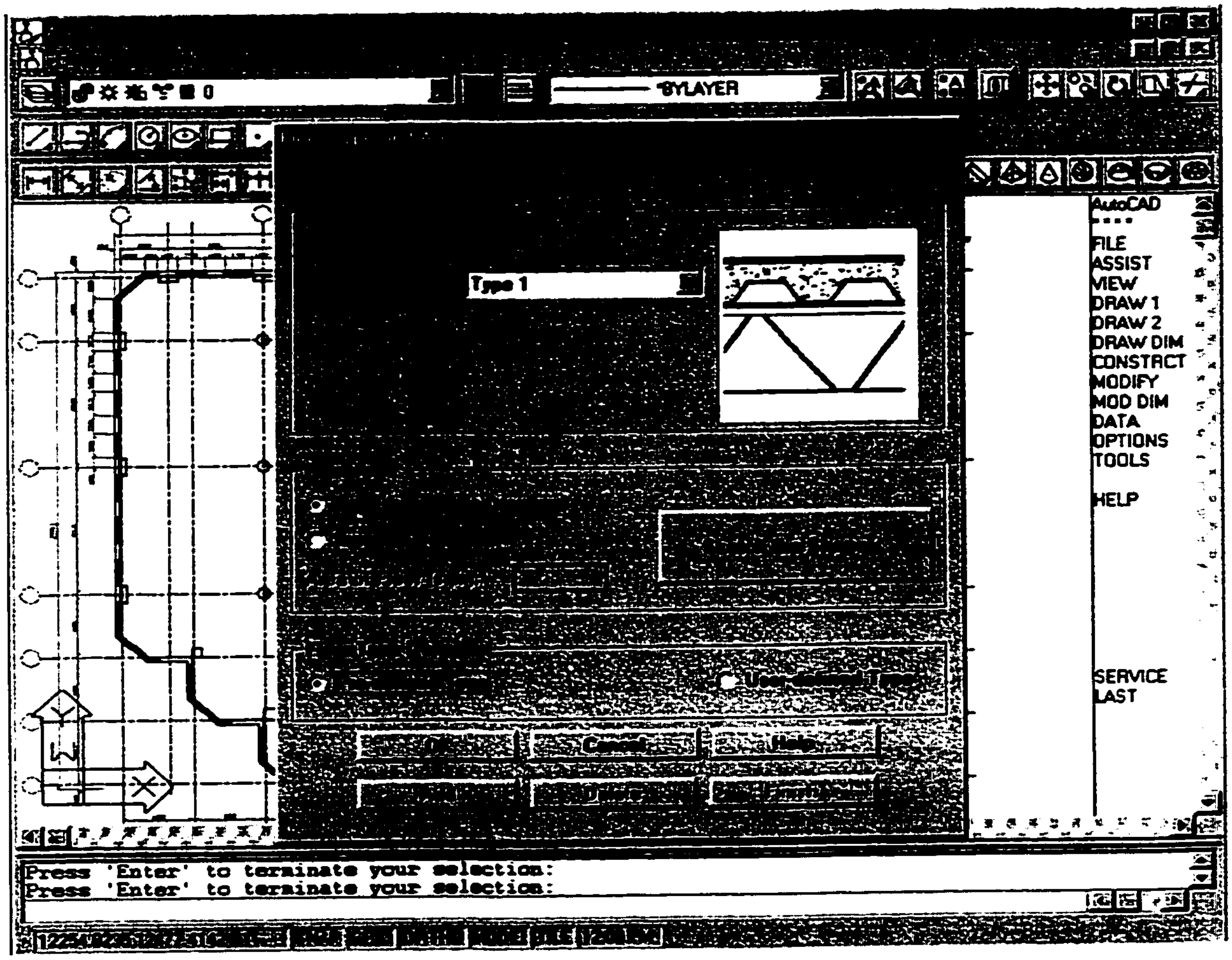
● Sliding door used for movement of vehicles or materials
○ Sliding door used for all other perposes
○ Swing door used for movement of vehicles or materials
○ Swing door used for all other perposes
○ Insulated steel doors prehung in a wood or steel frame
○ All other exterior doors

Is there an enclosed vestibule separating conditioned space from the exterior? ☐ Yes ☒ No

Figure 5-4: Collecting Design Data from Mandatory and Prescriptive Requirements Regarding Exterior Doors.

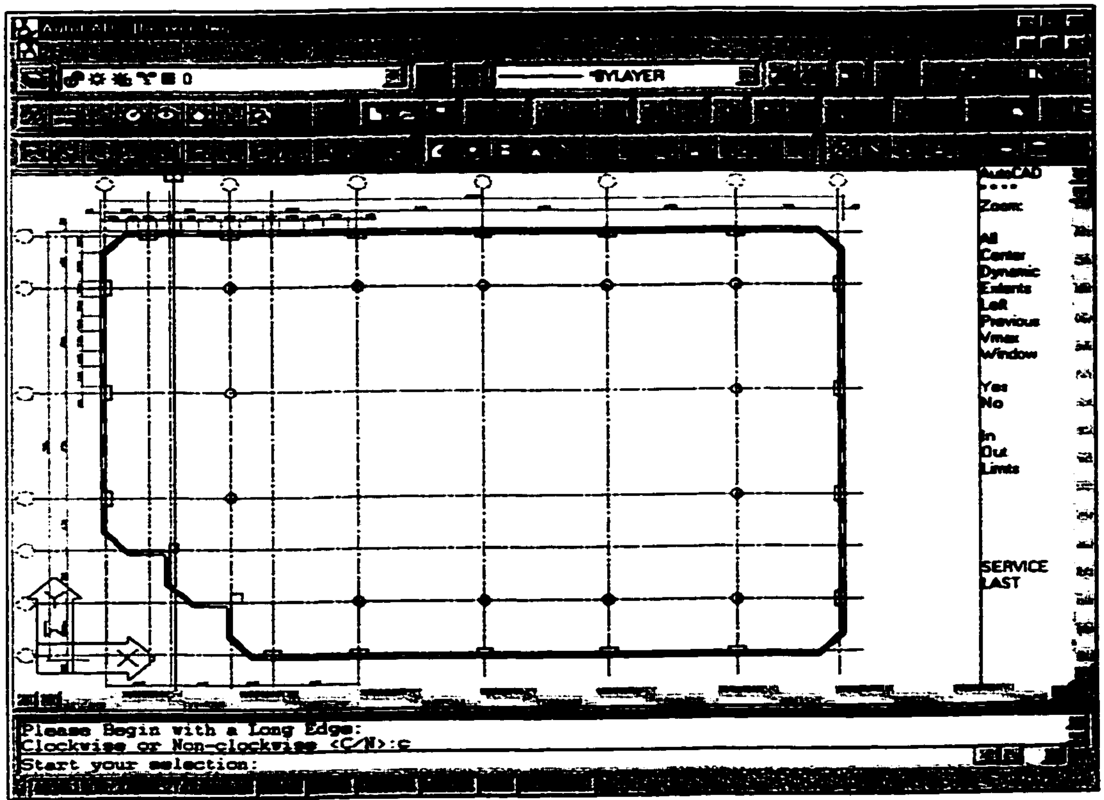
5.2.3. Dimensions and Areas

This information can be obtained in two ways. First, the user inputs dimension, when these are known or would be very difficult to obtain directly from drawings. Second, the designer draws the window or wall in an elevation drawing, or a floor in a plan drawing. This function requires the graphical user interface to be able to interact with the working drawing. For example in order to obtain a floor area, the user should do the following: (i) with the working drawing. For example in order to obtain a floor area, the user should do the following: (i) push the "Sketch the shape" button on Figure 5-5; (ii) the dialogue box disappears and the AutoCAD cursor appears to let users pick points on the plan drawing (Figure 5-6); (iii) after the sketch procedure is finished, the dialogue box returns with the floor area value shown on it (Figure 5-7). This input collection method is also used to gather wall or window areas from plan drawing. By giving the height of the wall or window, the data collection procedure only requires the length of walls for multiplication by the height.



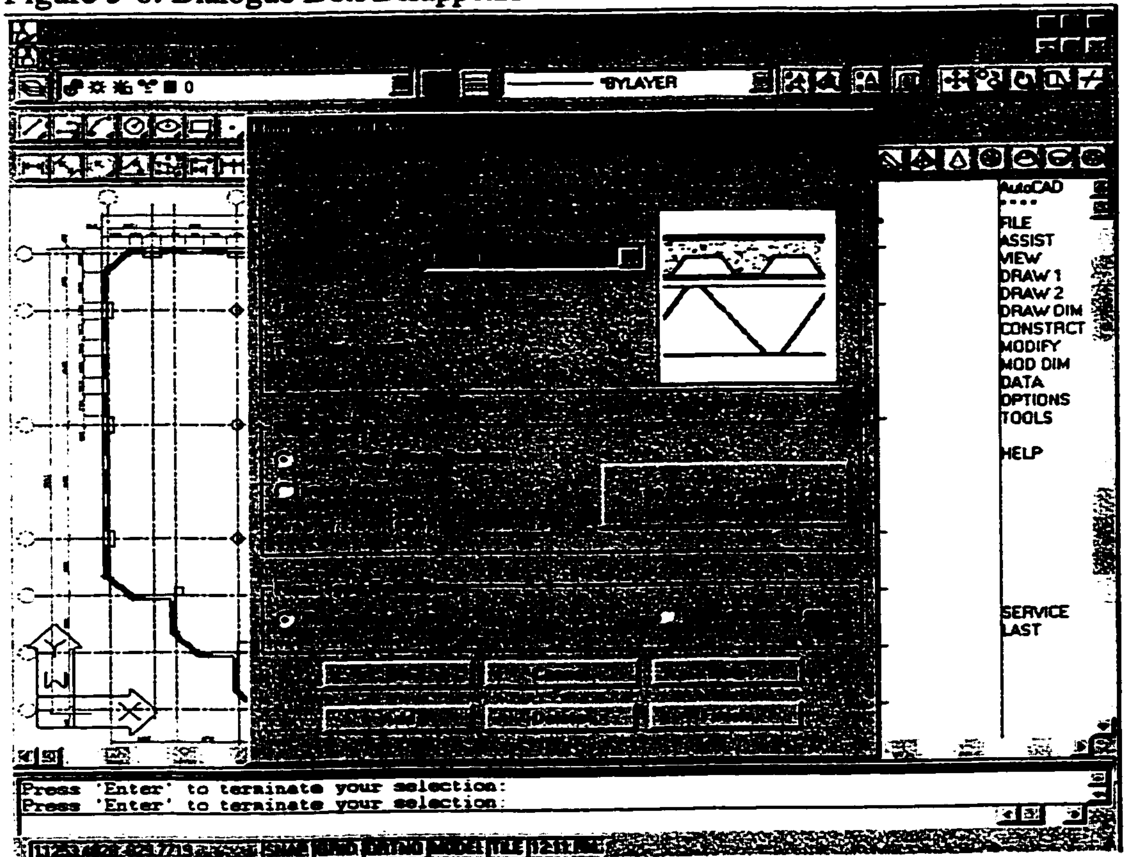
```
Press 'Enter' to terminate your selection:
Press 'Enter' to terminate your selection:
```

Figure 5-5: A Dialogue Box for Collection of Floor Design Data



```
Please Begin with a Long Edge:
Clockwise or Non-clockwise <C/N>:c
Start your selection:
```

Figure 5-6: Dialogue Box Disappears



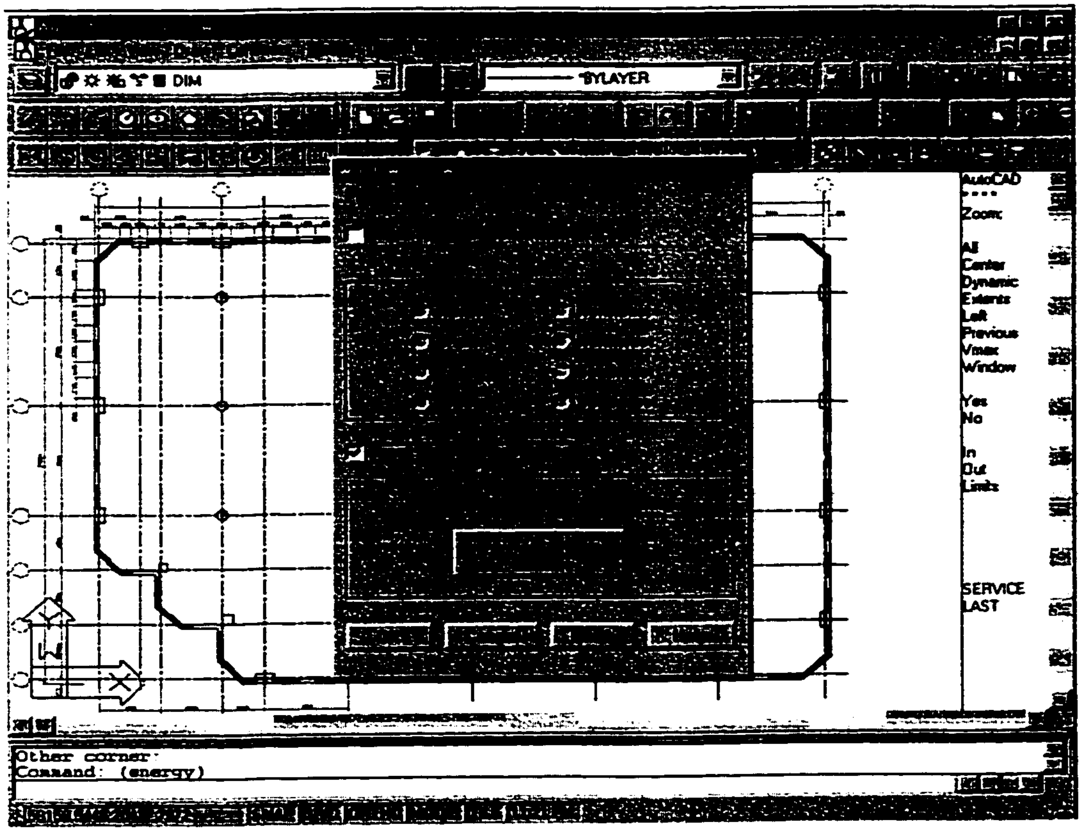
```
Press 'Enter' to terminate your selection:
Press 'Enter' to terminate your selection:
```

Figure 5-7: Dialogue Box Resumes with a value for the Area of Floor

5.2.4. Building Shape and Orientation

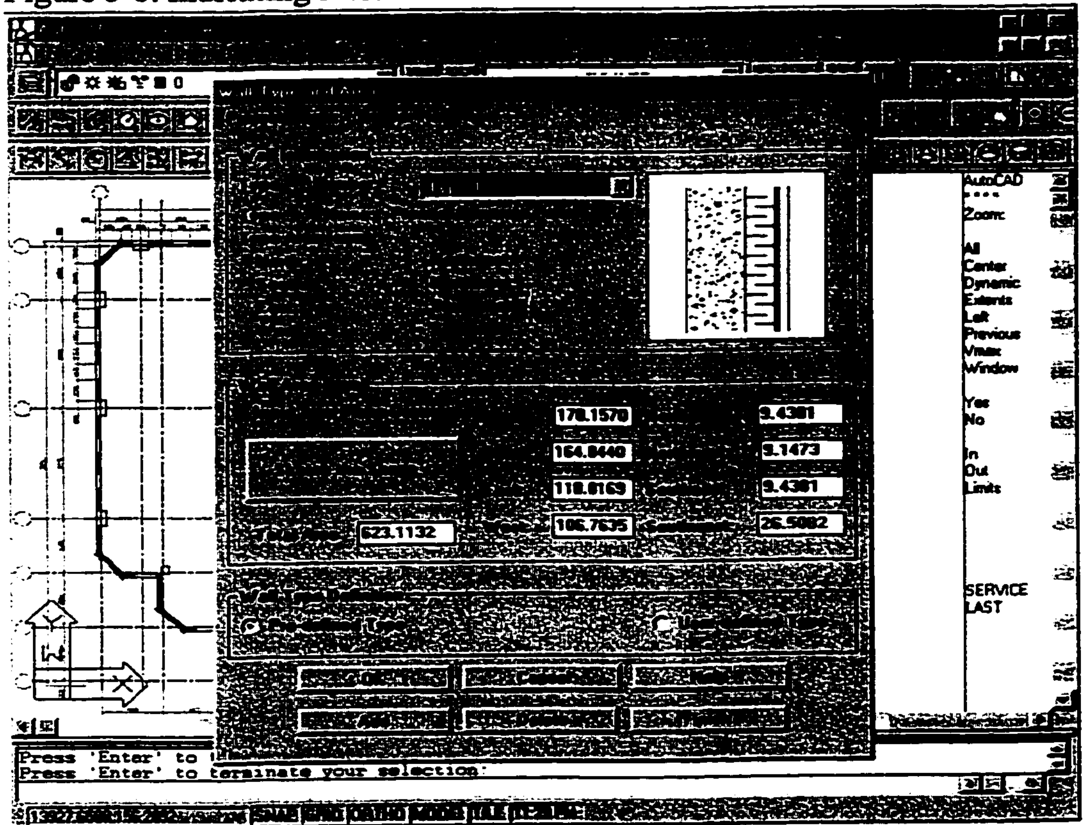
A complex building shape can be very difficult to describe. It is even more difficult to determine the areas of walls and windows for each orientation. The trade-off method (which is described in Section 2.2.2) evaluates the energy performance of walls and windows based on their orientations. It defines different adjustment factors for eight orientations: north, south, east, west, northeast, northwest, southeast and southwest. Hence it is important to have a fast and accurate way to input information about the orientation.

To determine the orientation of a wall or a window from plan drawings, a reference direction is required (Figure 5-8). This is specified graphically by pushing the button "North" on the dialogue box of Figure 5-8, following which the dialogue box disappears and the cursor is already located at one corner of the drawing. The user indicates the north direction by picking any point in this direction on the working drawing. Then the user can start to sketch the shape of the building in the drawing. The points specifying building corners must be entered in sequence. The system can calculate the angle formed by a line jointing two of those points with the north direction as indicated before. The length between these lines are easily calculated. Knowing the wall or window height, the area of the walls or windows can be found and stored according to their orientation (Figure 5-9).



```
Other corner:
Command: (energy)
```

Figure 5-8: Indicating North Direction



623.1132

178.1570

164.8440

118.8169

106.7635

9.4381

9.1473

9.4381

26.5082

```
Press 'Enter' to
Press 'Enter' to terminate your selection:
```

Figure 5-9: Wall Areas in Different Orientations

5.2.5. Thermal Characteristics of Building Envelope

Thermal characteristics of building envelope components have always been difficult to evaluate by architects. Wall assemblies are generally composed of several layers and the windows have usually more than one layer of glazing. It is difficult for an architect to obtain the physical properties of every material. It is even harder for them to master the overall heat transmittance calculation method when air space, studs, columns or channels are incorporated in a wall assembly, or in the case of multi-glazed windows with various types of frames, glass color, glass coating and in-fill gas conditions.

In order to eliminate this problem, two programs are incorporated to calculate the U-value of opaque envelope assembly and the U-value of the window system. The program used to calculate the U-value of opaque envelope assembly is called CONDENSE [1993] and was originally designed to check the risk for condensation in the envelope assembly. The calculation of U-value is performed within the AutoCAD environment which makes it important for the present prototype. Another advantage of using the CONDENSE software is the access of a database which contains hundreds of building materials, which are available on the market, as well as their physical characteristics. CONDENSE builds up the proposed wall section on the drawing as the user chooses building materials from the database. This is helpful to illustrate the actual wall section made up of layers and to understand how the U-value is determined (Figure 5-10).

The second program, called VISION [1992], calculates the U-value and the SHGC (Solar Heat Gain Coefficient) of glazing systems. It shows the drawings of the window section with different numbers of layers, coatings, in-fill gases (Figure 5-11). Calculation results are also presented graphically with a curve showing the changing of temperature (Figure 5-12). The VISION program does not take into consideration window frames. Therefore, a calculation method provided in the ASHRAE Handbook of Fundamentals [1993] is implemented in the presented prototype to evaluate the impact of center of glass, glazing, frame and edge. The prototype system provides a list of commonly used frames and initiates calculation automatically (Figure 5-13).

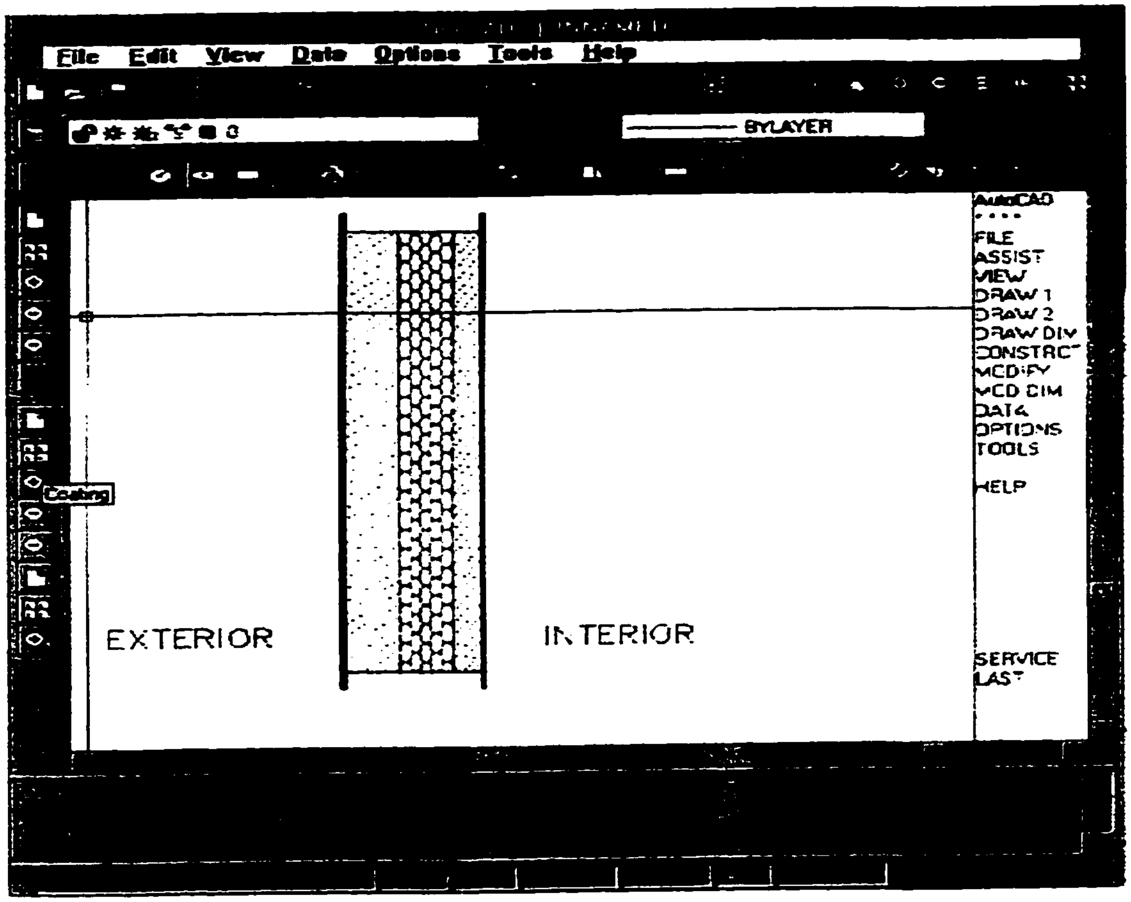
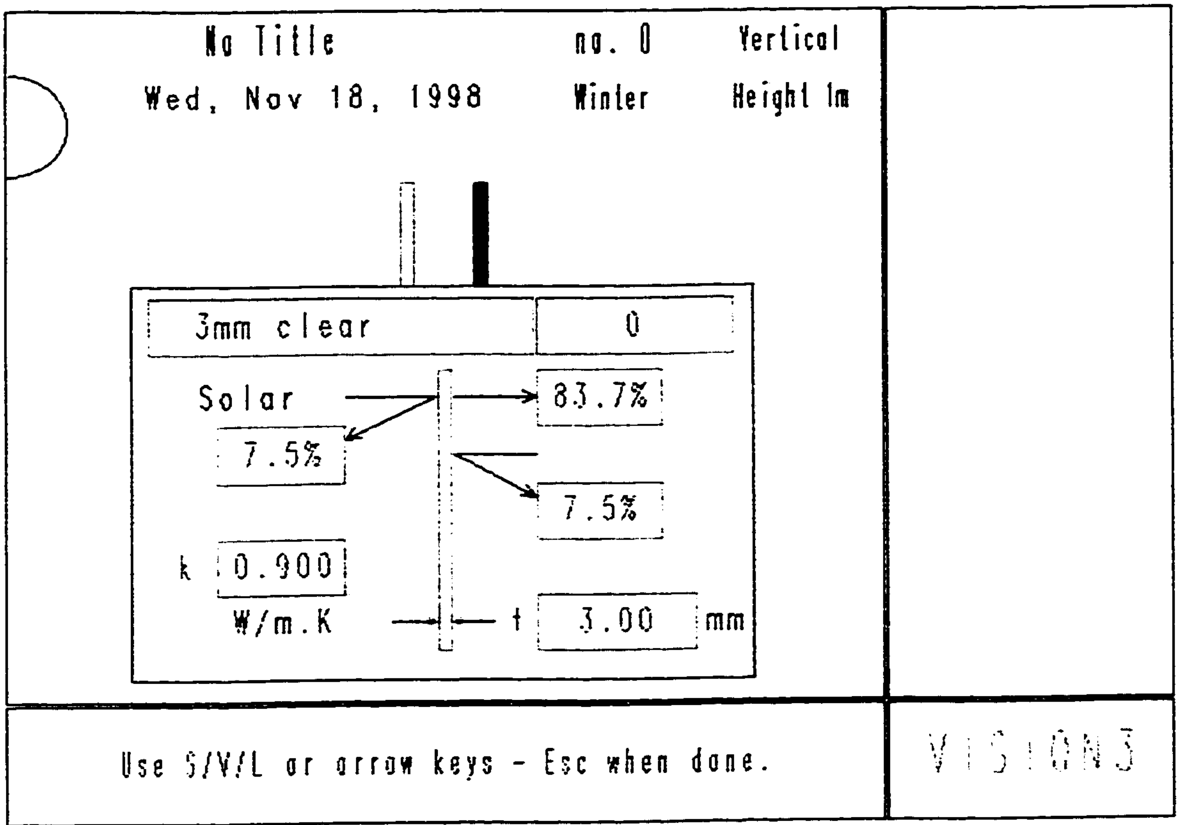


Figure 5-10: A Wall Section as Drawn by CONDENSE



No Title no. 0 Vertical

Wed, Nov 18, 1998 Winter Height 1m

3mm clear 0

Solar 83.7%

7.5%

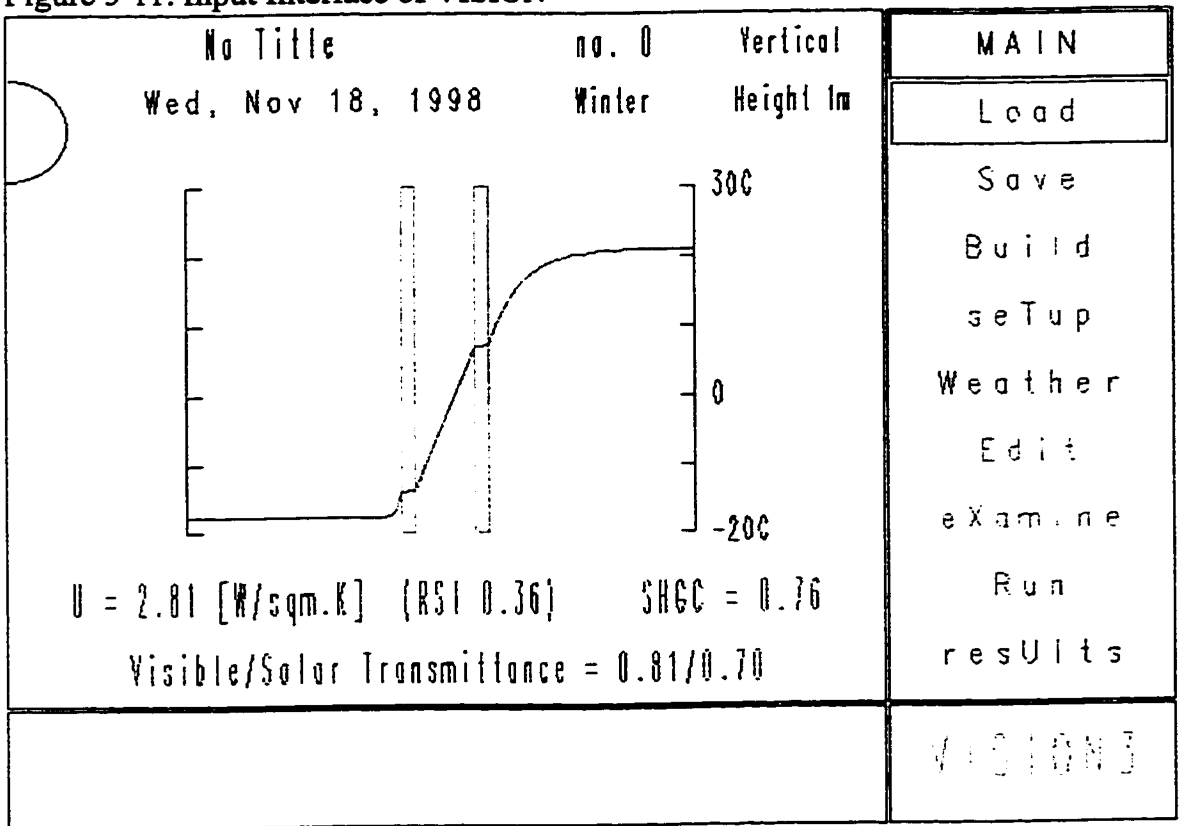
7.5%

k 0.900 W/m.K

t 3.00 mm

Use S/V/L or arrow keys - Esc when done.

Figure 5-11: Input Interface of VISION



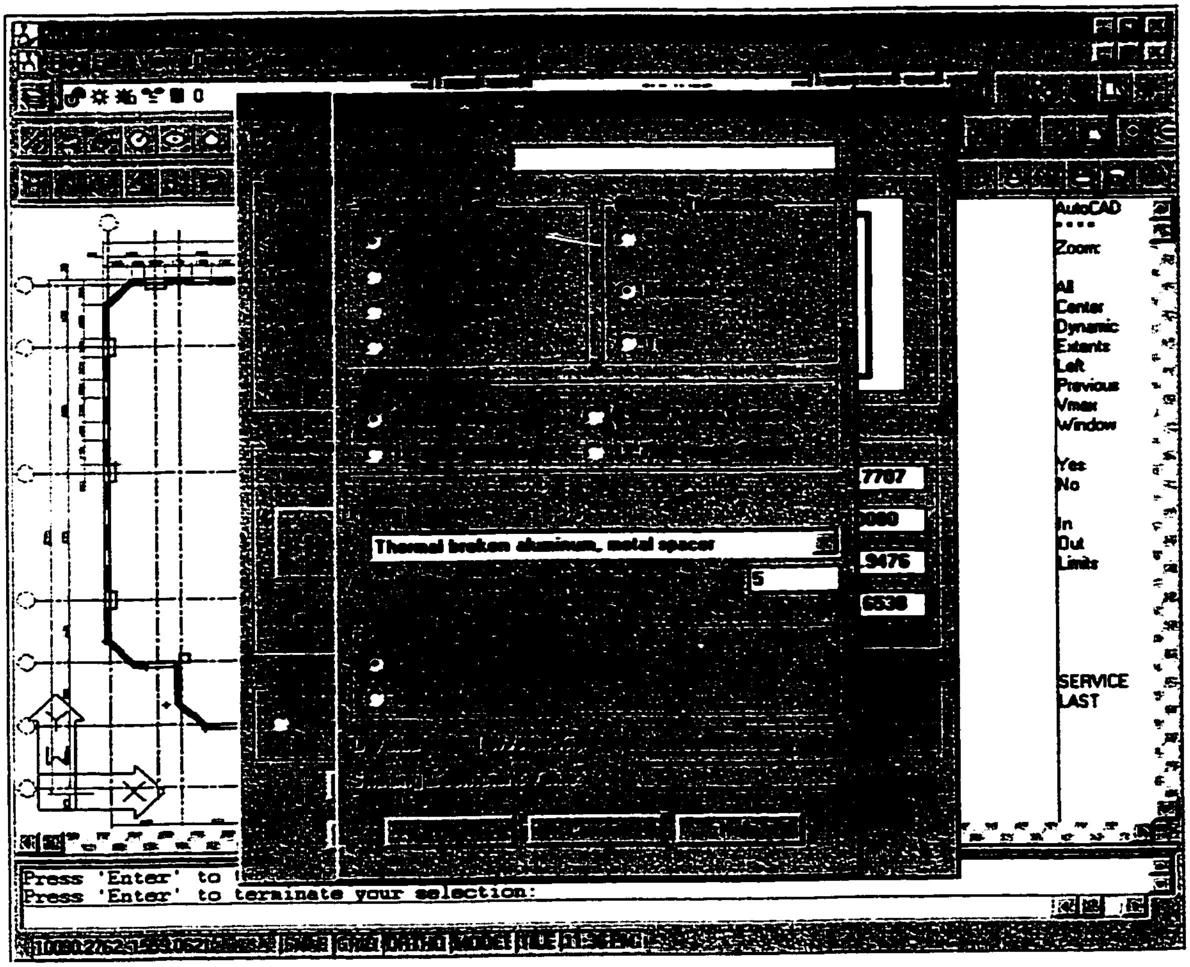
No Title no. 0 Vertical

Wed, Nov 18, 1998 Winter Height 1m

U = 2.81 [W/sqm.K] (RSI 0.36) SHGC = 0.76

Visible/Solar Transmittance = 0.81/0.70

Figure 5-12: Result Interface of VISION



```
Press 'Enter' to
Press 'Enter' to terminate your selection:
```

Figure 5-13: Window U-value Calculation

5.3. Design Data Input Procedure

The entire proposed system works within the design drawings environment, which is developed in AutoCAD Autolisp [1995]. Three steps must be taken to input all the necessary information into the system.

First, the general information concerning project name, building location (e.g. the province and city), building type (e.g. office building or retail building), type of cooling system, if any, energy source type (e.g. electricity, propane, oil or heat pump) are gathered from the designer. This non-graphic information has to be entered manually.

Then the graphic information incorporated in the drawings is collected directly from plan or elevation drawings, or from both. For every type of building component such as window, wall, floor and roof, the data collection engine provides three input modes: collect data from plan drawings, elevation drawings or from the user directly. The use of plan drawings is preferable in the case of complex buildings because of the automatic determination of orientation. Dialogue boxes for windows and walls are connected with each other; the system automatically subtracts the areas of windows from that of exterior walls. Lighting areas required by the design of the lighting system can only be obtained from plan drawings while the height of space can only be obtained from elevation drawings.

After all design data is collected from drawings and user, the proposed design is checked for compliance with the Code, using the knowledge base and the correlation-based model.

Chapter 6

Implementation and Validation

6.1 System Design

A prototype system named Building Energy Code Advisor (BECA) is developed using the proposed methodology. The BECA system is implemented in the AutoCAD environment in Autolisp [1995] with the integration of Level 5 Object [1994]. Autolisp is used to program the interactive interface that collects design data from building drawings. Level 5 Object is a knowledge-based expert system development tool that can utilize a database within a rule-processing procedure in an object-oriented programming environment.

The architecture of BECA system consists of (i) a pre-processor, (ii) the main module integrating requirements from the MNECCB, and (iii) a post-processor (Figure 6-1). The role of pre-processor is to gather general design information. The post-processor reports results at the end of a consultation session. The main module consists of three main blocks: databases, knowledge base and correlation model.

6.1.1 Pre-Processor

The pre-processor, developed in Autolisp, collects the general building information from both the design drawings and the user input. The general information includes: building location, energy source and function of the building. When the building location is determined, the corresponding climatic data is loaded from the database.

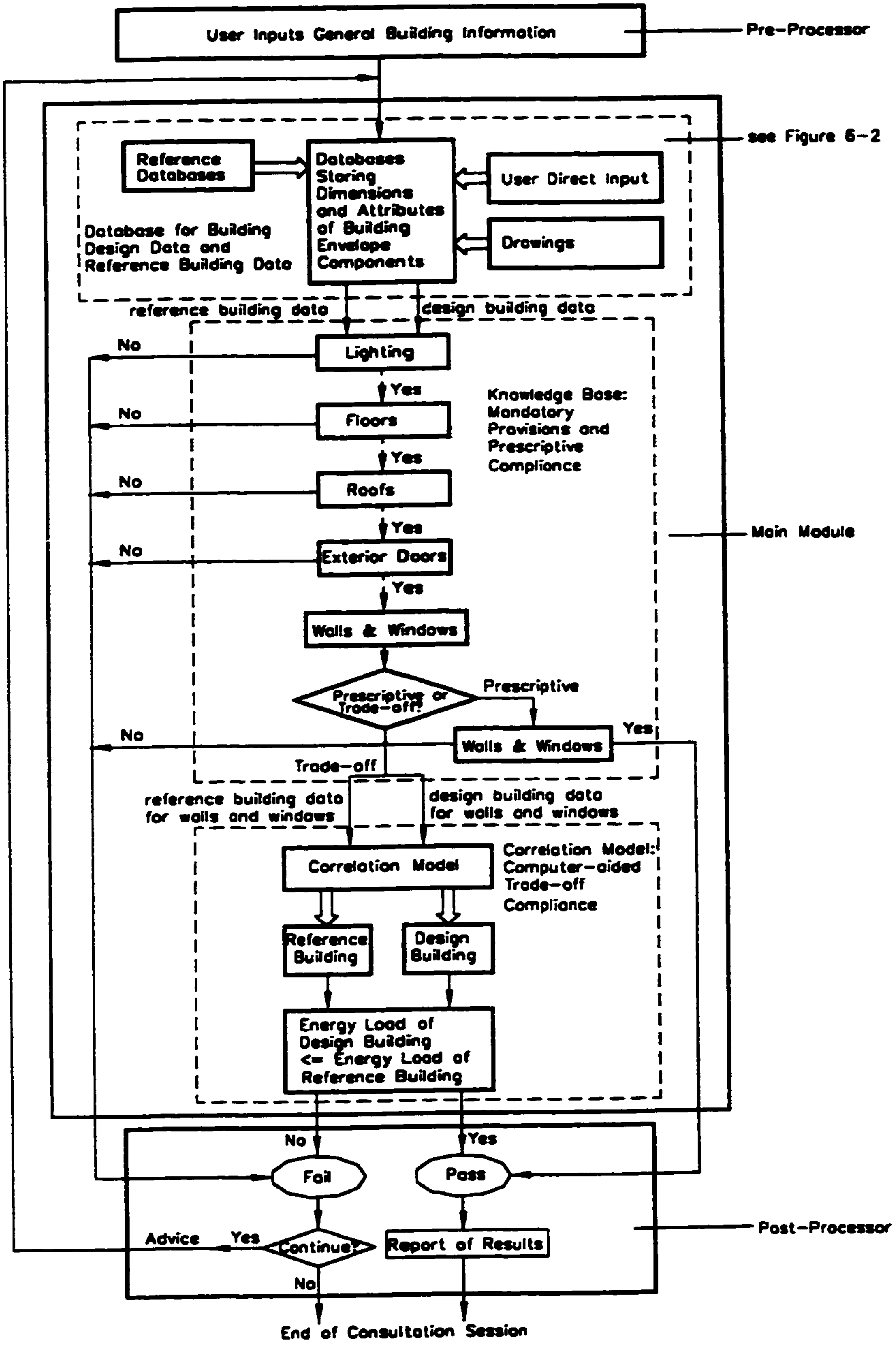


Figure 6-1: Prototype System Overview of BECA

6.1.2. Main Module

The knowledge base is developed in Level 5 Object whereas the database and correlation-based model are developed by using Autolisp. The knowledge base contains rules to control the use of data in the database and the operation of the correlation-based model.

The database contains three categories of data:

(i) Climatic data such as heating degree days, or cooling degree days, that are extracted from NBCC [1995]. They are selected in terms of the location of the building.

(ii) Specific databases used for selecting the reference building data (Figure 6-2). These databases are classified with respect to building envelope components and are mostly obtained from MNECCB. The U-values of window frames are obtained from ASHRAE Fundamentals. Air leakage rates are compiled from the corresponding regulations on windows, sliding doors and doors. The reference building databases store possible design materials and thermal characteristics permitted by MNECCB (Figure 6-2).

(iii) Design building data that is entered directly by the user or collected from the design drawings.

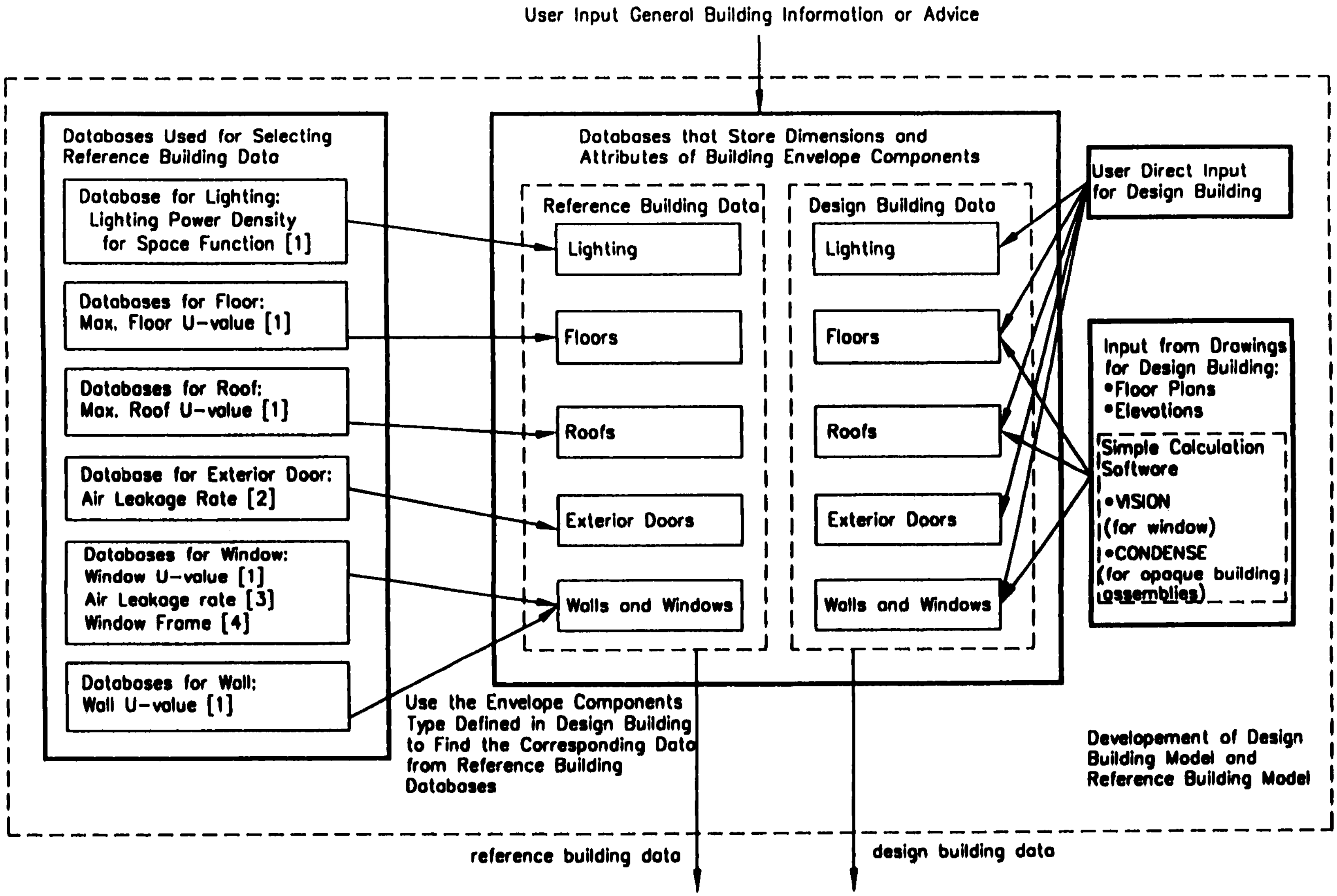


Figure 6-2: Reference Building Databases

[1]: Data from MNECCB [1995]

[2]: Data from CAN/CGSB 82.1-M89, "Sliding Doors"[1989]
Data from CAN/CGSB 82.5-M88, "Insulated Steel Doors"[1988]

[3]: Data from CAN/CSA-A440-M90, "Windows"[1990]

[4]: Data from ASHRAE Fundamentals [1993]

The knowledge base contains the design requirements given in the Code. Mandatory and prescriptive requirements are first analyzed, then formalized into the knowledge base as decision diagrams that use logical relations to connect descriptive statements (Figure 6-3). Twenty-three decision diagrams are developed and are presented in Appendix C. They include the mandatory and prescriptive provisions for wall, window, roof, floor, exterior door and lighting system. The development procedure of decision diagrams has been explained in detail in section 3.4.2 and the object-oriented approach is used in the encoding procedure.

The system prompts the designer with statements and the designer can choose whether his design is in accordance with it or not (Figure 6-4). The compliance with one or more requirements will lead to further investigations of other requirements. Each decision diagram ends up with a "pass" or a "fail". "Pass" confirms the design technique chosen by the designer. "Fail" initiates the system to retrieve back the failed requirements and provide the user with solutions to improve the corresponding design. After satisfying the mandatory requirements in the case of walls and windows, the user has the choice to use prescriptive compliance or computer-aided trade-off compliance to accomplish the rest of the compliance procedure.

The trade-off compliance method provides the user with a correlation-based model. The simplified method uses the design building data and reference building data stored in databases to calculate the annual thermal load for both design building and reference building. A design is considered successful if its thermal load is less than that of the corresponding reference building. By increasing or decreasing the values of the inputs, correlation-based model tries to reach a desired solution. As soon as one is reached, the correlation model stops calculation and gives that solution as an advice.

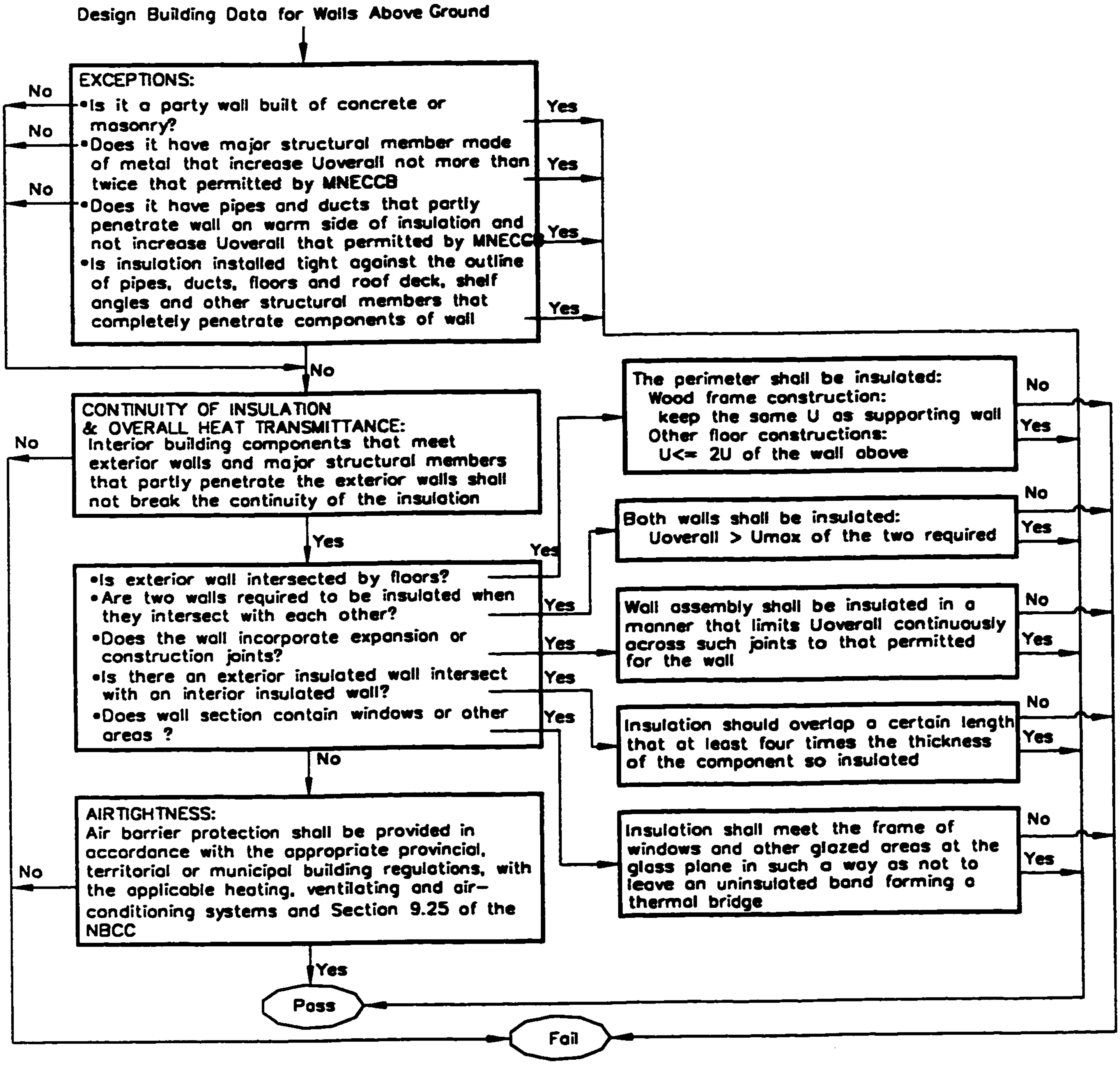
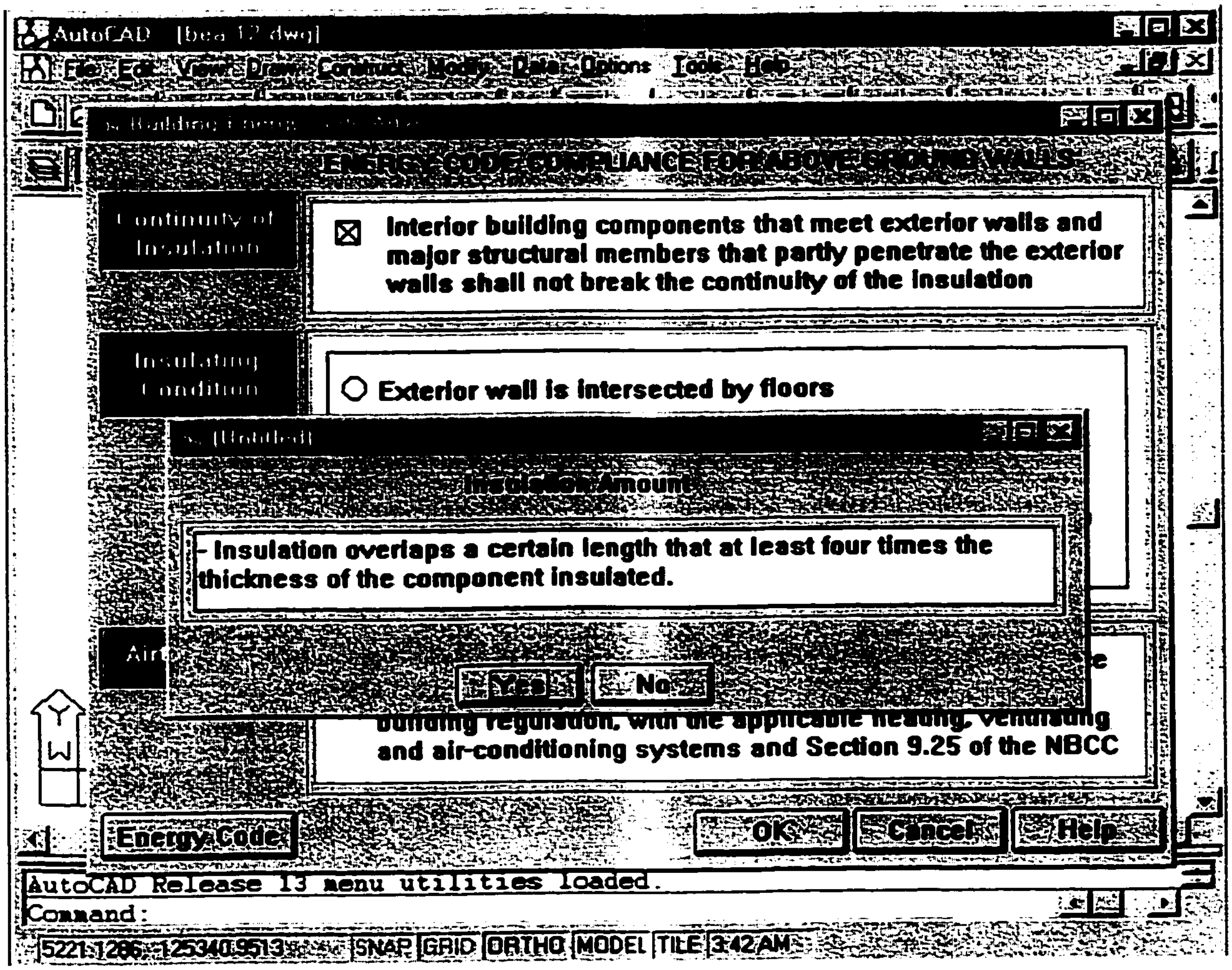


Figure 6-3: Mandatory Provisions for Above Ground Level Walls



☒ Interior building components that meet exterior walls and major structural members that partly penetrate the exterior walls shall not break the continuity of the insulation

○ Exterior wall is intersected by floors

- Insulation overlaps a certain length that at least four times the thickness of the component insulated.

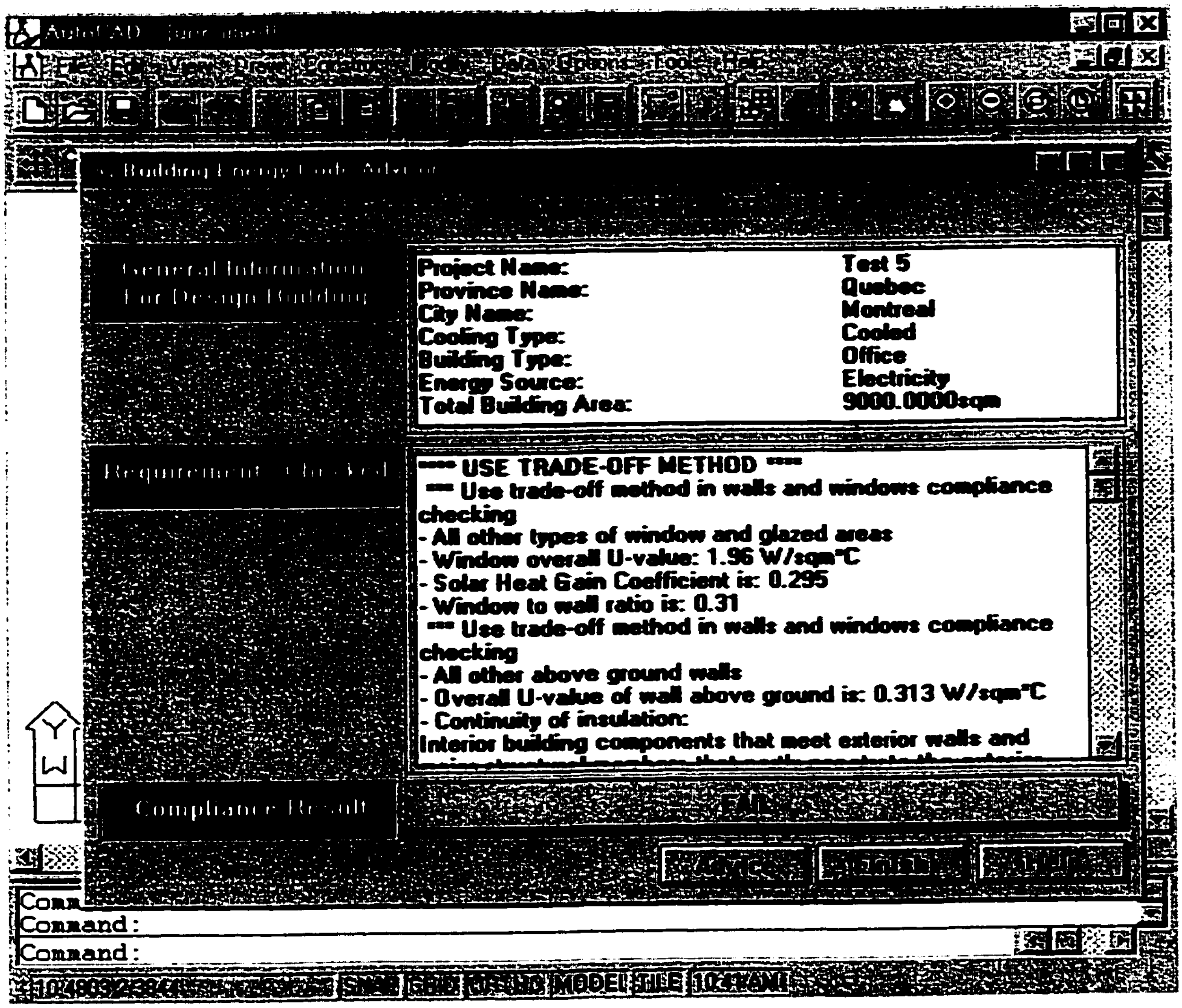
building regulation, with the applicable heating, ventilating and air-conditioning systems and Section 9.25 of the NBCC

```
AutoCAD Release 13 menu utilities loaded.
Command:
```

Figure 6-4: Collecting Design Information from Code Requirements.

6.1.3. Post-Processor

The post-processor is developed in Level 5 Object, and can display the conclusions and present technical advice, when the "advice" button is pressed (Figure 6-5). If the conclusion is "Fail", all the data stored in the current design building database are saved and the user can first modify the design and then ask for another compliance check.



Project Name: Test 5
Province Name: Quebec
City Name: Montreal
Cooling Type: Cooled
Building Type: Office
Energy Source: Electricity
Total Building Area: 9000.0000sqm

```
**** USE TRADE-OFF METHOD ****
 *** Use trade-off method in walls and windows compliance
checking
- All other types of window and glazed areas
- Window overall U-value: 1.96 W/sqm°C
- Solar Heat Gain Coefficient is: 0.295
- Window to wall ratio is: 0.31
 *** Use trade-off method in walls and windows compliance
checking
- All other above ground walls
- Overall U-value of wall above ground is: 0.313 W/sqm°C
- Continuity of insulation:
Interior building components that meet exterior walls and
```

Figure 6-5: Interface of Post-Processor

6.2. Main Functions of BECA System

The BECA system performs the following major operations:

6.2.1. Collects, Stores and Modifies Design Data

The design data collection directly from CAD drawings is one of the main characteristics of the BECA system. The architects can perform the Code checking along with the development and modification of the design. They do not have to exit the CAD program as it is the case when using conventional energy evaluation software. The direct data collection is convenient, time-saving and easy to adopt in practical work.

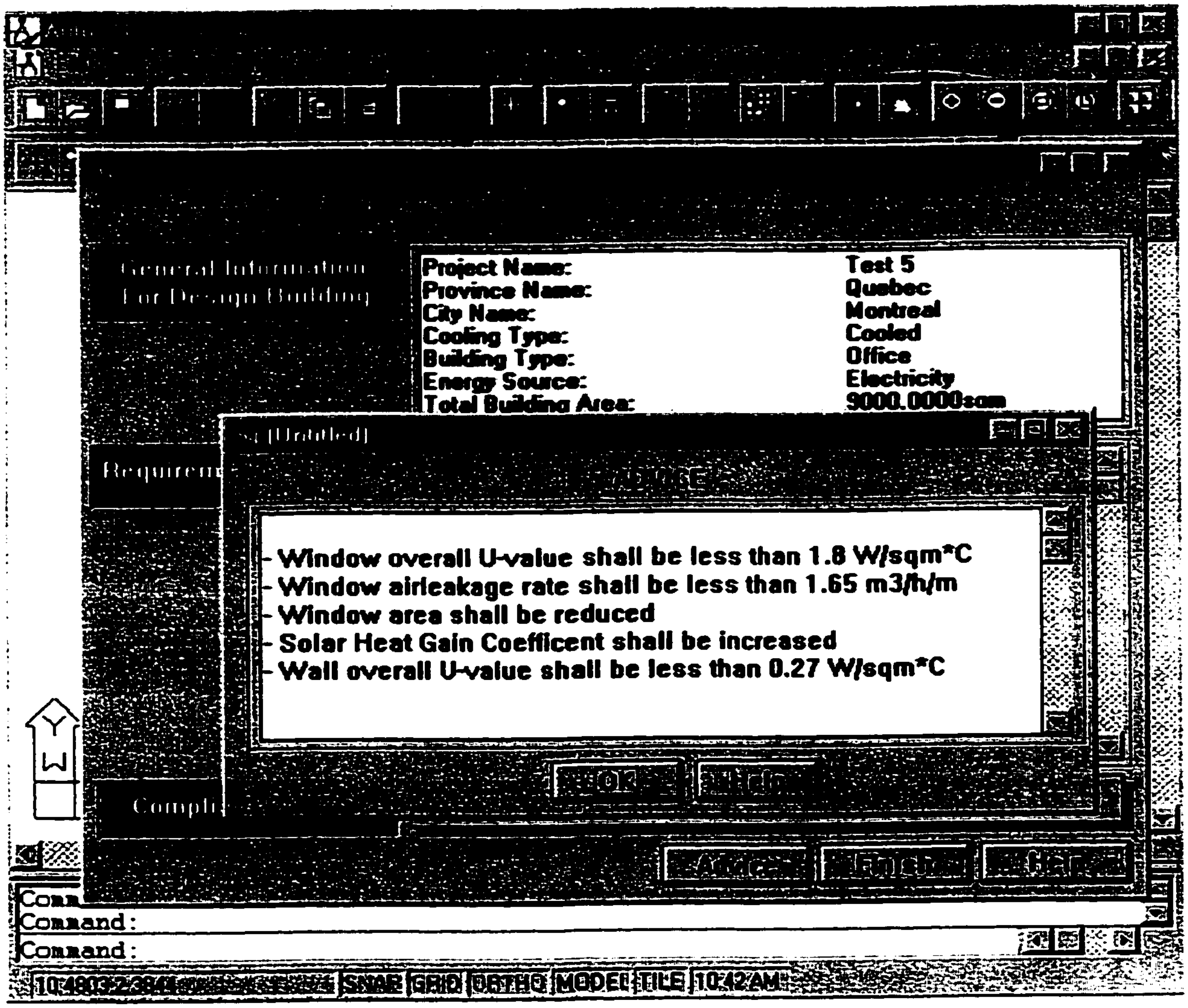
The graphical collection of design data utilizes the interactive user interface that allows to directly select and transfer information from the drawings. The dialogue boxes developed in Autolisp disappear when the user wants to collect graphic information from the drawing (e.g. the shape of a window). They reappear with the numerical data (e.g. the area of that window) after the collection action is done. This technique proves to be most efficient when the building shape is complex.

The building data stores in the database includes: (i) building background information: building name, location, building type, energy source type etc., (ii) construction information: construction type and area of each envelope component, thickness of each layer and material used, (iii) thermal properties of each envelope component. All data concerning one building is stored in one file.

The data for a single design building can be modified by user (modify the working drawing and input again) or by program (alternative data generated by correlation-based model) with the user's intention. The user can open an existing file to make design modifications and get the re-evaluation results in a very short time.

6.2.2. Displays Checking Result and Advice, Provides Access to Code Text

On completion of an evaluation session, the post-processor presents the evaluation results together with the original design data to help the designer to review his work. This includes general information of the design, the descriptions of the enclosure components that are evaluated and concluded by the decision with respect to the MNECCB (i.e. Pass or Fail). They are stored in the data file for this design project. This is displayed in a report format (Figure 6-5).



Project Name:	Test 5
Province Name:	Quebec
City Name:	Montreal
Cooling Type:	Cooled
Building Type:	Office
Energy Source:	Electricity
Total Building Area:	9000.0000sqm

- Window overall U-value shall be less than 1.8 W/sqm*C
- Window airleakage rate shall be less than 1.65 m3/h/m
- Window area shall be reduced
- Solar Heat Gain Coefficent shall be increased
- Wall overall U-value shall be less than 0.27 W/sqm*C

Figure 6-6: Giving Advice after Design Failure

It also gives the Code requirements and advice to help designers improve the design in the case of failure. In Figure 6-5, the button named "Advice" pops up another dialog box which contains the advice provided by the prototype system (Figure 6-6). The user also can check the original text in the Code at any time during the checking procedure by using content search and word search provided in a button named "Energy Code" in the dialog box.

6.2.3. Provides Flexibility in the Checking Process

The BECA system helps the designer to make decisions regarding individual envelope components as well as the entire envelope. Although the system contains Code requirements for all building envelope assemblies such as wall, window, floor, roof, exterior door and lighting design, it is not necessary to verify the compliance of all of them in one single sequence. For instance, if roof is the only envelope component that has been designed, the user can still use the BECA system to check whether the roof design is in accordance with the Code or not. Walls and windows are combined when the trade-off compliance method is used, which allows high thermal performance of one element (e.g. wall) to compensate for poor characteristics of the other elements (e.g. surface glazing area, shading coefficient) which are inferior to the minimum prescriptive values.

6.3. Validation of the System

To evaluate a computer-based system like BECA, two levels of validation are usually used. The first level is sometimes called verification, which means to ensure that a system has been developed and coded correctly and does not contain technical errors [Geissman and Schultz 1998]. The second level of validation ensures that the system satisfies user's needs. The domain knowledge of the system should be correct and the system expected to solve problems within the domain correctly and accurately [Gonzalez and Dankel 1993].

6.3.1. First Level of Validation

The verification of the program is done in the development procedure of the BECA program. Every individual part of the system is tested before being connected together. In the development of knowledge-base and the procedure of coding the decision diagrams, every possible input and its output is tested and the "history tool" provided by Level 5 Object [1994] is used to monitor the values at the run time.

It is very hard to do the verification works for programs developed by Autolisp [1995] because there is no compiler available. Autolisp is specially designed to do programming work inside AutoCAD [1995], a drafting software used by most of the architect firms in Canada. Some features of this language are prone to create errors. For example, in Autolisp, a variable can be used without definition, a default type and initial value are given in this case. This causes problems when the required data is not defined and the required data type does not match the default type. Without a compiler, all the debuging works have to be done manually. Many different conditions have to be tested to ensure functions get correct data under all circumstances. Some strategies are summarized after working with Autolisp for a while, yet it is still tedious and time-consuming. The graphical interface that working in AutoCAD and the correlation-based model are implemented by Autolisp.

Once the individual parts are connected and can work together properly, the overall system is ready to be tested under the second level of validation.

6.3.2. Second Level of Validation

6.3.2.1 Validation Criteria and Methods

Validation has the objective of demonstrating that the completed prototype system performs the required functions and achieves the intended purpose. This indicates the system has an acceptable accuracy, is reliable and functionally complete [Bielawski and Lewand 1988].

Accuracy can be defined as how many acceptable answers are generated by the knowledge-based system [Bielawski and Lewand 1988]. Yin [1984] defines reliability as to demonstrate that the operations of a system can be repeated with the same results. An accurate system should also be reliable. Completeness measures how much of the problem domain is covered by the system.

Some researches prefer to integrate validation during the development [Adelman 1992, Geissman and Schultz 1987] because they believe that the verification and validation occur at the transitions between stages in a development process and apply to the various modules produced. Green and Structured Systems & Software, Inc. [1987] developed a "cut-and-try" approach which includes: define requirements, verify the knowledge base and supporting software, prepare test cases, execute the tests and evaluate the results.

Gonzalez and Dankel [1993] suggest many useful methods including: (i) informal validation which consists of the system developers meeting with one or more domain experts and users to discuss the validity of each conclusion reached by the system; (ii) sensitivity analysis which uses several given sets of inputs containing slight variations and the impact on the variations in the outputs is studied; (iii) field test that allows the developer to see the system performs in its actual operating environment and it will reveal unexpected errors or undesirable side effects; and (iv) test case validation.

Test case validation is a widely used and effective method that is used to test the working conditions of BECA system. It is a method requiring prepared cases. The resulting answers are compared to the opinion of an experienced user. Usually this method only emphasizes the system inputs and outputs [Gonzalez and Dankel 1993].

6.3.2.2. Case Study One: Trade-off Path Testing

Two test cases are prepared to validate the two compliance checking methods provided in the Code. The first case is mainly used to test the accuracy, reliability and completeness of the correlation-based model that is used by trade-off compliance path.

A ten-story office building in Montreal is used [Zmeureanu and Fazio 1990]. The floor size is 30m x 30m and the envelope thermal characteristics meet the requirements of ASHRAE Standard [1989]. The main characteristics of the building envelope are presented in Table 6-1 and are compared with the prescriptive requirements from the MNECCB. The design data are entered into the program by always selecting the "User input" option in the graphical user interface (Figure 6-7). The corresponding values from MNECCB are listed for convenience because they are not usuallyshown to the user.

Table 6-1: Thermal Characteristics of Building Envelope (after [Zmeureanu and Fazio 1990])

	Design Building	Reference Building (Data from MNECCB)
Glazing-to-Wall Ratio (%)	31	31
Solar Heat Gain Coefficient	0.295	0.295
Window U-value (W/ m^2°C)	1.960	1.800
Wall U-value (W/ m^2°C)	0.313	0.270
Roof U-value (W/ m^2°C)	0.284	0.290
Internal Heat Gain (W/ m^2)	30.33	25.78

Note: U = Overall heat transmittance; thermal resistance = 1/U.

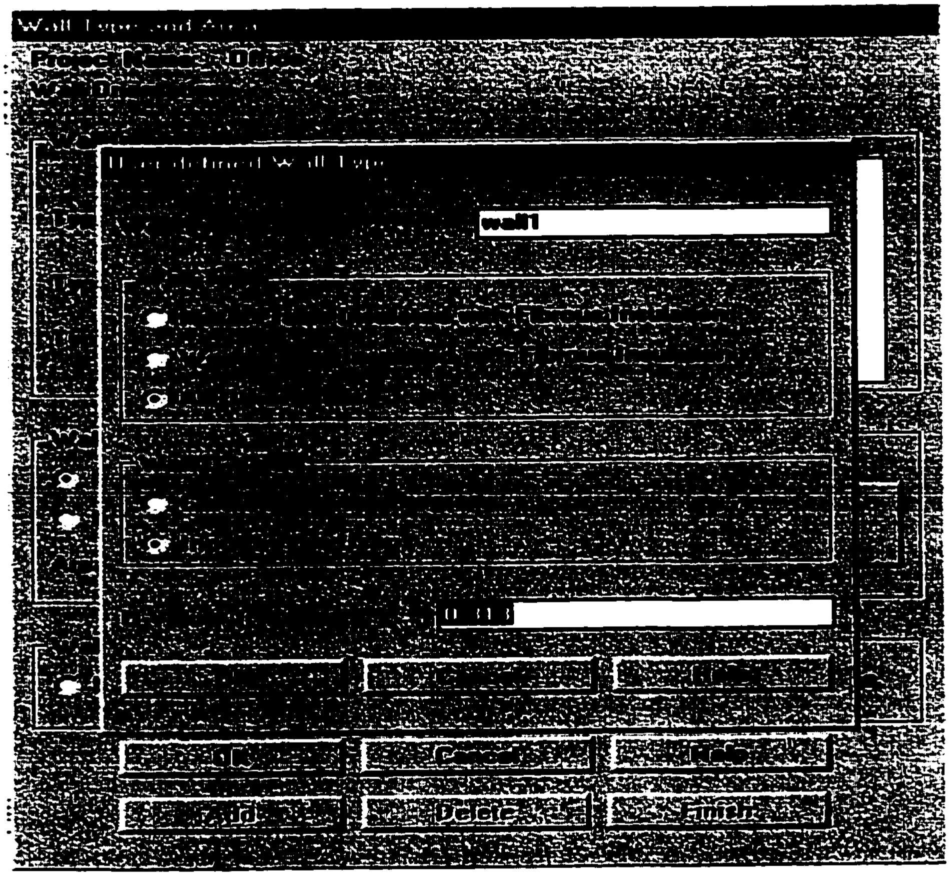


Figure 6-7: Data Input of Case Study One

The trade-off compliance method is used and the thermal loads for the design building and the reference building are calculated as listed in Table 6-2. The original design fails to comply with the MNECCB since the thermal load of the design building (851.3 MJ/m^{2}year) is greater than that of the reference building (835.3 MJ/m^{2}year). The design building is improved by increasing the thermal resistance of windows and walls to satisfy the minimum requirements of the MNECCB (e.g. the windows with the thermal resistance of 1/1.96 = 0.51 m^2°C/W are replaced by windows having thermal resistance 1/1.8 = 0.56 m^2°C/W). The best results indicate the total thermal load of the design building is 823.1 MJ/m^{2}year compared with 835.3 MJ/m^{2}year for the reference building.

Table 6-2: Thermal Loads of the Design Building and Reference Building

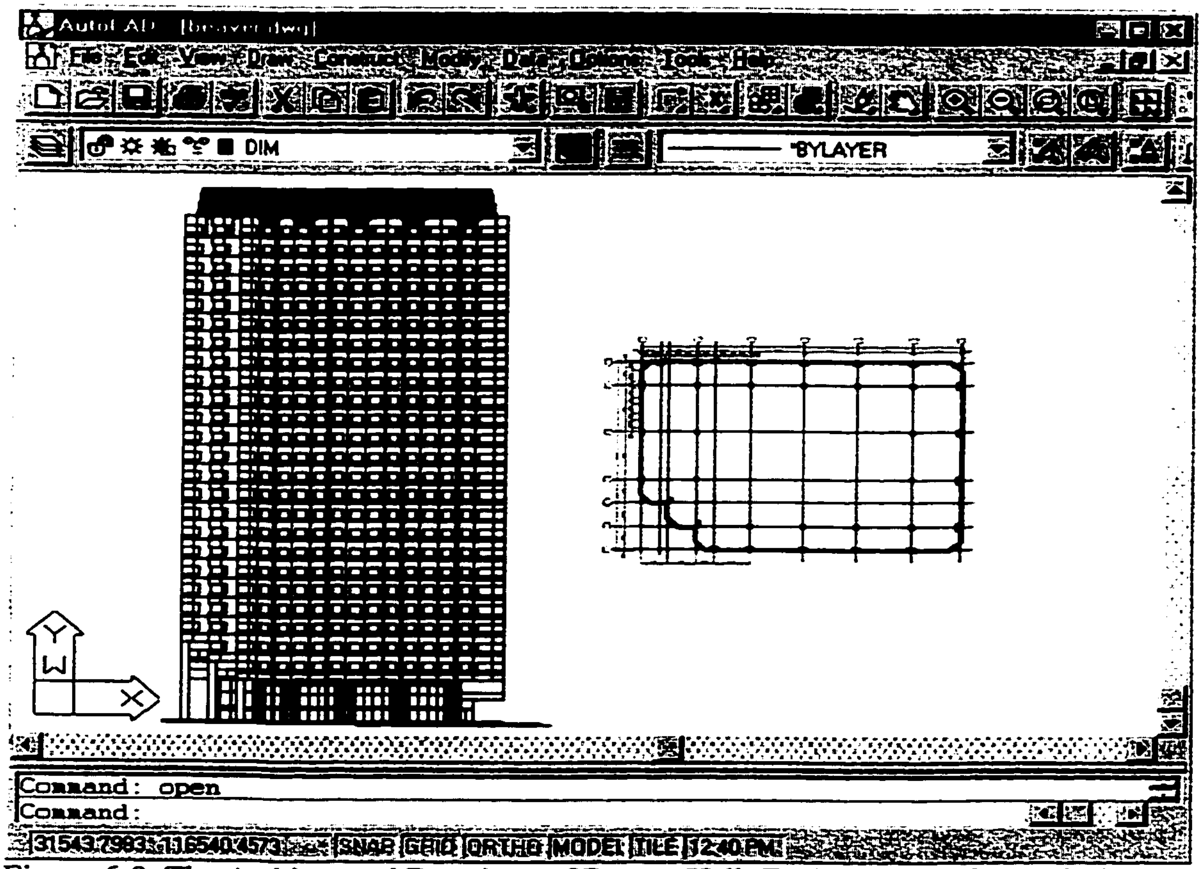
		Heating Load (MJ/m^{2}year)	Cooling Load (MJ/m^{2}year)	Total Thermal Load (MJ/m^{2}year)
Reference Building		713.5	121.8	835.3
Design Building	Original Design Building	722.5	128.8	851.3
	Increase Window Thermal Resistance	706.8	129.4	836.2
	Increase Wall Thermal Resistance	708.9	129.4	838.3
	Increase Both Window and Wall Thermal Resistance	693.2	129.9	823.1

It is worth mentioning, in the case of the four design alternatives in Table 6-2, that the increase of thermal resistance of exterior envelope leads to the reduction of heating loads (from 722.5 MJ/m^{2}year for the original design building to 693.2 MJ/m^{2}year). Although cooling loads increase from 128.8 MJ/m^{2}year to 129.9 MJ/m^{2}year, the decision of acceptance of the design building is based on the total thermal loads.

The energy loads stated in Table 6-2 are not necessarily the real energy consumption of the building. They represent the effects of the different inputs to the output and are good enough to decide on which inputs should be changed and whether to increase or decrease them. The values calculated for both reference and design building are checked by Mathcad [1993] (a software that can calculate mathematical equations at run time) to ensure the values are correct. For all the thermal loads calculated in Table 6-2, values for the design building fall in a range of 10% from the values of reference building. It is a fairly good result in terms of reliability of the system. In the three alternative designs shown in Table 6-2, besides the possibility of only changing one parameter, the improvement on more than one parameter at a time is evaluated. This covers essentially most of the trade-off options in the trade-off compliance method.

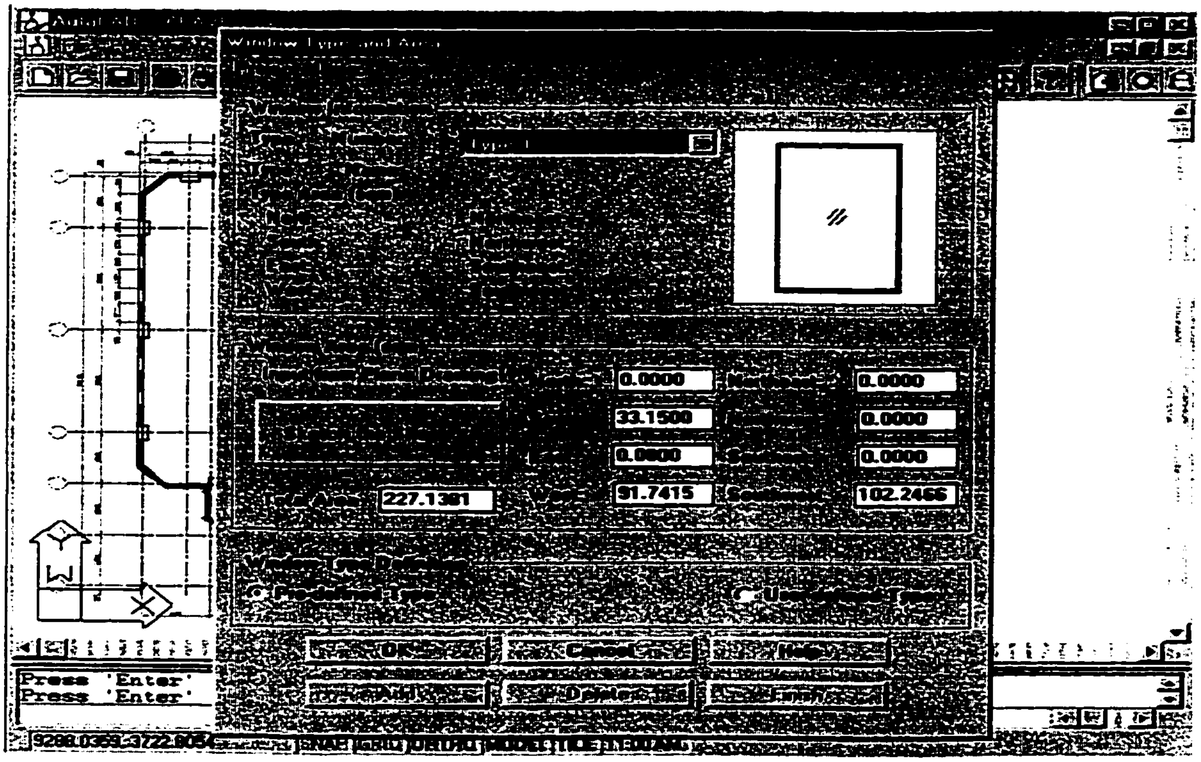
6.3.2.3. Case Study Two: Prescriptive Path Testing

In the second case study, an existing building in Montreal named Beaver Hall is used to test the performance of the graphic data collection function, as well as the verification of compliance with the mandatory and prescriptive requirements. It is a 26-story office building located in downtown Montreal. The computer generated working drawings with typical floor plan and elevation shown in Figure 6-8 come from the blue prints of Sankey Acrop Architects [1981]. Most of the exterior walls are composed of pre-cast concrete panels and aluminum windows. The typical floor plan is close to rectangle shape with many recesses. As the actual characteristics of the building envelope are no longer available, the U-values of the window, wall and roof, the solar heat gain coefficient of window are taken from case study one. The area of windows, walls and roof are collected from working drawings (Figure 6-9) and the internal heat gain is determined by building type. Completing data collection from the working drawing, prescriptive compliance path is chosen by "Prescriptive Method" option in Figure 6-10.



```
Command: open
Command:
31543.7993,116540.4573   SNAP GRID ORTHO MODEL TILE 12:40 PM
```

Figure 6-8: The Architectural Drawings of Beaver Hall: Typical Floor Plan and Elevation.



Type 1

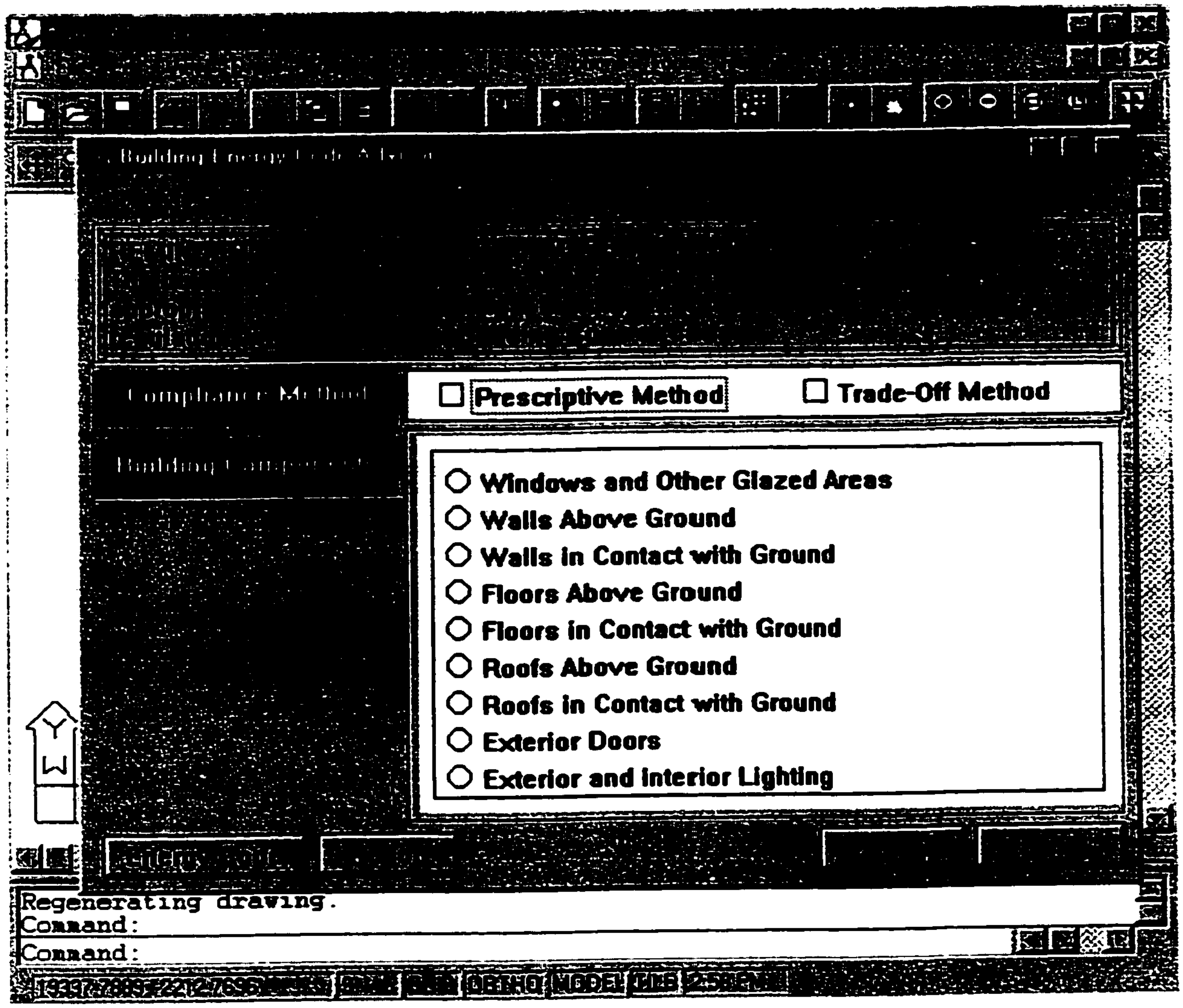
Total Area 227.1381

0.0000
33.1500
0.0000
91.7415

0.0000
0.0000
0.0000
102.2466

```
Press 'Enter'
Press 'Enter'
```

Figure 6-9: The Determination of Window Area from Working Drawing.



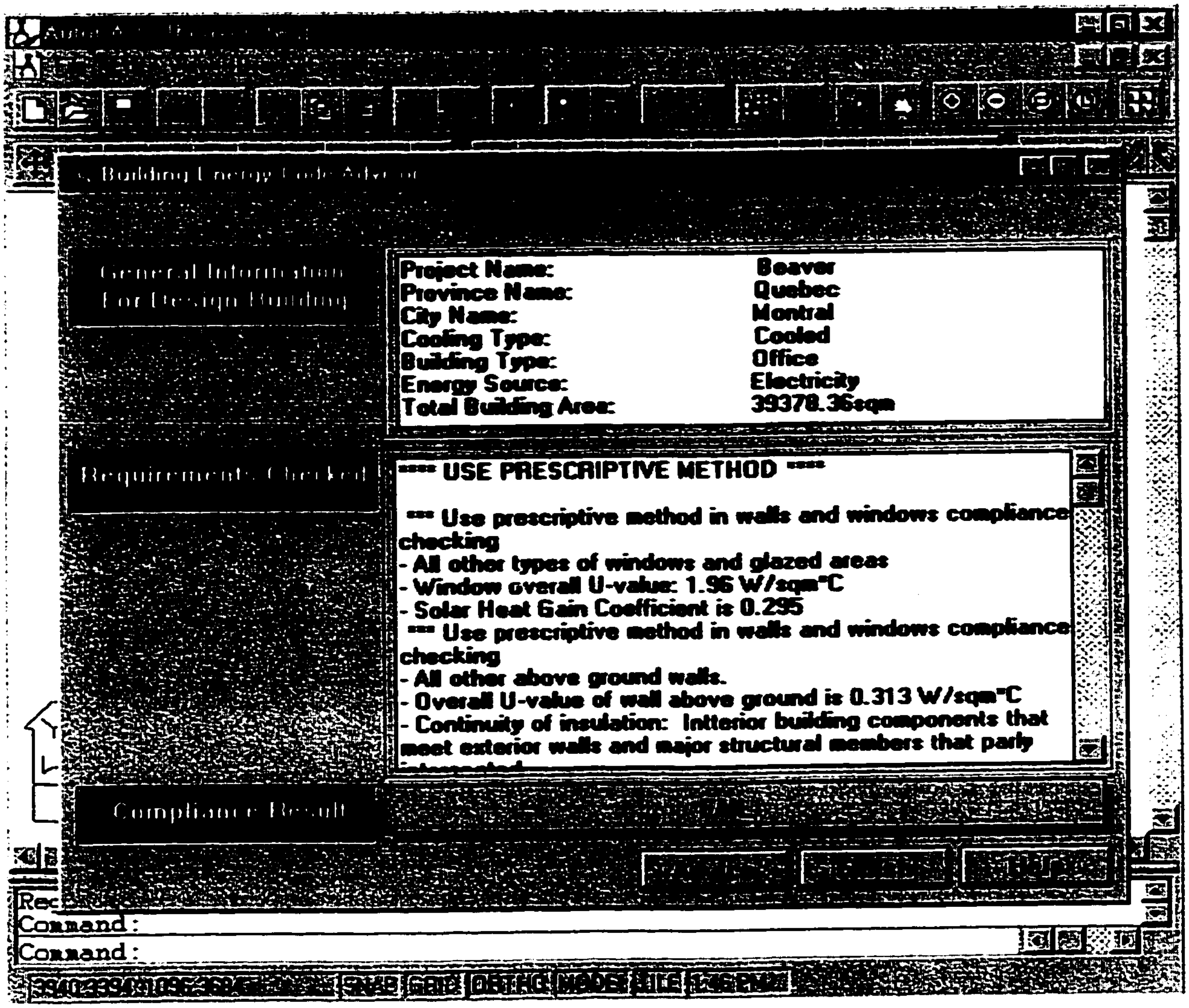
☐ **Prescriptive Method** ☐ **Trade-Off Method**

- ○ **Windows and Other Glazed Areas**
- ○ **Walls Above Ground**
- ○ **Walls in Contact with Ground**
- ○ **Floors Above Ground**
- ○ **Floors in Contact with Ground**
- ○ **Roofs Above Ground**
- ○ **Roofs in Contact with Ground**
- ○ **Exterior Doors**
- ○ **Exterior and Interior Lighting**

```
Regenerating drawing.
Command:
Command:
```

Figure 6-10: Use of Prescriptive Method in Case Study Two

Figure 6-11 shows a report provided by BECA system from running the case study two. In the first part of the report, general information of the building is described. The second part records checking method used (prescriptive or trade-off method), envelope components evaluated (wall and window), the value of these envelope components (U-value, Solar Heat Gain Coefficient etc.). The third part presents the evaluation result: case study two fails to comply with the Code requirements.



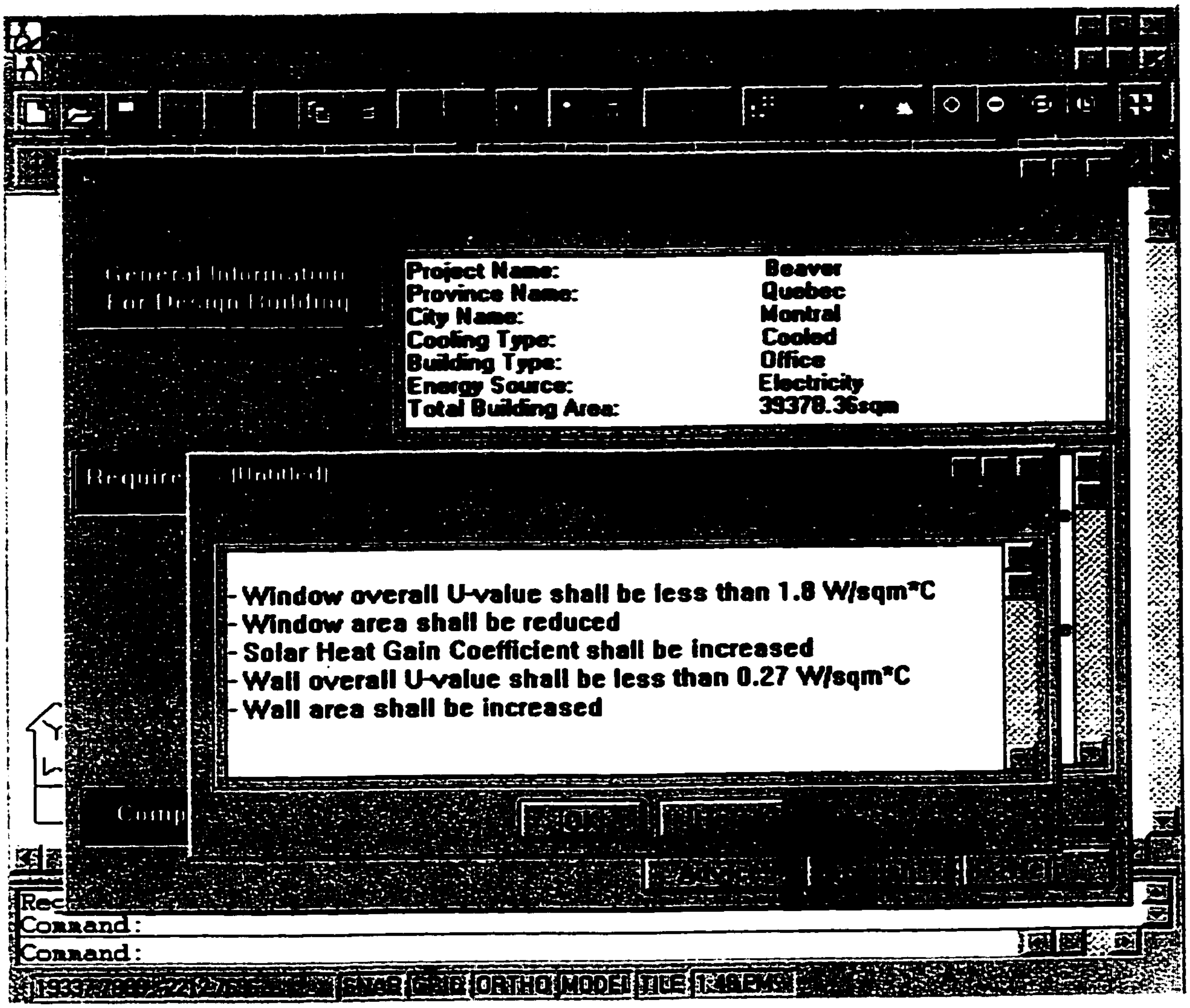
```
Project Name:          Beaver
Province Name:         Quebec
City Name:             Montral
Cooling Type:          Cooled
Building Type:         Office
Energy Source:         Electricity
Total Building Area:   39378.36sqm
```

```
**** USE PRESCRIPTIVE METHOD ****

 *** Use prescriptive method in walls and windows compliance
checking
- All other types of windows and glazed areas
- Window overall U-value: 1.96 W/sqm°C
- Solar Heat Gain Coefficient is 0.295
 *** Use prescriptive method in walls and windows compliance
checking
- All other above ground walls.
- Overall U-value of wall above ground is 0.313 W/sqm°C
- Continuity of insulation:  Intterior building components that
meet exterior walls and major structural members that parly
```

Figure 6-11: Checking Report for Case Study Two.

As the prescriptive method is used, the U-values of walls and windows are directly compared to their corresponding MNECCB values (Table 6-1). Unfortunately, both of them fail to satisfy the Code requirements. The knowledge base (which performs the prescriptive path checking) determines that there are two parameters the affects the maximum allowed window U-values: fenestration to wall ratio (FWR) and solar heat gain coefficient (SHGC). Actually, the three values work together and have influence on each other. Furthermore, FWR connects the dimensions and thermal characteristics of walls with that of the windows. So the design of walls and windows should always be considered together. Therefore improvements to any or all above parameters (window U-value, wall U-value, window area, wall area and SHGC for windows) are needed (Figure 6-12).



Project Name:	Beaver
Province Name:	Quebec
City Name:	Montral
Cooling Type:	Cooled
Building Type:	Office
Energy Source:	Electricity
Total Building Area:	39378.36sqm

- Window overall U-value shall be less than 1.8 W/sqm*C
- Window area shall be reduced
- Solar Heat Gain Coefficient shall be increased
- Wall overall U-value shall be less than 0.27 W/sqm*C
- Wall area shall be increased

Figure 6-12: Display of Advice for Case Study Two

From the study of the Code text and comparing to the case study one (which uses the same design building thermal characteristics), the conclusion that the design is not in accordance with the Code requirements is correct and the advice given is reasonable. The rules contained in the MNECCB are numerous, relatively simple and straight-forward.

To test the reliability of the BECA system, more test cases would need to be run. From the two cases studied here, the results are good and show the reliability of the system to some extent.

As the users of the BECA system are primarily architects in the early design stage, building envelope and probably lighting system design are major concerns. BECA system covers several aspects of the envelope and lighting system design (Figure 6-10): walls, windows, floors, doors and lighting system. The data collection for Code requirements with regards to all these aspects is shown in the Appendix C. BECA system is thus considered complete based on our objective which is to help building designers at the preliminary stage of design.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

The objective of this research is to develop a systematic methodology in computer-aided building Code checking for energy and investigate the potential value in the preliminary design process. A prototype system based on this methodology that assists architects to compare current designs to the MNECCB is attractive to many users because it is convenient to use (works in CAD environment as well) and covers knowledge on energy-efficient building design necessary for preliminary design phrase (energy Code requirements on envelope and lighting system design, original Code text and technical advice). By providing the Code text and technical advice to the user, the prototype system can also perform as a learning tool for the study of the MNECCB.

From the review of the relevant literature, a suitable methodology is proposed. It is an integrated knowledge-based system that combines knowledge base, database and correlation model into a CAD environment. The correlation model is based on the trade-off compliance path provided in the Code and it utilizes a simplified method. Mandatory and prescriptive requirements are analyzed and encoded into the knowledge base on the basis of decision diagrams. Databases store various data used in the compliance procedure and three category of data are included: (i) climatic data, (ii) reference database which store possible design materials and thermal characteristics permitted by MNECCB, and (iii) design building data and reference building data.

The name of the research prototype system is Building Energy Code Advisor (BECA). It relies on the specific knowledge, calculation and regulatory requirements on building energy issues that are contained in Parts 2 and 3 of the MNECCB. It can directly collect design data from working drawings, store and modify design building data, help designers make decisions regarding individual envelope components as well as the entire envelope, and display checking results and original text in the Code. By the use of the hypertext technique, the Code text can be accessed anytime during the checking process by searching through both the contents, index and words used in the Code.

7.2 Contributions

This research represents an attempt to develop an acceptable methodology for compliance checking with the MNECCB and to demonstrate the feasibility of this methodology. The contributions are summarized as follows:

1. Investigation of computer-aided systems for compliance checking with building energy performance Codes. Knowledge-based systems are found powerful in diagnosing problems and providing technical advice with limited building information in both building energy performance area and building Code compliance

checking area. The integration of knowledge-based system with database and correlation model are found to be suitable according to the characteristics of the MNECCB.

2. Creation of a framework for automatic energy Code checking. The BECA system implementation demonstrates the feasibility and practicality of developing a computer-based tool to assist building designers in the energy Code compliance checking. It is developed under the proposed methodology, and it contains: (a) the pre-processor which collects general design information, (b) a main module which contains the Code requirements, and (c) a post-processor which displays the conclusions and technical advice. The BECA system has the following advantages: (a) easy to verify Code compliance due to the automatic checking mechanism and accessibility to Code text and reference materials, (b) convenient and time saving in trying different design options due to its incorporation with a CAD system.

3. Interpretation of Parts 3 and 4 of the MNECCB. The design requirements contained in Parts 3 and 4, envelope and lighting, have been utilized as the main source of information for establishing the knowledge base and correlation model. They include many sections, subsections, articles, tables and several different compliance paths. Most of the Code text is written in natural language. The interpretation process include several steps: first the Code text is analyzed, then the logic relations are put into decision diagrams, the last step is to implement them into the computer system as rules that control the Code compliance procedure.

4. Analysis of the types of energy-related data and presentation of different data collection methods. Many of the design building data are collected directly from the drawings in a CAD environment. The direct communication between working drawings and Code checking system through the graphic data collection interface is easy to use and time saving when the design is changing rapidly and with different design options. This is especially suitable in the early design stage when design options are evaluated.

5. Implementation of a simplified correlation-based model in the compliance checking procedure. This is especially suitable for the preliminary design stage because many parameters are not available at this stage.

7.3 Future Work

In order to fully exploit the capability of computer-aided building Code checking approach, further developments are recommended for implementation:

- Propose more case studies to inspect the BECA system knowledge base: case studies are helpful in providing suitable recommendations for a less experienced user to understand the Code requirements. The information contained in the case studies is a reliable source to consult in the implementation of Code requirements for remedial measures and to develop solutions when the design building is in conflict with the

MNECCB. More efforts on testing and validation are essential and crucial before the prototype system could be used in the real design practice.

- Complete the BECA system to cover the rest parts (HVAC system, electronic and service water system) in MNECCB. More engineers from different disciplines may use the same prototype system and it is beneficial for the designers to gain a more comprehensive understanding over the new energy Code.

- Incorporate other electronic building Codes into the BECA system. NBCC is another important building Code used in preliminary design. The integration of NBCC and MNECCB would further simplify the Code checking procedure and is more appealing to the architects.

- Expand the BECA system database: make it possible for the user to add whatever database is useful to him/her. It would be convenient because the prototype system cannot satisfy all the users to the same extent. The ability to customize the system is an important way to compromise and allows the system to work satisfactorily under different circumstances.

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Appendix A: Decision Diagrams

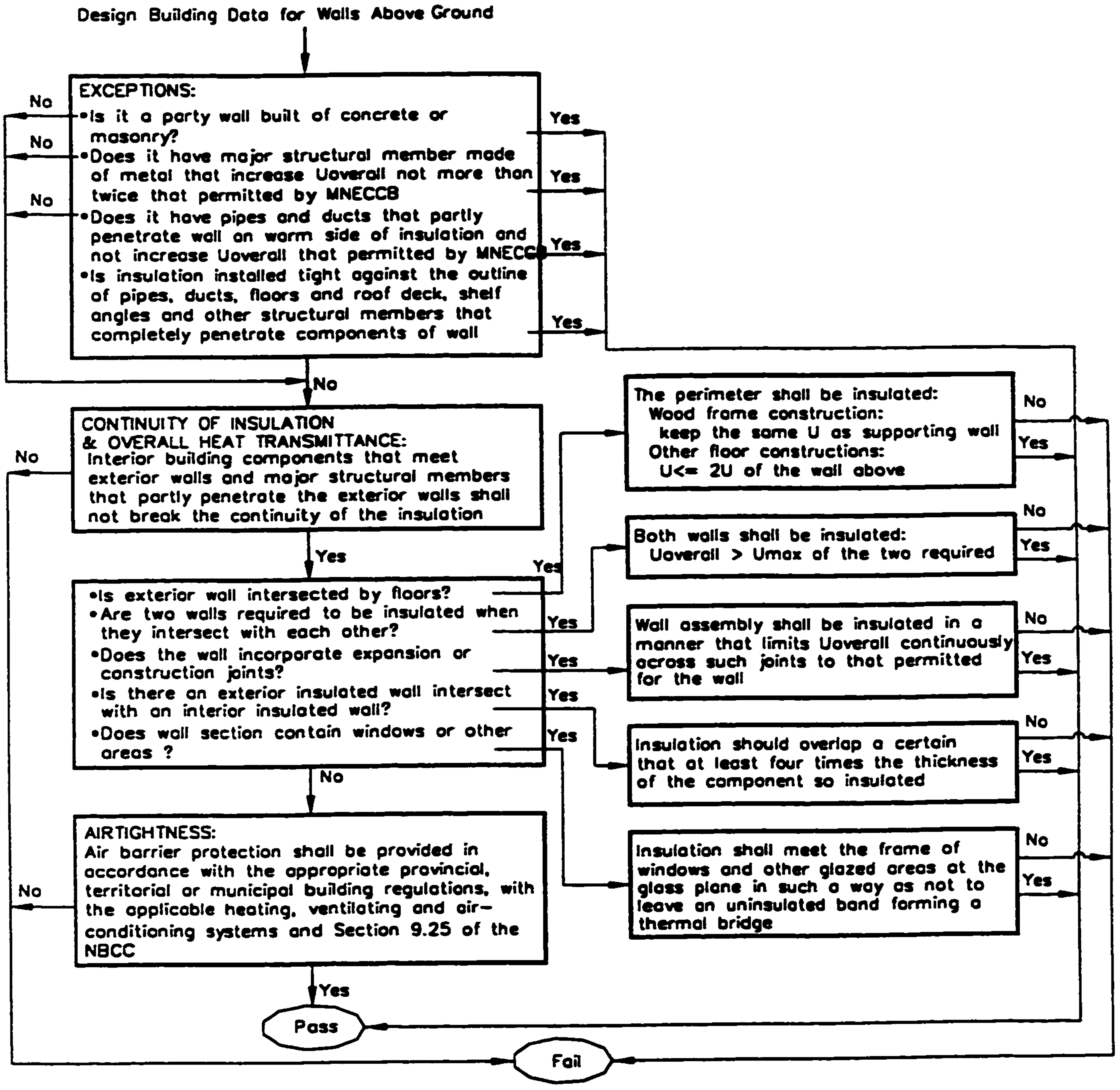


Figure A-1 : Mandatory Requirements for Walls above Ground Level

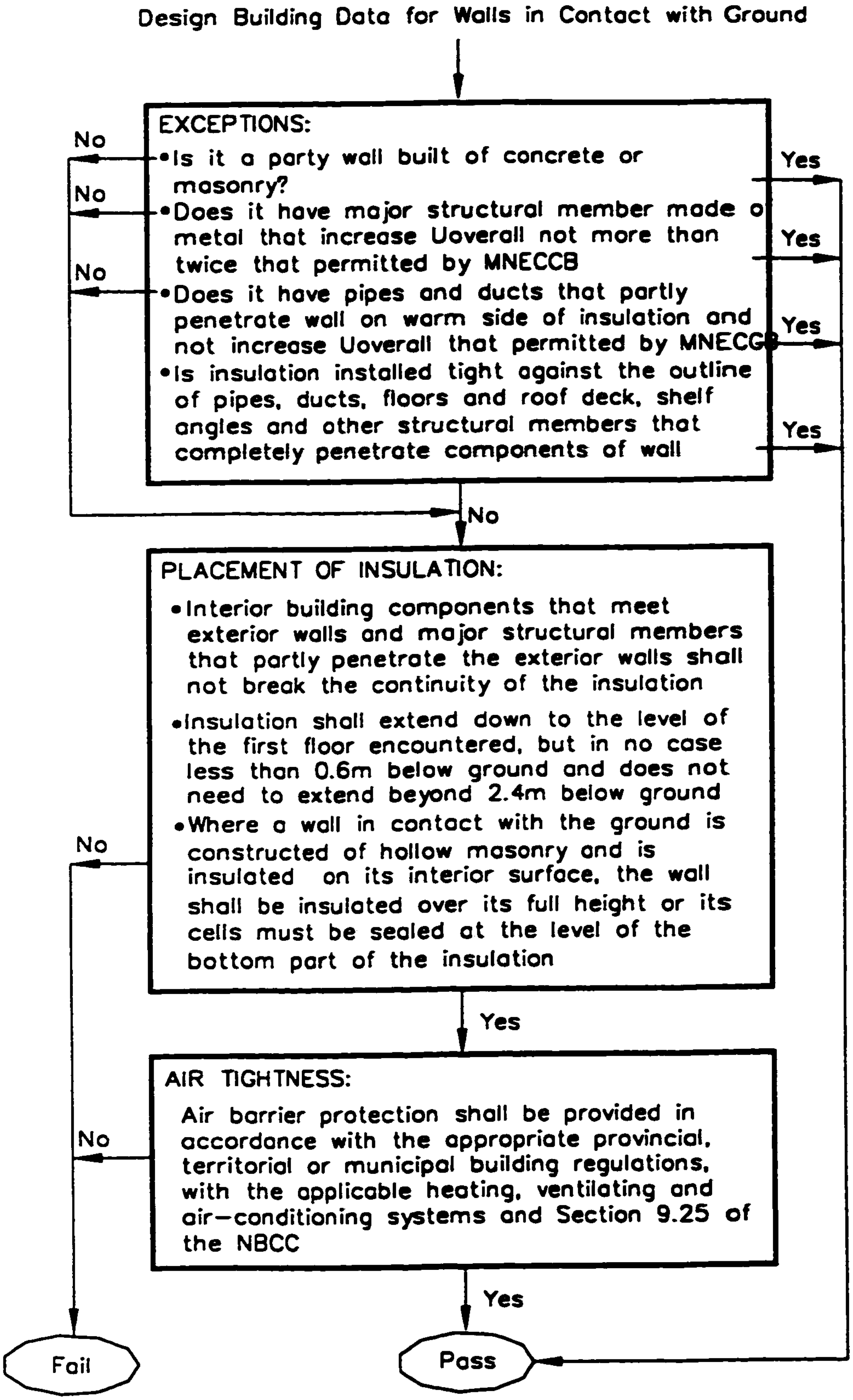


Figure A-2: Mandatory Requirements for Walls In Contact with the Ground

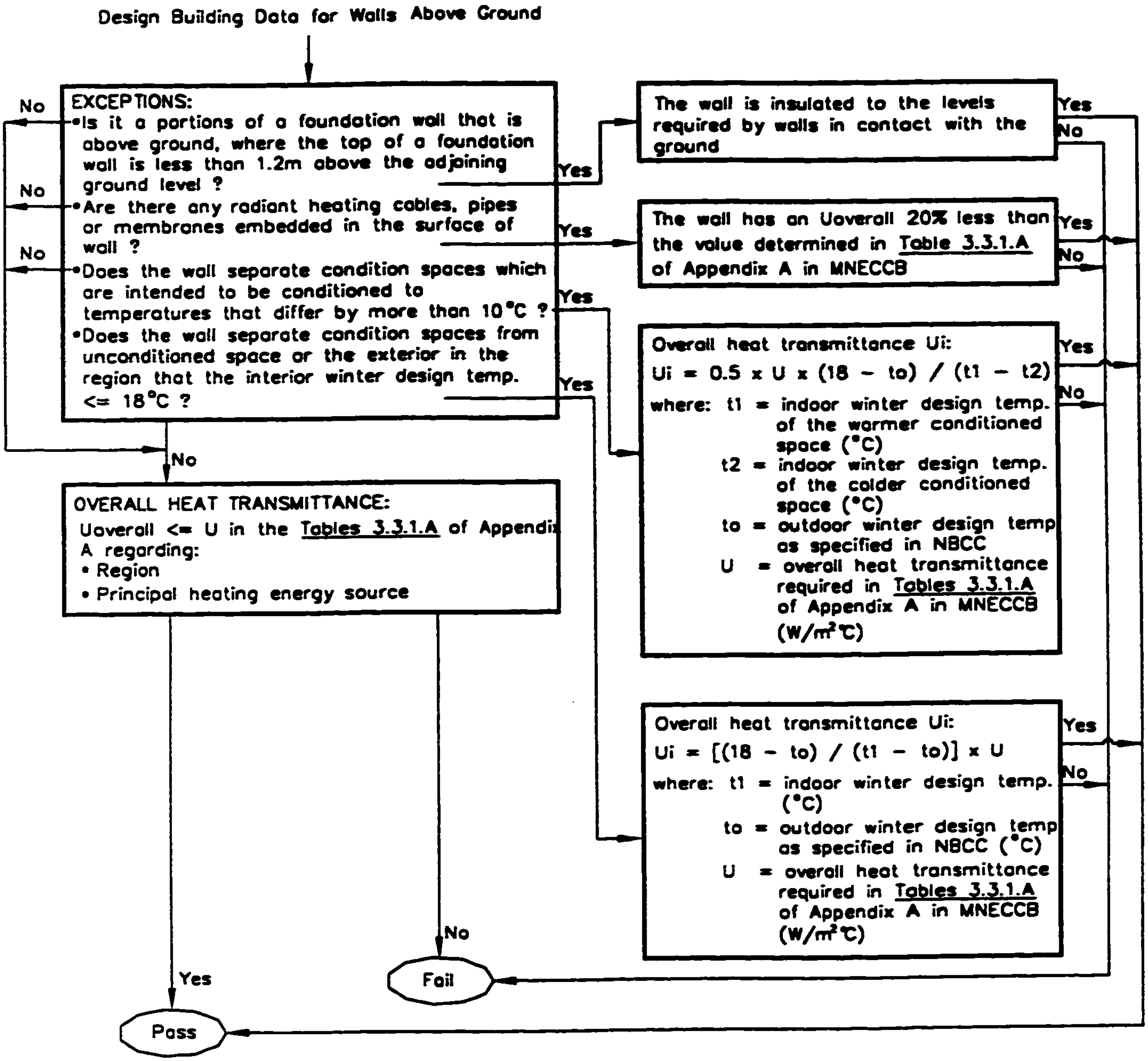


Figure A-3: Prescriptive Provisions for Walls above Ground Level

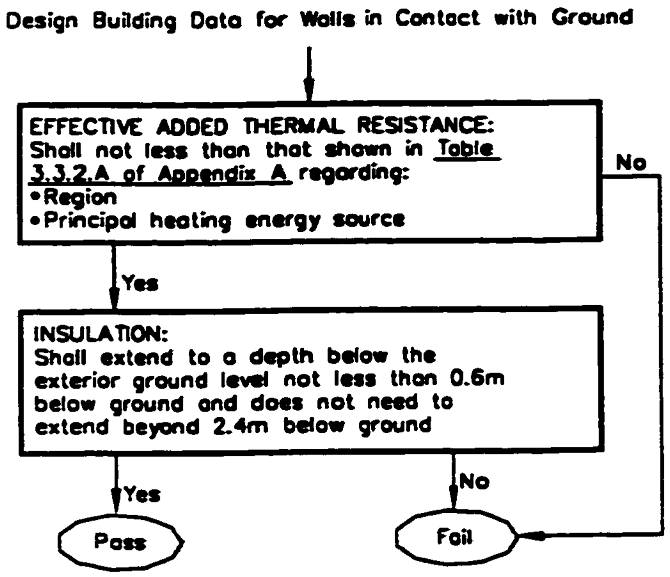


Figure A-4: Prescriptive Provisions for Walls In Contact with the Ground

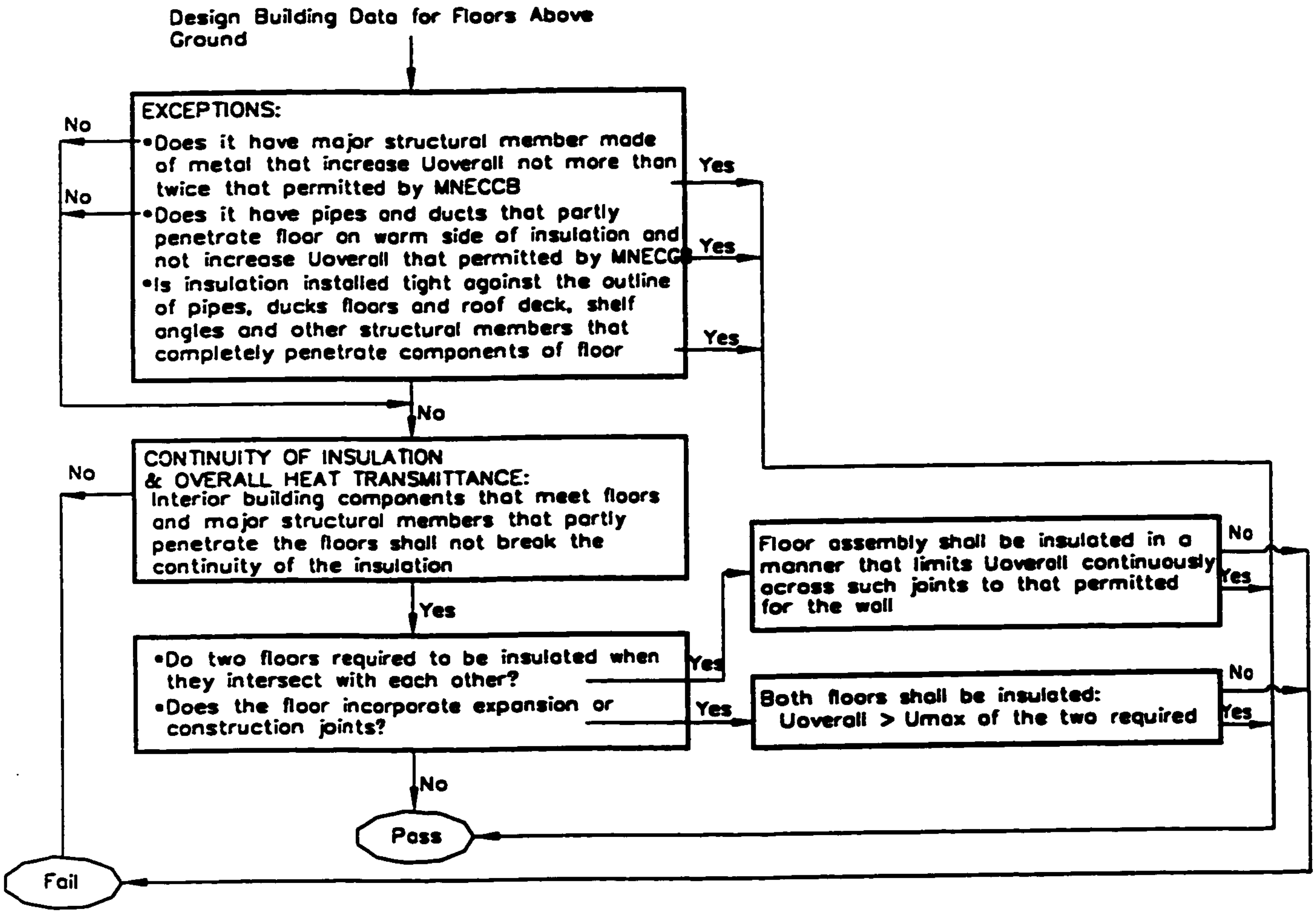
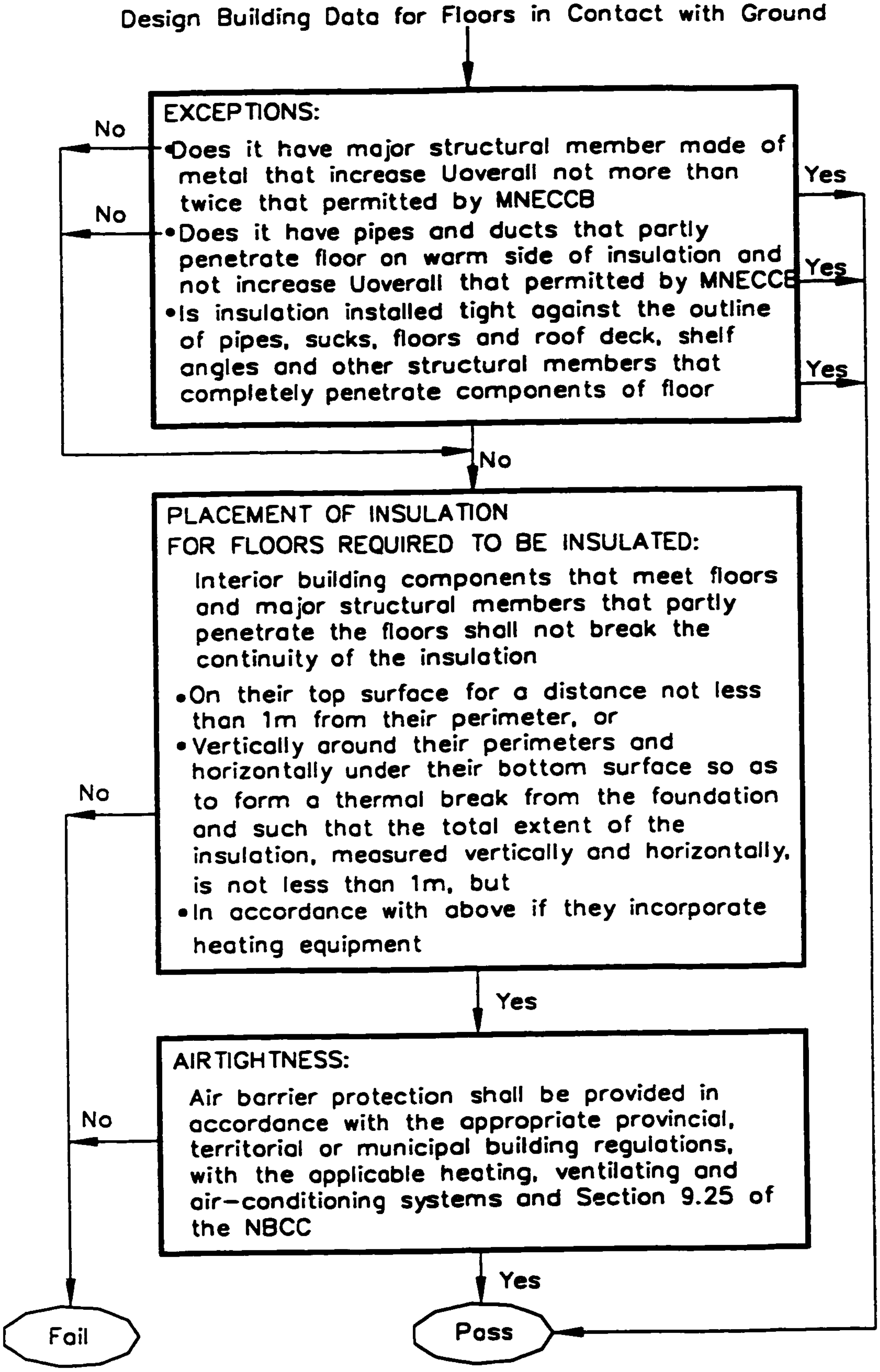


Figure A-5: Mandatory Requirements for Floors above Ground Level



Design Building Data for Floors in Contact with Ground

EXCEPTIONS:

- Does it have major structural member made of metal that increase Uoverall not more than twice that permitted by MNECCB
- Does it have pipes and ducts that partly penetrate floor on warm side of insulation and not increase Uoverall that permitted by MNECCB
- Is insulation installed tight against the outline of pipes, sucks, floors and roof deck, shelf angles and other structural members that completely penetrate components of floor

PLACEMENT OF INSULATION FOR FLOORS REQUIRED TO BE INSULATED:

Interior building components that meet floors and major structural members that partly penetrate the floors shall not break the continuity of the insulation

- On their top surface for a distance not less than 1m from their perimeter, or
- Vertically around their perimeters and horizontally under their bottom surface so as to form a thermal break from the foundation and such that the total extent of the insulation, measured vertically and horizontally, is not less than 1m, but
- In accordance with above if they incorporate heating equipment

AIRTIGHTNESS:

Air barrier protection shall be provided in accordance with the appropriate provincial, territorial or municipal building regulations, with the applicable heating, ventilating and air-conditioning systems and Section 9.25 of the NBCC

Figure A-6: Mandatory Requirements for Floors in Contact with the Ground Level

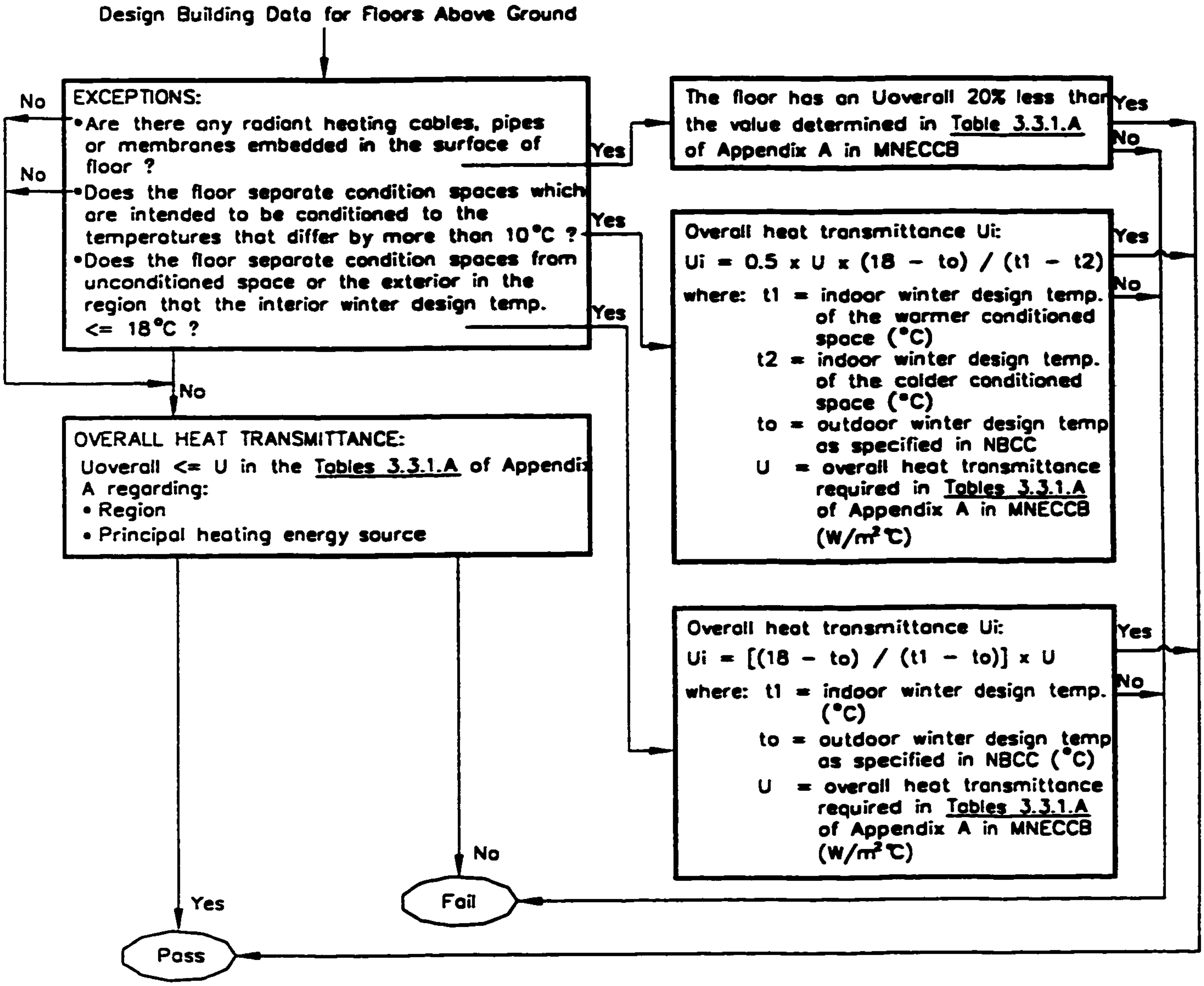
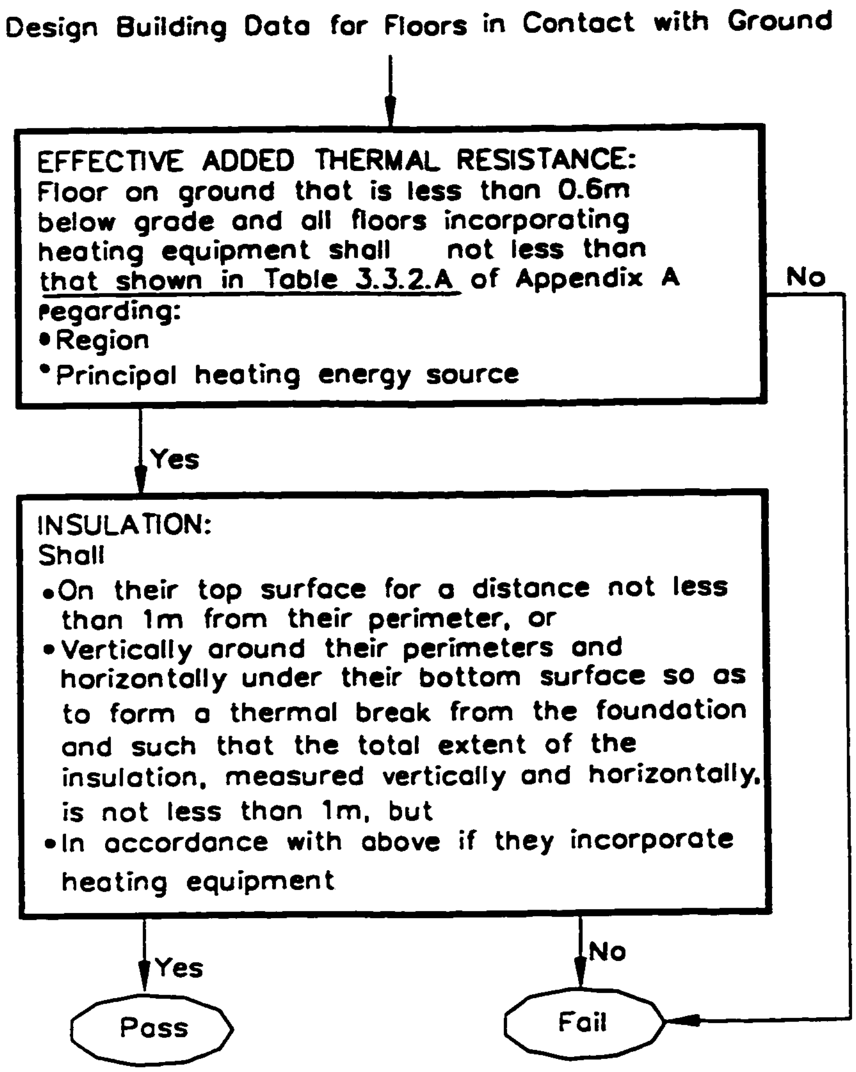


Figure A-7: Prescriptive Provisions for Floors above Ground Level


Design Building Data for Floors in Contact with Ground

EFFECTIVE ADDED THERMAL RESISTANCE:
Floor on ground that is less than 0.6m below grade and all floors incorporating heating equipment shall not less than that shown in Table 3.3.2.A of Appendix A regarding:
- Region
- Principal heating energy source

INSULATION:
Shall
- On their top surface for a distance not less than 1m from their perimeter, or
- Vertically around their perimeters and horizontally under their bottom surface so as to form a thermal break from the foundation and such that the total extent of the insulation, measured vertically and horizontally, is not less than 1m, but
- In accordance with above if they incorporate heating equipment

Figure A-8: Prescriptive Provisions for Floors in Contact with the Ground Level

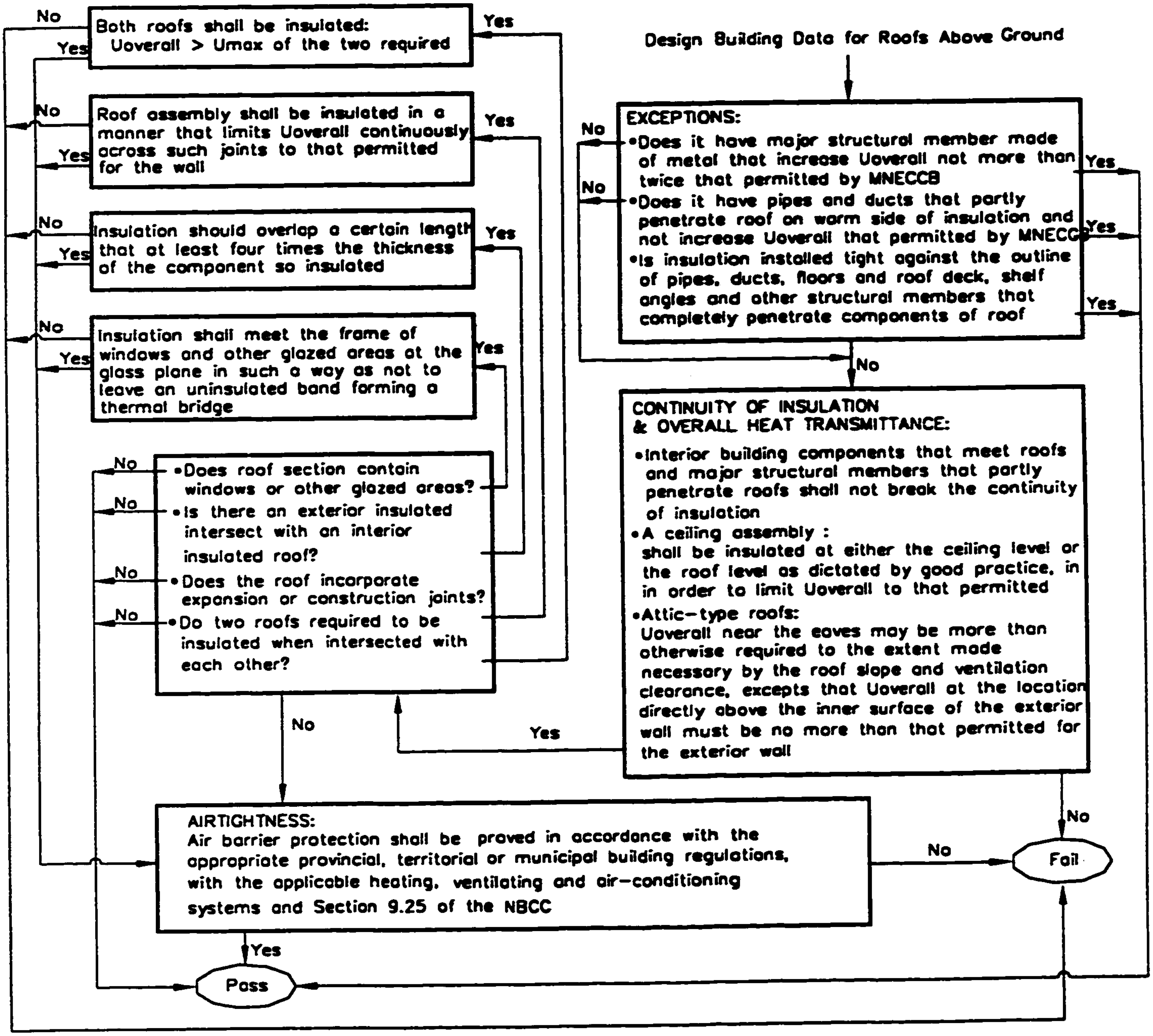


Figure A-9: Mandatory Requirements for Roofs (1)

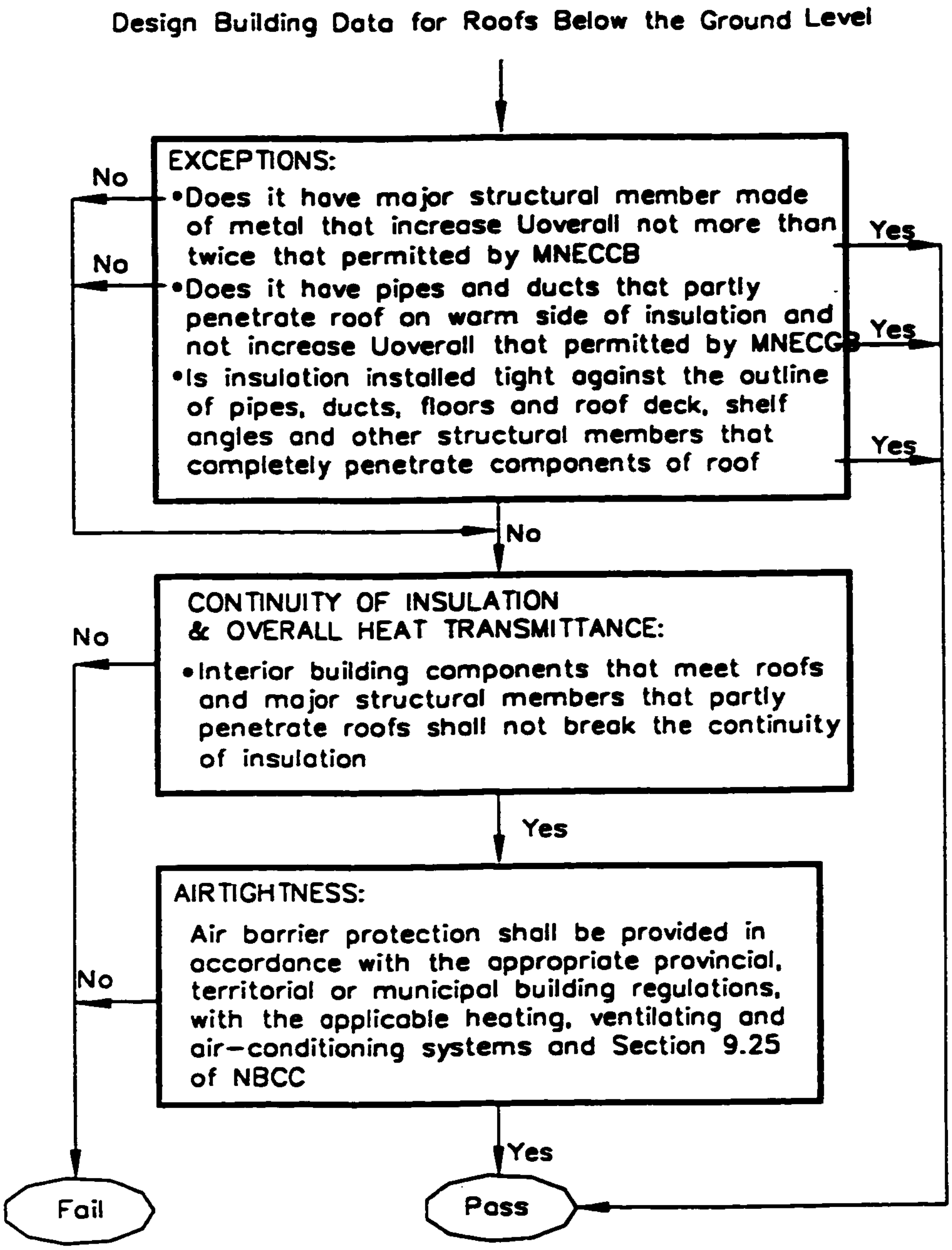


Figure A-10: Mandatory Requirements for Roofs (2)

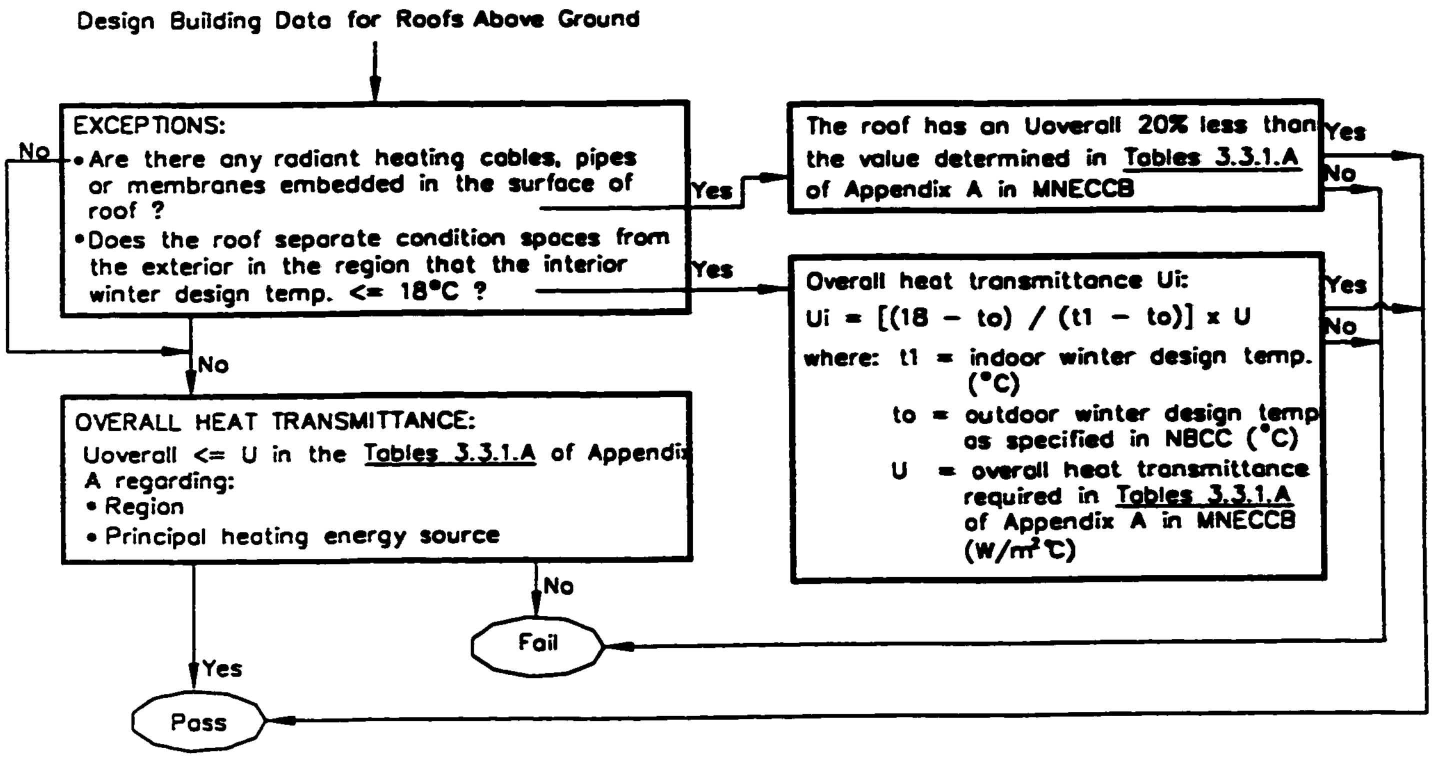


Figure A-11 : Prescriptive Requirements for Roofs (1)

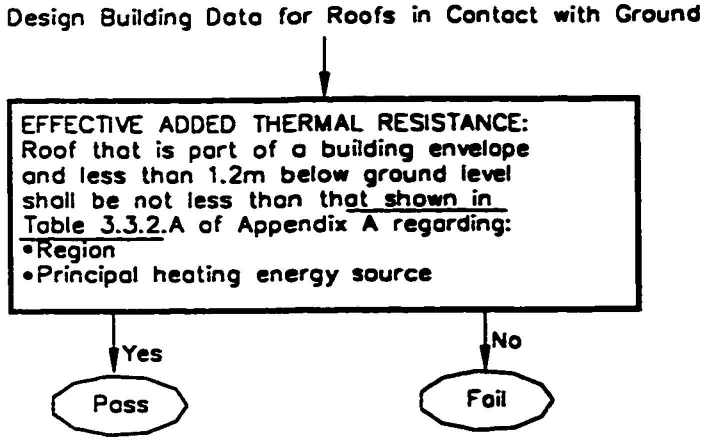


Figure A-12: Prescriptive Requirements for Roofs (2)

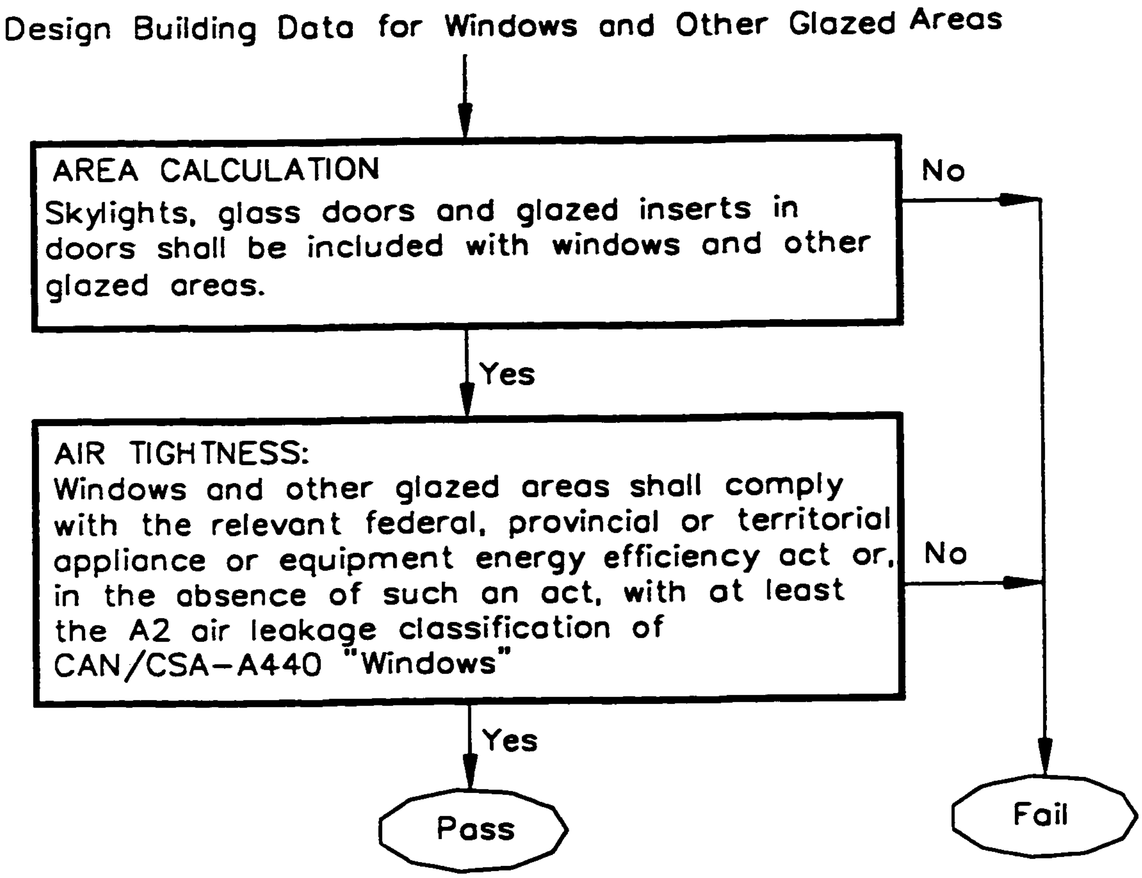


Figure A-13: Mandatory Requirements for Windows and Other Glazed Areas

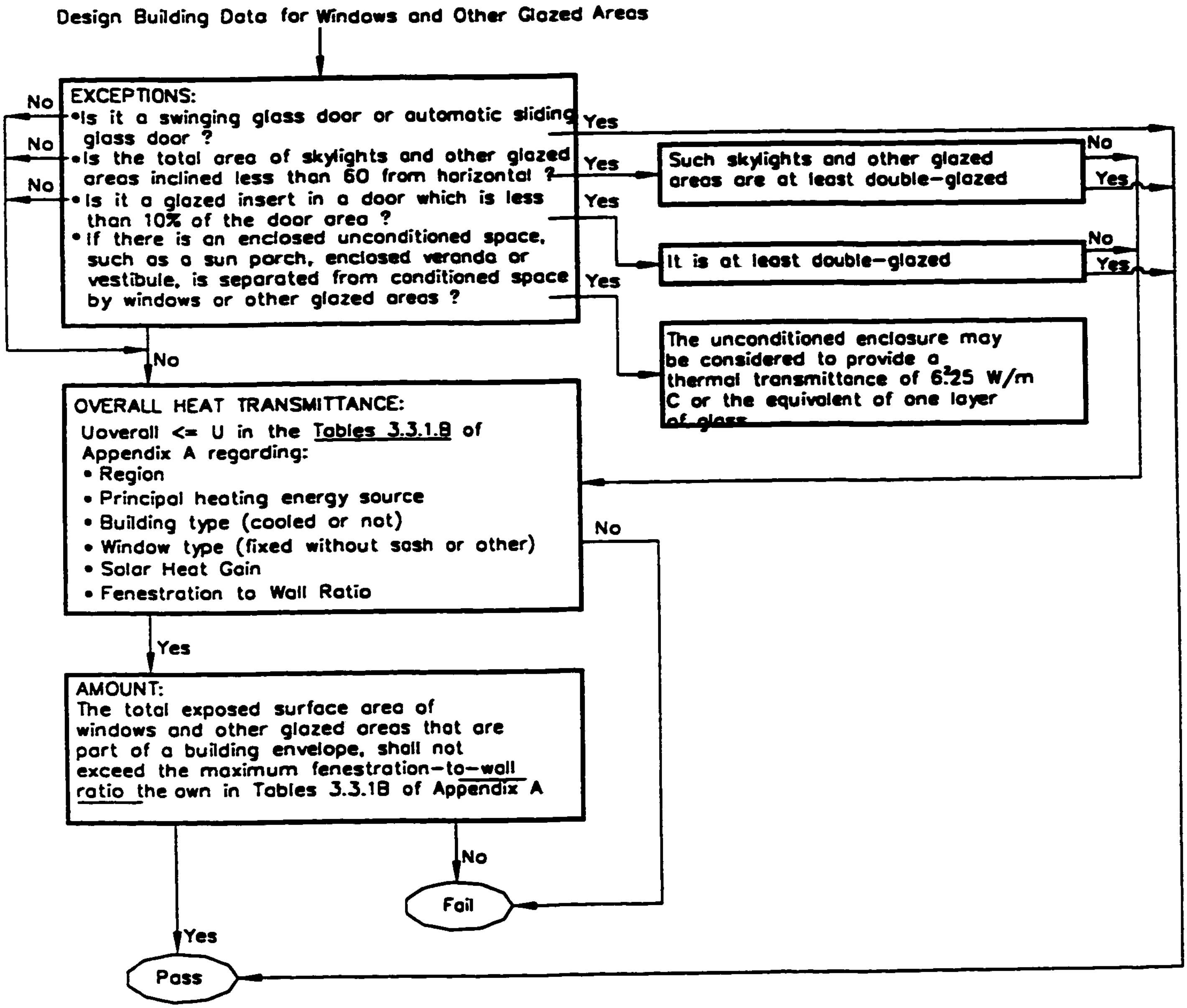


Figure A-14: Prescriptive Requirements for Windows and Other Glazed Areas

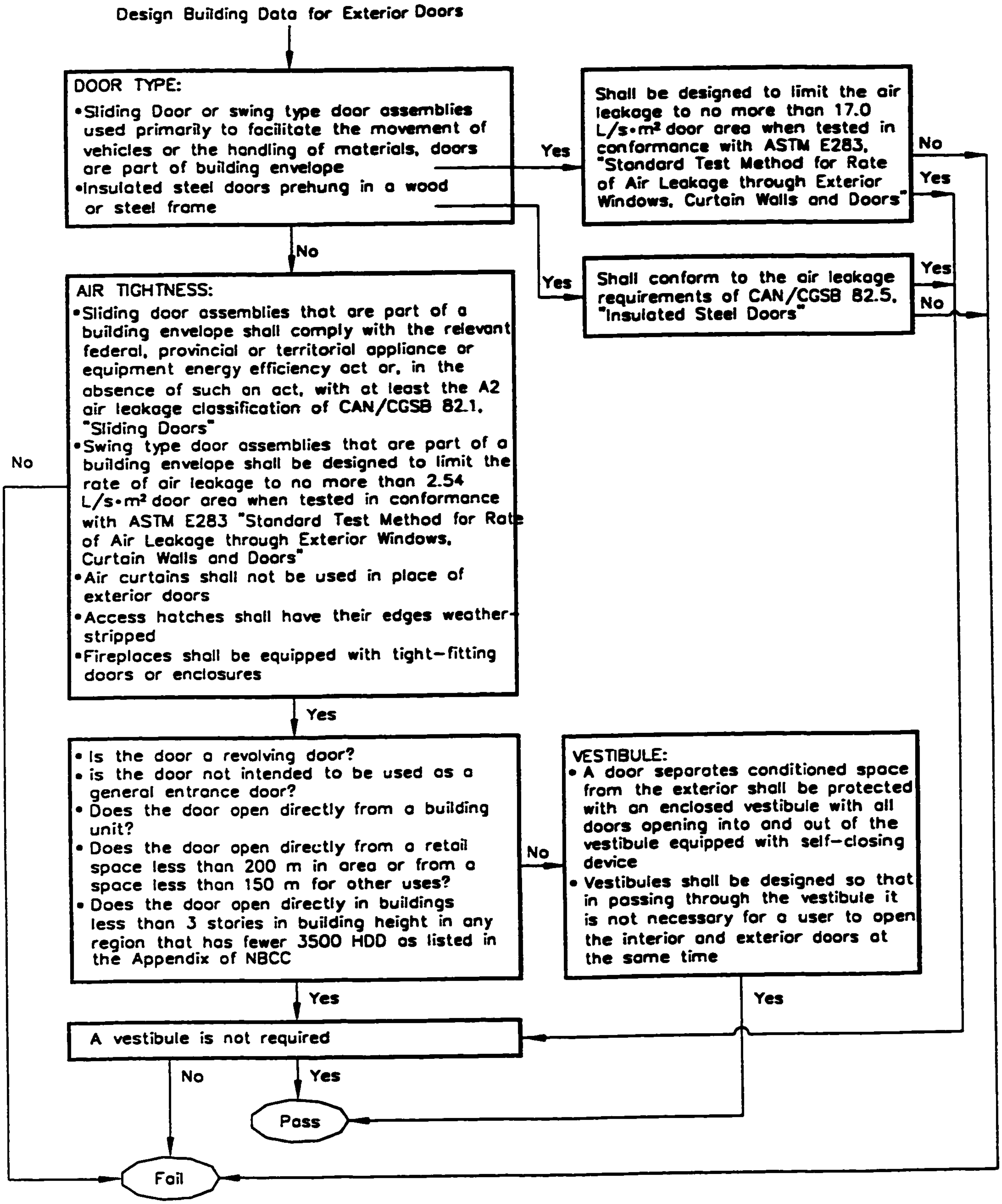


Figure A-15: Mandatory Requirements for Exterior Doors

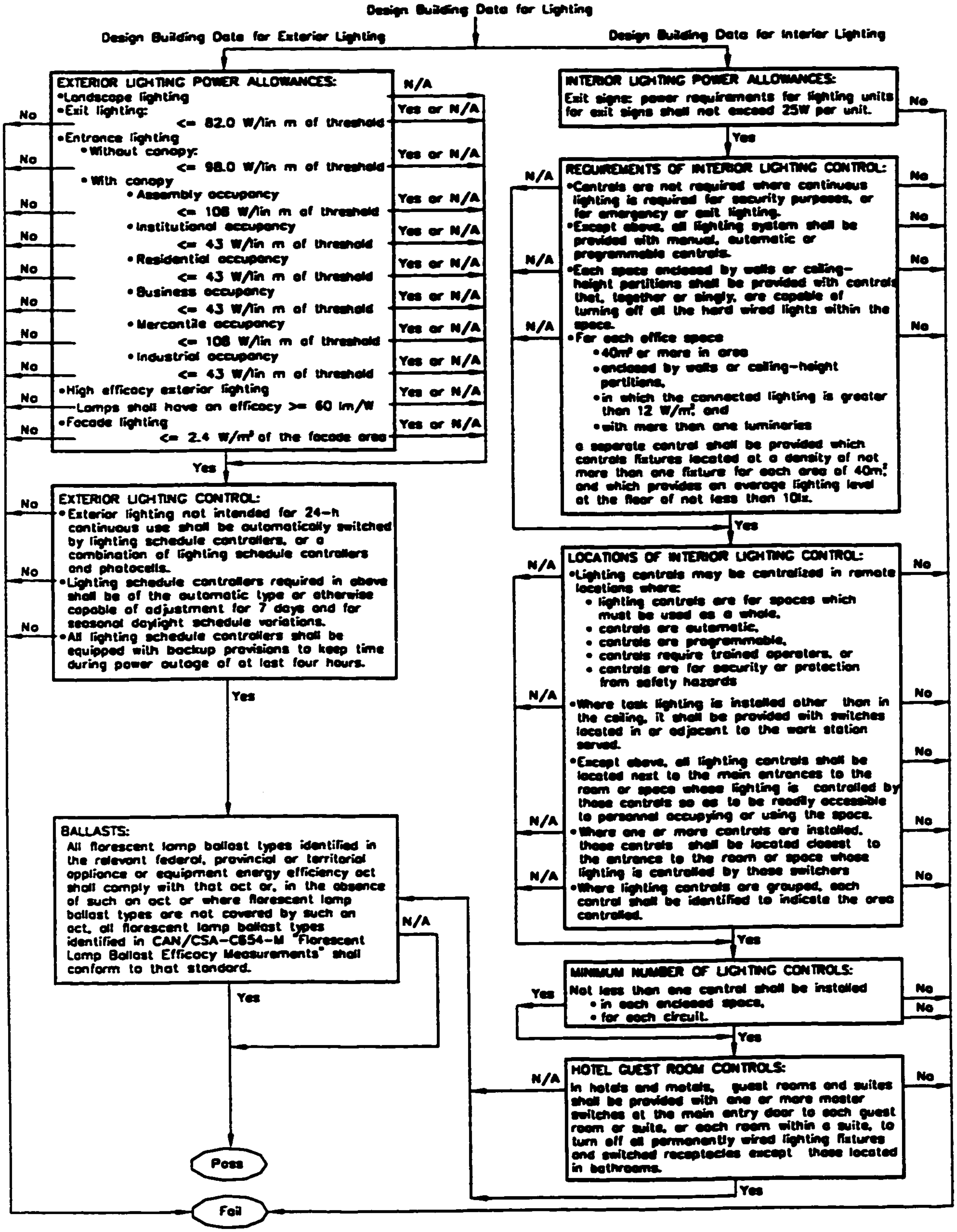


Figure A-16: Mandatory Requirements for the Lighting System

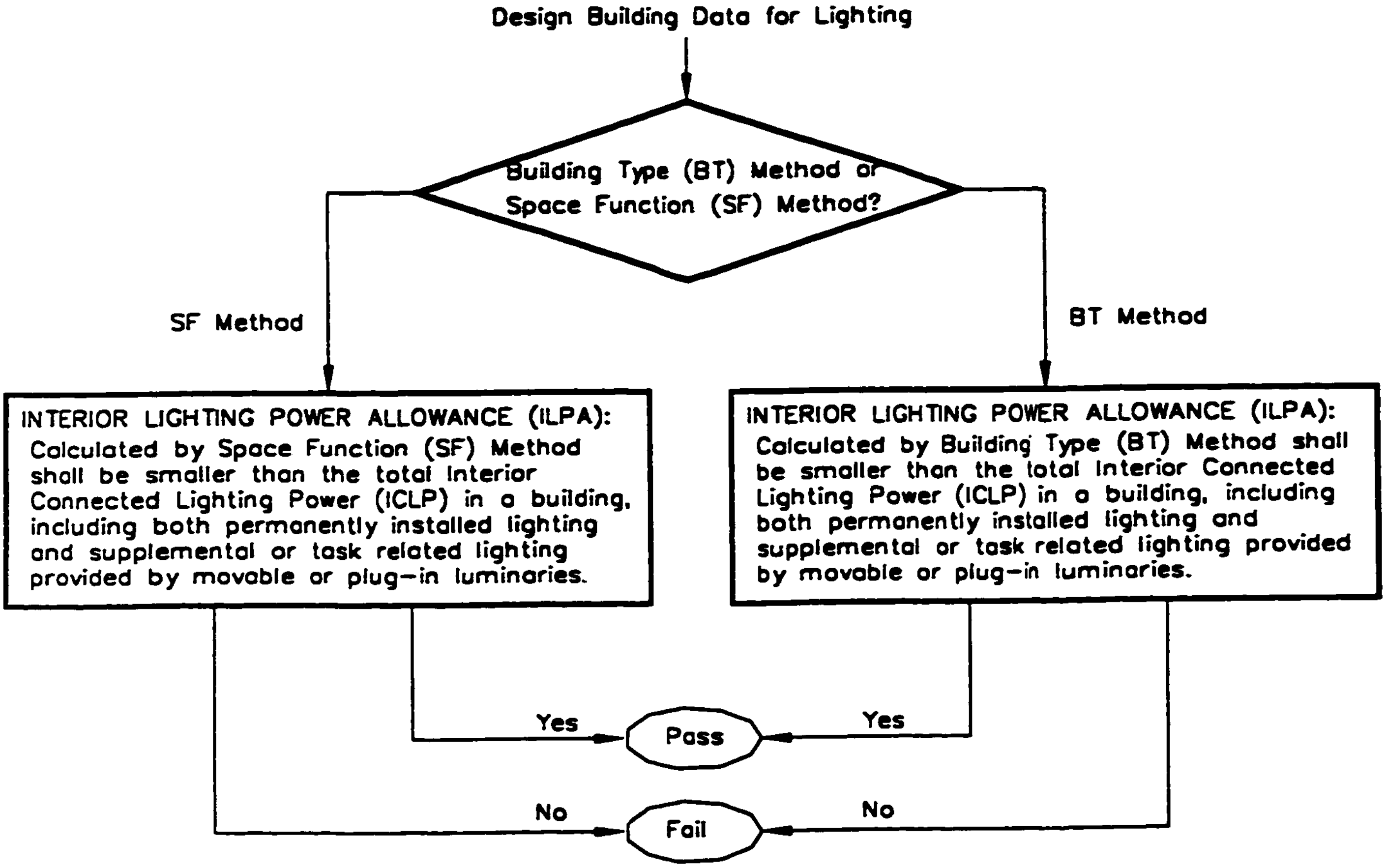


Figure A-17: Prescriptive Requirements for the Lighting System

Appendix B: Climatic Coefficients

Table 1: Coefficients for Ottawa [Cornick and Sander 1995]

	East	West	North	South
b_0	728.8679	722.127	721.3787	729.1496
b_1	431.2615	444.9293	463.3301	421.1035
α_1	2528.154	2436.595	1396.895	3344.05
α_2	-896615	-873968	-274133	3672654
α_3	144E+09	1.48E+09	3.36E+08	1.6E+09
β_1			-15.6865	
β_2			2.002871	
β_3			-593.541	
δ_0			-7.631	
δ_1			24.608	
δ_2			-26.340	
δ_3			9.3629	
a_0	22.0343	24.824	15.103	19.473
a_1	857.662	816.929	506.308	789.254
a_3	4.076	4.111	4.175	4.115
a_4	-41.259	-46.518	-52.063	-43.619
C_{min}			87.684	

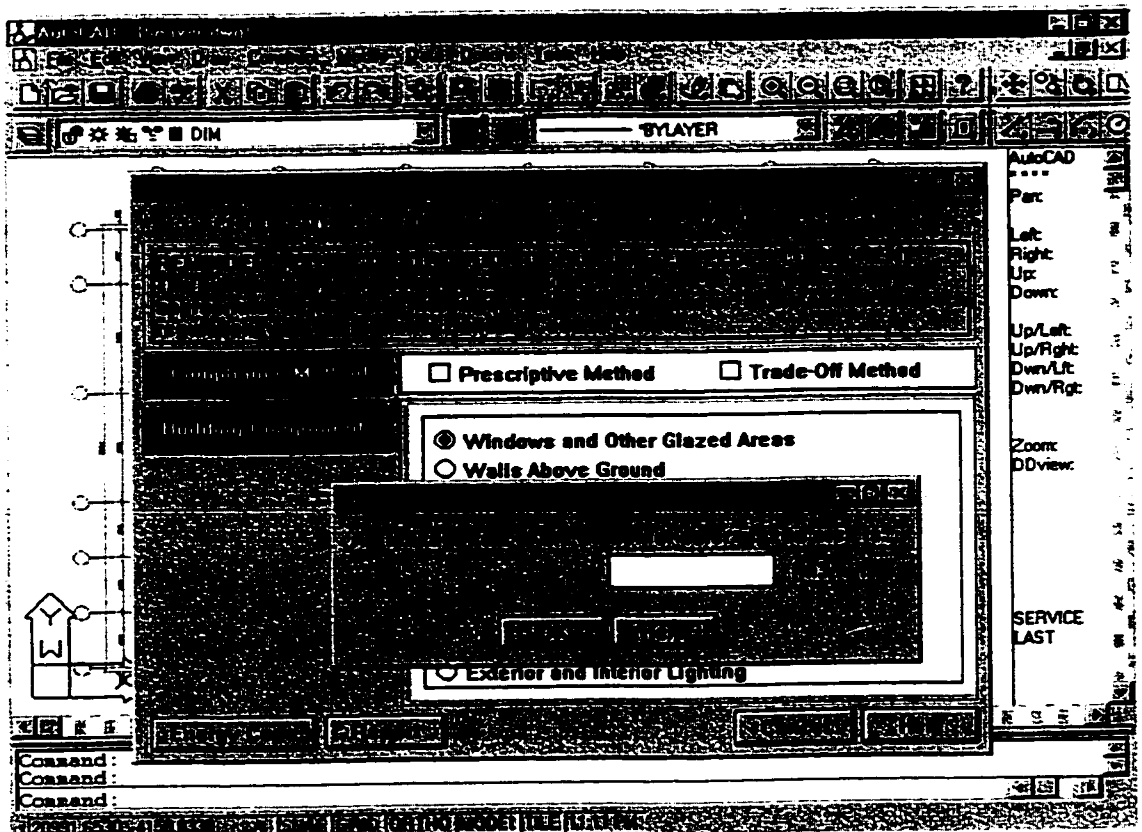
Table 2: Climate Correlation [Cornick and Sander 1995]

	East	West	North	South
E_0	-18.628	-8.00885	-11.168	-10.859
E_1	0.074	0.0821	0.0734	0.0686
E_2	0.035	0.0106	0.0302	0.0152
E_3	0.0403	0.0101	-0.0128	0.0177
E_4	-5.3E-05	-1.5E-05	1.19E-05	-1.8E-05
E_5	-0.017	0.00102	0.0237	-0.007
L_0	-521.244	-378.88	-495.692	-87.828
L_1	0.182	0.261	0.211	0.356
L_2	0.474	1.1087	13.395	-9.209
L_3	-0.008	-0.00905	0.0104	-0.0213

Table 2(Continued): Climate Correlation [Cornick and Sander 1995]

	East	West	North	South
L_4	1.299	0.988	0.687	0.820
L_5	0.000236	0.0000823	-0.00063	0.0000591
G_1	0.00116	0.00124	0.0012	0.00117
G_2	-0.0118	-0.0115	-0.0119	-0.0121
G_3	7.81E-07	8.96E-07	7.42E-07	8.37E-07
G_4	0.00627	0.00589	0.00641	0.00639
T_0	-182.239	-112.926	-102.649	-161.768
T_1	0.116	0.0728	0.082	0.102
T_2	-1.6E-05	-9.9E-06	-1.3E-05	-1.4E-05
T_3	0.0146	0.00115	0.0127	0.00966
T_4	-1.825	-1.335	-2.265	-1.628
T_5	-0.00025	-0.00056	-0.00026	-0.00042
X_1	0.0242			
X_2	-1.1E-05			
X_3	-0.318			
X_4	6.92E-05			
X_5	0.171			
A_0	176.797	169.889	173.548	170.561
A_1	0.0609	0.0612	0.0608	0.0615
B_0	106.531	111.498	131.917	97.449
B_1	0.0379	0.0382	0.0378	0.0376
C_0	2.294	2.656	1.681	2.098
C_1	-0.00054	-0.00052	-0.00036	-0.00054
C_2	-0.00032	-0.0005	-0.000076	-0.00042
C_3	3.38E-07	6.61E-07	-7.8E-08	5.23E-07
C_4	0.000618	0.000167	0.00304	0.00494
C_5	-1.4E-08	-3.2E-08	-1.2E-08	-4.7E-08
C_6	2.28E-05	1.04E-05	-2.1E-05	3.21E-05
S_0	1.366			
S_1	-0.00023			
S_2	-0.00046			
S_3	3.67E-06			

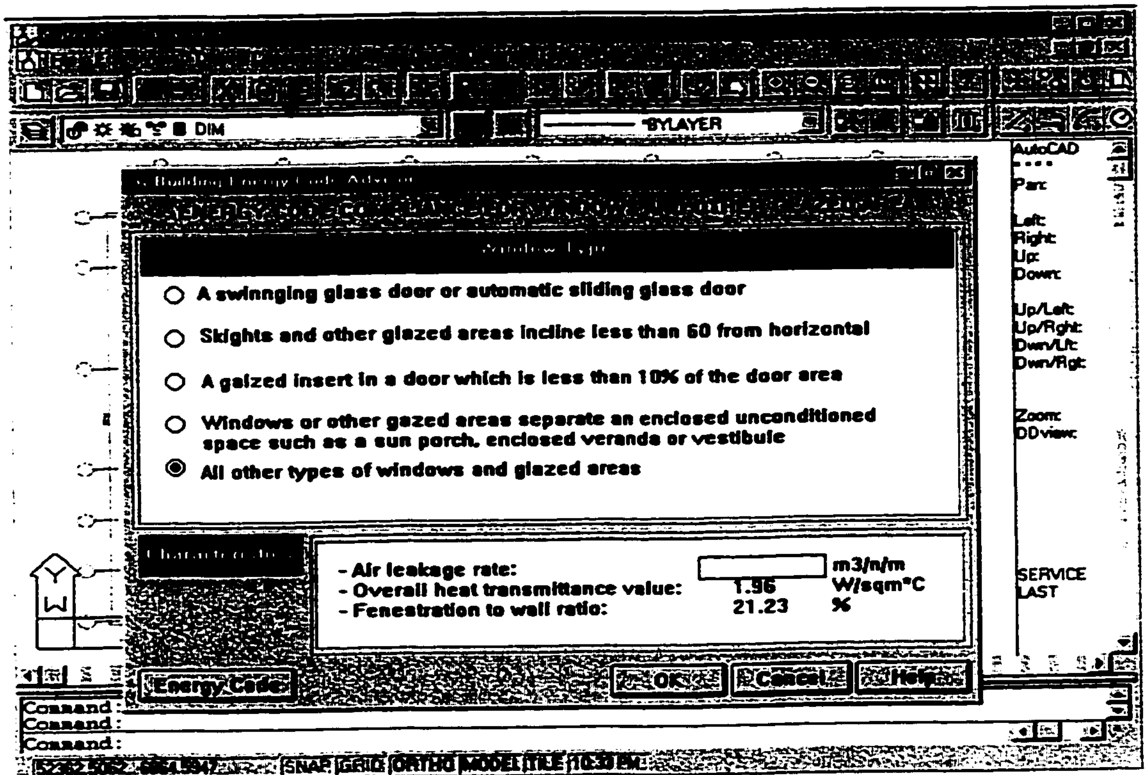
Appendix C
Examples of Design Data Collection for Code Requirements



☐ Prescriptive Method ☐ Trade-Off Method

● Windows and Other Glazed Areas
○ Walls Above Ground
○ Exterior and Interior Lighting

Figure A-18: Collection of Mandatory Requirements for Window Design

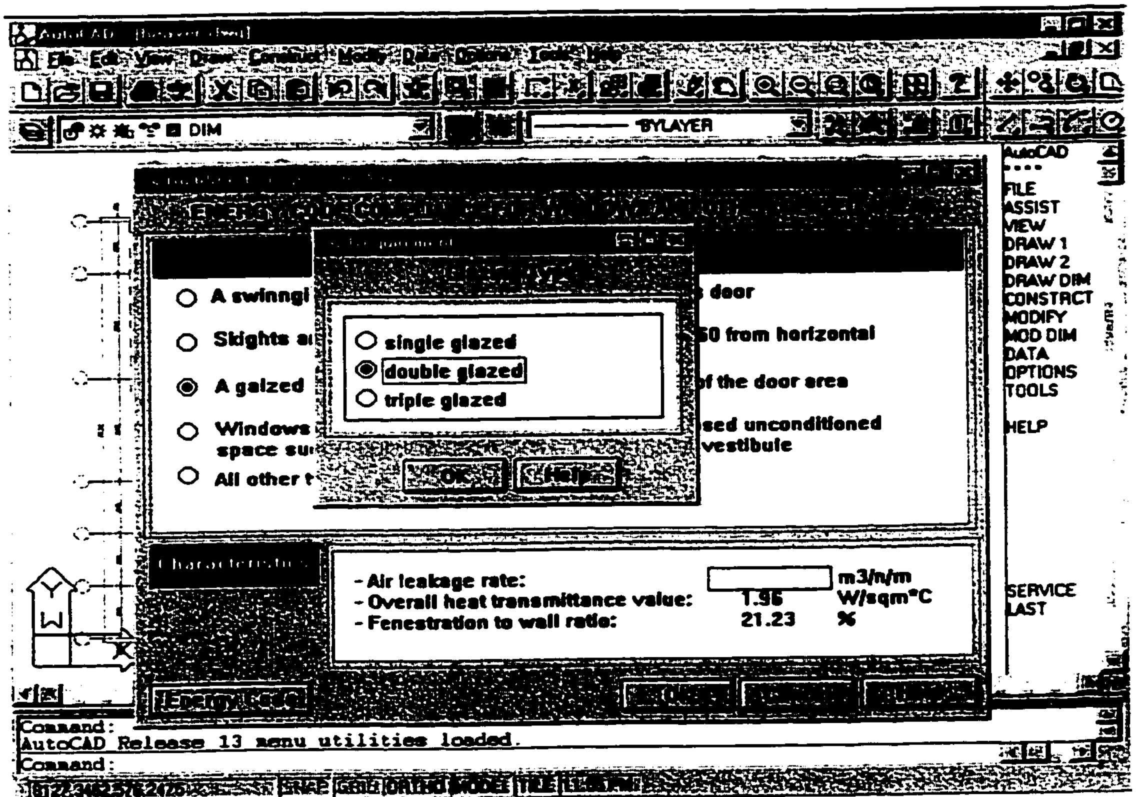


Window Type

○ A swinnging glass door or automatic sliding glass door
○ Skights and other glazed areas incline less than 60 from horizontal
○ A gaized insert in a door which is less than 10% of the door area
○ Windows or other gazed areas separate an enclosed unconditioned space such as a sun porch, enclosed veranda or vestibule
● All other types of windows and glazed areas

- Air leakage rate: m3/h/m
- Overall heat transmittance value: 1.96 W/sqm°C
- Fenestration to wall ratio: 21.23 %

Figure A-19: Collection of Prescriptive Requirements for Window Design (1)



○ A swinngi … door

○ Skights a… 60 from horizontal

● A galzed … of the door area

○ Windows … sed unconditioned space su… vestibule

○ All other t…

○ single glazed

● double glazed

○ triple glazed

- Air leakage rate: ☐ m3/h/m
- Overall heat transmittance value: 1.96 W/sqm°C
- Fenestration to wall ratio: 21.23 %

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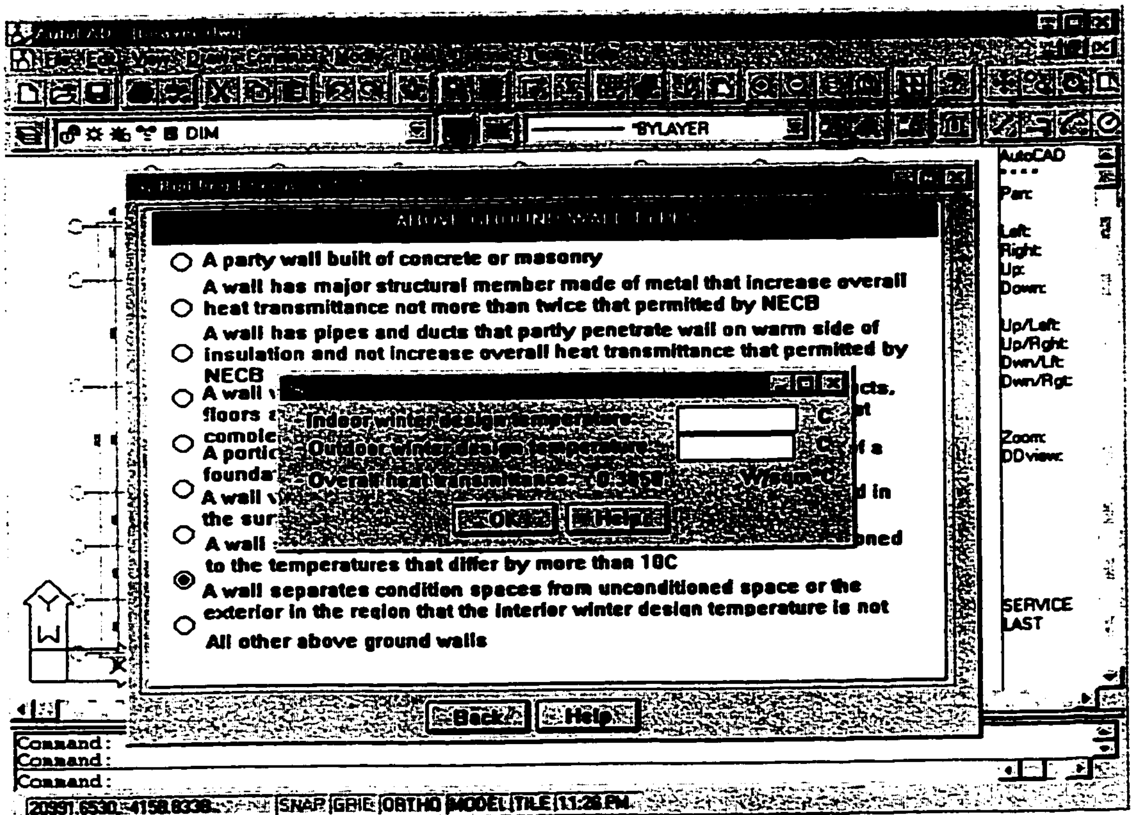
Figure A-20: Collection of Prescriptive Requirements for Window Design (2)



ABOVE GROUND WALL TYPES

○ A party wall built of concrete or masonry

○ A wall has major structural member made of metal that increase overall heat transmittance not more than twice that permitted by NECB

○ A wall has pipes and ducts that partly penetrate wall on warm side of insulation and not increase overall heat transmittance that permitted by NECB

○ A wall … cts, floors … t comple…

○ A portio… of a founda…

○ A wall … d in the sur…

○ A wall … oned to the temperatures that differ by more than 10C

● A wall separates condition spaces from unconditioned space or the exterior in the region that the interior winter design temperature is not

○ All other above ground walls

Indoor winter design temperature: ☐ C

Outdoor winter design temperature: ☐ C

Overall heat transmittance: 0.3858 W/sqm°C

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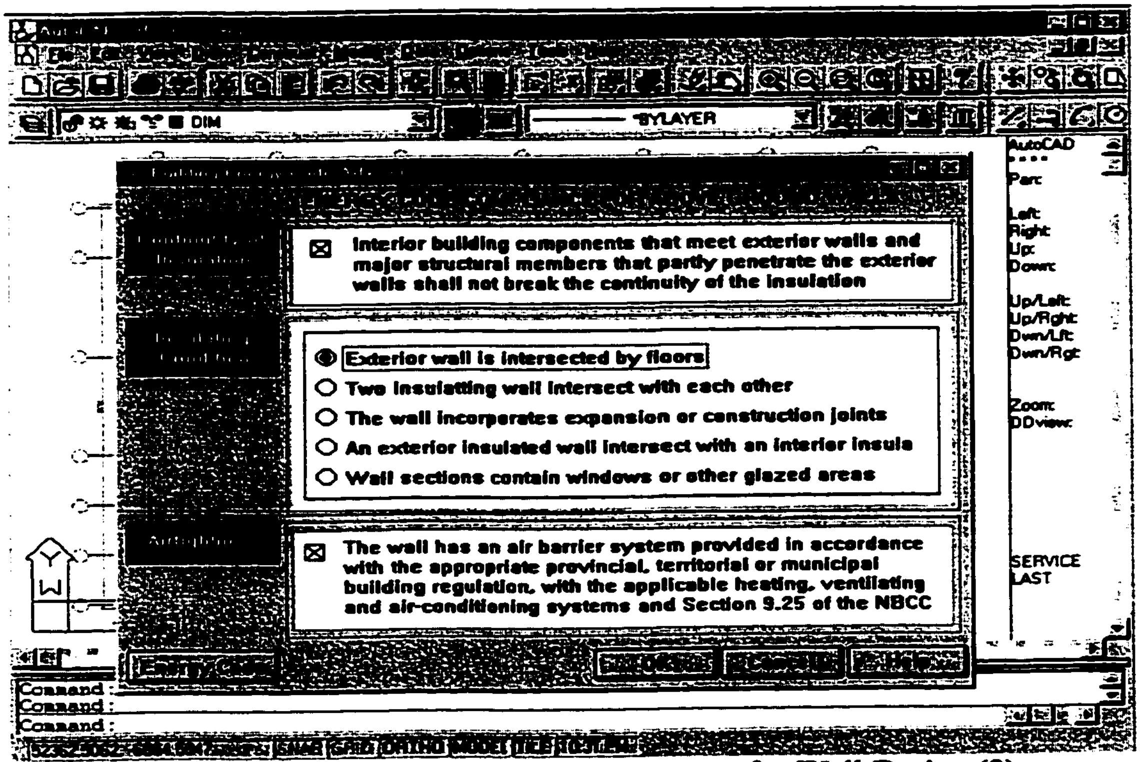
Figure A-21: Collection of Mandatory Requirements for Wall Design (1)

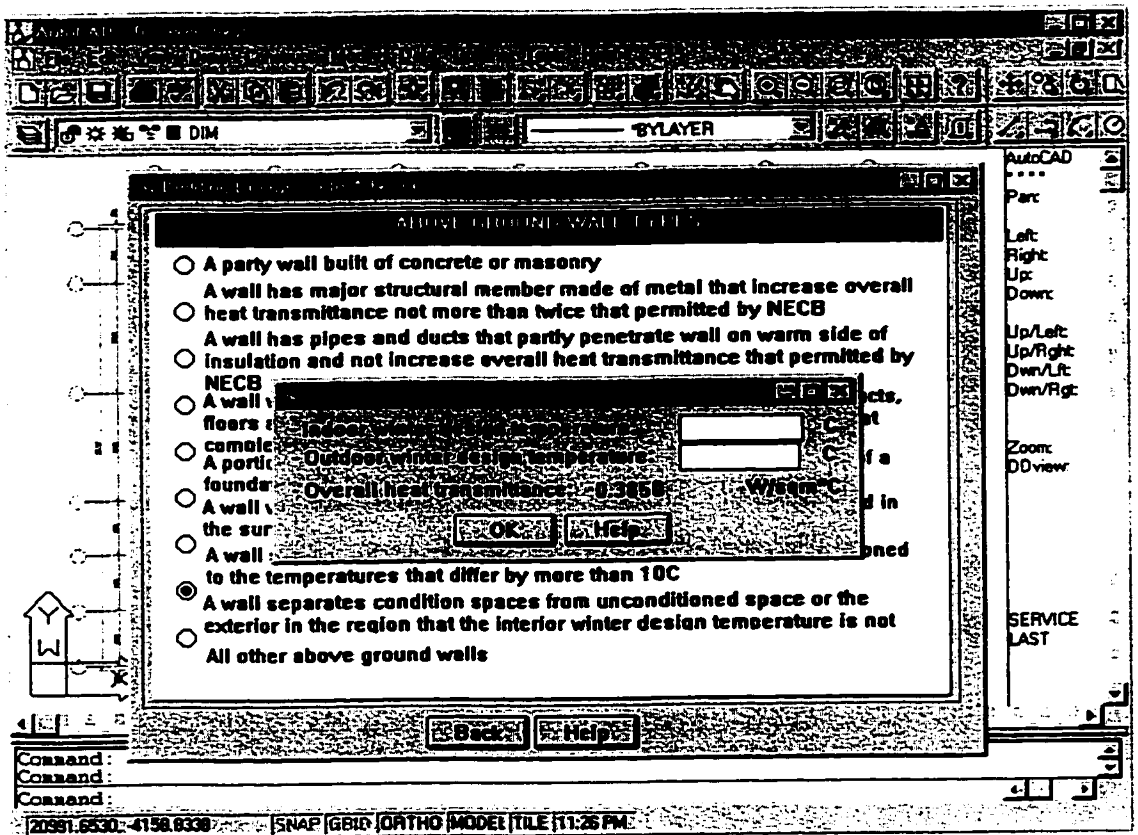


☒ Interior building components that meet exterior walls and major structural members that partly penetrate the exterior walls shall not break the continuity of the insulation

● Exterior wall is intersected by floors
○ Two insulatting wall intersect with each other
○ The wall incorperates expansion or construction joints
○ An exterior insulated wall intersect with an interior insula
○ Wall sections contain windows or other glazed areas

☒ The wall has an air barrier system provided in accordance with the appropriate provincial, territorial or municipal building regulation, with the applicable heating, ventilating and air-conditioning systems and Section 9.25 of the NBCC

Figure A-22: Collection of Mandatory Requirements for Wall Design (2)

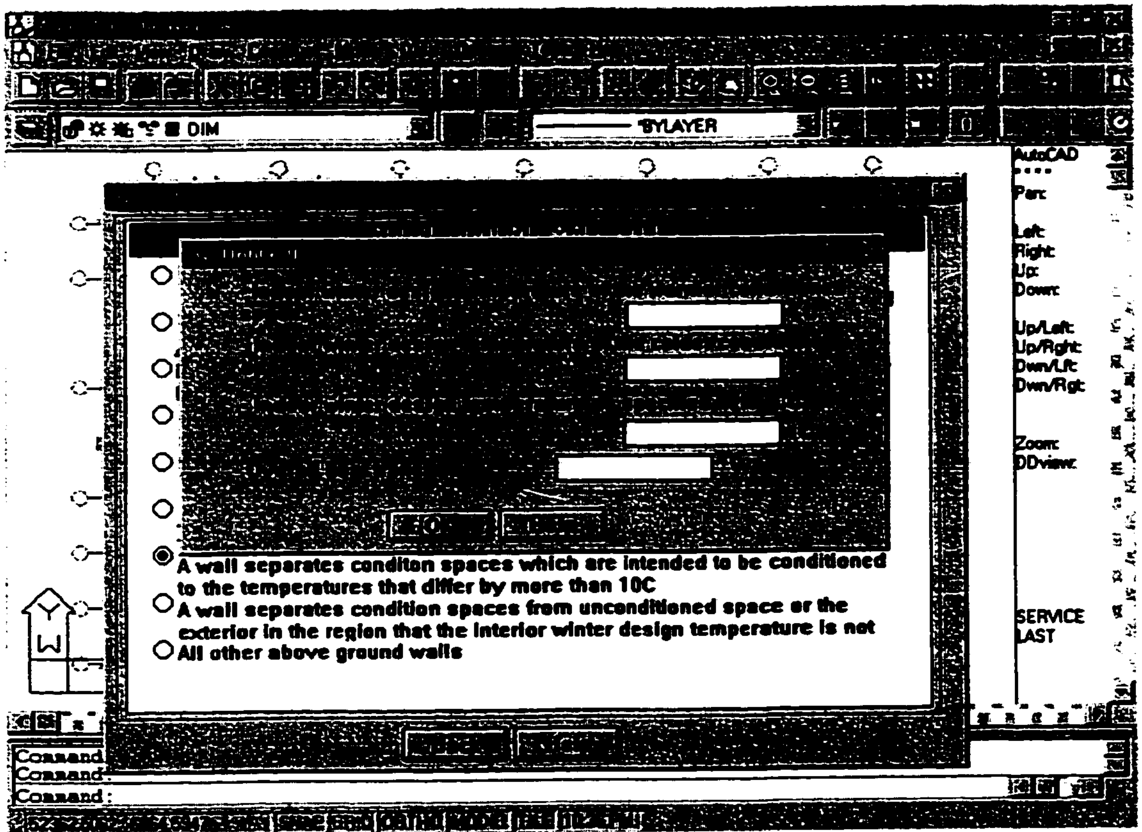


ABOVE GROUND WALL TYPES

○ A party wall built of concrete or masonry
○ A wall has major structural member made of metal that increase overall heat transmittance not more than twice that permitted by NECB
○ A wall has pipes and ducts that partly penetrate wall on warm side of insulation and not increase overall heat transmittance that permitted by NECB
○ A wall … cts, floors … t complet…
○ A portic… f a founda…
○ A wall … d in the sur…
○ A wall … oned to the temperatures that differ by more than 10C
● A wall separates condition spaces from unconditioned space or the exterior in the region that the interior winter design temperature is not
○ All other above ground walls

Indoor winter design temperature: C
Outdoor winter design temperature: C
Overall heat transmittance: 0.3858 W/sqm°C

Figure A-23: Collection of Prescriptive Requirements for Wall Design (1)

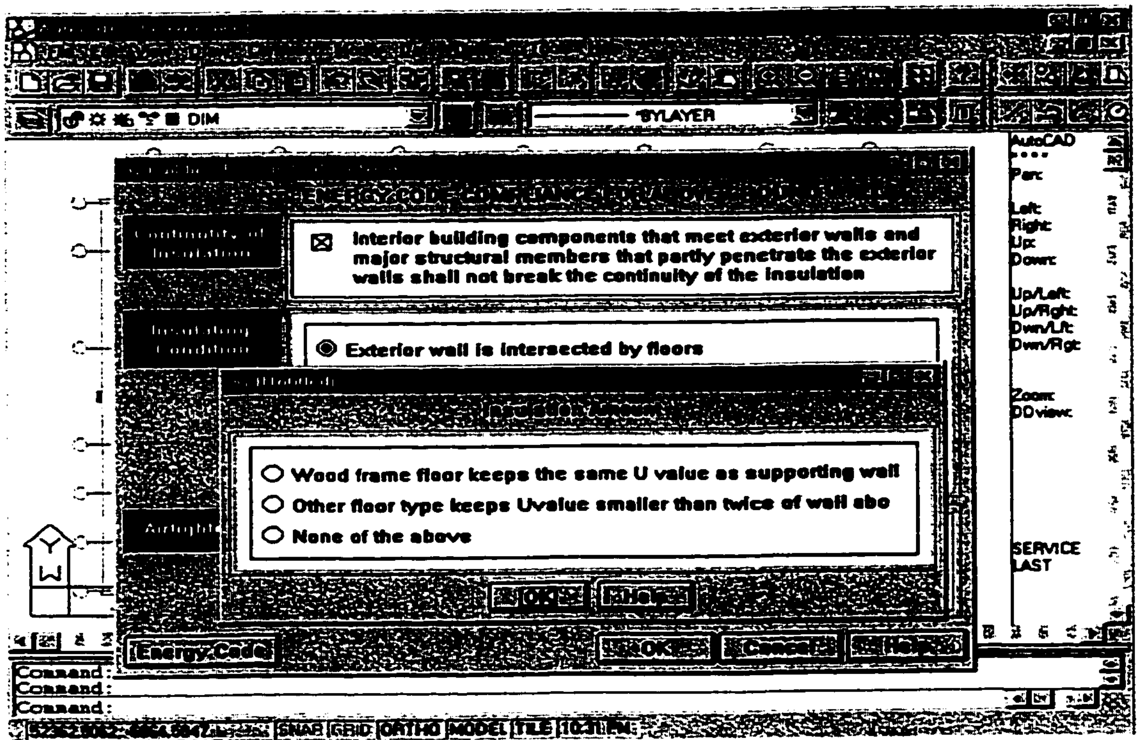


● A wall separates conditon spaces which are intended to be conditioned to the temperatures that differ by more than 10C

○ A wall separates condition spaces from unconditioned space or the exterior in the region that the interior winter design temperature is not

○ All other above ground walls

Figure A-24: Collection of Prescriptive Requirements for Wall Design (2)



☒ Interior building components that meet exterior walls and major structural members that partly penetrate the exterior walls shall not break the continuity of the insulation

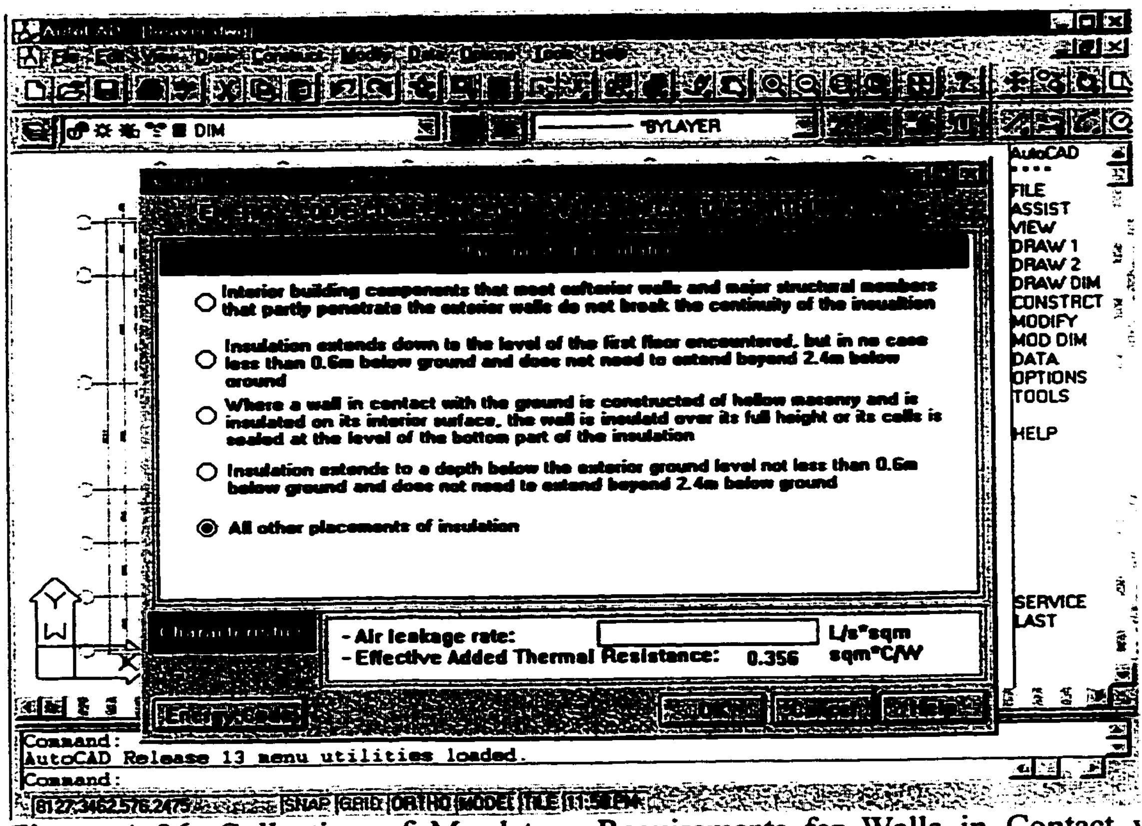
● Exterior wall is intersected by floors

○ Wood frame floor keeps the same U value as supporting wall

○ Other floor type keeps Uvalue smaller than twice of wall abo

○ None of the above

Figure A-25: Collection of Prescriptive Requirements for Wall Design (3)



○ Interior building components that meet exterior walls and major structural members that partly penetrate the exterior walls do not break the continuity of the insulation

○ Insulation extends down to the level of the first floor encountered, but in no case less than 0.6m below ground and does not need to extend beyond 2.4m below ground

○ Where a wall in contact with the ground is constructed of hollow masonry and is insulated on its interior surface, the wall is insulaid over its full height or its cells is sealed at the level of the bottom part of the insulation

○ Insulation extends to a depth below the exterior ground level not less than 0.6m below ground and does not need to extend beyond 2.4m below ground

● All other placements of insulation

- Air leakage rate: ☐ L/s*sqm
- Effective Added Thermal Resistance: 0.356 sqm*C/W

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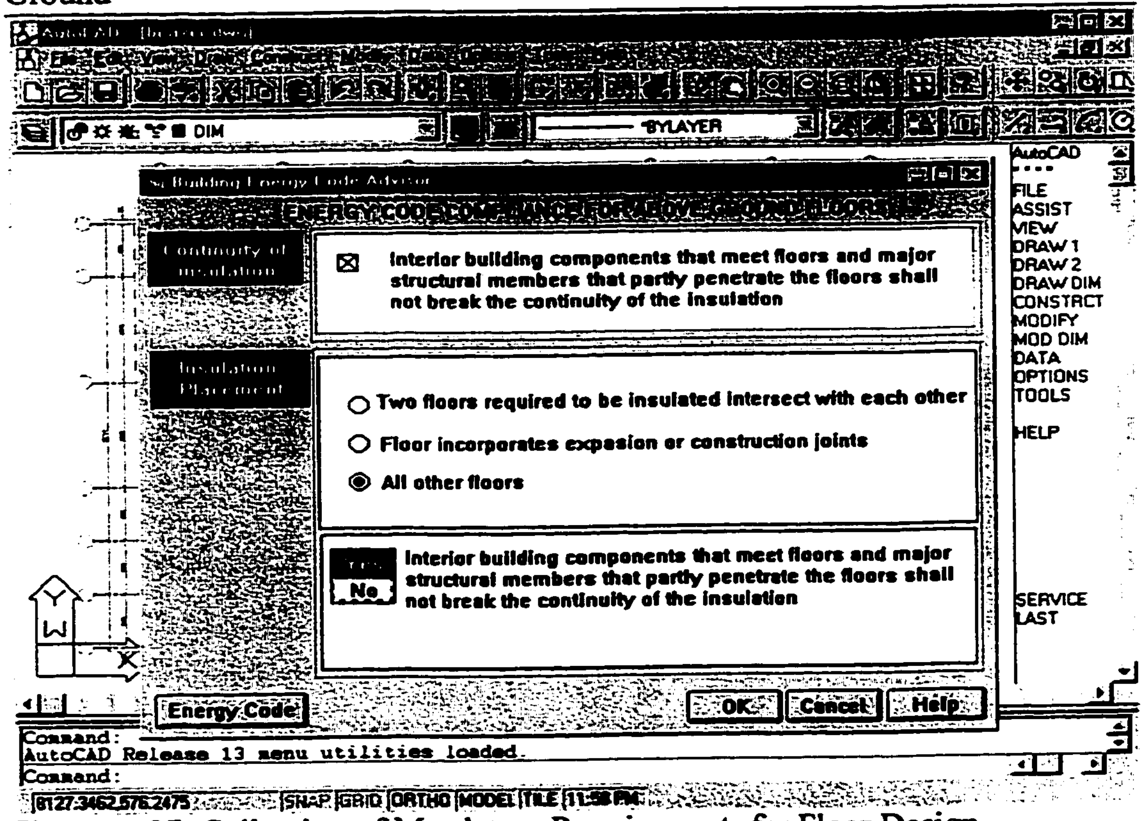
Figure A-26: Collection of Mandatory Requirements for Walls in Contact with the Ground



☒ Interior building components that meet floors and major structural members that partly penetrate the floors shall not break the continuity of the insulation

○ Two floors required to be insulated intersect with each other

○ Floor incorporates expasion or construction joints

● All other floors

Interior building components that meet floors and major structural members that partly penetrate the floors shall not break the continuity of the insulation

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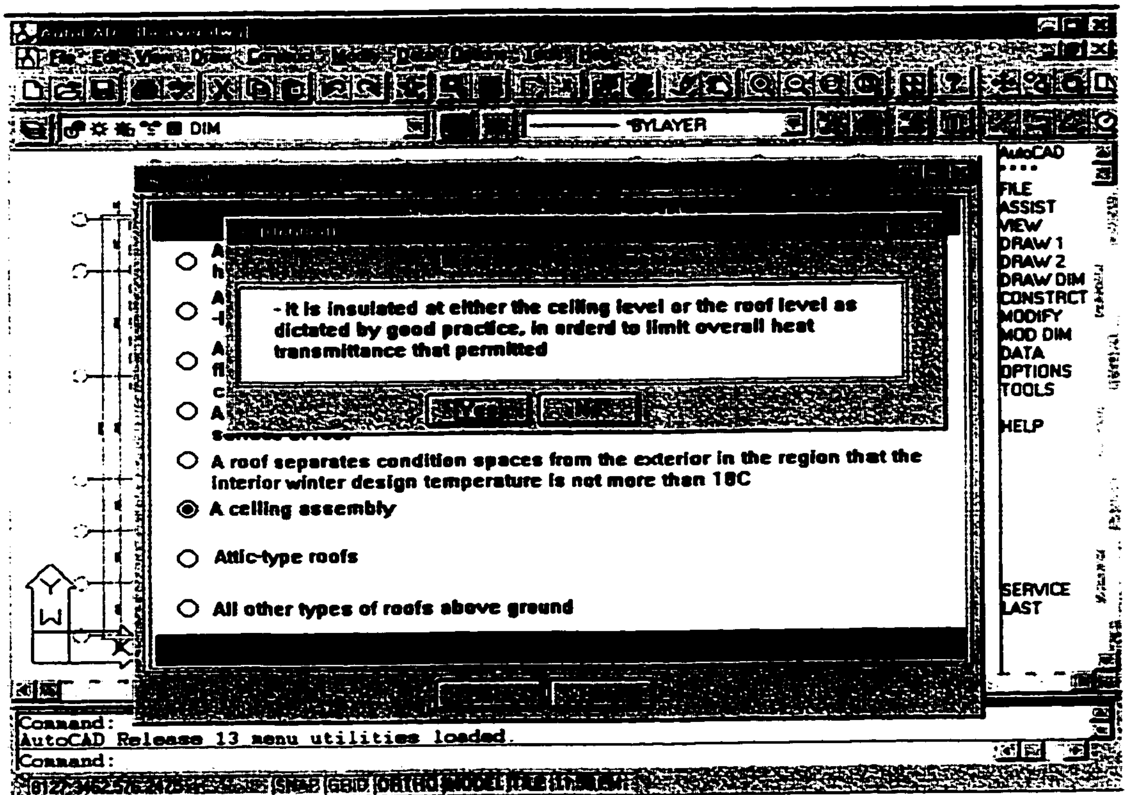
Figure A-27: Collection of Mandatory Requirements for Floor Design



- It is insulated at either the ceiling level or the roof level as dictated by good practice, in orderd to limit overall heat transmittance that permitted

○ A roof separates condition spaces from the exterior in the region that the interior winter design temperature is not more than 18C

● A ceiling assembly

○ Attic-type roofs

○ All other types of roofs above ground

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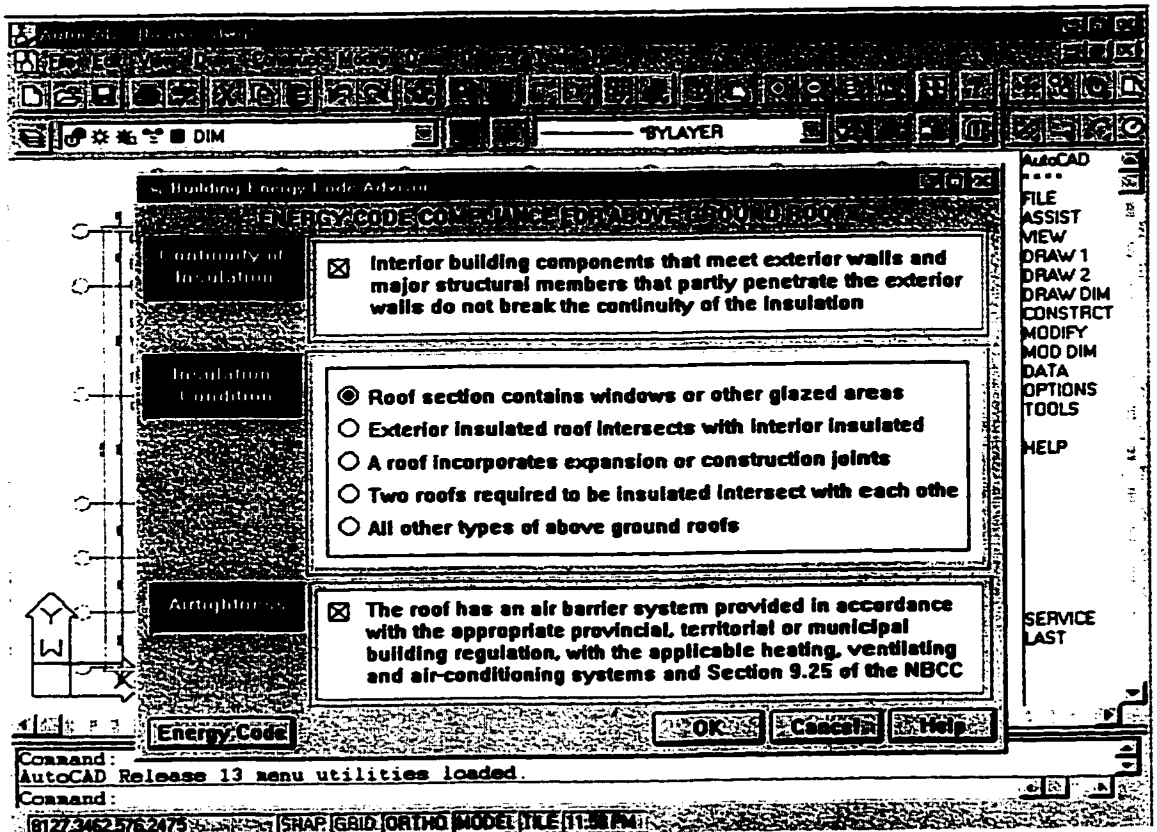
Figure A-28: Collection of Mandatory Requirements for Roof Design (1)



ENERGY CODE COMPLIANCE FOR ABOVE GROUND ROOFS

Continuity of Insulation

☒ Interior building components that meet exterior walls and major structural members that partly penetrate the exterior walls do not break the continuity of the insulation

Insulation Condition

● Roof section contains windows or other glazed areas

○ Exterior insulated roof intersects with interior insulated

○ A roof incorporates expansion or construction joints

○ Two roofs required to be insulated intersect with each othe

○ All other types of above ground roofs

Airtightness

☒ The roof has an air barrier system provided in accordance with the appropriate provincial, territorial or municipal building regulation, with the applicable heating, ventilating and air-conditioning systems and Section 9.25 of the NBCC

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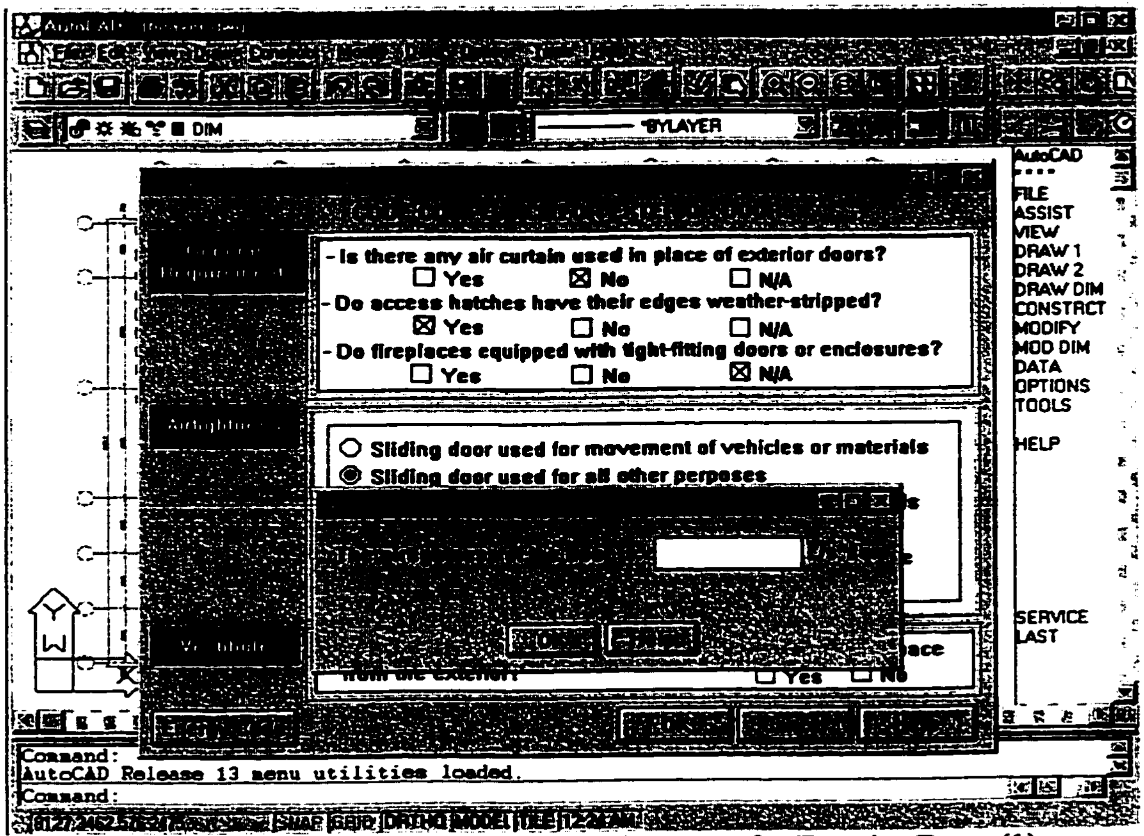
Figure A-29: Collection of Mandatory Requirements for Roof Design (2)



- Is there any air curtain used in place of exterior doors?
  ☐ Yes ☒ No ☐ N/A
- Do access hatches have their edges weather-stripped?
  ☒ Yes ☐ No ☐ N/A
- Do fireplaces equipped with tight-fitting doors or enclosures?
  ☐ Yes ☐ No ☒ N/A

○ Sliding door used for movement of vehicles or materials
● Sliding door used for all other perposes

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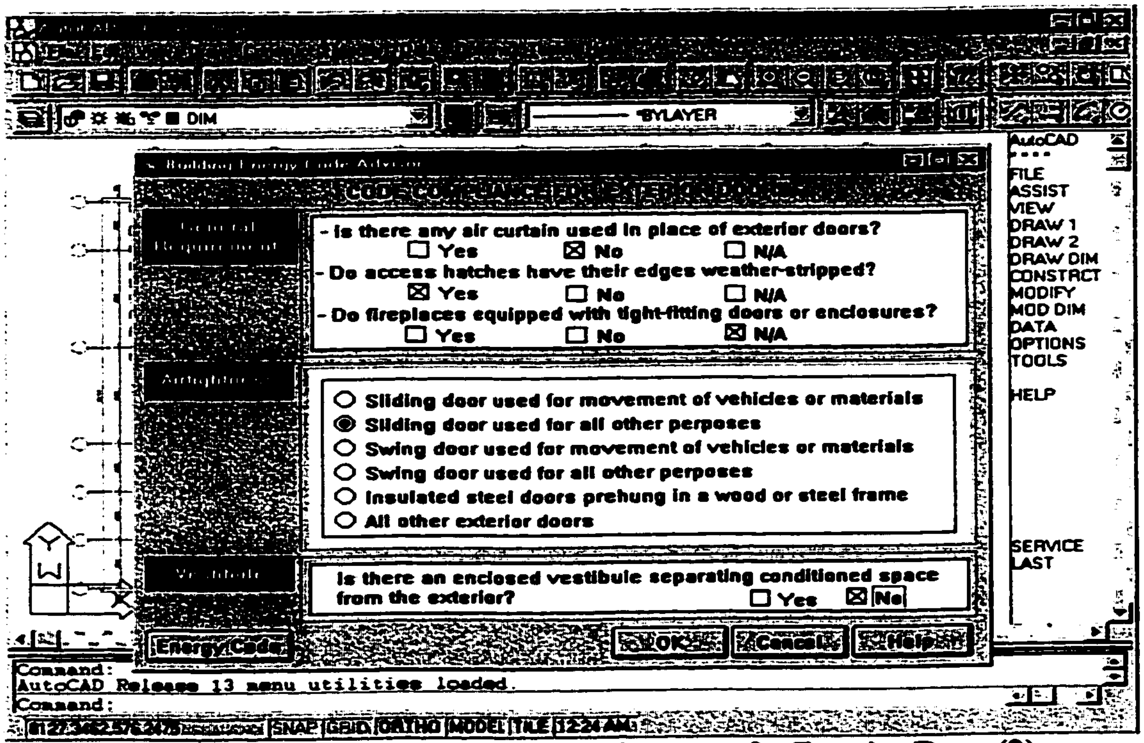
Figure A-30: Collection of Mandatory Requirements for Exterior Door (1)



- Is there any air curtain used in place of exterior doors?
  ☐ Yes ☒ No ☐ N/A
- Do access hatches have their edges weather-stripped?
  ☒ Yes ☐ No ☐ N/A
- Do fireplaces equipped with tight-fitting doors or enclosures?
  ☐ Yes ☐ No ☒ N/A

○ Sliding door used for movement of vehicles or materials
● Sliding door used for all other perposes
○ Swing door used for movement of vehicles or materials
○ Swing door used for all other perposes
○ Insulated steel doors prehung in a wood or steel frame
○ All other exterior doors

Is there an enclosed vestibule separating conditioned space from the exterior? ☐ Yes ☒ No

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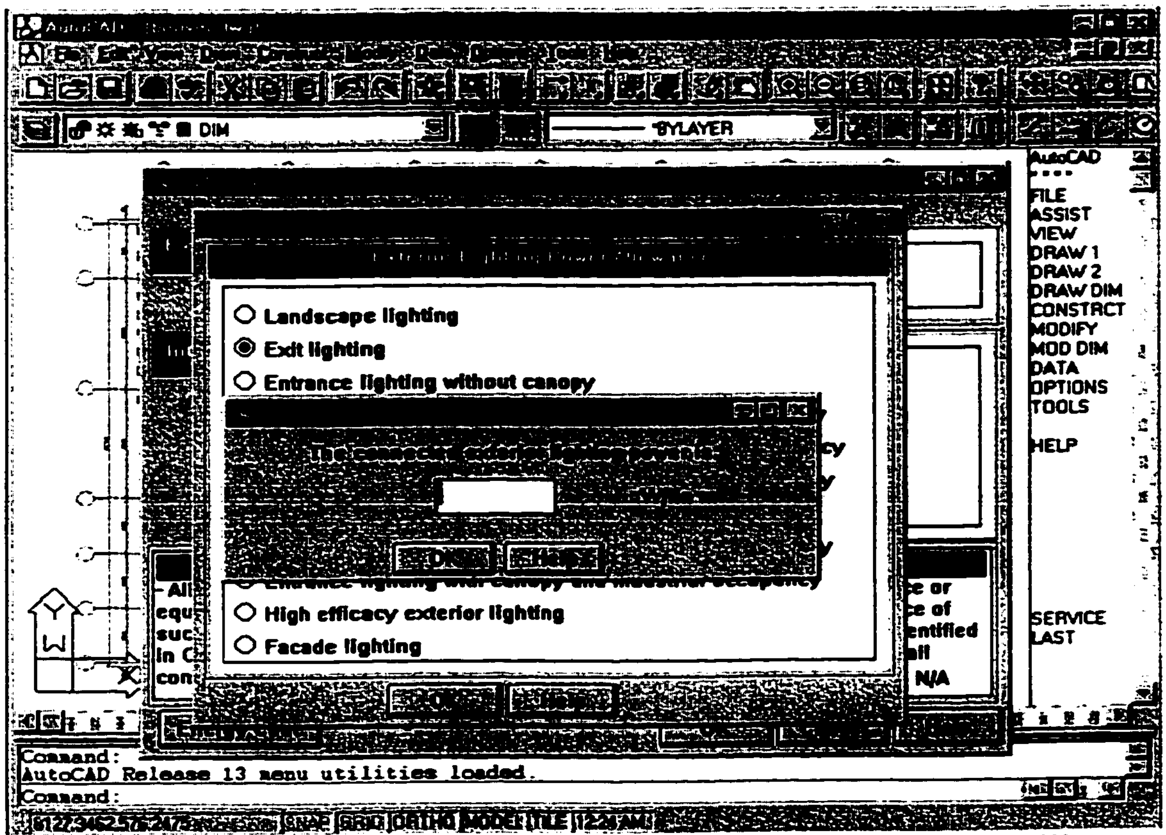
Figure A-31: Collection of Mandatory Requirements for Exterior Door (2)



○ Landscape lighting

● Exit lighting

○ Entrance lighting without canopy

○ High efficacy exterior lighting

○ Facade lighting

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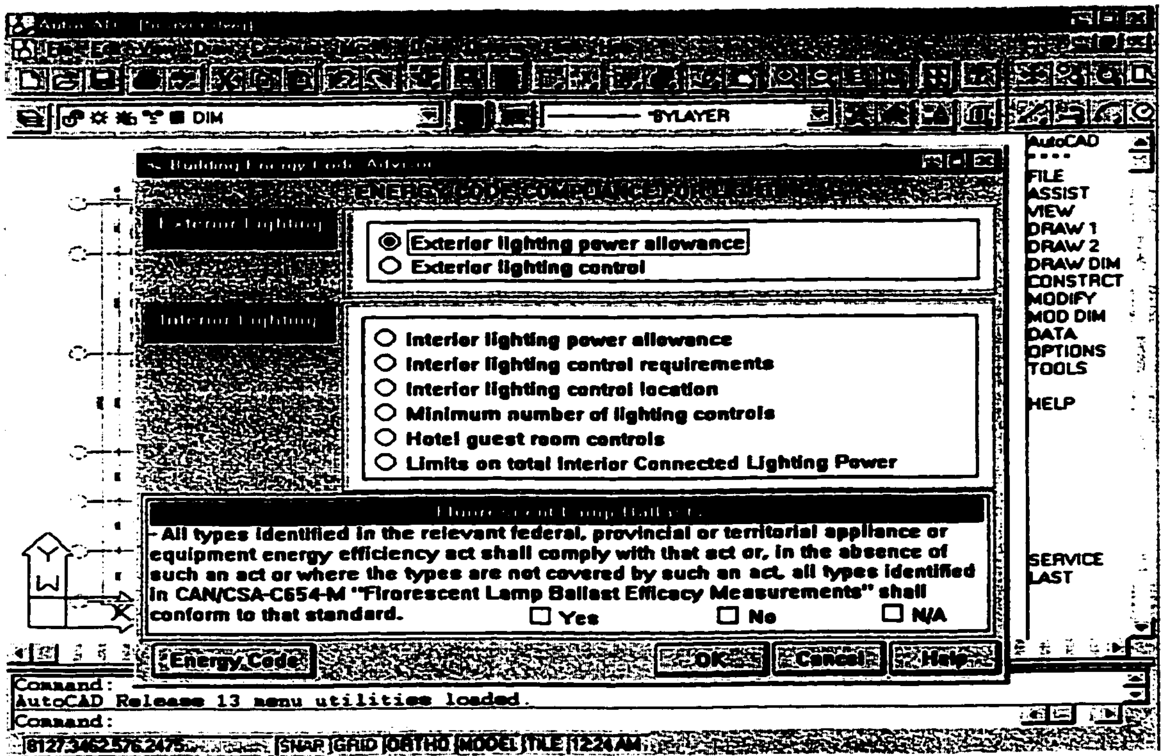
Figure A-32: Collection of Mandatory Requirements for Lighting System (1)



● Exterior lighting power allowance

○ Exterior lighting control

○ Interior lighting power allowance

○ Interior lighting control requirements

○ Interior lighting control location

○ Minimum number of lighting controls

○ Hotel guest room controls

○ Limits on total Interior Connected Lighting Power

- All types identified in the relevant federal, provincial or territorial appliance or equipment energy efficiency act shall comply with that act or, in the absence of such an act or where the types are not covered by such an act, all types identified in CAN/CSA-C654-M "Fluorescent Lamp Ballast Efficacy Measurements" shall conform to that standard. ☐ Yes ☐ No ☐ N/A

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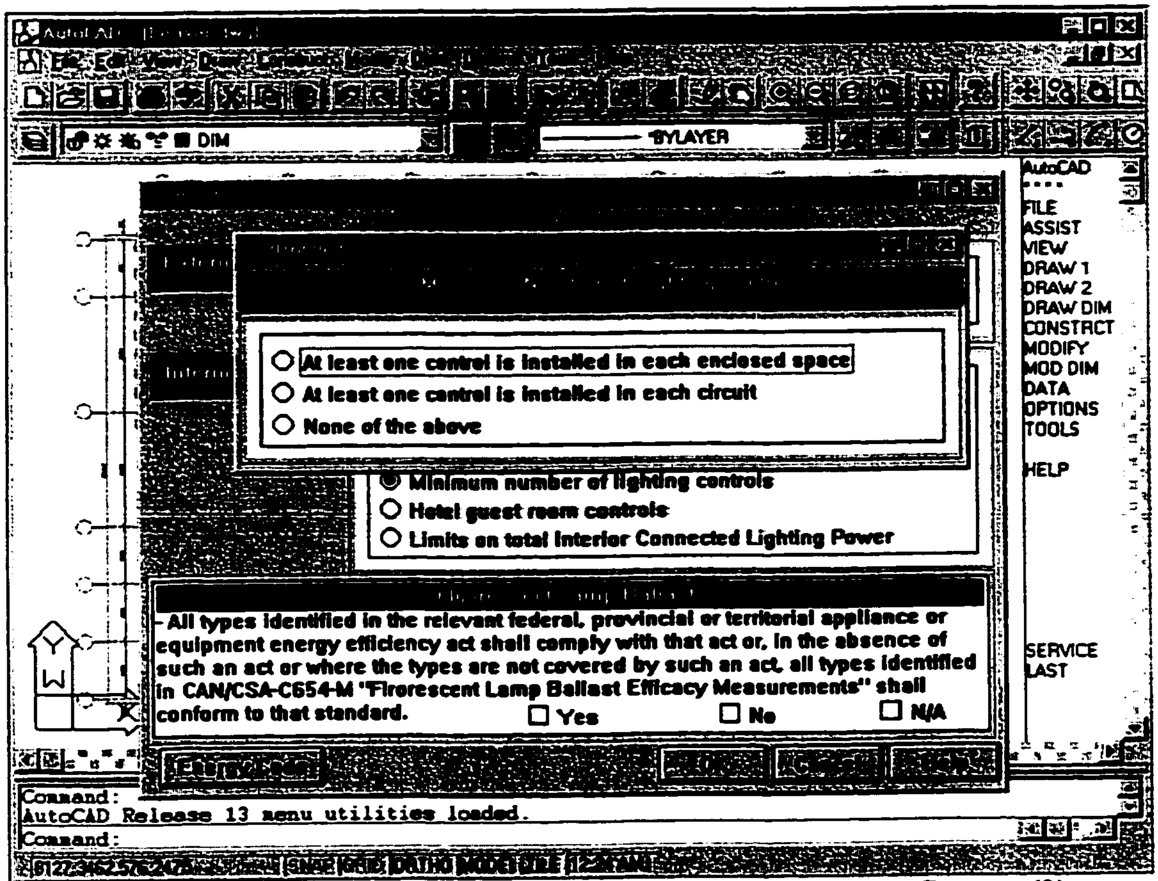
Figure A-33: Collection of Mandatory Requirements for Lighting System (2)



○ At least one control is installed in each enclosed space
○ At least one control is installed in each circuit
○ None of the above

● Minimum number of lighting controls
○ Hotel guest room controls
○ Limits on total Interior Connected Lighting Power

- All types identified in the relevant federal, provincial or territorial appliance or equipment energy efficiency act shall comply with that act or, in the absence of such an act or where the types are not covered by such an act, all types identified in CAN/CSA-C654-M "Florescent Lamp Ballast Efficacy Measurements" shall conform to that standard. ☐ Yes ☐ No ☐ N/A

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Figure A-34: Collection of Mandatory Requirements for Lighting System (3)