An Integrated Computer Tool to Support Building Envelope Design Process

Sathyanarayanan Ramachandran

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Abstract

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Due to the increase in demand of energy efficient and durable buildings, design of building envelope sub-system is an important focus area in the building design process, especially in cold climate countries like Canada. The envelope is a major part of the building cost and is expected to last 30, 50, even 100 years.

Nevertheless, building envelope design is a complex process. It has to reconcile two value systems: the qualitative aspects stemming from architectural design and the scientific requirements of building science and engineering. It also requires the support of knowledge from several other focus areas such as material science, thermodynamics, chemistry, project management, structure, heat and mass transfer, acoustics, aesthetics, etc. Moreover, the building envelope design process, as is the case with other design processes, does not follow any specific design methodology. It is subjective to experience, knowledge and attitude of the designer. The product, the building envelope, is the result of a selection process among numerous materials, systems and their configuration. Computerized systems as design tools are capable of effectively supporting the building envelope design process with this increase in amount of methodologies and knowledge. This explains the development of some tools that are available in

the industry. However, the tools developed so far to support the building envelope design process exhibit undesired qualities like non-holistic approach, inappropriate user friendliness in terms of working trends of the designer, and ineffective or insufficient knowledge base. Hence, there is a need to develop an integrated computer tool. An integrated tool to support envelope design would incorporate existing rules of thumbs, proven design practices, knowledge about envelope technologies and some analysis capabilities.

The objective of this research is to model the building envelope design process and conceptualize a computer tool that could support the designers during the building envelop design process. It develops a concept for an integrated tool through a comprehensive study to understand the available design methods and their knowledge: by defining a generic model that could represent the design methods studied and their corresponding knowledge bases; subsequently, by defining a concept of the design tool with functions suiting the design process; and finally, translating some of the functions into a program to test, resulting in a prototype.

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Dedicated to my grand mother, Late G. Nagabushanam, and

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Chapter 1

Introduction & Research Objective

1.1 Introduction

Building design involves the application of a large number of scientific principles, analytical calculations and logical evaluations from multiple disciplines. Even the design of the building envelope, a sub-system, is a complex task, where issues such as energy efficiency, durability, structural soundness and aesthetics should be assured at the design stage. Building envelope design is a specific concern in cold climate countries such as Canada, especially since the energy crisis in the 1970s.

Building envelope behaviour is becoming more and more understood through scientific investigations. Knowledge development in the area of building envelope comes from diverse disciplines, mainly architecture and building engineering with support from material science, thermodynamics, chemistry, project management, structure, heat and mass transfer, acoustics, and aesthetics. Government agencies focus on the development of knowledge in building envelope design and direct designers by providing prescriptive and mandatory rules. Such knowledge is presented to the designer in the form of principles, codes, guidelines and other directives. The building industry has developed proven design practices that are continuously modified due to the availability of new materials, the desire to reduce construction time and as well as pressures to reduce costs.

The building envelope design process must reconcile two value systems: the qualitative aspects stemming from architectural design and the scientific and quantitative requirements of building science and engineering. The decision-making approach on subjective issues such as colour, texture, form and pattern (in architecture) is open-ended, and is lightly bound by guidelines, theories or regulations. On the other hand, the building science and engineering aspect of the building envelope design process depends more on analysis, logics and facts. This diversity in domains and working trends illustrates the complexity of the design process.

One would think that, nowadays, envelope design would be supported by a computer tool. Efforts to support the designer during the design process have generated a handful of computer tools for analysis and evaluation. However, tools developed thus far focus only on a few specific functions. Most of the tools are highly sophisticated primarily supporting research activities in laboratories rather than the design process. Those developed to handle the design process provide support solely for verification in the final stages, especially analysis. Tools to analyze condensation and heat flow, such as Condense and Moist, or moisture content variation, like WUFI, are examples of such tools. Thus, current tools do not participate in the genesis of envelope solutions supporting both the qualitative and quantitative developments. Finally, such existing tools are also devoid of a knowledge base, thus they neither aid the designer in the knowledge quest nor do they present the designer with new information.

1.2 Research Objectives

The aim of the research is to conceptualize an integrated computer tool to support designers in the design of the building envelope. The design tool should have the capacity to function with a minimal amount of data input, respecting the design process characteristics and providing comprehensible outputs. As mentioned above, the building envelope design is a specialized domain, straddling the disciplines of science, engineering, and architecture. Establishing a support tool for the design process requires a comprehensive study of the methodology employed for the building envelope design process. On the basis of the study, a model should be developed protecting and enhancing the existing techniques, and integrating the industry knowledge at appropriate junctures. Such a model can then be the basis of the computer tool and the features it requires to handle. Introducing computers to support the design process does not mean to affect the existing problem solving techniques of the designers, which varies from one designer to another.

To summarize, the specific objectives of the research are,

1. to review the existing building envelope design methods and the required fields of knowledge;
2. to develop an explanation (model) of the flexible building envelope design methods used in the industry;
3. to find the appropriate computer tool structure with functions to support the building envelope design process as modelled; and
4. to develop a working prototype of the computer tool as a proof-of-concept.

1.3 Research Methodology

The research followed a three-stage process to identify an appropriate design tool to support the building envelope design process: (i) understanding and representing the building envelope design process and the current computer support available; (ii) listing of the requirements and development of a concept for the integrated design tool; and (iii) designing and implementing a prototype to validate the features of the proposed concept.

Understanding the building envelope design process involves the study of envelope systems and design methods as separate issues; the study of the available design methods of the building envelope design process; and the study of knowledge and its intervention in the building envelope design process. The analysis of the building envelope design was handled using three distinct methods: literature review, exercise on building envelope design, and evaluation of existing tools. Based on the analysis, conclusions were drawn as to the issues regarding the building envelope design process. A generic model for the design process was proposed.

The need, the requirements and the methods of implementation of the computer tool to support building envelope design were developed. A representation of an appropriate computer environment with features supporting the identified requirements of the tool was drawn. As a proof of concept, a text-based prototype was developed using Java language, demonstrating some of the functions of the computer tool in supporting building envelope design.

1.4 Presentation of Thesis

This thesis is divided into six chapters. The next Chapter, 'Literature Survey', divides the building envelope design into two issues: the building envelope system, and design methodologies. It reviews the available information of each issue separately, and presents the building envelope design process. It discusses the knowledge supporting the building envelope design process. It also includes a review of the existing conceptual models and computer support.

Chapter 3, 'Review of Building Envelope Design Process and its Knowledge', appraises the building envelope design process, based on the literature survey, on the evaluation of existing computer tools (discussed in Chapter 2), and the exercises on the building envelope design. Appendix A, 'Exercise on Building Envelope Design' and Appendix B, 'Exercise on Design of Building Envelope Wall Section' supports the discussion in order to understand the building envelope design process. Chapter 3 proposes a model to represent the building envelope design process. It presents a design method suitable to be adopted for the design tool. It also classifies and documents the knowledge supporting the building envelope design process.

Chapter 4, 'Analysis and Design of the Integrated Tool', discusses the requirements of the tool, introduces the concept and scope of the tool, and proposes the design tool. It elaborates on the environment and its features for the design tool, and the working of the tool. Chapter 5, 'Implementation and Evaluation of the Prototype', deals with the proof of concept prototype for the design tool. It discusses the few functions that were implemented, thus demonstrating the appropriateness of the approach retained. It explains the capabilities and design of the prototype, along with the knowledge included. Appendix C documents the software engineering process of the prototype. Chapter 6 concludes by summarizing the research findings, detailing the contributions and providing recommendations for future work.

Chapter 2

Literature Review

The building envelope design process as a research area has not received much attention. Research efforts along this topic are limited, peripheral and fragmented, contrary to the field of structural design and HVAC system design. There is no available proposed model or systematic approach for the building envelope design process, which might be extended or reformed and developed as an integrated computer tool. Hence, an extensive literature survey about the basics of the building envelope design process was carried out, and documented in this current chapter. It comprises five major sections examining the proposed research subject. Firstly, the subject building envelope design process is reviewed in the two sections 'Brief Description and Function of Building Envelope Systems' and 'Brief Review of Methodology Studies on Design'. Secondly, the available information about the building envelope design process and its relevant knowledge is discussed in the two sections 'Review of Studies on the Building Envelope Design Process' and 'Review of Available Knowledge Supporting Building Envelope Design Process'. Finally, the evaluation of existing tools is presented in the last section in order to study their successful features and limitations under 'Summary of Evaluation of the Existing Design Tools'.

2.1 Brief Description and Function of Building Envelope Systems

The building envelope system is one of the four major systems of a building [Rush, 1986]. It is closely related to the other systems: interior, structure and services. In turn, a building envelope system could be perceived as an assembly of entities, composed of envelope subsystems [Derome, 1999]. Major envelope subsystems are exterior walls, roofs, foundation walls, cantilevered floors and openings such as windows and doors [Rivard et al., 1995]. From a design point of view, the junctions and connections may also be included as subsystems.

Rivard et al. [1998] developed a shared conceptual model to support an integrated building envelope design process by organizing data in a logical and abstract manner using entities. From a building envelope design perspective, entities could be perceived as the basic elements that require definition. The building envelope system is perceived as a composition of entities: envelope planes, envelope areas, envelope sections, envelope layers, openings, connections, indoor entities and other entities.

- An envelope plane is the bounding flat surface of a building volume, e.g. roof, exterior walls, slab-on-grade and cantilevered floors. The shape of the envelope plane could be simple or complex. It may be broken down into several regions of envelope area and openings, where the total sum of the envelope areas and openings would give the area of the envelope plane;

- An envelope area is defined to be a region in the envelope plane with only one type of section and corresponds to only one indoor space. There is a need to divide the envelope plane into discreet areas corresponding to different indoor spaces, as the performance requirements of a given envelope section varies significantly with one indoor space to another;
- An envelope section is an assembly of components placed in a predetermined sequence. A component can be an envelope layer (polyethylene sheet as a vapor barrier is an example of an envelope layer) or an element (brick ties and wood studs are examples of elements that are not layers). A typical envelope section may be used in more than one envelope area. The envelope section entity has characteristics that apply to the set of components it comprises such as total thickness and total thermal resistance;
- An envelope layer represents one construction material within an envelope section. Envelope layers may be classified according to their function [Rivard, 1993]: cladding, coating, membrane, structure, panel, insulation, finishing and others. The envelope layer entity contains data

pertaining to the physical characteristics of the construction material such as thermal resistance, emissivity, vapor resistance and cost;

- An opening is an element that pierces an envelope plane to allow light, view, access and ventilation. Openings may span more than one envelope area;
- Connection entities define the details of how two or more envelope entities are joined together. They are important as they often determine how a given envelope design will perform (e.g. wall-roof connection). Connection entities may require to undergo 2D/3D thermal analysis for thermal bridge assessment;
- An indoor space is an entity characterized by occupancy and desired environmental conditions. The volume of the building is divided into several indoor spaces by indoor divisions (e.g. floors dividing stories);
- Other entities identified in the shared conceptual model were building, city and protruding elements. The building entity refers to all of the above envelope entities, and contains other general project information. The city entity helps to specify the outdoor environmental conditions that affect the envelope design such as outdoor design temperature, relative humidity, wind pressure and seismic data. The data for each city is generally provided in a building code such as the National Building Code of Canada. The protruding element is an entity that extends out from the

building envelope, such as external columns and balconies. These elements must be accounted for in the shared conceptual model since they typically act as thermal bridges and provide complicated detailing junctions.

2.1.1 Functions of Building Envelope System

As stated by Archer [1974], "design is the preparation of a prescription for some artefact or system in the light of all relevant functional/constructional, economic, marketing, ergonomic, and aesthetic requirements". The primary purpose of the building envelope design is to enclose the habitable living spaces from the fluctuating outdoor conditions [Hutcheon and Handegord, 1989; Rivard et. al, 1995; Derome, 1999]. Hutcheon [1963] breaks down the purpose of the building envelope into eleven specific functions to be satisfied by the building envelope: control of heat flow; control of airflow; control of water vapor flow; prevention of ingress of rain; control of light, solar and other radiation; control of noise; control of fire; strength and rigidity; economy; durability; and aesthetics. In addition to the above functions, ASHRAE [1997] recommends two more functions: control of liquid water entry and control of indoor air quality. The control of liquid water entry includes the already mentioned prevention of rain ingress and control of liquid water seepage. The elements of a building envelope are designed considering the above functions to the required levels through design objectives expressed in quantitative and qualitative terms. The functions to be considered and the precedence of each function for the selection of an envelope assembly depend on the performance requirements of the design project. For example, in the selection of an envelope for a theatre, acoustics is a major function to be considered among other common functions, such as structural stability, control of heat, air and moisture, and liquid water entry. The following subsections discuss, briefly, the quantitative and qualitative parameters of functions to be considered during the design process, applicable for exterior walls. Nevertheless, they could be extended to other subsystems.

2.1.1.1 Structural Stability

Structural stability of the building envelope is the first function to be satisfied. The main concerns addressed are the soundness and structural sufficiency providing safety to the inhabitants, against the physical loads such as the self load of the structure (in case of load bearing walls), wind load and impact load [Hutcheon and Handegord, 1989]. It is more often taken care of by the elements of the main building structure (e.g. wood studs of a wood-framed house) or elements attached to the main structure (e.g. steel stud framing in a concrete structure). In Canada, wood stud structure is predominantly used as the main structural system for low-rise residential buildings. The wood framed structure is primarily single-stud structure. The other layers of the envelope are affixed onto the main stud structure, directly pinned or through supplementary support. Chapter 9 of the

National Building Code of Canada [1995] provides regulation for the design of wood stud structures.

2.1.1.2 Control of Heat Flow

Control of heat is a major function of the building envelope, due to its impact on the energy costs. A typical Canadian residence consumes 50 to 70 percent of its total energy use for heating [CMHC, 1999]. It also affects the durability of the building envelope when combined with the effects of moisture, through hygrothermal behaviour. Heat flow from the interior to the exterior through the building envelope system occurs three ways: conduction, convection and air leakage. Radiation is another mechanism, which normally happens through the openings in the building envelope.

Heat loss by conduction is traditionally controlled using one or more layers of insulation material (i.e. a material with high thermal resistance) in the assembly. The amount of thermal resistance to be achieved is a design objective determined based on the energy efficiency requirements, prescribed as regulations by the local authorities, specified by the owner as a requirement or defined by the designer. Some benchmarks or official requirements for the amount of thermal resistance are available to the designer in order to achieve the specified standard levels of energy efficiency as shown in Table 2.1. The table provides samples of standard values that are followed traditionally in the industry and those prescribed by regulatory

Standard	Roofs	Exterior Walls	Foundation Walls
R-2000	RSI 7.0 (R 40)	RSI 4.1 (R 23)	RSI 3.1 (R 17.5)
Regulations respecting the energy efficiency of buildings, Quebec	RSI 5.3 (R 31)	RSI 3.4 (R 20)	RSI 2.2 (R 12)
NovoClimat	RSI 7.3 (R 41)	RSI 4.3 (R 24.5)	RSI 3 (R 17)
Model National Energy Code of Canada for Houses	RSI 7.0 (R 40)	RSI 4.1 (R 23)	RSI 3.1 (R 17.5)

Table 2.1: Standard Levels of Insulation (in RSI and R values) for Cold Climate

bodies in Canada such as R-2000, regulations respecting the energy efficiency of buildings, NovoClimat (Government of Quebec) and Model National Energy Code of Canada for Houses for subsystems, exterior walls, roofs and foundation walls. The values are indicated in both British units (R-value - $hr.ft^2.°F/Btu$) and International Standard units (RSI value - $m^2.°C/W$).

The design solution for control of heat is normally the selection of appropriate insulation materials, and its configuration in terms of dimension and localization. Decisions about the insulation layer should also consider the support system required. ASHRAE [2001b] discusses two types of insulation based on the method of application: surface applied insulation and cavity fill insulation. The surface applied insulation may be either located to the exterior or interior of the structural system, thus perceived as exterior insulation or interior insulation. Based on the physical structure and form, insulation materials are classified as loose-fill, rigid, semi-rigid, and foamed-in-place [ASHRAE, 2001a]. Exterior and interior insulation are normally applied using rigid, foamed-in-place and semi-rigid types of materials, while the cavity spaces are normally filled with batt, loose-fill, and foamed-in-place types. Figure 2.1 outlines the types of insulation and relevant materials applicable with the appropriate structural support. Each insulation type requires a distinctive support system. For instance, the cavity fill insulation using batt or loose-fill type of material requires cavity closure from both sides; semi-rigid insulation requires battens or sheathing as support; and foamed-in-place requires sheathing as a base. Thermal bridge, a problem due to the application of cavity insulation between wood studs, may be solved by using additional insulation layers. Rigid insulation is normally supported by the main structure (e.g. wood stud) in the absence of which sub-structures such as battens are used for support. Rigid insulation in the exterior and interior may act as cavity closure sheathing for cavity-fill insulation, if applied. The two types of formed in-place insulation, foamed-in-place and blown insulation, are effective means to insulate irregular surfaces and spaces that are not easily accessible [Shirtliffe, 1972]. Foamed-in-place insulation is normally applied on top of the exterior sheathing such as OSB, plywood, or gypsum board [ASHRAE, 2001b].

Convection has an indirect impact on the performance of the building envelope. For instance, a wider air cavity space in the assembly causes more convection current, which reduces the performance of insulation materials such as

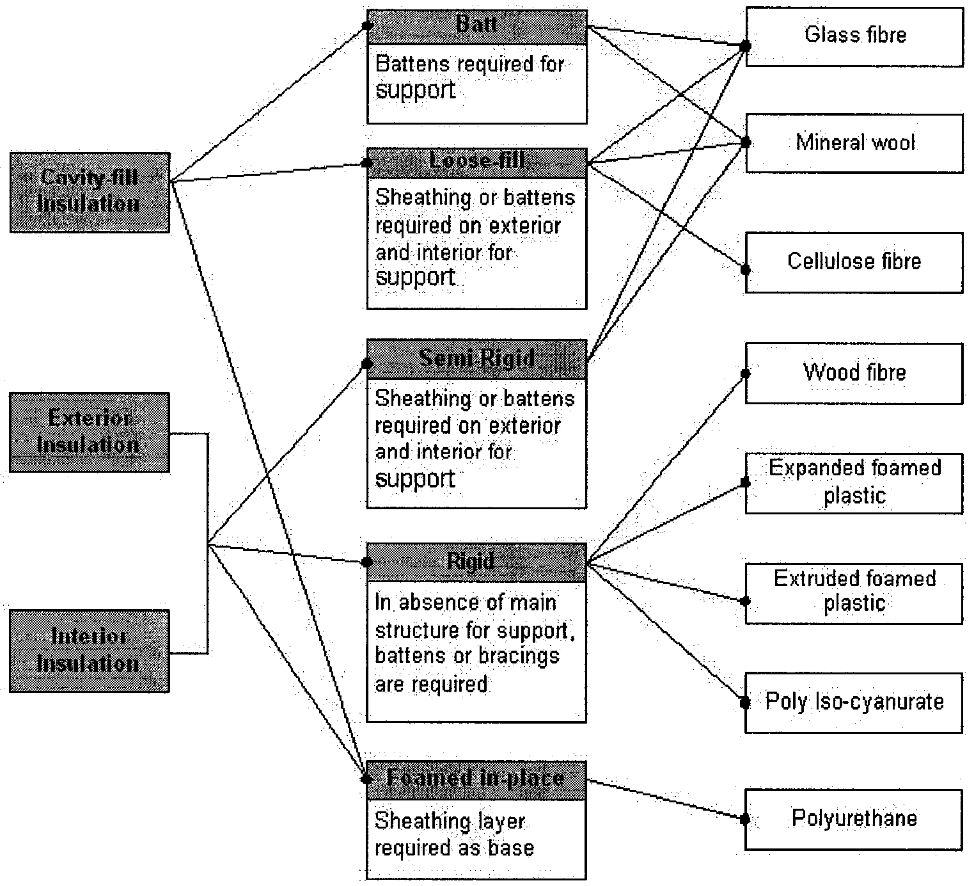

Figure 2.1: Insulation Types and Materials, with Support System

glass fibre, mineral fibre and cellulose [CMHC, 1999]. Air leakage is covered in the following subsection on control of airflow.

2.1.1.3 Control of Moisture Diffusion

Of all the environmental factors, moisture poses the biggest threat to integrity and durability. It accounts for up to 80% of damage in the building envelopes [Bomberg, 2002]. It mainly affects the durability, and indirectly the energy efficiency and indoor air quality. Hence, control of moisture is important for the performance of the building envelope. Moisture is transferred across the building envelope through air leakage and diffusion. Though the amount of moisture transferred due to air leakage is greater than the amount of moisture transferred by diffusion, the potential damage caused to the building envelope by diffusion is significant. For instance, vapor diffusion may cause interstitial condensation, a major problem that affects the performance of the building envelope. The expenditures incurred to repair diffusion problems such as condensation, fungal growth, and physical defects due to moisture accumulation (which are consistent throughout the envelope) are considerably expensive as that of the problems due to mass movement that are centric to the leakage area [Trechsel, 2001]. Vapor diffusion occurs due to vapor pressure differentials across the layers of the assembly. Water vapor flows from the high vapor pressure layer to the low vapor pressure layer. Condensation is caused due to the air attaining saturation vapor pressure as the air temperature decreases because of a thermal gradient. The rate of water vapor flow due to diffusion and condensation possibilities in the assembly could be analytically estimated using simplified models (e.g. simple steady state method [ASHRAE, 2001a]).

A prominent design solution to prevent vapor diffusion is to include a vapor retarder [ASHRAE, 2001b]. The vapor retarders are materials or systems that adequately retard the transmission of water vapor under specified conditions. For residential constructions it is assumed that the permeance of an adequate retarder does not exceed 45 ng/Pa.m.s. In cold climate conditions, as per the guidelines in the industry, the vapor retarder should be located on the warmer side of the envelope (i.e. the RSI value of the components outside of the vapor retarder should be 2/3rd of those inside [Trechsel, 2001]). The other solutions include the application of vapor resistant coatings on interior finishes and, although not the object of a methodology yet, inclusion of material layers with moisture storage capacity in the assembly. Liquid water entry is a major problem to be considered during the design of the building envelope. It is discussed in detail in a separate subsection 'Control of Liquid Water Entry'.

2.1.1.4 Control of Airflow

Control of airflow across the building envelope is another significant function concerned with mass and energy transfer through the envelope. The air leakage is more significant in transfer of heat and moisture than conduction and diffusion, respectively [ASHRAE, 2001b]. The designer of a building envelope cannot predict accurately or even approximately the as-built air leakage performance of the designed envelope, as there are no methods to evaluate the eventual defects caused by field conditions, construction failures and operation and maintenance of the building [Trechsel, 2001]. The strategy to minimize the effects of air movement is the provision of a continuous material layer or a composition of material layers to act as an air barrier, ensuring the envelope to be airtight. Air barriers also prevent mass moisture movement. For practical purposes it is assumed that the rate of air leakage through air retarders should not exceed 0.15 L/s.m2 @ 75 Pa (0.06 cfm/ft2 at 0.3 in of water at 75 Pa) [ASHRAE, 2001b]. A material applied as an air barrier (which could be positioned anywhere across the envelope assembly), may also act as vapor retarder provided the location of the layer is suitable for the vapor control strategy.

Wind load on the building envelope is most significantly a concern in high-rise buildings. Air pressure difference across the envelope determines the wind load, which is not uniform throughout the building and depends on orientation and level. Calculation of pressure difference at various parts of the building envelope to gauge the wind load during the design process is not necessary, particularly in low-rise residential projects.

The control of heat, air, water vapor, and radiation, are seldom possible to deal with individually [Hutcheon and Handegord, 1989]. A design solution serving one of these functions has at least a partial impact on the other functions, either as a solution or a problem. For instance, a polyethylene film provided as an air retarder also acts as a vapor retarder, which depending on the localization may create a favourable or an adverse condition (i.e. in cold climates, the Polyethylene (PE) film applied on the interior of the insulation may be a solution as a vapor barrier, while acting as a trap for moisture when applied on the exterior) [Trechsel, 2001].

2.1.1.5 Control of Liquid Water Entry

Liquid water entry is a recurring moisture problem of building envelopes caused by leaking roofs or foundations, or through the walls due to wind-driven rain or rain splashing. The liquid water entry can be classified into two types: rainwater ingress and water seepage. The rain screen principle, by introducing an air cavity in the envelope assembly, minimizes penetration of moisture into walls due to raindrop momentum, capillarity, gravity and air pressure difference [AHSRAE, 2001b]. Currently two layers of defence are applied to solve the liquid water entry problem (mostly caused by rainwater): cladding and air cavity (as first layer of defence) and weather resistive membrane (as second layer of defence). A waterproof membrane applied in the envelope assembly is a common design solution to block the seepage of moisture through foundation and roof elements. Rising damp in foundations is another cause of moisture seepage, which could be limited using less porous materials or by locating or installing a membrane layer as a blockade. Design details such as flashing, gutters, downspouts, and positive grading are also some effective methods of reducing moisture seepage.

2.1.1.6 Economy in Construction, Operation and Maintenance Costs

Rivard [1995] discusses economy as a function vis-à-vis three costs at different phases during the building envelope design process: (i) the initial construction costs that account for the design, fabrication and installation of the envelope; (ii) the operating costs that correspond to the yearly energy consumption; and (iii) the maintenance costs that correspond to the cleaning and repair of the envelope components during their service life and the replacement cost once their service life is over. The initial construction cost is traditionally significant in the analysis of the performance of the building envelope system. However, the building envelope utilizes only about 10-20% of the initial building construction costs, but it has a significant impact on the operational and maintenance costs throughout the life of a building [Rivard, 1998]. Hence, considering all the three types of expenses is important during the building envelope design process. Hutcheon and Handegord [1989] state that the building envelope should have reasonable maintenance and operation cost to achieve economical design solutions. Too often, during the building envelope design process, only the initial construction cost is evaluated overlooking the evaluation of the other two types of costs.

2.1.1.7 Durability

Durability can be defined in terms of the length of time until significant deterioration causes under-performance to an unacceptable degree. The main concerns of the durability function are health and safety, cost, and disruption to building use [Hutcheon and Handegord, 1989; NBCC, 1995]. The Canadian Standards Association [CSA, 1995] addresses the durability function by way of guidelines and by providing a framework with the following notions: (i) durability that is achieved by considering the life expectancy in the design process for buildings and their components; (ii) decisions about building components taken during the life of a building and even before the development of actual design documents, which affect all subsequent decisions and resultant performance; and (iii) beginning with the initial concept for a building, the design process should take into account the environmental loads and deleterious agents to which the building components will be exposed. The design service life of the building itself is to be taken into account for the determination of the design service life of the building components. The CSA [1995] categorizes buildings as temporary, medium life, long life, and permanent, based on the design service life in years, 10 or less, 25 to 49, 50 to 99, and more than 100 years, respectively. Other major factors to consider in determining the design service life of building components are: (i) exposure conditions; (ii) difficulty and expense of maintenance; (iii) the consequences of failure of the component in terms of costs of repair, disruption in operation, and hazard to building users; (iv) current and future availability of suitable components; (v) the design service life of the building; and (vi) technical or functional obsolescence [CSA, 1995]. The CSA [1995] discusses the following design considerations in achieving durability requirements:

- Convention and innovation: The existing standards, and proven design and construction practices are relatively safer than the use of innovative technologies, which require sufficient modelling or testing;
- Materials selection: The materials selected should have compatible physical and chemical properties when in contact or close association; have physical

and chemical properties appropriate for the environment; and have physical properties compatible with anticipated differential movements;

- Detailing: The envelope section should be clearly detailed. It should provide barriers and seals to resist the infiltration or deposition of moisture or other deleterious agents. It should provide air-seals, drainage and venting between and through assemblies to minimize the accumulation of moisture or other deleterious agents. It should minimize the risk of local concentrations of moisture and deleterious materials through appropriate geometry, form and placement of components. It should minimize exposure of components to environmental loads;

- Ease of construction: Buildability is an important factor to be considered to achieve the necessary level of quality in terms of durability;

- Operation and maintenance: An allowance for ease of access for inspection, testing, maintenance, repair and replacement of components and assemblies during the construction phase and throughout the service life of the building; and identifying building components requiring special care are two important issues of durability to be considered;

- Functional obsolescence: The designer has to consider probable alterations in the future due to the changes in function; and

- Life cycle cost.

2.1.1.8 Aesthetics

The significance of aesthetics as a function is dependent upon the project requirements. Aesthetics as a concern is normally considered when the designer defines the form of the building and selects the exterior cladding and interior finishes [Rivard et al., 1995]. Aesthetics is a function of texture, color, shape and form. Aesthetics can be considered as a function that has no purpose other than to decorate [French and Vierck, 1970]. For instance, from a building envelope design point of view, the selection of exterior cladding and interior finish could be considered as decoration elements not serving other functions. Nevertheless, French and Vierck [1970], also discuss a category of design where aesthetics and other main functions are closely allied. For instance, the selection of exterior cladding layer for embellishment purpose may also prove to solve the rainwater ingress problem. To state some examples, a particular texture to the surface of the exterior wall may provide good run off for rainwater thus aiding in the reduction of moisture absorption, and applying light colors in the exterior surface may lower the surface temperature thus reducing the heat loss. The aesthetics aspect of the building envelope is a subjective issue, normally handled by virtue of the designer's experience, intuition and judgement. Added to the above functions, aesthetics has proved to have other purposes, such as psychological impact.

Archer [1963] categorizes aesthetics into two broad divisions: descriptive aesthetics and ethical aesthetics. Descriptive aesthetics as Archer [1963] defines,

"...passes no judgments and sets no standards, they only measure observable facts". It deals with empirical facts about perceivable qualities and the statistics of preference. It is a natural science. Natural science (or physical or pure science) seeks to understand the nature of a phenomenon, but passes no judgment upon them. Ethical aesthetics deals with taste and appropriateness. It is a practical science. This involves a theory of perception of the beautiful. Beauty, like truth and goodness, is among the subject matters of ethics. Hence, decisions regarding aesthetics, though they may contain fractions of descriptive nature, are prominently perceived as ethical [Archer, 1963].

2.1.1.9 Other functions - Control of Solar Radiation, Noise, Airborne Pollutants, and Smoke and Fire Propagation

Apart from the functions discussed above, depending on the project requirements, the design of the envelope has to consider the following special functions: control of solar radiation, control of noise, control of airborne pollutants and control of smoke and fire propagation. In some cases, the requirements of these special functions play a more important role than the usual functions of the building envelope system.

Heat gain by solar radiation in a cold weather climate is desirable in winter. Normally, this is achieved with fenestration facing directions where there is sunlight (e.g. facing south in Canada). However, control of solar radiation is required for other parts (such as wall sections, roof etc.), as there are indirect effects on the performance of the building envelope systems. For instance, exposure of insulation to direct sun light may cause deterioration caused by ultra-violet rays thus eventually lead to a failure in control of heat.

Control of sound through the envelope assembly is required to prevent exterior air-borne noise from entering the interior space. Normally, this control is achieved by the materials applied to satisfy other functions of the envelope section. Special measures are taken in design projects such as auditoriums and theatres.

Smoke and fire propagation are important issues that require attention when selecting the components of the building envelope. They are a special concern in the case of commercial and multi-storey buildings. All building materials are provided with a fire rating that aids in the selection process.

Control of airborne pollutants is normally handled by the building components selected to counteract other functions, and hence this normally does not require special attention.

2.1.2 Other Design Objectives of the Building Envelope System Design

In addition to the design objectives of each function discussed in the previous sections, the envelope system is evaluated through other design objectives such as energy efficiency, buildability, and construction time, in order to validate the design decisions. Analysis of energy efficiency is relatively new in the design of building envelope since it emerged after the energy crisis of the 1970's [Bomberg and Brown, 1993]. Currently it is of high concern among designers, building owners and various government agencies. Analytical models and efficient computer tools such as EnergyPlus, EE4, ESP-r, and Hot 2000 are available to evaluate the energy performance of the building envelope during the design process. In addition, there is a growing trend of knowledge development vis-à-vis prescriptive rules and suggestions. For example, the R2000 home program entitled 'Incremental Costs of Residential Energy Conservation Components and Systems', of CANMET, a division of Natural Resources Canada, established priority

Basic R2000 Building - Walls: Use 140 mm (nominal 6 in.) studs and RSI 3.52 (R-20) insulation - Basement Walls: Use RSI 3.52 (R-20) insulation - Attics: Use RSI 7.04 (R-40) insulation - Airtightness: Use air tight construction - Use triple glazing
First Upgrade Priority - Increase basement wall insulation to greater than RSI 3.52 (R-20) - Increase attic insulation to greater than RSI 7.04 (R-40) - Use high-performance windows
Second Upgrade Priority - Add slab perimeter insulation
Third Upgrade Priority - Add slab centre insulation - Increase wall insulation greater than RSI 3.52 (R-20)

Table 2.2: Priority Guidelines for Thermal Performance - R2000 Home Program adapted from [CMHC, 1999]

guidelines, as shown in Table 2.2, for improving thermal performance in two-storey houses [CMHC, 1999].

Constructability is another significant design consideration in the building envelope design process. CSA [1995] lists some of the buildability issues to be considered in order to design efficient envelope sections: (i) use the knowledge from fabricators, suppliers, and contractors; (ii) use normally available and commonly used durable materials; (iii) use standard approaches and methods of construction; (iv) consider the achievable level of workmanship (i.e. expect and allow tolerances); (v) consider sequence of construction; (vi) use simple construction techniques; and (vii) incorporate flexibility to allow future alterations.

2.2 Brief Review of Methodology Studies on Design

Design methods have been extensively studied in the fields of architecture, engineering, and industrial design in the 60s, 70s and early 80s. Nevertheless, the design process could not be clearly demarcated with theories. It is identified to be a process which may be learned and practiced in a variety of ways, but cannot be theoretically defined [Kalay, 1989]. Moreover, the situation itself influences the practice of design process [Jones, 1983]. Thus, there is a lack of design theories on methodologies for building envelope design. However, a methodology is needed in order to develop a computer tool. This section presents a study of the existing general theories on design to help define the basis for a methodology.

2.2.1 Analysis of Design Definitions

Archer [1965], Asimow [1962], Matchett [1968], and Simon [1968] perceive design as a goal directed decision-making activity in which the objectives are known at the start of the design process. Most engineering design situations fall under this category. Following are the significant characteristics of the design process identified from the above sources: (i) goals or needs as objectives direct the design process; (ii) design involves problem solving and decision making; (iii) design aims at optimum solutions; (iv) circumstances and constraints direct the design process; and (v) design involves planning or devising methods to derive design solutions.

Diverging from the common idea of design as an objective governed process, Archea [1987], Bijl [1985], Page [1966], and Reswick [1965] look at the design process as a purely creative and exploratory activity of possibilities, where the exact outcome is unknown at the start of the process. It is determined by the investigative process itself. Industrial design projects could be quoted as examples. Some of the characteristics notable from the above sources are: (i) design exploration through a combination of various components; (ii) a pre-defined set of rules guide the design process; (iii) the actual path of the design process is not known; and (iv) current knowledge is applied to evolve creative and innovative solutions.

Building envelope design predominantly falls in the former category, where the designer is aware of the final outcome (building envelope) and the objectives (the functions of the building envelope). Occasionally, the designer might propose new solutions by creativity, as explained in a later category.

2.2.2 Review of Design Methods

Jones [1983] compiles 35 different design methods identified from architecture and industrial design. The methods include logical procedures such as systematic search and systems engineering; data gathering procedures such as literature searching and the compiling of questionnaires; innovative procedures such as brainstorming and synectics; taxonomic procedures such as morphology and system transformation; and evaluative procedures such as specification writing and the selection of criteria. Depending on the particular design situation the appropriate procedures are applied.

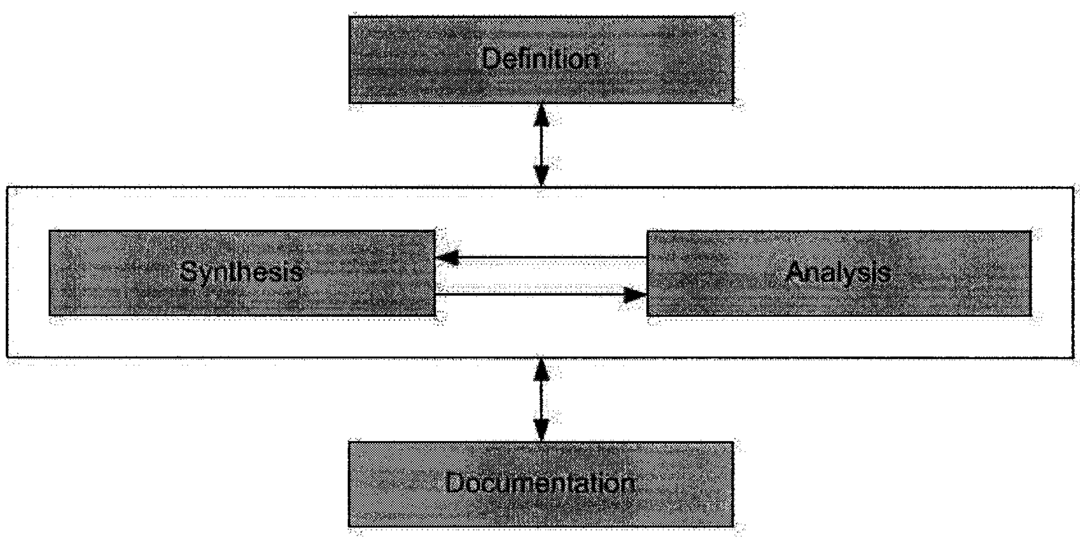

Figure 2.2: Rational and Systematic Design Approach

Jones [1983] classifies the design methods generally into two distinct approaches: rational and systematic approach, and intuitive approach. In a rational and systematic approach, the designer works with the available information and follows through a planned sequence of analytical, synthesis and evaluative steps in cycles until the recognition of a satisfactory solution. This approach follows a four-stage process, as represented in Figure 2.2: (i) definition of objectives, variables, and criteria; (ii) synthesis of design solutions; (iii) analysis and evaluation of design solutions; and (iv) documentation of solution for execution.

The intuitive approach is common in practice among designers. It may be an inherent characteristic of the humans (designer) to generate output without being able to explain where this motivation originated. The common characteristics identified in this approach are: (i) in addition to the problem inputs, the designer also considers the previous problems and experiences; (ii) the outputs are random, but often fast; (iii) the generation of output requires time to assimilate and manipulate the design problem with a mental picture and then there may be a sudden 'leap of insight' through which a complicated problem is transformed into a simple one; and (iv) the generation of solutions is dependent on the problem definition [Jones, 1983].

Archer [1965] discusses two radical approaches of the designer: imitation and innovation. Imitation is a method in which the designer uses the already worked-out solutions of his/her own work or the work of experts. This requires a library of solutions from where the designer may pick a solution based on the project conditions. It also requires a technique to co-relate the new problem with the cases in the library. It involves human intervention for logical analysis or intervention of analytical methods to analyze the solutions. Traditionally, design by imitation is followed widely in almost all design disciplines [Jones, 1983]. Innovation is a method in which the designer tries to come up with a new solution. This involves design generation and analysis of the generated solutions. The design generation requires objectives, inspiration, and creativity. The analysis part requires a logical mind, rules of thumb and scientifically proven methods for analysis. In general, the design process is a mix of both attitudes [Archer, 1965].

Technological innovations are increasingly emphasizing a systematic approach in order to solve problems of the society rather than an artefact approach. Particularly for automating any process using information technology a systematic approach is required. Archer [1963] proposes a systematic process for the architectural design based on constraints. Constraints influence the design process and set a field of manoeuvre (an imaginary framework within which the designer controls the thoughts for a solution), which lead to the design goal. The field of manoeuvre can either lead to an open design situation or a closed design situation, depending on the number and size of constraints. They can be tracked as fragments of a design problem and can be charted as a checklist, in which solving the fragments of the checklist would provide the solution to the design goal. This checklist strategy helps the designer to make a comprehensive and informed design decision. Rowe [1987] states that the "the design process is a mixture of both design by constraints and design by personal attitudes and prejudices, as designers move back and forth between the problem as given and the tentative proposals they have in mind".

In practice, the diverse challenges of a design problem, such as architectural production, are tackled through a process of graphical thinking. Graphical language as denoted by Laseau [1980] serves two purposes: it reinforces the logical thinking of the architect, and it helps to convey the idea to other members involved in the project. Laseau mentions, "Most creative architects had developed impressive freehand sketching skills and felt comfortable sketching while thinking. Some architects drew observations or design ideas in small sketchbooks they carried with them at all times [1980]." The successive stages of a process are most often recorded graphically. In the early stages, the conceptual drawings are, made of free hand (quick sketches and diagrams), and in the later stages, they are in highly formalized graphic languages such as those provided by descriptive geometry [Laseau, 1980]. Laseau reports that the design process can be thought of as a series of transformations morphing from uncertainty to information.

2.2.3 Review of Characteristics of the Design Process

Design is one of the most distinguished human traits. It is an intelligent behaviour in evolving solutions. Some of the basic qualities expected of a designer are knowledge in the field, working experience, inventive ability, knowledge of materials and processes, and the ability to represent the thoughts and design solutions [French and Vierck, 1970]. Jones [1983] perceives the characteristics of designers from different viewpoints, such as: (i) from the creative viewpoint, the designer is a black box from where originates the mysterious creative leap; (ii) from the rational viewpoint, the designer is a glass box inside which can be discerned a completely explicable rational process; and (iii) from the control view point, the designer is a self-organizing system capable of finding shortcuts across unknown territory.

The following characteristics are essential to find effective solutions:

- Design is a complicated act where information related to the subject is mixed-up and overlapped. The designer is required to be organized in the design process;
- The designer should be capable of approaching the design in a holistic fashion. For each decision, a designer needs to consider multiple functions and factors at a time;

- The graphical language is used to serve two purposes: it reinforces the logical thinking of the architect, and it aids in conveying the idea to other members involved in the project;

- Design is an iterative process where a solution is refined at every stage of the design process. The designer normally traverses back and forth between the different design paths, components and design stages [Rowe, 1987; Parker et al., 1998];

- The design process contains stages of decision making with respect to the entities of the subject. Decision-making about each entity at every stage of the design process requires the cross-referencing and evaluation of other entities and the preceding stages. Hence, one of the inherent characteristics of a designer is to verify across different entities and different stages;

- The generation of a design solution is accompanied with analysis and evaluation, especially in engineering design problems. Apart from the support of proven scientific principles and calculations for analysis and evaluation (referred as analytical methods), the experience and knowledge applied through logical thinking of designers (referred to as logical methods) also aids in attaining efficient design solutions. Hence, the designer requires both analytical evaluation capabilities and logical evaluation capabilities;

2.3 Brief Review of the Building Envelope Design Process

Bedard [1989] represents the research space of building design through a 3P model, as shown in Figure 2.3, which aids to understand the scope of the building envelope design process. Building design is perceived as a three dimensional model, with the product, process, and participant along the X, Y and Z-axis, respectively. The envelope system, as indicated in the diagram, is identified to be comprised of exterior walls, roofs, windows, and doors as product components. In addition, Rivard et al. [1995] include slab on-grade and cantilevered floor to the product component list, and classify the exterior walls as either above ground wall or foundation wall. Although the design of these product components makes up the major part of the building envelope system, the design of junctions and connections are required to complete the building envelope design. The conceptual stage, preliminary stage, and detailed stage are represented as the design stages of the process. In the conceptual stage, more abstract design decisions are made such as the form and dimension of the building, structural system, spatial requirements and zoning. This stage is handled manually by the designer, using sketches, schematic drawings and rough specifications of exterior as well as some interior materials. At the end of the conceptual design stage of a building, most of the following aspects of the envelope are known: (i) shape of

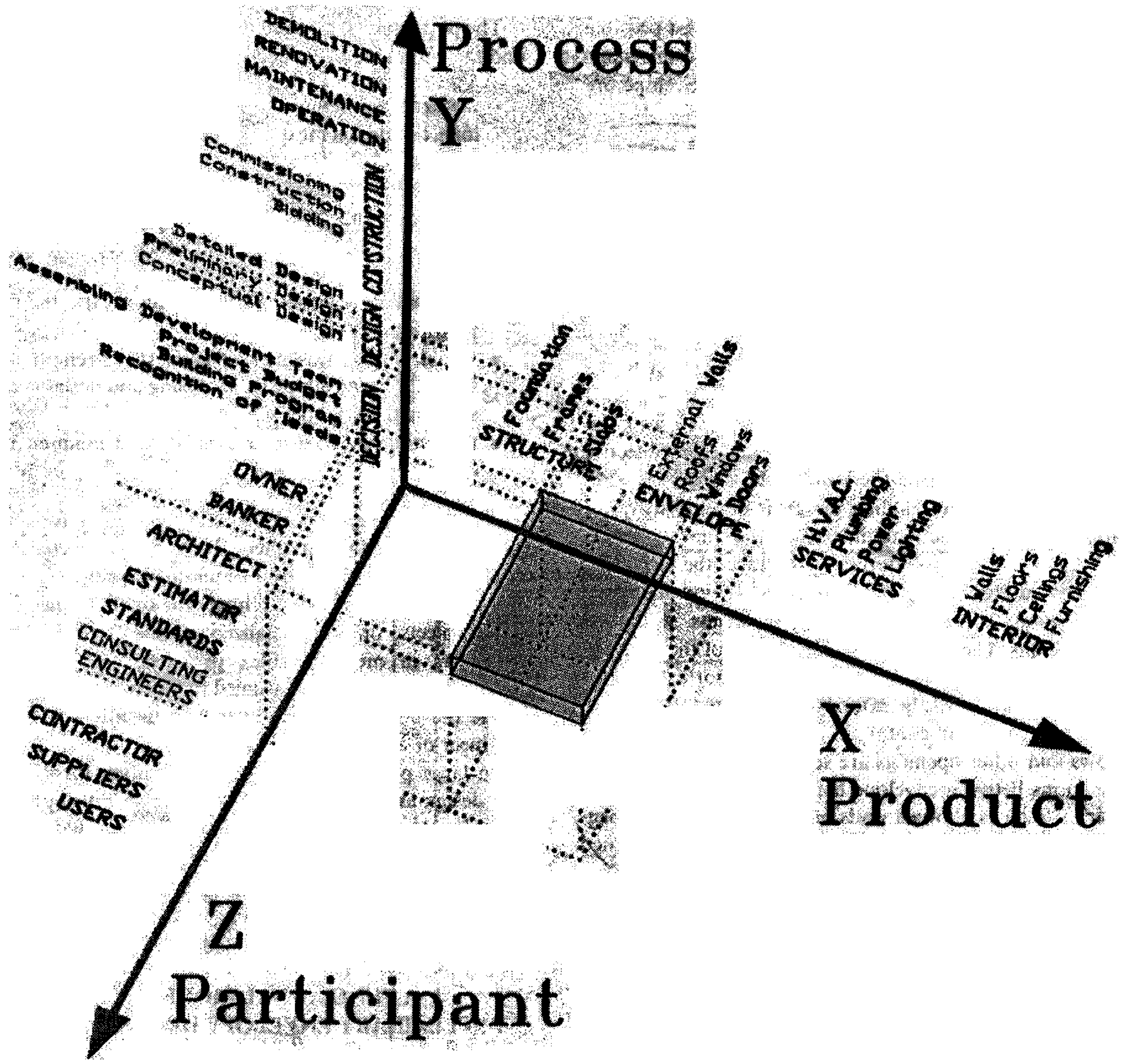

Figure 2.3: 3P Model Representation of Building Design Process as per [Rivard et al., 1995]

building; (ii) types of cladding; (iii) whether the envelope components are load bearing or not; and (iv) the type of structural system within the envelope. It is difficult to computerize the conceptual stage. In the preliminary stage, the building is brought to a higher level of resolution by defining more detail in the building systems. During the preliminary design stage, with respect to the building envelope system, the designer deals primarily with the composition of major envelope assemblies such as exterior walls, foundation walls, slabs on grade and roofs. In this stage, the design of windows, doors, connections and junctions are also handled. The decisions of the envelope system are predominantly handled at the preliminary stage. In the detailed design stage, a complete description of the building is provided by specifying and dimensioning the components. The information and instruction for the execution of the designed building is provided through construction drawings, shop drawings and specifications.

The functions of the envelope system, which are viewed as design objectives, also determine the participants to be involved in a design process. For example, in case of a theatre design where the main design objectives of the building envelope are to control noise from the exterior and reflect interior sound as desired, the project may involve an acoustician. The participants and the kind of support rendered by each participant may vary depending on the stage of the building envelope design. For example, the architect may be the sole participant in the conceptual stage, whereas consultation from other specialists may be required in the preliminary stage of the design process. Each of the participants exhibit different attitudes and working trends in the design process. For example, an architect relies more on logical thinking and intuitive decisions than on analytical methods, whereas specialists such as the building envelope designers, estimators, and acousticians rely more on analytical methods and scientific calculations. The variety in the approaches of the participants in terms of the methods used and parameters considered, amplifies the complexity of the building envelope design process.

Building envelope design entails the selection, composition, and specification of all the components of the building envelope system. The process is integrated into the building design process. It extends from the conceptual stage to the detailed stage. The design of each component of the envelope involves the selection and configuration of its constituents from among the numerous materials and system components available [Gowri, 1990]. A sequence of materials is selected and configured based on the traditional strategies developed in the industry either through proven design practices or scientific investigations. Some strategies traditionally followed to compose the envelope section are (as explained in greater detail above): insulation to control heat flow, air retarder system to prevent air leakage, vapor barriers to limit water vapor diffusion, cladding and flashing along with proper design of junctions and connections to avoid rain penetration, glazings to allow lighting and views and to control radiation, sound barriers to reduce noise transmission and evaluation of fire propagation characteristics of materials to achieve prescribed level of fire safety. The order of materials is significant in the composition of the envelope assembly [Rivard et al., 1995]. Nevertheless, the selection of materials is seldom straight forward, as the strategies and decisions in the design process to achieve each function are strongly inter-related, particularly in the case of control of heat, air, and moisture.

A large part of the identified functions deal with the control of heat and mass transfer, which contributes directly to the energy efficiency performance. Hence, in most cases the configuration of each of the building envelope components and the process through which the decisions are made largely depend on the difference between the indoor and outdoor environmental conditions [Hutcheon and Handegord, 1989]. The greater the difference between the inside and outside environments, the greater the stress or load imposed on the envelope [Rivard et al., 1995]. In the case of cold climates such as Canada, not only the difference between the indoor and outdoor conditions is high, but also seasonal conditions reach extremes. In such extreme climatic conditions, the deterioration of envelope components may be rapid. Hence, the performance of the envelope system in terms of durability is significant, which goes hand in hand with the control of flows of heat and mass. This increases the complexity of the selection process of appropriate building envelope systems.

The selection process is normally directed by design objectives, which are framed on the basis of project requirements. It reconciles two value systems: the qualitative aspects stemming from architectural design and the scientific requirements of building science and engineering. The decision-making approach on subjective issues, like colour, texture, form and pattern, in architecture is open-ended, and is lightly bound by scientific rules, codes or regulations. It requires the intervention of the designer to evaluate and make design decisions. In the case of building science and engineering, there is limited support available in terms of analytical methods, ranging from simplified methods to sophisticated methods, to understand and evaluate the performance of the building envelope in different design conditions. Nevertheless most of these methods are only useful to evaluate and seldom aid the design process. There is a larger dependency upon logical methods to support the building envelope design process.

2.3.1 Modelling of the Building Envelope Design Process

The building envelope design process has not been defined with any specific systematic model, as is the case with other design processes such as architectural design and industrial design. It is a process involving diverse methods, disciplines, and participants. Moreover, it is a relatively new discipline requiring developments in the understanding of the behaviour of building envelope performance. Nevertheless, there are attempts to model the building envelope design process, mostly in the development of tools for automation. The attempts at modelling the building envelope design process focuses primarily on the science and engineering aspects, and are more often concentrated on one or few issues. An analysis of the existing models would provide an understanding of the characteristics of the building envelope design process.

Rivard et al. [1995] through a functional model retraces the preliminary building envelope design process, as represented in Figure 2.4, broken down into

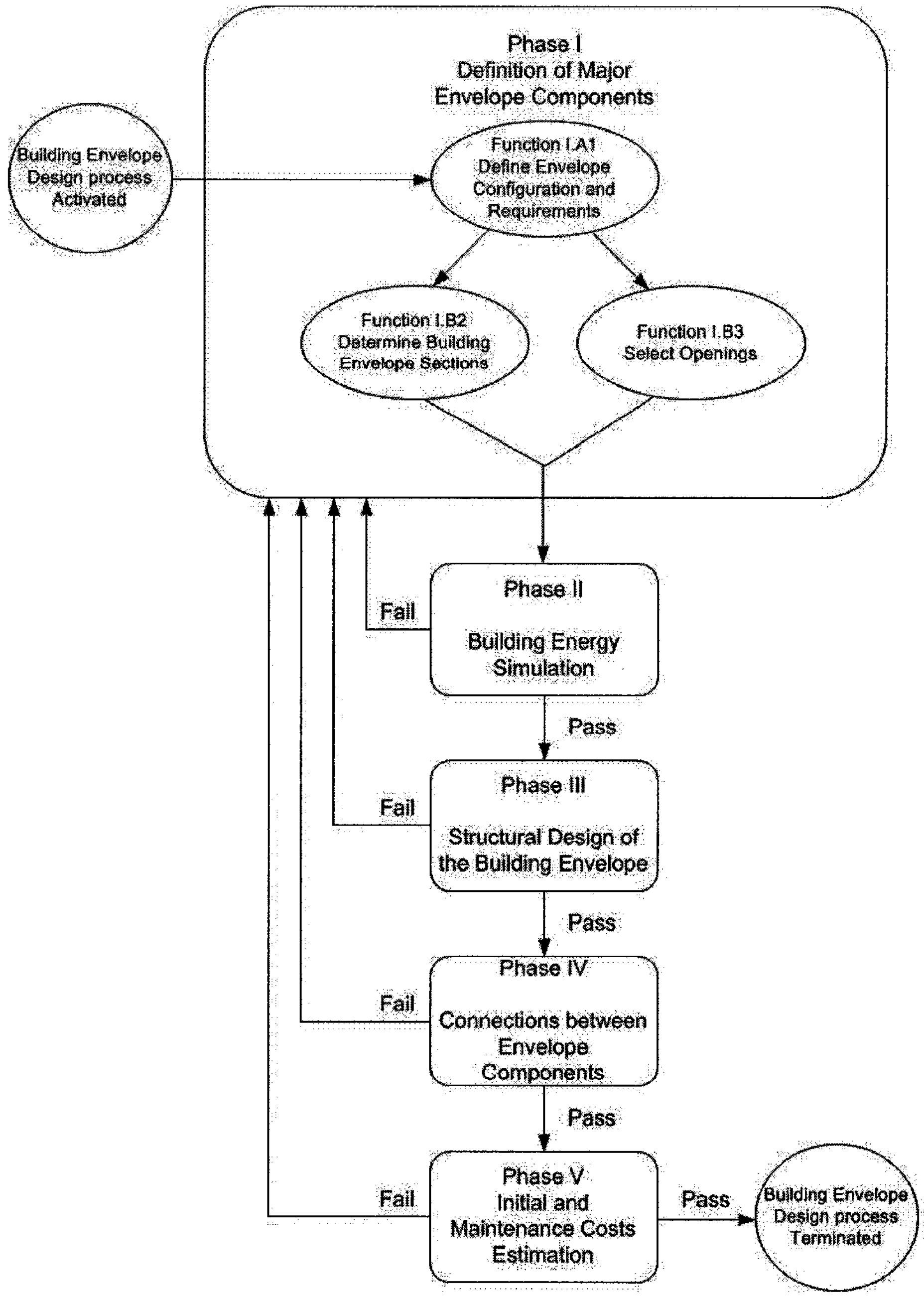

Figure 2.4: Preliminary Building Envelope Design Process as per [Rivard et al., 1995]

five major phases: (i) definition of major envelope components; (ii) building energy simulation; (iii) structural design of the building envelope; (iv) detailing of connections between envelope components; and (v) initial and maintenance costs' estimations. The model suggests a procedural approach, assuming phase 1, the definition of major components, as the core of the building envelope design process. The phase 1 is subdivided into three major functions: (i) definition of envelope configuration and requirements; (ii) determination of building envelope sections; and (iii) selection of openings. The determination of building envelope sections involves the selection of a sequence of materials, as discussed earlier, for the various envelope components. The resulting envelope sections are evaluated with respect to the design objectives such as control of heat flow, control of vapor diffusion and condensation. Following the design decisions about the envelope components; the process handles energy performance analysis, structural design of the building envelope, design of connections and junctions, and economical evaluations. In case the design decisions of the components in any of the stated stages fail to meet the requirements the process is iterated from the start.

The determination of the building envelope section process is demonstrated in figure 2.5 using a functional and data flow analysis. A functional and data flow analysis helps to understand the data requirements, data generation, usage of data in the process, data transfer between activities and the participants involved in each activity [Rivard et al., 1995]. It was represented using the PArtitioned eNgineering DAta flow model (PANDA) developed by Phan and Howard [1992], and is the second step of the Primitive-Composite approach, used to identify a structured methodology for modelling facility engineering processes and data to achieve integration. PANDA was adopted to analyze the operation and the data flow in the preliminary building envelope design process since it can represent together the participants, the activities, and the data involved. Three partitions, as shown in the figure, were used to represent the participants, various activities involved in the process, and the various data items required by the activities of the process.

The environmental control (control of heat, air, and moisture) in building design, the core functions of the building envelope, requires iterative analysis and a flexible design process. Bomberg [2002] proposes the following major stages for the building envelope design process for environment control:

- Selection of a suitable material: The designer searches for a suitable material considering the material properties. For example, in the case of an air barrier system design, the materials are analyzed primarily for the air permeability. Along with it, the pliability, adhesion, and means of attachment, connection and support, long-term performance, material aging, stress and deformations during service as well the projected cost of repairs and maintenance are considered;
- Detailing of the building envelope: The designer specifies architectural details such as intersection and joints between building elements;

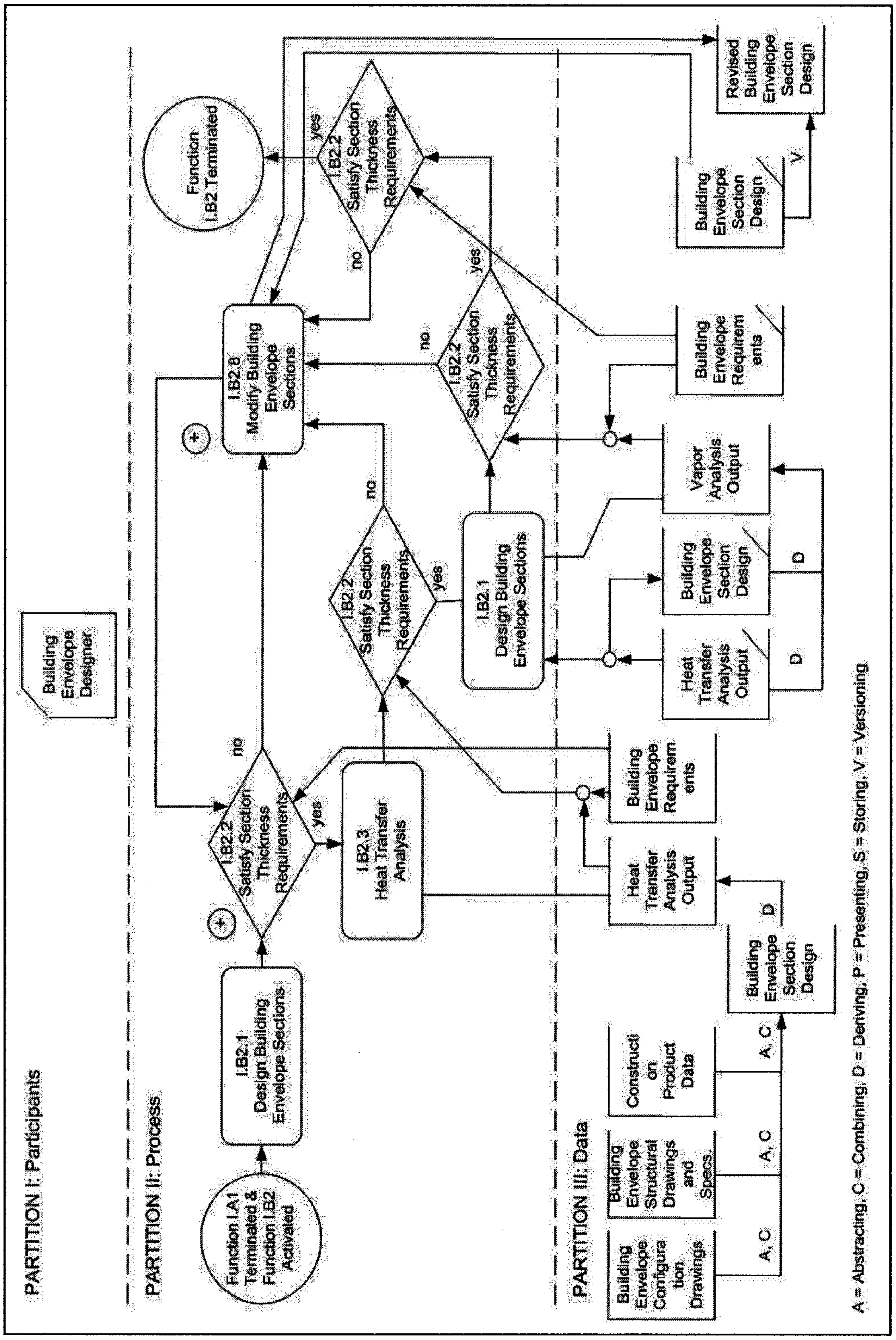

Figure 2.5: Functional and Data Flow Analysis of Determination of Building Envelope Section as per Rivard et al. [1995]

- Analysis of the performance of the building envelope: The building envelope is analyzed for rate of air leakage, location of leakage, risk of drafts and impact on condensation. The designer verifies the performance with the experts of other systems such as structural, mechanical, and electrical systems;

- Constructability: The designer reviews the constructability aspects such as material installation under the design conditions, level of labour skill required for installation, and construction tolerance;

- Risk identification and management: The building envelope design should comprise redundancy, in order to manage risks and failures. For instance, the air barrier may be punctured or interrupted, leading to air exfiltration. Depending on the likelihood of such failure, the designer may consider methods to drain or dry out the moisture accumulation resulting from such failures.

Gowri [1990] derived a model for the building envelope design process in order to automate the generation of alternatives to be used in the Building Envelope Analysis and Design System (BEADS) tool, as shown in Figure 2.6. BEADS is explained in detail in the 'Existing computer tools' section. The generation of design alternatives begins with the selection of a basic wall type based on the designer specified structure type, building type and maximum

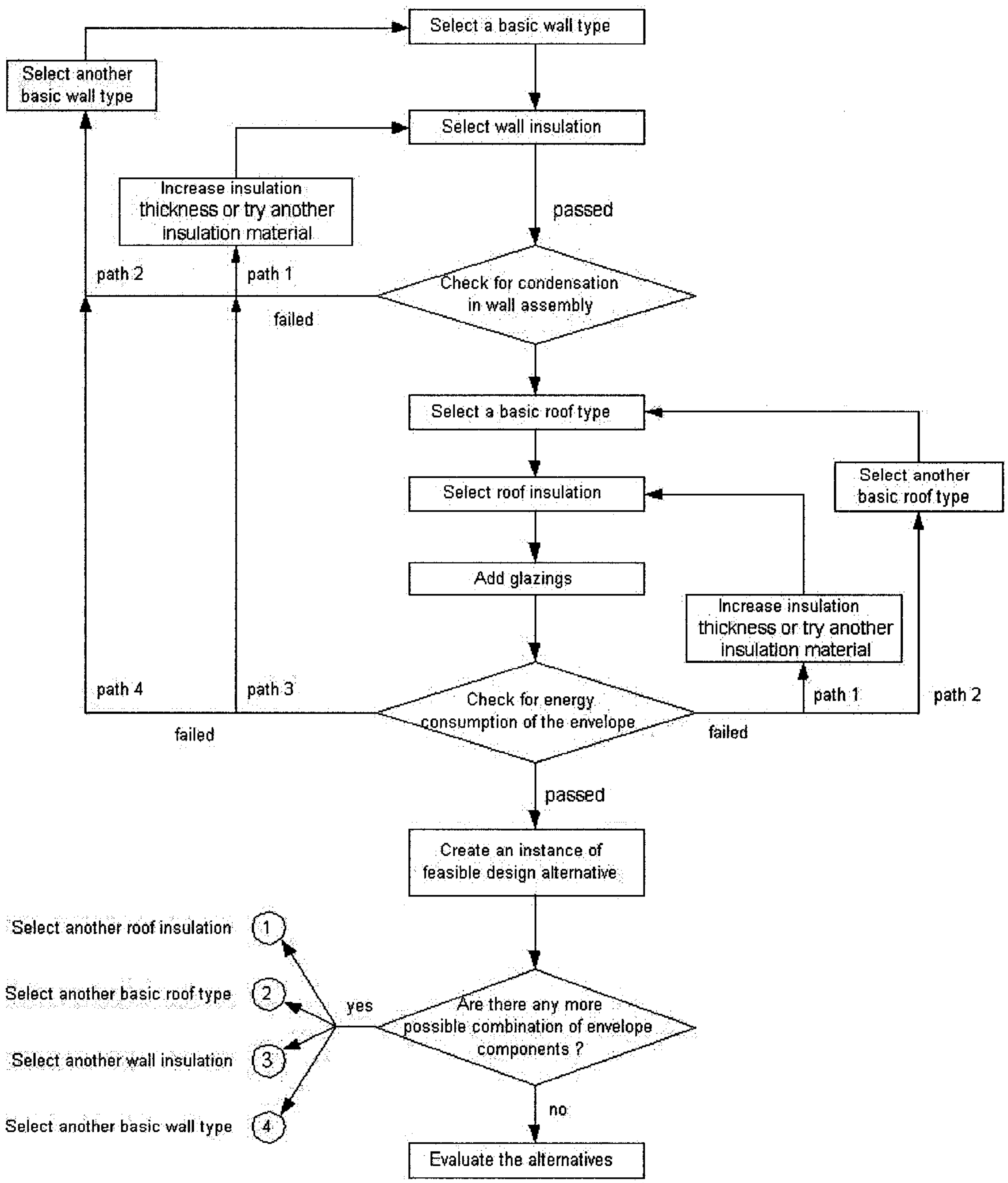

Figure 2.6: Building Envelope Design Process as modeled in BEADS

permissible thickness. If required, the basic wall type is redefined with an appropriate structural material. An appropriate insulation with a particular thickness is selected by considering the total thickness requirement and total thermal resistance to be achieved. The redefined wall is then analyzed for moisture diffusion, particularly interstitial condensation using a simple static model. The alternative is eliminated if it shows some signs of condensation in the wall assembly. If the condensation check is verified successfully, then the generation process proceeds to identify a suitable basic roof type and the roof insulation.

Simon and Hauglustaine [2003] elaborated a building envelope design process for masonry cavity walls with the following steps: (i) selection of exterior cladding; (ii) selection of interior cladding; (iii) selection of strategies to control water and vapor; (iv) selection of structural support for the claddings already selected; (v) selection and localization of thermal break in terms of insulation; (vi) check for total thickness; and (vii) choice of construction.

2.3.2 Issues of Architectural Design

Although the issues in terms of functions, methods, and design objectives are predominantly science and engineering oriented, architectural issues are significant as they are an integral part in the building envelope design process. For instance, the selection of cladding of a building envelope in terms of aesthetics and style (an architectural issue) is important, as the façades of structures in certain cities, are considered to define the character of an urban environment. Moreover the building envelope design process is normally handled by an architect, thus making the architectural issues increasingly important. The working trend and attitude of the designer influences the design process.

In the case of the building envelope design process, achieving aesthetical requirements is identified as purely an architectural issue. Aesthetics is dealt with in detail in section 2.1.1, 'Functions of Building Envelope System'. Design for aesthetics is inter-related with the selection of exterior and interior finishes [Rivard et al., 1995], which in turn may influence the strategies for selection of other components such as selection of structural elements and strategies to control liquid water. For example, the designer's choice for a curtain wall as an exterior cladding could lead to a change in the choice of structural elements from wood structures to steel frames. Similarly, the selection of other components could also impact the choices for exterior and interior finishes, in which case the designer's intervention is required to make a logical evaluation as well as subjective design decisions.

Architectural issues are subjective to the designer's knowledge, experience, and intuition. It is open-ended, and is less bound by scientific rules, codes or regulations. However, a systematic approach proves to be more advantageous than an artefact approach: (i) it is required for more technological innovations and advancements; (ii) it provides a clear understanding of the goal, the problem, and the process of design; and (iii) it attempts to provide a holistic solution for any design problem [Archer, 1963]. A systematic design approach could be developed to support and refine the architectural design process; however the incapability of evaluating design decisions entails a logical approach which can only be handled by the capabilities of a human designer. Architectural design involves a complex array of analytical, logical and subjective issues. The primary challenges of the architectural design are to be more responsive to needs and to be more predictable and reliable [Laseau, 1980]. It involves synthesis and judgment on the basis of tradition, intuition and experience.

Archer [1963] identifies a systematic approach for design process, through fragmentation and systemizing. A design process such as building design is a goal-seeking activity, which can be divided into fragments of design problems using guidance factors like constraints in case of a close-ended project (a problem primarily driven by constraints) [Archer, 1963]. The fragmented design problems can be more easily solved than the un-fragmented whole design problem. In the case of the building envelope design process the main goal is fragmented into design objectives. Some of the primary characteristics of the architectural design process are generating creative ideas, graphical thinking, logical reasoning, case-based reasoning (reasoning by experience), and fragmentation and systemising the design process.

2.3.3 Building Science and the Engineering Approach

Building science provides the base to understand the performance of building envelope systems. It embraces the principles and methods from multiple disciplines such as material science, physics, chemistry, climatology, and project management. A design process in which the designer is aware of the behaviour of the envelope system through the aid of building science provides better building envelope performance results specifically in terms of building failures and energy efficiency. Although research in building science principles to help building envelope design commenced around the late 1930's, it was mostly introduced in practice after the energy crisis of the 1970's [Bomberg and Brown, 1993]. The advancements in understanding the behaviour of building science principles have reached good heights.

Nevertheless, building science and engineering issues of the building envelope design process cannot be solely solved using the available analytical capabilities with confidence and completeness. In almost all instances, there is interdependence between the various scientific methods, such as experimental, numerical and analytical, and the decisions carried out by humans. These issues must be handled using both analytical and logical approaches. For instance, from a heat, air and moisture (HAM) control point of view, the analysis of the performance of envelope assemblies must consider the envelope as an integrated system where constituents are connected to each other and where heat, air and moisture have interrelated effects. Hence the building envelope design problems related to HAM control in practice are usually tackled by logical thinking with the help of a knowledge base or through the support of experts, seasoned with proven design situations and scientific results. The analytical approach involves specific testing and analysis considering the material, structural, and environmental factors through the use of a complex array of tools, models and data. The logical approach encompasses broad qualitative assessments based on experience, judgement and knowledge that make a building envelope function [Bomberg, 2002].

2.3.3.1 Review of Principles of Heat, Air, and Mass Transfer

Building science gives a better understanding and formulation of the behaviour of physical factors such as heat, air, moisture and acoustics in envelope systems. Thermodynamics contributes to the understanding of the behaviours of heat flow in building envelope sections. Hygrothermal research is the division in building science aiding in understanding the heat and moisture performance of a building envelope. Analytical models support the understanding of heat, air and moisture behaviour in a building envelope. Nevertheless, there are two types of evaluation: assessment based on logical perception, evaluated by the virtue of knowledge and experience of the designer, and quantitative evaluation based on results of testing and analysis.

The goal in order to control the environment is to provide better energy efficiency. The energy performance of the building envelope includes three main considerations: heat transfer through the envelope (the quantity of heat transferred through the walls, windows and other elements of the building envelope), air leakage characteristics or air exchange rate (the quantity of heat needed to bring the temperature of the outdoor air to that of the indoor air) and differences in temperatures between the inner and outer surfaces of the building envelope [Bomberg, 2002]. Bomberg [2002] categorizes heat transfer evaluation under four different manners of calculating conductive heat transfer, each with increasing precision. The first approximation considers only the plain, insulated areas of the envelope, ignoring the multidirectional heat flows. The second level of accuracy additionally considers how the actual thermal resistance of the wall differs from the one-dimensional flow model. The third level of accuracy adds two- or three-dimensional calculations of heat flows, while assuming that the steady-state representation sufficiently describes the thermal performance of the building. The fourth level incorporates transient weather conditions and the effect of the thermal mass on the overall thermal performance.

Airflow through the envelope section is quantified by air change per hour. The envelope section should be as airtight as possible. NBCC [1995] and other regulations consign a small allowable value for air leakage. Though the direct effect of the airflow is not the major concern, the mass transfer of heat and moisture through air infiltration and exfiltration causes problems at three levels: human health and comfort; deterioration of building envelope components; and deterioration of building structure [Kumaran, 2001]. Nevertheless, prediction of airflow is seldom used in the building envelope design process, except in supplementary cases such as standardization, renovation and testing of the finished building. A logical approach for design synthesis and evaluation is applied for airflow control.

The primary modes of moisture transfer through the building envelope are liquid water ingress and water vapor migration [ASHRAE, 1997]. ASHRAE [1997] lists some of the most important moisture transfer mechanisms: liquid flow by gravity or air pressure difference; capillary suction of liquid water in porous building materials; adsorbed water movement and liquid diffusion by moisture content differences; movement of water vapor by air movement; and water vapor diffusion by vapor pressure differences. Vapor diffusion through the building materials across the envelope section is directly proportional to the area of the building material, the vapor pressure differential between the two faces, the resistance coefficient (function of the material), and is inversely proportional to the thickness. Condensation is the effect due to vapor diffusion and is a function of both the moisture content of the air and its temperature [Trechsel, 2001]. It is the process of conversion of water vapor into liquid moisture, which occurs at the point where the air reaches the saturation vapor pressure. In practice, the control of liquid water-flow and control of vapor flow by air movement through envelope sections are primarily handled using logical approaches over analytical approaches, as there are seldom any simplified models available.

The analysis of the performance of envelope assemblies with respect to HAM control must consider the envelope as an integrated system where constituents are connected to each other and where heat, air and moisture have interrelated effects [Derome, 1999]. Compared to heat transfer, moisture transfer is a more complex phenomenon that involves different materials (also affected by heat transfer), and moisture (vapor and liquid) movement and accumulation. Also, moisture transfer has a slower time of response. The many parameters involved in moisture movement (i.e. time, temperature, relative humidity, moisture content of material, sorption history) make the description of its physical process complex. Models aiding the evaluation of behaviour of heat, air and moisture can be first denominated into moisture models and non-moisture models, since 90% of building failures are due to moisture problems. On the basis of the capabilities to provide a realistic simulation situation, moisture related models can be categorized into three types: (i) simplified models, to simulate the effect of vapor diffusion and identify the possibilities of interstitial condensation and their location (e.g. Steady State Dew Point method or Glaser method [ASHRAE, 1997]); (ii) simplified models, to simulate the effect of vapor diffusion, effect due to rain load, identify condensation and quantify the amount of moisture contained in the envelope section with respect to time (e.g. Numerical Models recommended by International Energy Agency (IEA), Annex 24 [Hens, 1996]; and (iii) Advanced Hygrothermal Models capable of simulating realistic situations, considering complex phenomena such as air infiltration, rain penetration, moisture content dependent material properties etc., in two or three dimensions. On one hand, simplified models incorporate more limiting assumptions with respect to physics, environmental loads, geometry and material property inputs. As a consequence, simplified models cannot be applied to all building envelope conditions of interest [Karagiozis, 2001]. On the other hand, the advanced models are sophisticated to the level where they may not be used directly by designers.

2.3.3.2 Material Information

Appropriate information about materials is essential for evaluation purposes in the building envelope design process. The material information required for analysis varies with the type of model used, whether simplified or sophisticated. A database of materials and their properties are normally maintained and referred to in the building envelope design process. Generally, the properties of common materials, traditional or innovative, are obtained from various literature sources, mainly by manufacturers or testing laboratories. Also, the availability, model variations and options are provided by the manufacturer.

Kumaran [2001] enlists the following relevant material properties used for performance analysis of the building envelope generally used in simulation models with respect to environment loading:

- Thermal conductivity of the dry material as a function of temperature;
- Thermal conductivity as a function of moisture content;

- Water vapor permeability/permeance as a function of relative humidity;
- Equilibrium moisture content as a function of relative humidity;
- Moisture diffusivity as function of moisture content;
- Water absorption coefficient;
- Heat capacity of dry material (constant);
- Heat capacity as a function of moisture content; and
- Air permeability/permeance as a function of pressure differential;

Designers and builders are interested in knowing the long-term performance of the building envelope. However the global differences in construction practices, building materials, weather conditions and indoor climate are so great that it is impractical to develop this knowledge only through experimental investigations. However such knowledge when required, to some extent can be generated through calculations. Building physicists, over the past four or five decades, have been attempting to develop reliable calculation methods for this purpose [Kumaran, 2001].

Added to the above properties for the use in analysis of environment control, information such as cost, available thickness, geometrical shape, color and texture are also important.

2.3.3.3 Design Conditions

Climatic information is vital for the design of building envelope, specifically, temperature, humidity, wind velocity and direction, rain and sunshine. The envelope of any building continuously responds to changes in indoor and outdoor temperature, pressure and humidity conditions [Kumaran, 2001]. Recommendations for control of heat, air and moisture in buildings should be based on the specific climatic conditions that the building will experience [Tenwolde and Colliver, 2001]. For instance, the selection of moisture control options depends on whether the local climate is predominantly a heating or cooling climate [ASHRAE, 2001b]. ASHRAE Handbook [2001b] classifies climates as heating climates, warm and humid cooling climates, and mixed climates. Heating climates are defined as climates with 4000 (°C) heating degree days (base 65°F or 18°C) or more. Cooling climates are defined as warm, humid climates where one or both of the following conditions occur: (i) 67°F (19°C) or higher wet-bulb temperature for 3000 or more hours during their warmest six consecutive month of the year; (ii) 73°F (23°C) or higher wet-bulb temperature for 1500 or more hours during the warmest six consecutive months of the year.

In the case of cold climatic conditions, the low temperatures are a concern in the design of the building envelope. Nevertheless, the lowest condition typically experienced by a location is seldom used as a design condition for the building envelope. As per the standards, the designers are prescribed with the design values designated as 1% or 2.5%, which indicates the percentage of hours in

January that a temperature below the given value occurs. The common weather data required as design conditions for analytical purposes for the building envelope design process are outdoor air temperature, indoor air temperature, outdoor relative humidity, indoor relative humidity and degree day. Degree days are a measure of yearly heating requirements given by the sum of the departures of the daily mean temperature from 18°C for each day on which the temperature falls below that value. Although degree days do not take into account wind or sunshine, they correlate well with annual heating requirements. The base of 18°C is selected on the assumption that no heating is required until the outdoor mean temperature falls below this value. The use of such simple climatic data as degree day and design temperature is being progressively replaced by more inclusive data, e.g. full year, 10% coldest year, 10% warmest year, etc.

A database of climatic type and their relevant weather data is normally maintained by the designer with reference to various locations as the climatic data vary from place to place [Hutcheon and Handegord, 1989]. The climatic data for cities are normally provided in the local or national building codes. Some sources for weather data of Canadian cities are the National Building Code of Canada [NBCC, 1995]; the Climatic Data Information of AHSRAE Handbook [ASHRAE, 2001]; the Canadian Weather Energy and Engineering Data Sets (CWEEDS); the Weather Year for Energy Calculations (WYEC); and the Canadian Weather Year for Energy Calculations (CWEC) [Tenwolde and Colliver, 2001].

2.4 Knowledge Base

Building envelope design is an information-intensive process. One form of information is the data about the materials and design conditions, while the other form is the knowledge. Knowledge plays a major role by providing support and guiding the reasoning process in typical situations [Iliescu, 2000]. Knowledge in the building envelope design process supports the decision making of the selection and composition of components for envelope assembly. It is supported with basic knowledge of the domain added with the industry knowledge. The lack of expertise of designers, which is basically a lack of knowledge, is one of the major reasons for building envelope failures. For instance, Max Baker stated in 1971 at an NRCC seminar on walls, windows and roofs, "only with knowledge of science principles and an explicit philosophy can conflicts and inconsistencies in design and misunderstood requirements and faulty execution in construction be eliminated from the present building industry where there now is a proliferation of new building types, inadequately understood new methods and materials, and a quickened pace of construction". Prominent building scientists such as Neil Hutcheon, Kirby Garden and Max Baker, over the years underlined the need for combining the science and the practice of construction. The term technology transfer refers to the diffusion of new or existing technical know-how into and throughout the construction industry. It is important to distinguish between the transfer of technology and the transfer of expertise. In other words, it is not enough to simply know something, it is important to know how to use it [Boyd and Wilson, 1975]. Transferring technology is not easy; as the volume of information increases it becomes more and more difficult for the non-specialist user to cope with it [Crawford, 1978].

Knowledge is required about the materials, processes, production methods and other related aspects [French and Vierck, 1970]. The knowledge could be obtained from various sources. Fazio et al. [1989] enlists the source of knowledge incorporated in the knowledge-based system, BEADS: building codes, performance standards, design manuals, design heuristics, material properties and cost data handbooks. This knowledge is used in both the important actions of the BEADS tool: generation and evaluation of alternatives of envelope sections. Fazio et al. [1989] includes a requirement of the BEADS tool to provide the designer an option of modifying or updating the knowledge base. The other sources of knowledge are: traditional techniques, rules of thumb and proven design practices; or knowledge attached to weather and material databases; codes and standards; regulations of governing bodies; basic theoretical knowledge of envelope section and knowledge from research organizations; knowledge of building techniques and products.

2.5 Existing Computer Support for the Building Envelope Design Process

Computer-based tools can improve the productivity of design and planning process by assisting designers and planners in many of their tasks. They improve the quality and economy of the designed facility by permitting the exploration of more alternatives and more comprehensive evaluation of the selected alternatives [Fenves et al., 1994]. The generation of alternative design solutions, unlike the evaluation of identified alternatives, is not procedural and is normally guided by the designers experience, intuition and knowledge. This is why it is easier to develop tools focusing on the evaluation of solutions, leaving behind the synthesis to the designer. Nevertheless there are some attempts in developing design tools that support the design synthesis.

Of the two distinct approaches of the building envelope design process, analytical and logical, the available computer tools deal mostly with the support of the analytical approach, which incorporate analytical and numerical methods of building science and engineering. They primarily provide quantified evaluation of the design solutions. However, the logical approach is essential for a complete evaluation of the building envelope systems, and more importantly for the generation of alternatives. Few tools are developed to help with the synthesis. With regard to architectural and engineering issues, almost all the tools focus on engineering issues because they are more easily systemized. The architectural issues are left to the designer; the design paths are normally subjective to the participant. There are almost no attempts in handling the subjective issues other than few tools that indirectly support the architectural issues. The working trend of the designer is a significant factor, which primarily influences the user interface of the design tool. A common type of user interface found among the computer-based tools that support the building envelope design process is a sequence of alpha-numeric inputs and outputs.

Rivard et al., [1995] lists a series of packages used in Canada, under the following classification: (i) drafting packages; (ii) word processors; (iii) tools to analyze and design envelope sections; (iv) building energy simulation software; (v) estimating packages; (vi) tools to analyse window energy performance; (v) tools to evaluate the structural performance of the building frame; and (vi) tools to establish maximum percentage of glazing area. Some analysis and evaluation to aid the design of envelope sections are automated such as vapor diffusion and condensation analysis, moisture storage evaluation, cost estimation, energy simulation, and structural analysis. Apart from the above, systems have been reported in the areas of code specifications processing, architectural planning and structural system selection [Fazio et al., 1989]. All of the applications are independent of each other, generally self-contained in addressing the problems of their own domain, and seldom overlap domains [Rivard et al., 1995].

2.5.1 Design Generation Tools

As already discussed, there is a scarcity of design generation tools available for the designer due to the open-ended characteristics of the design process. The

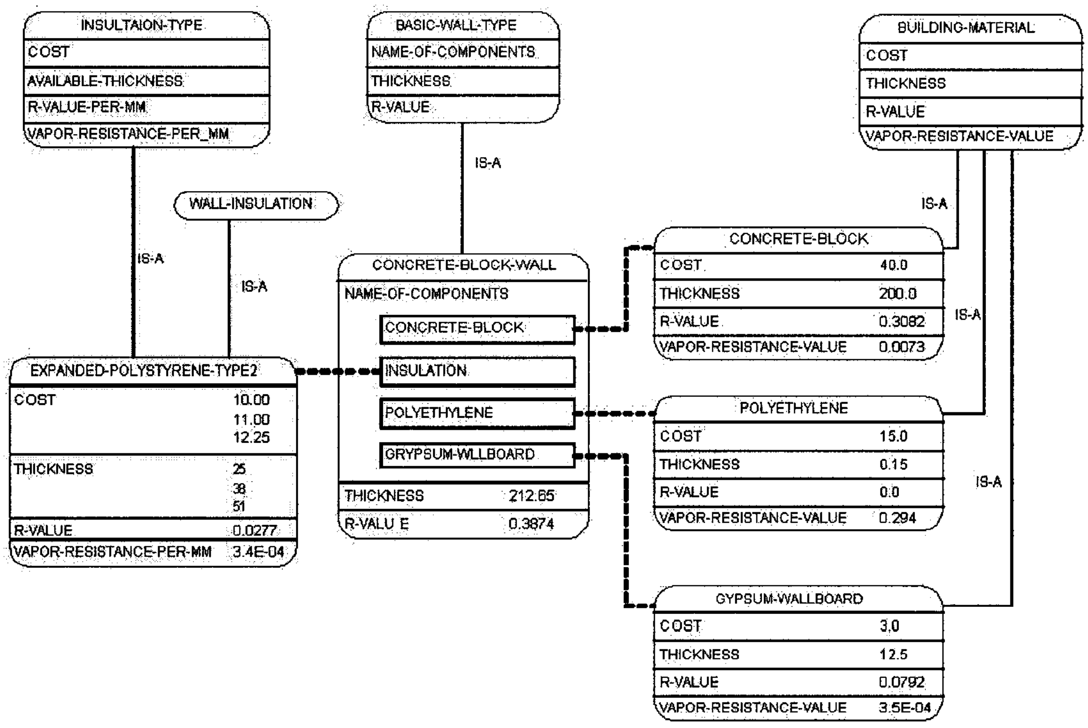

Figure 2.7: Knowledge Representation of Basic-Wall Type in BEADS

following sections discuss some of the design tools developed that support the building envelope design process.

The *Building Envelope Analysis and Design System* (BEADS) was developed to investigate the application of knowledge-based system techniques for automating the information-handling and decision-making problems encountered during the preliminary stages of the building envelope design process. It was aimed at supporting the design generation and evaluation activities of the building envelope design process. It was based on the principle that the design synthesis could be performed using a 'plan-generate-test' strategy to generate alternatives that satisfy a set of design criteria. The approach was an attempt to organize the existing knowledge of the building envelope design to create a practical design tool that assists a designer in establishing the design context, defining the performance attributes, generating feasible alternatives, and evaluating them at the preliminary design stage. A database of design weather data, material properties and constructional types for building envelope components are developed and integrated together with a knowledge base and a control mechanism for the synthesis and evaluation of design alternatives. The characteristic features of the methodology are the minimization of input information expected from the designer, as is the case in the early stages of design, and the progressive refinement of the performance objectives as design proceeds [Fazio et al., 1989].

The prototype was implemented with a limited number of performance attributes using the details of available constructional systems for building envelope components. The tool works in three stages: (i) establishing design context, using the design weather data and performance standard requirements; (ii) generation of design alternatives, satisfying the performance requirements; and (iii) evaluation of alternatives in order to select the best one. The design context is set by defining design objectives using a number of performance attributes such as thermal, acoustic and fire resistance, and the cost of materials as well as entering general information such as location of the building, building type and occupancy, gross area of external wall, gross area of roof and area of fenestration. Knowledge in terms of schema: a type of knowledge representation to describe an object as a collection of attributes (or slots) with corresponding values, are used to establish the design context. For example, the objects (or frames) 'City-Names', 'Degree-Days', 'Winter-Design-Temperature', and 'Summer-Design-Temperature' contain the attributes to define the design condition values for a specific location. The generation of alternatives involves primarily the selection of types of feasible constructional systems and the materials from a large knowledge base containing the available standard wall types, roof types, insulation materials and glazings. The prototype contains 17 basic wall types and 10 basic roof types. New basic wall types or roof types can be included in the knowledge base. From the pool of alternative design solutions, the feasible options are determined by evaluating the performance attributes such as condensation, R-value, total material cost, energy consumption, and the total thickness of wall and roof. Figure 2.7, represents a sample of knowledge for wall types contained in the system that was used for the generation of alternatives. The generated alternatives are evaluated and ranked in an order based on the specification of preferences of the designer over the performance attributes. A simple weighing method is used in the prototype implementation. The support of knowledge in the generation of design alternatives is a significant feature experimented in BEADS. Nevertheless, the alternatives generated are confined to few choices based purely on the basic-wall types pre-specified in the knowledge base providing limited scope for generation of alternatives. The selection of components, either the basic-wall type or insulation, depends completely on the discretion of the knowledge of the designer. The knowledge does not monitor the selection process of components with dos and don'ts type of support. Also, the generation of alternatives is instantaneous with the actual selection criteria hidden from the designer [Fazio et al., 1989]. This tool uses expert system with rule-based programming. The rule-based programming is one of the most commonly used techniques for developing expert systems. Rules are used to represent heuristics, or 'rules of thumb', which specify a set of actions to be performed for a given situation. The given rules are represented by 'if-then' condition statements, where the 'if' portion specifies the facts (or data), referred to as patterns, that cause the rule to be applicable and the 'then' portion specifies the set of actions to be executed when the rule is applicable. The process of matching facts to patterns is called pattern matching. A mechanism, called the inference engine automatically matches facts against patterns and determines which rules are applicable. The actions of applicable rules are executed when the inference engine is instructed to begin execution. The inference engine selects a rule and then the actions of the selected rule are executed (which may affect the list of applicable rules by adding or removing facts). The inference engine then selects another rule and executes its actions. This process continues until no applicable rules remain [Riley, 2003].

Woodbury and Chang [1995] present a design generation tool, SEED-Config, which supports the schematic design of building forms and technical systems. SEED-Config is a module within SEED (Software Environment to support the Early phases in building Design) that supports configuration designs. The configuration design is the design of a three-dimensional building model in terms of spaces, sub-systems and physical components. SEED-Config aids in generating: (i) three-dimensional building massings from schematic layouts; (ii) envelope systems; and (iii) structural systems within a building massing.

SEED-Config uses five of SEED's main concepts to organize the basic action in generating designs: (i) functional units (FU); (ii) design units (DU); (iii) technologies; (iv) states; and (v) design spaces. Functional units are the representation of the design problem and design units are the representation of the solutions. States comprises the problem (FU) and the solution (DU). SEED-Config acts to generate designs by creating and elaborating states comprising FUs and DUs to explore design spaces. Design spaces comprise states that are linked to each other by the operations required to derive one state from another. Technologies describe how a solution was solved. Woodbury and Chang [1995] defines technology as 'a collection of computational mechanisms to create and instantiate design and functional units satisfying the requirements of a class of functional units in a design context based on specific construction technology or form generation principles'. The generic SEED interface has four main components (or windows) for problems, problem hierarchies, design and design spaces. The problem and design windows display one active state at any time while the

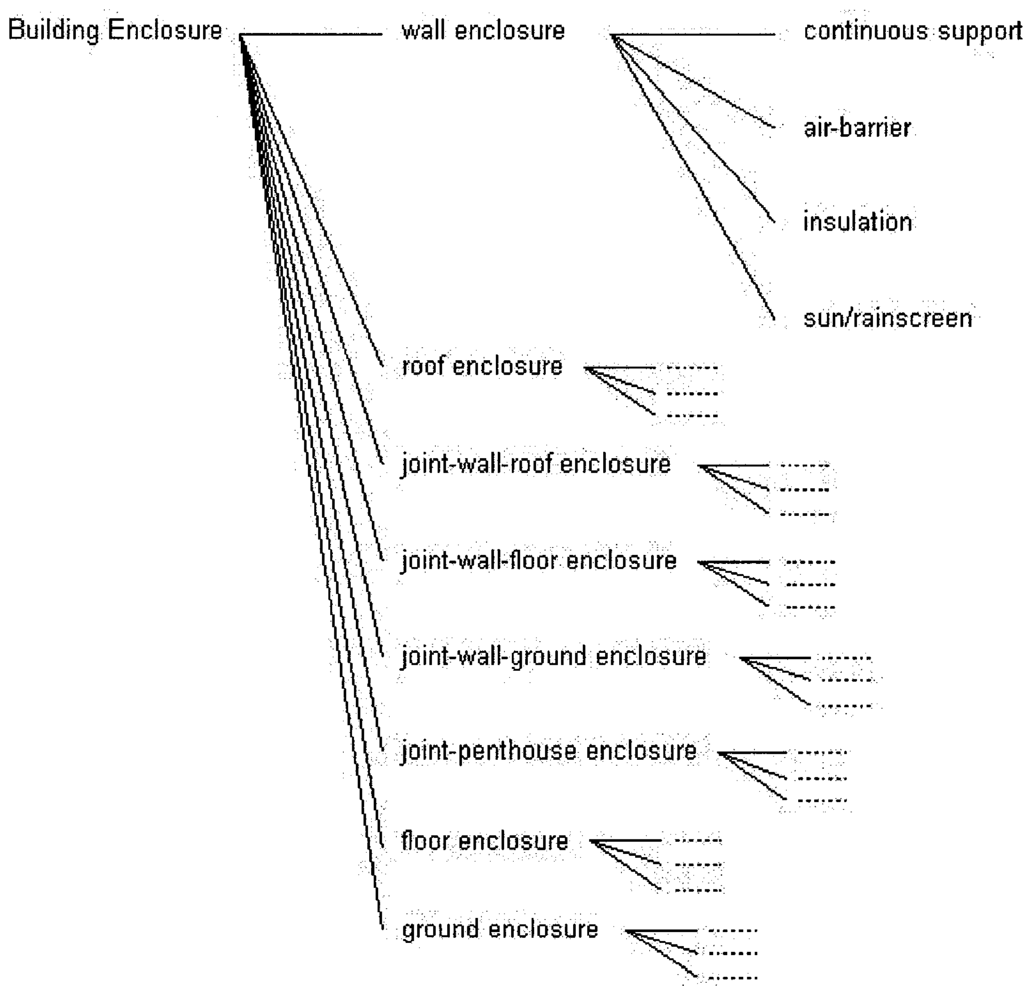

Figure 2.8: Partial Functional-Unit Hierarchy for Insulated Enclosure Adopted from [Woodbury and Chang, 2004]

related information is shown in the problem hierarchy and design-space windows. The active state is selected using the design-spaces window where all the states are listed [Woodbury and Chang, 1995].

SEED-Config defines the building envelope as a physical system that separates two spaces and includes exterior and interior walls, windows, roofs, ground slabs, and foundation walls. It focuses on one type of enclosure system that is insulated and airtight. It follows the abstract representation described by Brand [1990] that comprises four layers: continuous support, air barrier, insulation, and sun/rain-screen. Woodbury and Chang [1995] describes an FU hierarchy for insulated building enclosures, as shown in Figure 2.8, and elaborates the following insulated enclosures in terms of functional units, design units and technologies: technologies for insulated enclosures, technologies for wall enclosures, technologies for roof enclosures and technologies for wall-roof joint enclosures.

Unlike most other conventional tools that support design processes, the SEED-Config: (i) supports the generation of design alternatives; (ii) plays an active role in the development process of solutions; (iii) treats each generated design as a potential design case; and (iv) extends to creating and modifying technologies [Woodbury and Chang, 1995].

EsQUIsE is an experimental computer based prototype for capturing and interpreting the architect's sketch by locating: borderline, functional space and topology. The aim of this prototype is to compose a spatial semantic representation of the architectural project in order to feed diverse evaluation routines and serve as a tool with interface that complies with the designer's working technique. EsQUIsE uses a pen-based interface, which performs the capture and the synthesis of the lines drawn on the digital tablet. The lines are drawn in black, blue and magenta representing opaque walls, glazed walls and comments, respectively [Hauglustaine, 2001]. The tool captures and interprets an architectural sketch in real time and constructs the architectural representation of the building. A multi-agent system (MAS) extracts characters, words and some symbols (recognition) which are translated to captions and icons. The system then outlines the closed graphic borders which will be associated and interpreted as functional spaces in the architectural representation. EsQUIsE can then give the geometrical model and the topologic diagram of the design, as needed by basic evaluators and classical tools of architectural production such as cost estimation, thermal behaviour, and 3D models generation [LUCID, 2002]. This is an effort towards a better man-machine graphic mode of interaction.

To conclude, another example of a design generation tool; Archie is a prototype for a case-based design support developed by Pearce et al. [1992] for decision-making in architecture. The concept of Archie is based on the few initial decisions: (i) the system is able to support common design tasks but leaves all decisions to the user, (ii) the system applies only to the design of office buildings and (iii) the system supports the conceptual design stage [Pearce et al., 1992].

2.5.2 Evaluation Tools

The existing evaluation tools are based on scientific and analytical models obtained through numerical and experimental methodologies. Nevertheless, the tools normally do not provide complete support for the evaluation of the results. The tools normally consider only the analytical approach, leaving behind the logical approach. The functions other than the control of heat, air and moisture, such as cost and structural support are straightforward and independent. There are numerous independent tools available supporting those functions.

Based on the level of support, computer tools can be classified into simplified models that are usable by building practitioners, and conversely, sophisticated models that require trained knowledge [Trechsel, 2001]. Trechsel [2001] states that there are more than 30 computer models that can analyze the hygrothermal performance of building envelopes that have been developed due to the increase in concerns relating to moisture control in buildings since the 1980s. The book 'Moisture Analysis and Condensation Control in Building Envelopes' edited by Trechsel [2001], lists WUFI-ORNI/IBP, MOIST, WUFI 2D, MOISTURE-EXPERT, LATENITE, SIMPLE FULUV, TRAMTO2 (Transient Analysis of Thermal and Moisture behaviour of 2D-structures), TCCC2D (Transient Coupled Convection and Conduction in 2D structures), HMTRA (Heat Mass Transient Analysis), DIM3.1, FRET (A simulation program for FREezing-Thawing processes) and FSEC 3.0.

The sophisticated tools are excellent research tools however they are not appropriate for design purposes. For instance, computer models that include air infiltration and rainwater leakage (advanced models in terms of moisture analysis) fall short and thus are not efficient design support tools due to the following reasons [Trechsel, 2001]:

- Large demand of input data for air infiltration and water leakage;
- Inconsistent joint configurations throughout the building which normally depend upon the workmanship, and hence, the infiltration and leakage performance data are generally unknown;
- Uneven nature of air infiltration and rainwater leakage, unlike diffusion;
- Transitional nature of rainwater leakage and air infiltration with duration measured in hours, days or weeks. Both depend on wind direction and unlike diffusion mechanisms they have unpredictable behaviour.

Therefore, simpler models available to practitioners that do not deal with these complexities are more usable sophisticated tools. CONDENSE, and WUFI-ORNL/IBP are good examples of simplified models.

CONDENSE 2.0 developed based on the Ph.D. thesis of K. Gowri (1992) by Siricon is a tool to support condensation analysis using the Steady State Method as prescribed by ASHRAE [2001a]. The tool can also analyze the thermal resistance (RSI) of individual layers and the total assembly, location and rate of condensation (g/sec m^2), heat loss (W/m^2), and the estimated cost of the envelope. It works within AutoCAD and can simulate the one-dimensional moisture transfer through a given building envelope by diffusion only. CONDENSE 2.0 is provided with a built-in material database of more than 700 building materials, with the flexibility to add and modify material information in the database. CONDENSE 2.0 contains weather data for 203 cities in Canada [Rivard, 1993]. The user inputs required for

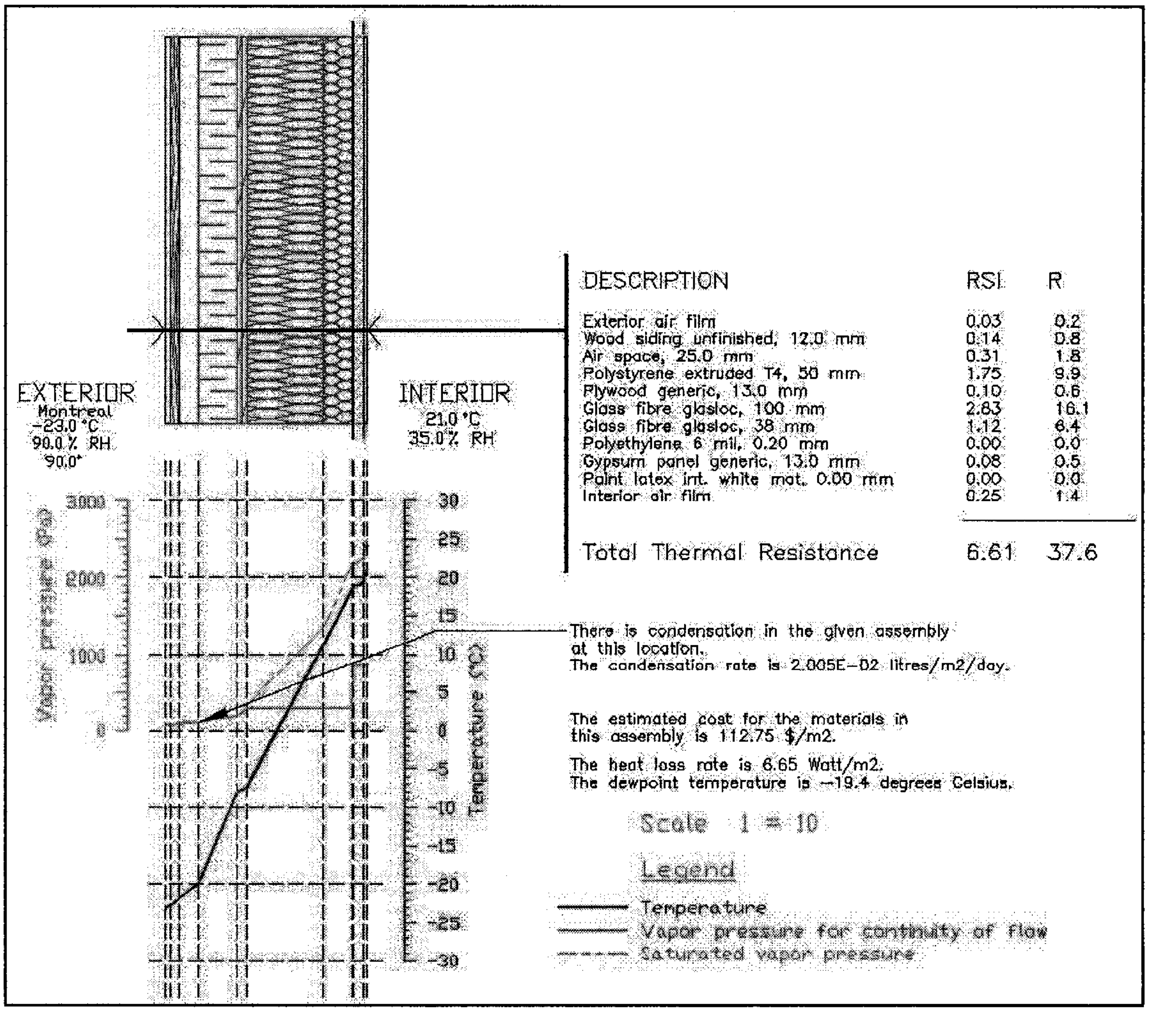

Figure 2.9: Extract from User Interface of Condense 2.0 with the results of an Analysis

the analysis are indoor and outdoor conditions and the envelope section details. The types of envelope sections that can be analyzed are the wall, flat roof, slope roof (with the options of any slope angle) and cantilevered floor. CONDENSE provides a level of user-friendliness and data interpretation that designers appreciate for an analytical model in supporting design. The user friendliness, ready-to-use interpreted results, and graphics, as shown in Figure 2.9, are the significant features of the tool.

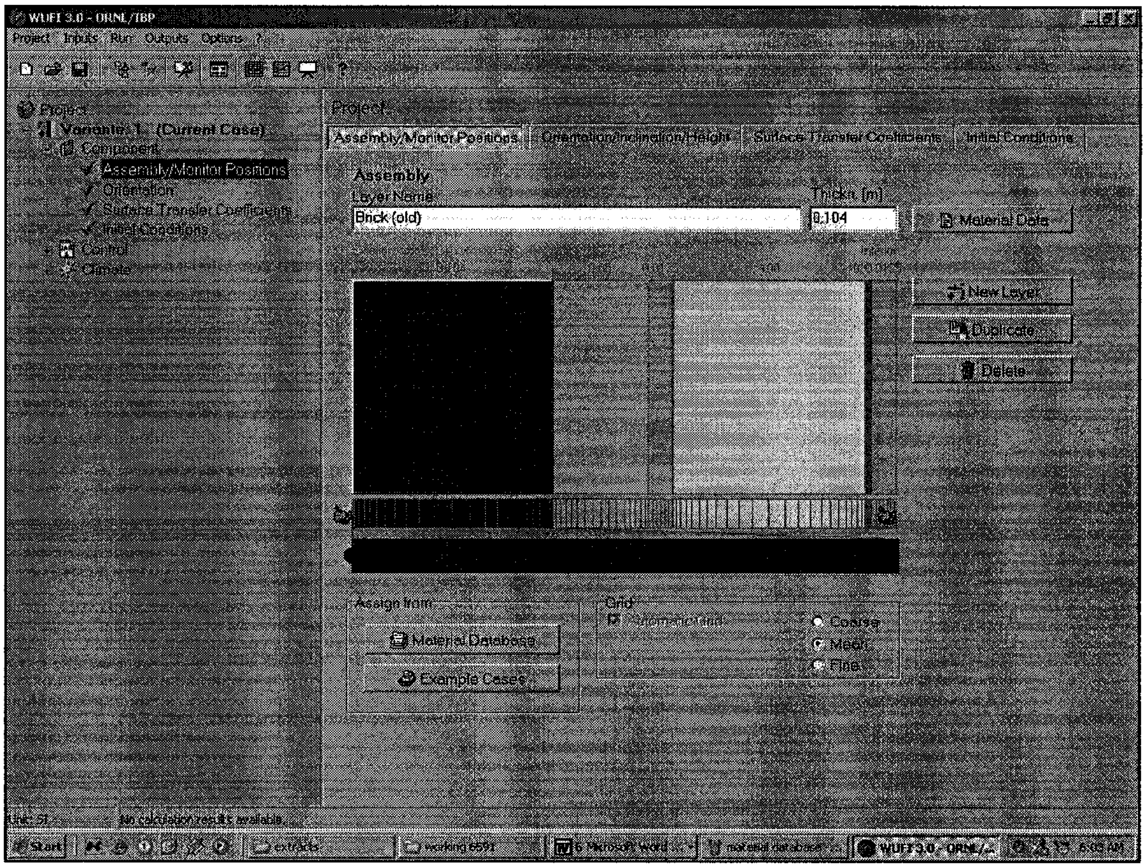

Figure 2.10: User Interface of WUFI-ORNL/IBP composing an Envelope Assembly

WUFI-ORNL/IBP, jointly developed by Oak Ridge National Laboratory, USA and the Fraunhofer Institute for Building Physics, Germany, is a version of the WUFI model specifically developed to provide an educational overview of the complicated moisture transport phenomenon occurring in construction assemblies. The WUFI-ORNL/IBP model is a transient, one-dimensional heat and moisture transfer model that can be used to assess the hygrothermal behaviour for a wide range of building material classes under climatic conditions found in North America. It provides the method(s) through which the building envelope designers and architects make informed design decisions [Karagiozis, 2001]. It can also be applied for other purposes similar to WUFI 2D, as stated by Kuenzel

[2001], which are to assess: (i) the drying time of masonry with trapped construction moisture; (ii) the chances of interstitial condensation; (iii) the influence of driving rain on exterior building components; (iv) the analysis of the effects of repair and retrofit measures; and (v) the hygrothermal performance of roof and wall assemblies under unanticipated use or in different climatic zones.

WUFI-ORNL/IBP is a window-based menu driven program with inbuilt and user managed data input parameters like material properties, building profile, interior and exterior environmental conditions. The building envelope assembly is composed as shown in Figure 2.10. The source for inbuilt material database is a North American Material Database [Karagiozis et al., 2001], which provides

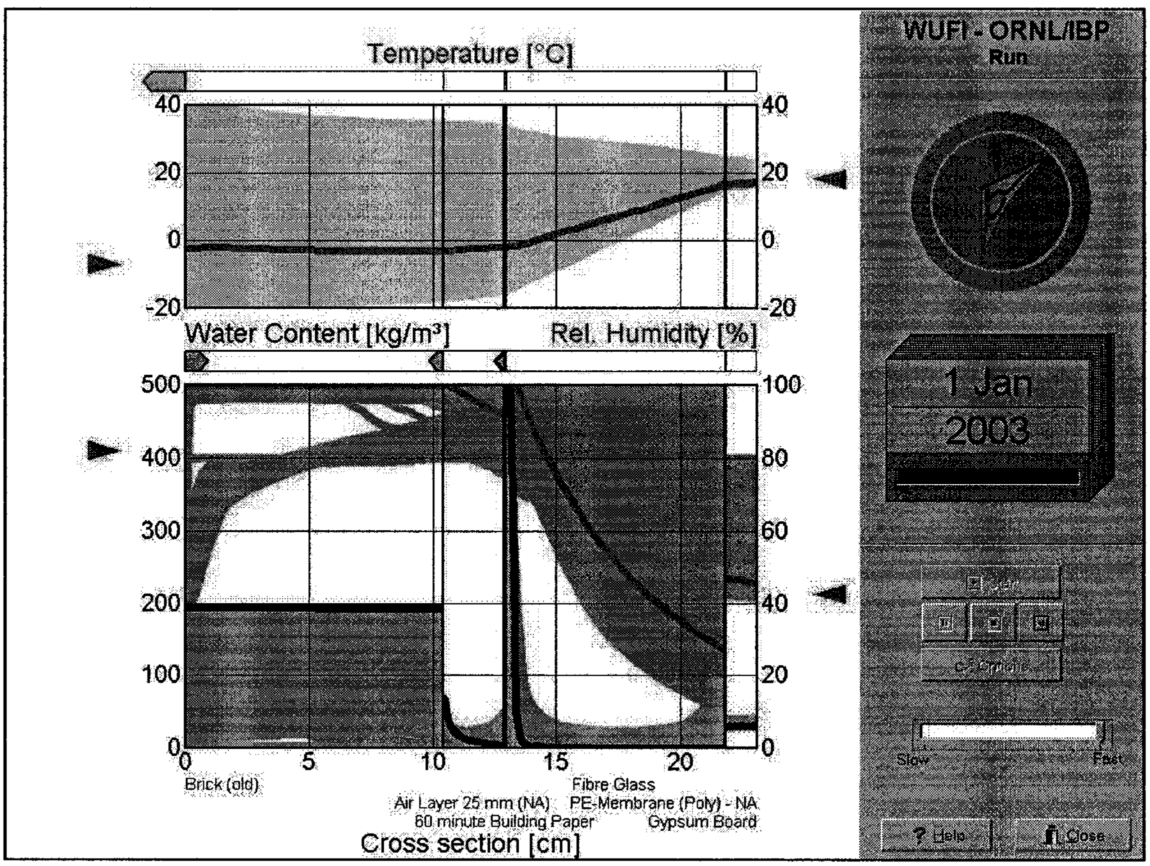

Figure 2.11: Results of an Analysis in WUFI-ORNL/IBP in Graphics Generated using Animation

material properties such as density (kg/m^3), porosity (m^3/m^3), heat capacity (J/KgK), thermal conductivity (W/mK) and moisture differential resistance factor. The characteristics of the materials are represented in both graphical and tabular format. The characteristics of materials represented are: (i) moisture storage function; (ii) liquid transport coefficient suction; (iii) liquid transport coefficient redistribution; (iv) moisture dependent thermal conductivity; and (v) water vapor diffusion resistance factor.

The boundary conditions for an analysis by WUFIORNL/IBP are indoor and outdoor air temperature; relative humidity; direct and diffuse solar radiation; precipitation, wind-speed and direction. The optional data for a refined performance analysis are clear sky radiation and driving rain. Input requirements concerning the building profile are orientation, inclination, height, exterior and interior finish properties. The analysis results may be presented by an animation as shown in Figure 2.11. The final results generated in this tool are represented in two formats: graphical representation and tabular representation, as shown in Figure 2.12. Graphs generated by the analysis are: (i) rain and solar radiation (exterior climate); (ii) air temperature and relative humidity (exterior and interior); (iii) heat fluxes (exterior and interior); (iv) total water content in construction versus time; and (v) water content of individual materials. The numerical data as an output are provided for the water content of the assembly and individual layers, and their maximum and minimum values.

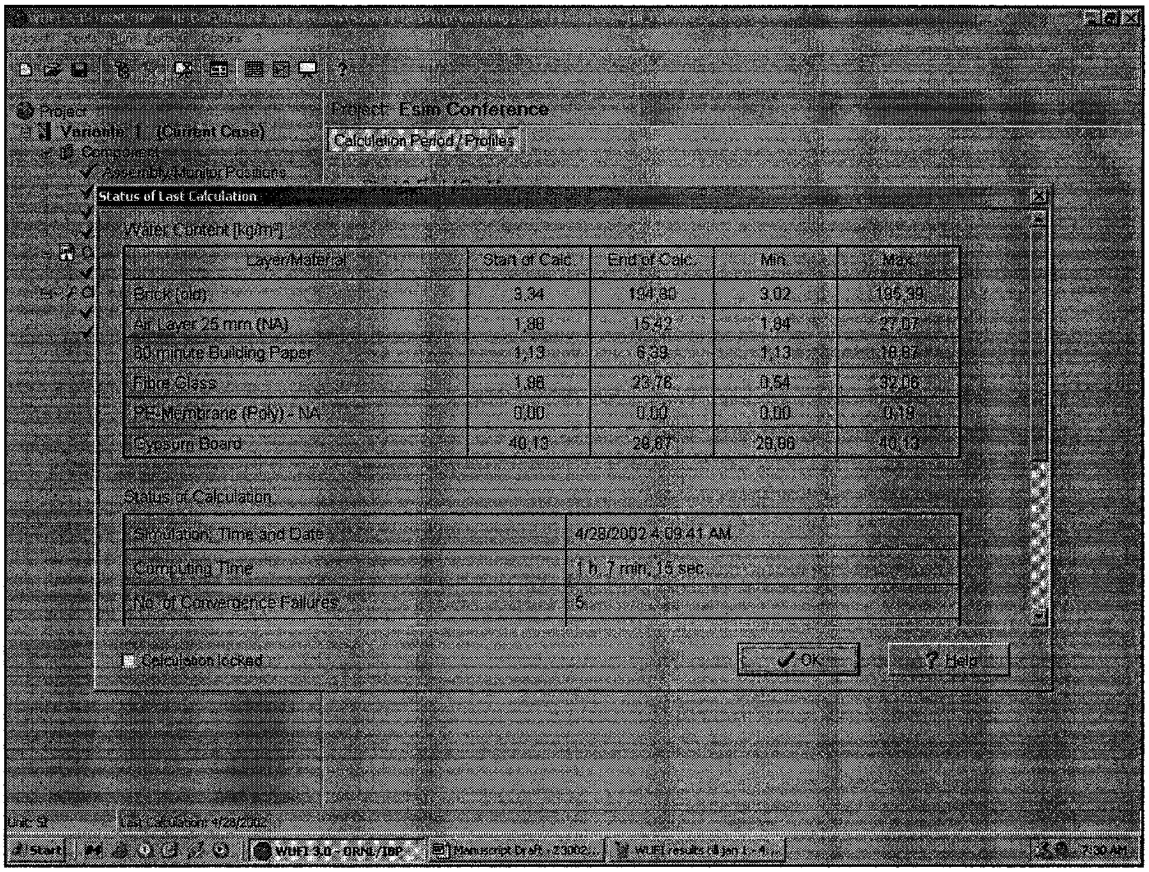

Figure 2.12: Results of an Analysis in WUFI-ORNL/IBP shown in Tabular Format

A valuable feature of the WUFI-ORNL/IBP tool is the computation of the moisture accumulation in all the layers of the envelope cross section. It can help in the prediction of the location of probable failures in the given envelope with respect to time. A drawback is the large demand for data to input.

2.6 Chapter Summary

This chapter presents a literature survey of the research in three stages: firstly, by dissecting the subject into two sections, building envelope systems and design methodologies; secondly, by reviewing the existing information on the building envelope design process and its relevant knowledge; and finally, by evaluating the existing computer tools for the building envelope design process.

In the sections for the building envelope systems, the chapter discusses the sub-systems, components and sections, the functions and a number of design objectives concerning the building envelope systems. It provides the background to understand the design of building envelope systems where the functions of the building envelope are the primary concern while determining the components of the envelope systems. In the sections for design methodologies, the chapter analyzes the design definitions, reviews some generic design methods, and analyzes the characteristics of the designer. It discusses the stages of the design process. It also discusses two radical approaches: a rational and systematic approach versus an intuitive approach. The most important characteristic of the design process is its nature subject to the designer's experience and knowledge. Some of the characteristics of the design process discussed are design by intuition, design by imitation, graphical thinking, maintaining alternatives, design through iteration and design with the support of analysis and evaluation. The following chapters gather all the available information about the building envelope design process. It studies the various attempts of modelling the building envelope design process by reviewing the two primary domains: the domain of architecture and the domain of building science and engineering. Upon discussing the building envelope design process, the chapter elaborates the relevant knowledge in the next section. Finally, the chapter reviews the characteristics evaluated by the computer tools presently available. It discusses two genres of computer tools supporting the building envelope design process: design generation tools and evaluation tools. On cross-examination of the study of the characteristics of the building envelope design process and the available models and computer tools, it is evident that there is a requirement for an integrated computer tool to support the building envelope design process. The tool should integrate the various stages of the building design process, knowledge in the building envelope industry and the functions that support the characteristics of the designer.

The upcoming chapters analyse further the topic and list the requirements for an integrated tool, derive an abstract model representing the design process and identify features satisfying the requirements. The chapters propose a concept of an integrated tool with the identified features and discuss the prototype to validate the features of the tool.

Chapter 3

Building Envelope Design Process and its Knowledge

The literature survey, discussed in the preceding chapter, explores some of the existing models of the building envelope design process. None of the design models explained in the literature review provides an integrated view considering all the methods, disciplines, and the characteristics of the participants involved. Moreover, there is more than one design methodology followed in practice, each one subjective to the knowledge and experience of the designer. Hence, in order to understand and provide a comprehensive representation, more investigations through exercises in building envelope design are required. Based on the findings of the literature review and exercises conducted on the building envelope design process for residential buildings (discussed in Appendices A and B), this chapter reviews the significant characteristics of the building envelope design process, and attempts to rationalize a conceptual design method that could be adopted in a design tool. It also investigates and classifies the knowledge supporting the building envelope design process.

3.1 Building Envelope Design Process

The core of the building envelope design process is the design synthesis, wherein the envelope system of a given building is generated. Prior to an effective start of the design generation, the designer goes through a problem definition stage where the design problem is established. In this stage, the required information from the project and site analyses of the building is extracted, and the design objectives in terms of performance requirements are fixed. Nevertheless, in practice the design process is so flexible that in most of the cases there are traces of design synthesis in the problem definition stage. And some of the investigations of the problem definition stage can be revisited during the design synthesis and afterwards, the evaluation stages. The design synthesis stage primarily handles the design of components of the envelope system, by trial and error, evaluated using the analytical and logical methods. It involves the selection, composition, and configuration of components of the sub-systems of the envelope system (wall, roof, window junction and floor/wall junction). In the design of the building envelope system, design of the wall and roof sub-systems is important. The other entities to be designed normally follow the design of these subsystems. Nevertheless, during the building envelope section design of walls and roofs, the compatibility with the other entities is considered. The design of each subsystem of the envelope system is carried out in big part, on the basis of the strategies well established in the industry. However, the design path of the selection process is subjective to the attitude, working trend, knowledge and experience of the designer. On

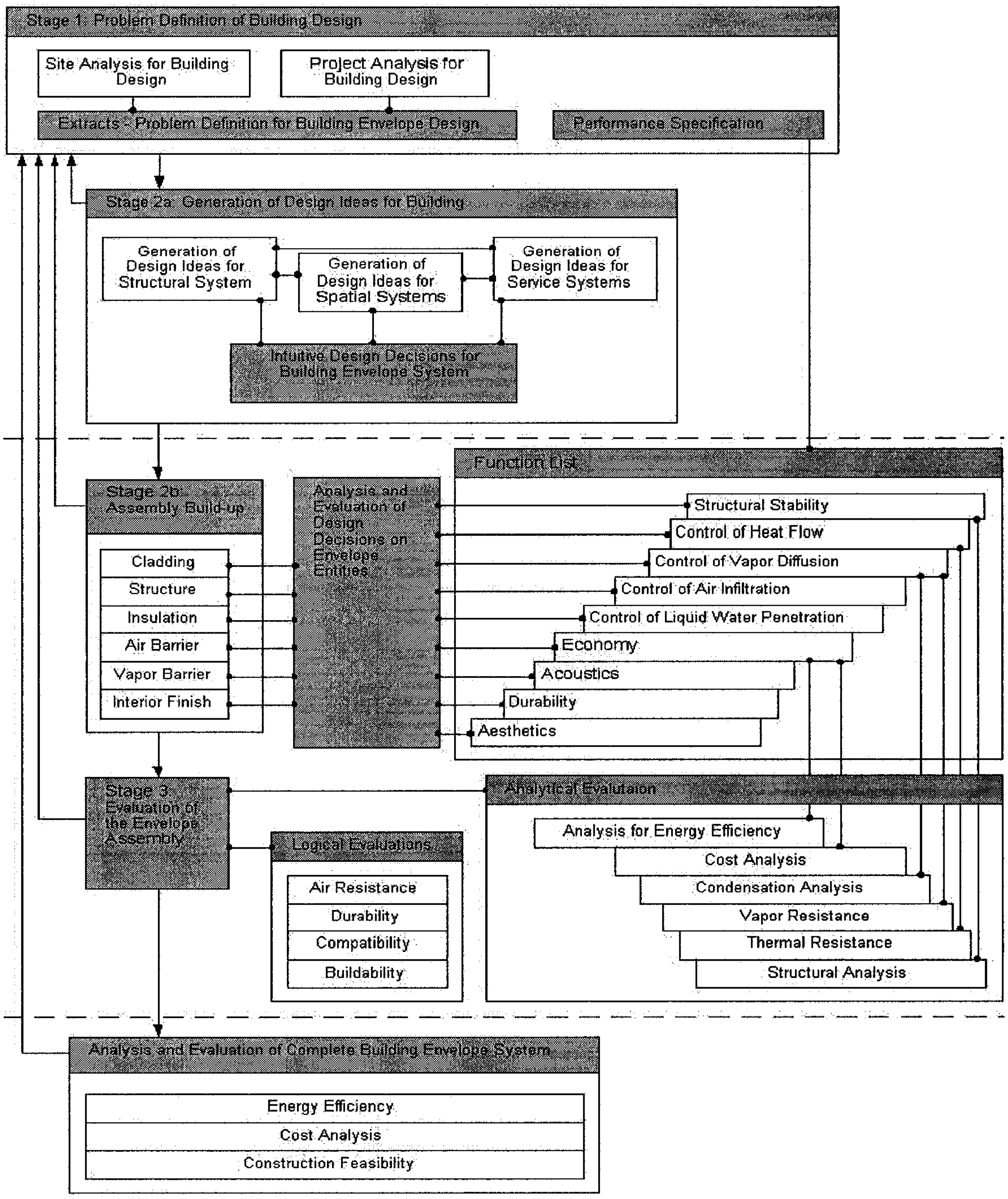

Figure 3.1: Representation of the Building Envelope Design Process

completion of the design of the components of the envelope system, the designer deals with the overall performance evaluation of the envelope system. Figure 3.1

gives an abstract graphical representation of the building envelope design process, which is discussed in detail in the following paragraphs.

3.2 Problem Definition Stage

To start, the designer establishes the design problem, which involves the analysis of the site conditions and the details of the project, shown in Figure 3.1 as 'Stage 1: Problem Definition of Building Envelope Design'. It includes the setting up of the design conditions for which the building envelope system is designed. Most of the design conditions entered in the problem definition stage are used for analysis and evaluation purposes, while some of them are used in handling the data and knowledge for design synthesis, and sometimes in deriving other design conditions. For example, depending on the location details established, the outdoor design conditions could be retrieved from the databases available. In most cases, the design conditions for the building envelope design are obtained from the analysis results of the project and site details of the building design. Table 3.1 lists some of the variables analyzed in the site analysis and project analysis of the building design process. Appendix A, 'Building Envelope Design Exercise of a Typical Residential Building', discusses the variables in detail with an example. Site analysis for a building includes the analysis of physical characteristics (location of the building, climate, surrounding area, soil conditions, topography, accessibility and landscape), visual characteristics and social characteristics (laws and regulations, standards, social status, and availability of materials). Location

Site Analysis	Project Analysis
Physical characteristics Location o Geographical location o Political location Climate o Hot climate o Cold climate o Mixed climate Surrounding area Soil conditions Topography Accessibility Landscape Visual Characteristics Social Characteristics Laws and regulations Standards Social status Available and unavailable materials	Designer requirements Spatial requirements – zones, dimension, quality etc... Aesthetical requirements – material type, shape etc... Client requirements Building type Spatial requirements - dimension, quality etc... Cost factor Aesthetical requirements – material type, shape etc... User requirements Spatial requirements – dimension, quality etc... Aesthetical requirements – material type, shape etc... Social requirements Common people's requirements Local govt./body requirements

Table 3.1: Representation of the Building Envelope Design Process

and climatic condition details such as city, country, degree days, outdoor design temperature, snow loads, and wind loads are pertinent to building envelope design. Project analysis includes the client requirements (spatial requirements such as dimension and quality, building type, budget, aesthetical requirements); designer requirements (spatial requirements such as zones, dimension and quality, aesthetical requirements such as material type and shape); user requirements (spatial requirements such as dimension and quality, aesthetical requirements such as material type and shape); and social requirements (requirements of the common people, requirements of the local governing bodies). Of the listed project analysis parameters, the building envelope design requires input of aesthetical requirements, cost factor and regulations of the governing bodies. Some of the other factors of the building project that may influence the envelope design: construction cost (cost of materials and labours, time-cost relation and its influence); operation cost (maintenance and energy); durability; and aesthetic importance (image, identity and style).

The building envelope design process is primarily a goal directed activity where the design objectives are mostly identified and set at the start. The design objectives are mainly the functions of the building envelope system to be achieved, some in terms of quantifying variables and logical rules, and some left to the subjective decisions of the designer. For example, the control of heat by conduction could be quantified using a minimum RSI value and evaluated logically, while the control of air infiltration requires a logical 'yes' or 'no' type of evaluation at the design stage (to be later measured on site if desired), whereas aesthetics is subjective and requires the intervention of the designer. In the case of the quantifying variables, there are standards for the functions recommending different levels to be achieved. In some cases, depending on the experience of the designer, the performance specifications are logically decided based on the problem definition. The specification of the design objectives that includes the expected results for both analytical and logical evaluations is referred as performance requirements specification, as in Figure 3.1. The specifications of the performance requirements for the building envelope design are handled in two ways: specifications of performance requirements based on the designer's knowledge, and specifications to achieve standard levels evolved by regulatory bodies and research organisations. The specifications are normally an outcome of the conversion of generic requirements imposed by the clients into specific requirements. They are solely based on the designer's experience and knowledge. The performance specifications by standards define the minimum levels of functions to be achieved according to building codes. For example, to achieve R-2000 standards for a building, the thermal resistance (RSI) value for roofs should be more than 7.0 $m^2 \bullet °C/W$ for Montreal. Table 2.1 in chapter 2, provides more such standard RSI values for roofs, exterior walls and foundation walls.

For the building envelope design process, the following building characteristics are identified to be the primary variables to be analysed in the problem definition stage: the building type and number of floors; the details about the location such as city or town and country; the design conditions such as, climate type, degree days, outdoor air temperature, outdoor relative humidity, indoor temperature, and indoor relative humidity; the envelope section description, if it is a wall, roof or floor section. Apart from the logical evaluations such as the presence of air barrier and presence of vapor control elements, the minimum RSI Value, maximum condensation amount, and minimum vapor resistance, are identified to be some of the variables to specify the performance requirements. Minimum values are found from building code and regulations, and other values from sources such as manuals, standards, and data book. In practice, often conditions for the above variables are known to the designer through experience.

Depending on the designer's knowledge and working trend, in practice, the variables required may not be completely analyzed in the problem definition stage. Although the problem definition starts in the beginning of the building envelope design process, it may be revisited during the design synthesis and evaluation stages. On the other hand, although the design synthesis does not start effectively at the problem definition stage, there is some amount of design generation by the designer that happens by intuition or through accumulated experience depending on the experience of the designer.

3.3 Design Synthesis

The design synthesis part of the building envelope design process is subjective to the designer's experience, knowledge and working trend. The abstract model for the building envelope design process, as represented in Figure 3.1, shows two different stages of design synthesis: intuitive design decisions (in 2a), as already discussed, and assembly build-up of envelope components (in 2b). The following sections discuss these two sub-stages of design synthesis.

3.3.1 Design by Intuition

Depending on the knowledge and experience of the designer, some ideas are instigated by finding a design solution that satisfies the requirements set in the problem definition. In Figure 3.1, 'Stage 2a: Generation of Design Ideas for Building' illustrates that the generation of design ideas for the building envelope by intuition is influenced by the design ideas generated for the other three systems of the building: structural system, spatial system, and service systems. For example, if a wood stud structure was selected as the structural system of the building envelope, the design options at the next level are narrowed down (i.e. the options for envelope systems primarily contain the wood studs as structural support and the other components are selected to be compatible with the wood stud structural support). The design decisions are also influenced by the information entered in the problem definition stage. For example, the designer on observing the values entered in the problem definition stage, such as the type of the building as residential, the cost factor as medium budget project, and the aesthetics influenced by the client's references, may decide intuitively to use a brick façade for cladding. The ideas generated are either design decisions or ideas that require verification. They could be about a single element, part of the assembly or the whole assembly. The design decisions could take the form of pieces of notes, thumbnail sketches or just thoughts. They are mostly generated by virtue of the designer's experience and knowledge about the building envelope systems that come from references such as manuals published by organizations (e.g. CMHC) or design cases handled previously, etc. The ideas generated influence further developments in the design process. There may be certain decisions that require verification. In case of an uncertainty about an idea, alternatives are maintained and verified by comparison at the end. The major design generation takes place through the assembly build-up process as discussed in the following sections.

3.3.2 Assembly Build-up

Assembly build-up is the core of the envelope section design. Most of the decisions about the selection, composition, and configuration of components of the envelope assembly are generated then. The assembly build-up mainly comprises the selection of a set of components and evaluation of the selected components by comparing their performance with requirement specifications and industry standards. The ease with which decisions are made depends on the knowledge and experience of the designer. Assembly build-up is influenced by the decisions of previous stages: problem definition for building design, design decisions of other systems, and design decisions of building envelope system by intuition. Commonly, the design decisions about the structural support or exterior cladding of the building envelope are handled in the above stages. It is also possible that the preceding stages do not provide any design decisions.

The assembly build-up could either follow a case-based approach or a step-by-step approach. Based on the thinking process, the step-by-step approach for the assembly build-up could be classified as either component-selection or function-satisfaction approach. The selection of an approach is subjective to the knowledge and experience of the designer. For instance, when a designer is experienced, the envelope section is designed instantly by picking up a design case already known, whereas an inexperienced designer handles the assembly build-up in a step-by-step process by considering various strategies, functions and through synthesis-analysis. Also, there could be a combination of both methods, in which a part of the wall is selected by case-based approach and the other part by a step-by-step approach. In Figure 3.1, 'Stage 2b: Assembly Build-up' provides an abstract representation of the selection of assembly components and how the analysis and evaluation are handled with the support of functions and their performance requirements. The functions such as structural stability, control of heat flow, control of vapor diffusion, control of air infiltration, control of liquid water penetration, economy, acoustics, durability and aesthetics, as indicated in the figure, are provided under functions list. They are specified with the performance requirements and are used for analysis and evaluation. The following paragraphs discuss the different approaches of assembly build-up in detail.

3.3.3 Case-based Approach

In the case-based approach the designer selects an envelope assembly or the components of the envelope assembly by correlating the problem attributes with the proven design cases. This method is based on the experience and knowledge of the designer, and the availability of relevant design cases. Traditional systems in a location and standard systems prescribed by research and social organizations are additional sources of design cases.

3.3.4 Component-Selection Approach

The words of Petroski [1992], "the process of engineering design may be considered a succession of hypotheses that such and such an arrangement of parts will perform a desired function without fail", forms the basis of the building envelope design process by component-selection approach. Building envelope design could be perceived as a process of composition of envelope section components to form an envelope system. It is observed that every component, usually a material layer or a combination of materials in the envelope section serves one of the functions. These material components are normally referred by the name of the function. For instance, the polyethylene sheet which has the capability to retard the moisture transfer by vapor diffusion is classified as a vapor retarder. Materials and systems are thus classified on the basis of the function they serve. However, in reality, materials often serve more than one function, partly or completely. All the functions satisfied by the material could be listed as the functional properties of the material. Based on these functional properties of the materials, the envelope sections are built-up by a step-by-step approach. It is an assembly build-up process that involves handling of all the functions one-by-one until all the specified functions are achieved to the required level. The basic components required to build an envelope section are cladding, structural components, rain screen provision, thermal insulation, air barrier, vapor retarder, and interior facing. Hence, the component-selection approach depends on the functional properties of materials, which the designer should be aware in addition to the core knowledge of the building envelope design. Also, the designer needs to follow a systematic design process in which the designer considers all the options at appropriate stages, extracted by correlating the function under consideration with the functional properties of the materials in the database. Also as mentioned in Chapter 2, the building envelope design process in addition to engineering consideration involves architects and architectural issues. Appendix A, discusses the building envelope design exercise, which follows the component-selection approach. It elaborates on the problem definition information required for the design process (as discussed above), and the synthesis by selection of components to compose envelope sections of wall, roof, foundation wall and window. The exercise discusses a process, in which the composition of the assembly is first carried out completely, and then an analysis and evaluation of the completed assembly. Analytical tools and models are used for this purpose.

3.3.5 Function-Satisfaction Approach

The function-satisfaction approach is an assembly build-up process that provides design solutions by satisfying the specified functions to required levels. Figure 3.2 provides an abstract representation of the building envelope design process by the function-satisfaction approach. The figure illustrates the overall stages of the building envelope design process from functions point of view: (i) list functions to achieve from the standard functions list; (ii) specify the initial level/amount of function to achieve; (iii) take initial design decisions by intuition; (iv) assembly

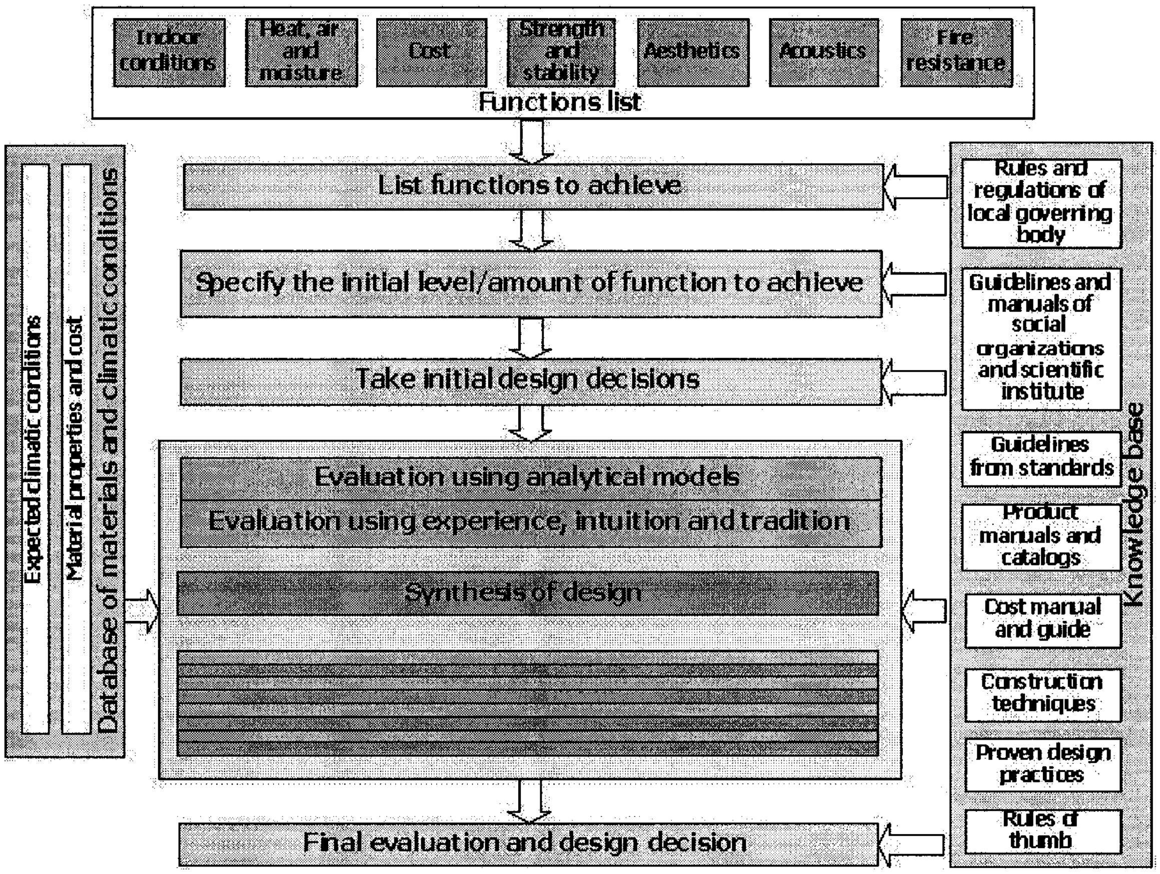

Figure 3.2: Function-Satisfaction Approach for Assembly Build-Up

build-up by synthesis and evaluation using analytical models, experience, intuition and tradition; and (v) final evaluation and design. The stages referred above correlate to the design synthesis stage of the representation of the building envelope design process in figure 3.1. The listing of functions to be considered and specifying the requirement specifications of each function relates to the problem definition stage, taking initial design decisions relates to the design by intuition, design by synthesis and evaluation relates to the assembly build-up, and final evaluation and design relates to the analysis and evaluation stage.

According to this approach the designer considers one of the functions to be satisfied and then contemplates an appropriate design solution, which is normally to add a component. The selection of each component is achieved through a series of decisions on strategies. The design paths through the options of strategies and solutions for each function could be represented by a tree. The tree of strategies and solutions for functions such as structural stability, control of heat flow, control of vapor diffusion, and control of rainwater penetration for walls are explained in the following paragraphs using Figure 3.3, 3.4, 3.5, and 3.6, respectively. Each decision, either the choice of strategy or component selection, is accompanied with analysis and evaluation either by scientific calculations or through the designer's knowledge and experience. All the basic functions of the building envelope are thus satisfied one by one.

The tree of strategies and solutions for the structure, as represented in Figure 3.3, focuses only on residential buildings. For the structural stability function, in the first layer of strategies, the options are the types of main structural systems such as wood structure, steel structure, masonry structure and reinforced cement concrete (RCC) structure. The wood structure could either be a post-beam structure or stud structure. The wood structure as a main structural system for a building is used in residential buildings with ground plus 2 floors or less (maximum 4 floors including basement). Wood stud structure could either be built up using the platform construction method or balloon construction method.

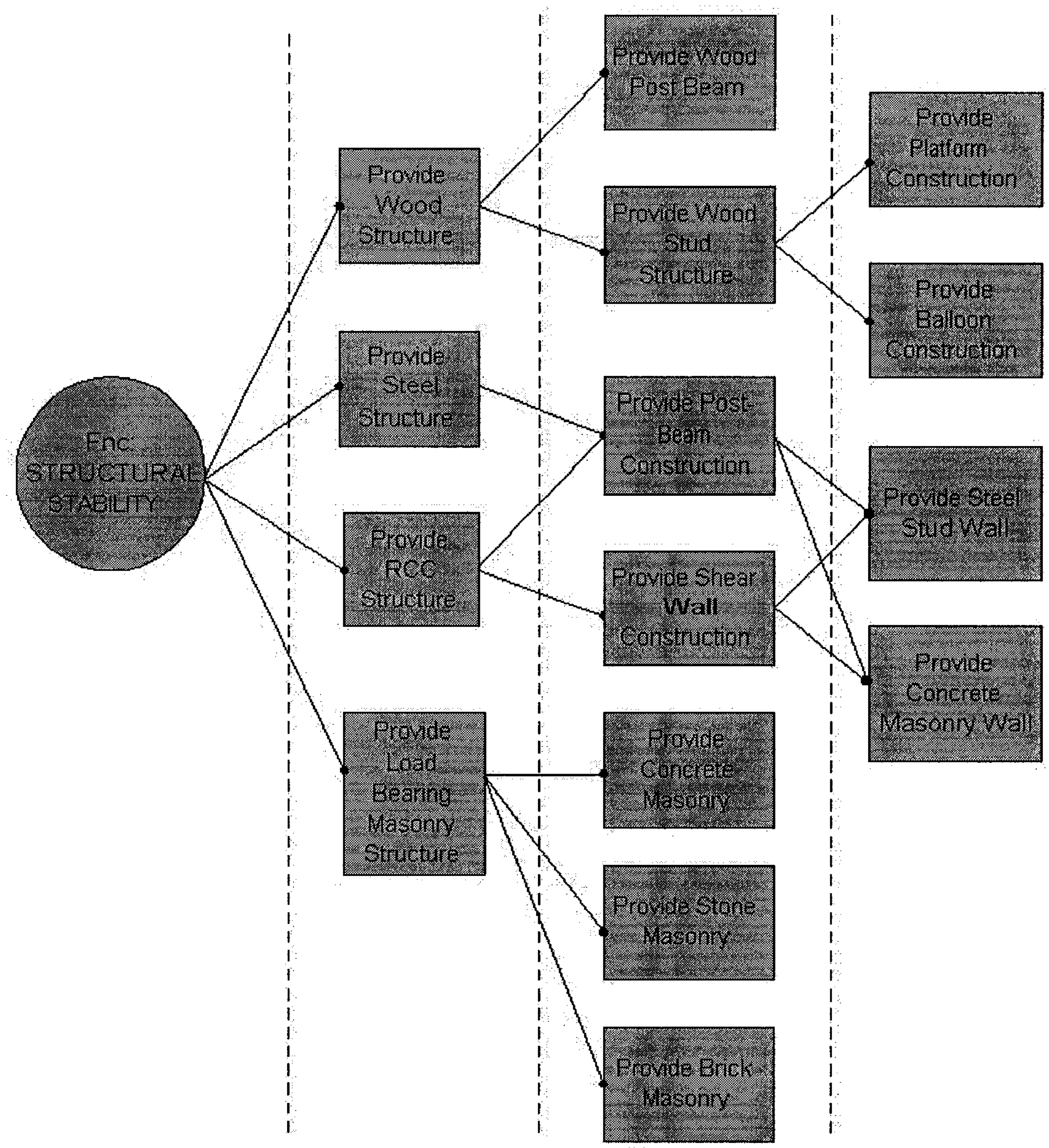

Figure 3.3: Tree of Strategies and Solutions for Structural Stability Function

Nevertheless, the construction technique widely used in the industry is platform construction. The steel and RCC structures are normally of post-beam construction types. In some cases RCC shear wall construction type are used as the main structural system. The structural stability for the building envelope system in case of RCC and steel structures is provided by the steel stud construction. The steel and RCC type of structural systems are widely used in commercial buildings where studs act as support for building envelope. Masonry structure, on the other hand, provides both the main structural support and the structural stability for building envelope.

As indicated in Figure 3.4, the control of heat flow function could be handled by either adding insulation or increasing the RSI-value of the existing assembly. The RSI-value of the assembly could be raised by either increasing the thickness of one or more of the existing insulation layers or by changing the material of one of the layers with better insulation value. The three strategies of adding insulation are cavity insulation, exterior insulation, and interior insulation. Cavity insulation could be provided only if the assembly has a cavity. Normally, the structural system, such as wood stud structure and steel stud structure, has a cavity formed between the spacing of two studs which can be filled with insulation. The cavity insulation could be either batt (if studs are added), loose-fill or semi-rigid materials. For exterior and interior insulation, batt, rigid, and foamed in-place materials can be used. As shown in the figure, based on the type of insulation, the materials could be selected from the available list of materials. The selection of a material for the control of heat flow is followed by its configuration, which includes positioning and thickness. In some cases, a design solution may require additional components in the assembly. In the case of cavity fill insulation while provided with either semi-rigid or loose-fill type of materials, there is a

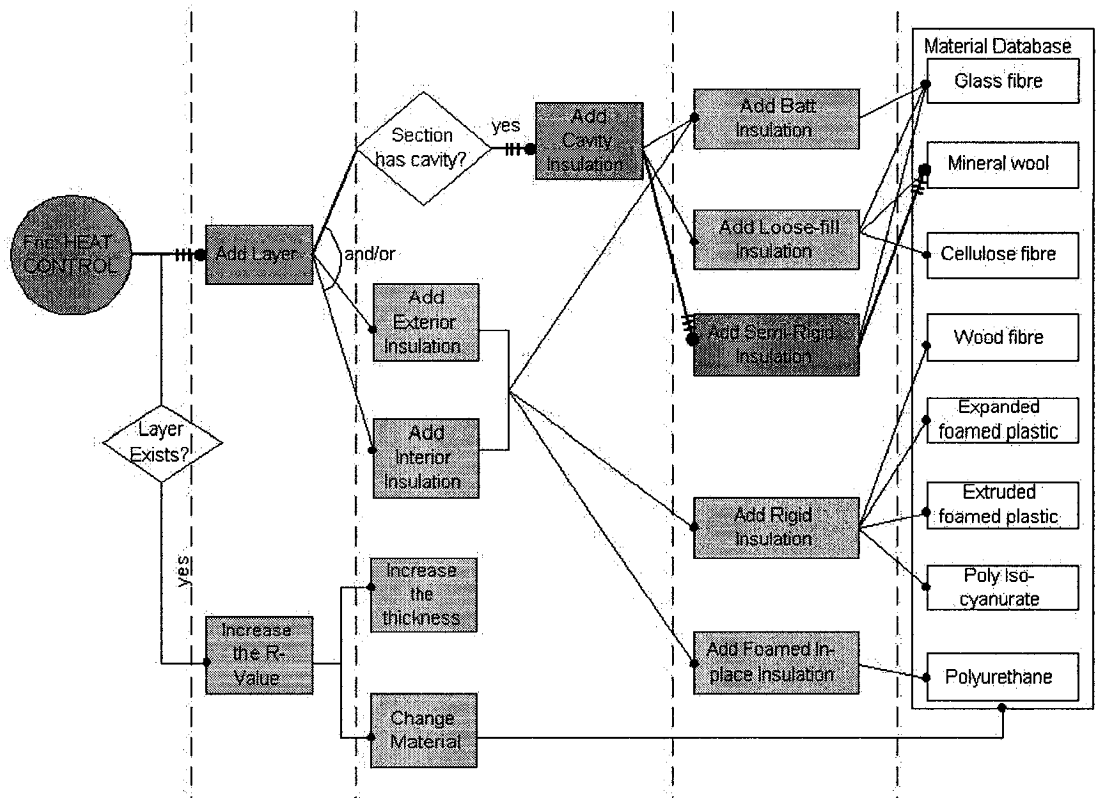

Figure 3.4: Tree of Strategies and Solutions for Control of Heat Flow Function

requirement to close the cavity to protect it from rainwater. The additional components may be a solution for other functions, e.g. cavity closure component could also be an additional structural support or a component to prevent rain infiltration. In case the choice is interior or exterior insulation, a base is normally required to hold the material. For example, to apply the rigid type of insulation material, a base such as wood studs, plywood sheathing, or battens is required to pin the insulation material and in case of the foamed in-place insulation a firm base such as plywood sheathing, concrete wall or brick wall is required. A typical use of the foamed in-place insulation in an assembly is a requirement to provide

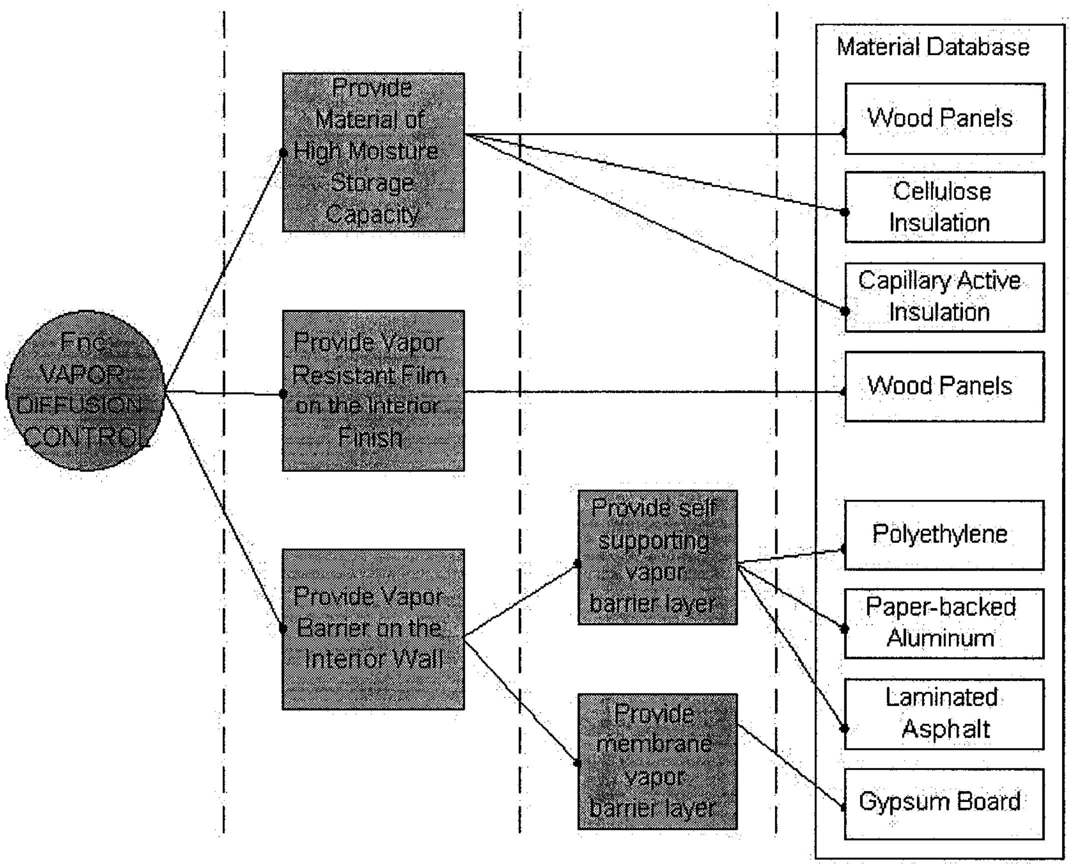

Figure 3.5: Tree of Strategies and Solutions for Control of Vapor Diffusion Function

insulation on an uneven surface (concrete or masonry wall surfaces) or an inaccessible point (corners of attic).

The control of vapor diffusion, as shown in Figure 3.5, is relatively straight forward, since it can be achieved by one of three strategies: providing a high moisture storage capacity material layer; applying a vapor resistant film on the interior finish; or providing a vapor barrier on the inner side of the wall. The vapor barrier on the inner side of the wall could be either a self-supporting vapor barrier material layer or a membrane layer that requires support from the inner wall of the assembly. The other methods to control vapor diffusion through the

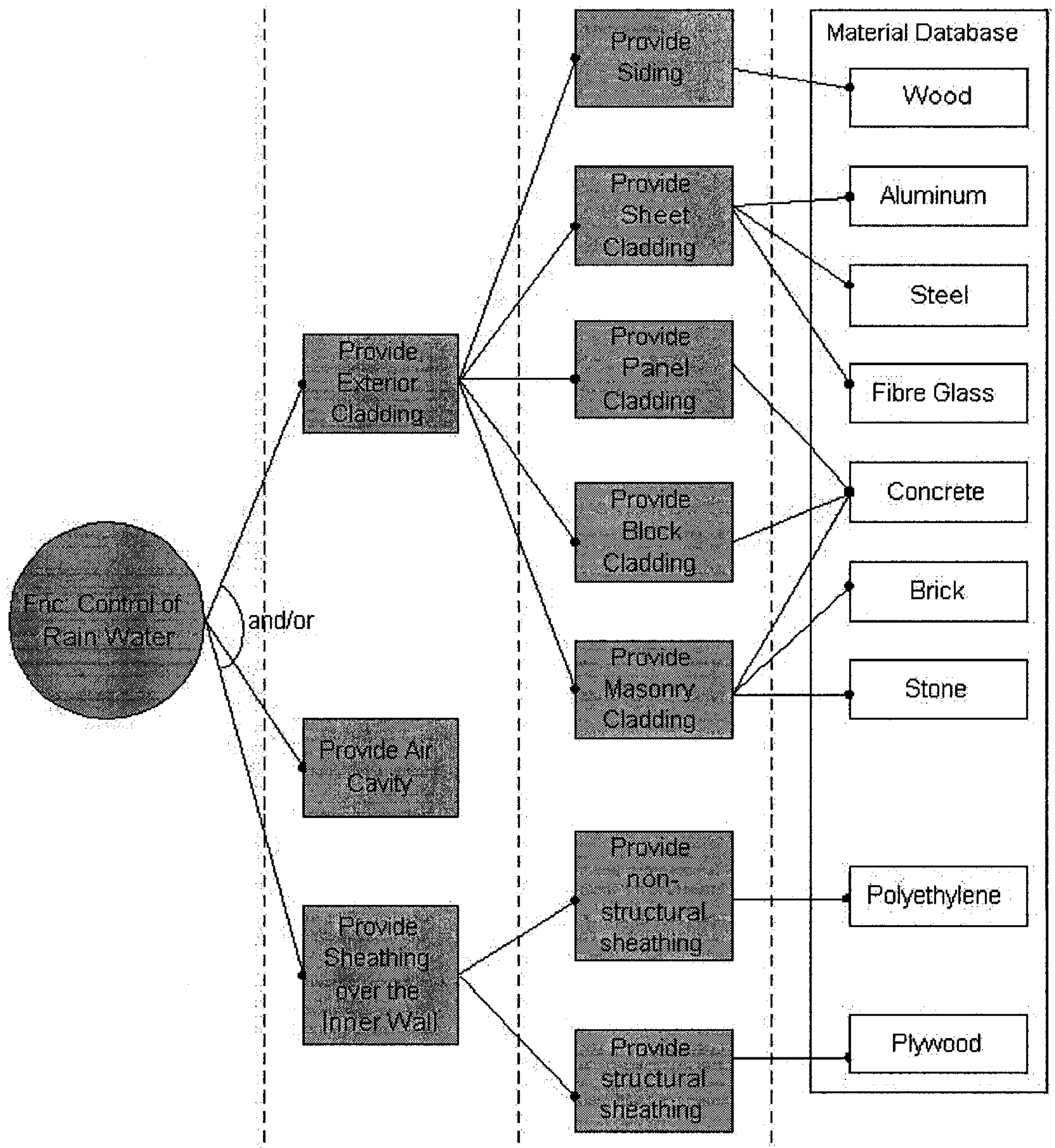

Figure 3.6: Tree of Strategies and Solutions for Control of Rainwater Penetration Function

assembly are by providing vapor impermeable insulation materials such as the extruded foam board insulation, and sheet metal walls.

The control of rainwater, as represented in Figure 3.6, is handled effectively by providing three components in the assembly: an exterior cladding, an air cavity, and sheathing over the inner wall. The exterior cladding and air cavity are considered to act as the first layer of defence, while the sheathing layer acts as the second layer of defence against the rainwater penetration. The exterior cladding, as shown in the figure, could be provided by siding, sheet cladding, panel cladding, block cladding, and masonry cladding. Wood siding is a popular method of providing siding as a cladding option. Aluminium, steel and fibreglass are the three options for the sheet type of exterior cladding. Concrete material could be used to provide panel, block, or masonry type of exterior cladding. Brick and stone are the other two types of masonry cladding. The configuration of each option varies with the type of strategy used. For example, wood siding is configured by the thickness of the siding and the wood panel thickness, whereas concrete masonry cladding is configured by its thickness. The sheathing over the inner wall could be provided either by a layer of self-supporting structural sheathing or a membrane sheathing supported by the inner wall layers, such as, the main structural system. The rigid type of insulation, such as polystyrene, provided on the exterior of the inner wall for control of heat could also act as a layer of sheathing.

Thus, a designer traverses through the strategies and solutions to achieve the specified level of performance. The required knowledge such as the options listed as strategies and solutions in the design process, the logical evaluations to make design decisions, and knowledge about the available materials and construction techniques are the outcome of the designer's experience. The design

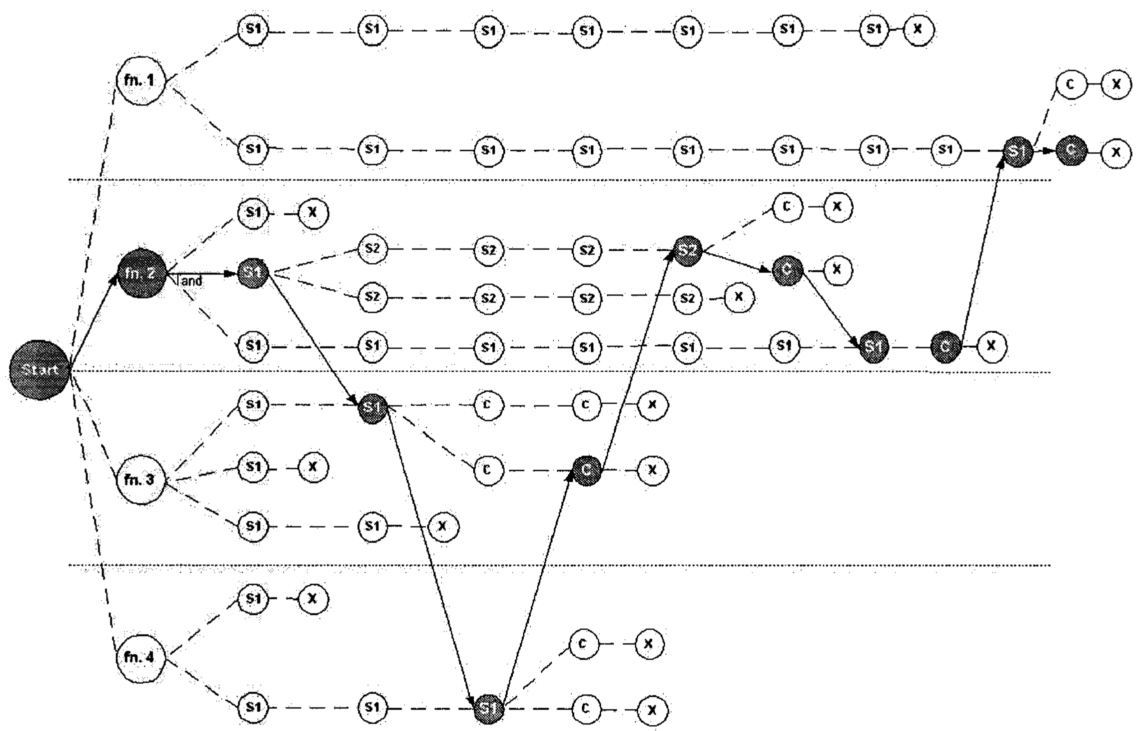

Figure 3.7: Design Path during the Building Envelope Design Process

path by this approach is a complex and iterative process. Figure 3.7 provides an illustration of the complex nature of the building envelope design process. In the start of the design synthesis, the designer is offered with many design paths, as there are more than one function to achieve ('fn. 1' – 'fn. 4', as shown in figure). Each function has one or more design options, called strategies (referred in figure as 'S1'). The designer decides to handle one function and selects one strategy. The selected strategy may produce more sub-strategies or component options as design options, shown as 'S2' and 'C' respectively, in the figure. The component options are the end of each branch of the tree of design options of each function. The sub-strategies or component options of the selected strategy and strategies already displayed are provided as further design options. Each option is checked for its validity at the end of each decision. In some instances, a strategy may become invalid after a decision is made. For instance, as already discussed in the control of heat, a design solution selected to achieve a function may help achieve another function thus making the design strategies of the second function invalid. In the figure, 'X' represents those options that become invalid after a design decision is made. As the designer proceeds with the design synthesis and makes decisions, the functions are gradually satisfied. As shown in Figure 3.7, the design path traced in this process, using arrow and shaded options, in relation with the time is a complex process traversing through the tree en route to achieve the various functions.

In reality, the building envelope design process could follow a combination of the different approaches discussed (step-by-step approaches and case-based approach). For example, the designer would select an air barrier and a vapor retarder by component-selection approach, basic wall type such as wood stud wall by case-based approach, and the insulation and other components by function-satisfaction approach.

3.4 Analysis and Evaluation

There are two stages of analysis and evaluation in the building envelope design process: evaluation during design synthesis and evaluation of the completed assembly. The analyses and evaluation of design decisions are handled through out the design synthesis stage. Some of the analysis and evaluation during design synthesis stage are verified using the analytical models, while most of them are handled by logical evaluations through the virtue of the designer's knowledge. The following are some of the common attributes used to evaluate the performance of the assembly by analytical models: thermal resistance; condensation; and cost. The factors such as stability, compatibility, and buildability are normally verified using logical methods, through support from knowledge. The evaluation during the synthesis stage is basically a first round of performance check for achieving the required results. The second round of analysis and evaluation is conducted on completion of the configuration of the envelope assembly to verify the performance of the building envelope system. The performance requirements specified in the problem definition of the design process are verified with the evaluated actual performance of the designed building. Also, the evaluation of the performance of factors of the functions of the envelope assembly could be compared with proven standards developed in the industry. Following are the factors relevant to the building envelope system: cost estimation; construction feasibility; detailing and specification; evaluations of buildability of assembly and junctions; continuity of air barrier by evaluation mostly in junctions and corners; and heat loss and energy analysis.

Figure 3.8, represents some of the scientific models for the evaluation of HAM control functions that could be used in the building envelope design process. The analysis such as the heat loss by radiation, heat loss by conduction, thermal gradient, analysis of openings, condensation analysis and moisture transfer by diffusion represented in white boxes use simple models. The other analyses illustrated can be handled using sophisticated models. The figure represents the sophisticated models using shaded boxes the analysis of moisture transfer as liquid water, moistures transfer by vapor, air infiltration, heat loss by convection, thermal bridge, moisture transfer by capillary and other forces, and moisture absorption analysis. The sophisticated models, as discussed in the literature review, are not used in design due to reasons such as heavy input

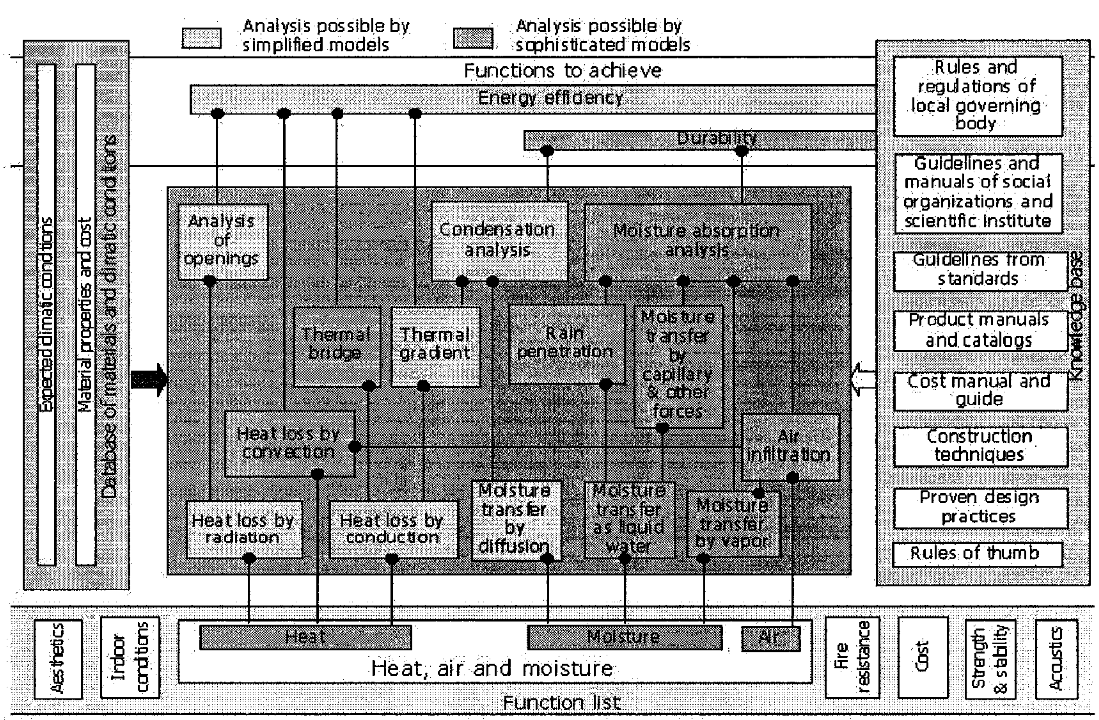

Figure 3.8: Analytical Models used for HAM Control

information, intensive domain knowledge required from users, adequacy of simplified models for design purposes, and lack of calibration/validation with actual measured data.

3.5 Summary of Characteristics of Building Envelope Design Process

The above sections provide an overview of the various design stages of the building envelope design process. It discusses the several attributes, methods, and approaches involved. From the discussions, it is inferred that the determination of the building envelope system does not follow any specific procedural model. Nevertheless, it demonstrates few significant characteristics to be considered, such as:

- The decisions made during the design of other systems of the building influence the building envelope design process. Hence, the designer must keep track of the decisions from the building design process and extract the essential information for the building envelope design process;
- The building envelope system is a composition of various envelope sub-systems. Nevertheless, the design of envelope sections, mainly wall and roof sections is the core of the design of the envelope system. Design of other envelope sub-systems are normally influenced by the design solution of the envelope sections;

- The design of envelope sub-systems requires input from the previous stages of the envelope system design: information from problem definition, design decisions of other systems, and intuitive design decisions about the envelope system. However, the design of the envelope sub-systems could be handled independently;
- Envelope section design is a process of composition of material components and systems with the support of knowledge from several sources. The process of addressing the functions of the building envelope, as in the function-satisfaction approach, provides efficient and informed design solutions rather than the method of working with component-selection approach. For instance, the industry knowledge may suggest selecting two components for two different functions, which in actuality could be handled using one component. Such redundant designs could be avoided when the assembly is designed by addressing the functions;
- The selection of a component to satisfy a function may follow a design path that traverses through a series of strategies of various functions, as discussed in the function-satisfaction approach;
- The actual design paths followed for design decisions vary based on the designer's knowledge, experience and attitude;

- The designer considers the options of strategies and components for each function depending on the knowledge in the discipline. Efficient designs could be drawn if the designer considers all pertinent options;
- The designer follows a holistic approach while handling the functions of the building envelope system (i.e. the designer considers multiple functions simultaneously and hence switches between the functions during the synthesis process);
- Iteration through the decisions handled during the design process is a characteristic of the design process;
- Analysis and evaluation are frequently conducted during the design process. It is handled at all levels: analysis in the choice of strategies; analysis in the choice of design decisions; analysis and evaluation of the envelope sub-systems; and analysis and evaluation of the envelope system by verifying the performance of the building. The evaluations may be analytically or logically handled.

3.6 Role of Database and Knowledge Base

Data and knowledge play a significant role throughout the building envelope design process. Chapter 2 on the literature survey reviews the sources of information relevant to the building envelope design. Based on the analysis of the

Database	Climatic data of various cities List of materials availabe Cost of listed materials Construction cost Properties of listed materials
Theoretical knowledge	Principles to evaluate the building envelope performance Analytical models (computer tools)
Rules of thumb, proven design practices and traditional techniques	Rules of thumb Proven design practices (assemblies / parts of assemblies / material / connections / junction details) Availability of materials Available construction techniques Time period for constrcution of building sections Knowledge of probable defects
Knowledge from research organizations	Guidelines from standards (e.g. providing specific building assemblies for any particular type of building) Guidelines and manuals of social organizations (e.g. CMHC) and scientific institutions (e.g. CBS)
Rules and regulations of governing bodies	Rules and regulations of local governing bodeis Regulations of local fire control body
Knowledge of building techniques and products	Product manuals and catalogues of manufacturers

Table 3.2: Sources of Knowledge and Information

building envelope design through exercises, as discussed in detail in Appendix B, the relevant database and knowledge base are categorized and listed in Table 3.2.

Knowledge could be categorized into:

1. theoretical knowledge, in terms of basic concepts and principles of the building science discipline;
2. rules of thumb, proven design practices and traditional techniques;
3. rules and regulations from local governing bodies;

4. knowledge from research organisations; and
5. knowledge of building techniques and products

The following sections briefly discuss the database and categories of the knowledge source listed above.

3.6.1 Databases

Weather data and material data are the most important information for a building envelope design process. Climatic data, analyzed in the problem definition stage such as temperature, relative humidity and degree-days, are required for the evaluation of design conditions for the building envelope design. A local designer is usually knowledgeable about the data required for his/her location. In the case of other locations the designer requires a reference manual. Data about the materials such as hygrothermal properties and cost per unit area are required during the selection of materials. The designer normally maintains access to information about the materials, their cost and properties. Apart from the data about the material properties, knowledge about its constructability, durability, aesthetic appeal, etc. are also important. In relevance to the location of the project, knowledge about the traditionally used materials for specific functions is important. Also, the functional properties of the materials in the database play a major role. Availability of the material data and intervention of the above stated knowledge in the building envelope design are required for effective design solutions.

3.6.2 Theoretical Knowledge

Theoretical knowledge in terms of concepts and principles aids to understand the behaviour of the building envelope system. However, the number of principles and analytical models for the building envelope design are limited, and fall-short for design purposes. Either they are not comprehensive with many limitations, or they are sophisticated requiring specialized knowledge and time. Nevertheless, being aware of the available theoretical knowledge is important. It helps in interpreting the available knowledge and making informed design decisions.

3.6.3 Rules of Thumb, Proven Design Practices and Traditional Techniques

Prior to the development of building science, the building envelope design was handled primarily by certain amount of practical knowledge. Such knowledge existed in the form of rules of thumb, proven design practices, and traditional techniques. They were developed in the industry through practice. Almost all the issues of the envelope design such as construction techniques; cost estimation; durability; risk prediction; and performance analysis are handled using this type of knowledge. The availability of such knowledge increases day-by-day due to the ongoing developments in the building envelope industry. Every designer acquires rules of thumb, proven design practices and traditional techniques through experience. They are reliable, but only when used in appropriate situations. Understanding the scientific reasons of the knowledge aids efficient design. Building envelope design requires the intervention of these types of knowledge more often in the conceptual design stages. Apart from the rules of thumb, which are specific to the techniques employed, the other types vary with the location.

3.6.4 Knowledge from Research Organizations

There is a trend of release of suggestive knowledge by research organizations, e.g., guidelines and manuals from financial and social organizations such as the Canadian Mortgage and Housing Corporation (CMHC), and scientific institutions such as the Centre for Building Studies, Concordia University (CBS). Also, there are organizations prescribing standard buildings and building components for efficiency (e.g., R-2000 standards and NovoClimat). These types of knowledge aid in providing efficient design solutions.

3.6.5 Rules and Regulations

The envelope system like other systems is required to follow rules and regulations of local governing bodies (e.g. the National Building Code of Canada) to meet the minimum performance requirements. The rules and regulations change with respect to the location. Rules and regulations are mandatory, and hence are required to be followed. The designer is required to be informed of the mandatory regulations during the building envelope design.

3.6.6 Knowledge of Building Techniques and Products

Updated information about the building techniques and products are significant for the building envelope design. Some of the information relevant to building techniques and products pertinent to the building envelope design are aesthetic appeal, construction cost, time period for construction of building sections, availability of materials, and available construction techniques. The common sources of information for this type of knowledge are product manuals, catalogues and web sites of manufacturers.

3.6.7 Intervention of Knowledge in the Building Envelope Design Process

The application of appropriate knowledge at right junctures is important for the building envelope design process. Appendix B (Section 3) lists the knowledge used in the exercise on the building envelope section design. The following paragraph provides an overview of the knowledge used in the exercise classified on the basis of the functions. It is pertinent to the design of a wall section of a residential building of up to ground plus two floors:

1. Generic knowledge applied in handling all the functions of the building envelope design process:
    - Knowledge of primary materials and construction types for each component of the assembly envelope;

- Knowledge of traditional materials and construction types for each component of the assembly envelope;
- Design cases from the literature, manuals, and previous design cases for each component in reference with the design conditions;
- Knowledge to evaluate the results of scientific analysis;
- Knowledge of the unit price of the components;

2. Knowledge related to structural stability function:
    - Classification of structure and all the options available, based on the building type;
    - Classification of wood structure based on the construction type;
    - Options available for wood stud sizes in case of wood-stud structure;
    - Regulations for wood stud structure, minimum stud size, maximum spacing, and maximum unsupported height from governing bodies such as National Building Code;
3. Knowledge related to control of heat flow:
    - Knowledge specifying the insulation level required by code/regulations;
    - Options of strategies for insulation components, primarily the classification of the insulation based on the insulation material type;

- Knowledge specifying the thickness of the material used as exterior or interior insulation, usually provided by the manufacturer;
- Knowledge indicating the use of loose-fill or semi-rigid insulation in the cavity between studs;
- Analytical capability and knowledge to evaluate the results of heat resistance;
- Knowledge indicating the positioning of vapor barrier adjacent to the insulation layer;
- Material options on the basis of the type of insulation selected;
- Knowledge handling the thickness of the insulation to be less than the thickness of the stud depth;

4. Knowledge related to control of vapor diffusion:
   - The strategies of the various methods of vapor diffusion control;
   - Knowledge indicating the possibility of vapor diffusion control by other means, basically by using material layer with high moisture storage capacity and by using vapor resistant paints;
   - Knowledge indicating the positioning of the vapor barrier depending on the design conditions, especially the climatic type;
   - The material options that comply to the regulations of the National Building Code;

- Knowledge indicating the use of low-permeance material layers for other components such as sheathing, and exterior cladding;
- Knowledge about the allowable vapor permeance, based on the building type and section type;

5. Knowledge related to rain-water control:
   - Knowledge specifying the thickness of the material used as an exterior cladding, usually provided by the manufacturer;
   - The necessity of the rain screen from the proven design practices;
   - Knowledge indicating the need of presence of air cavity and its position, and the minimum thickness to be at least 12.5 mm and the effective thickness to be 25 mm (considering the material of cladding and constructability aspects);
   - Knowledge to check the weather resistance capability of the inner wall, and to indicate the requirement of a weather resistant sheathing layer;
6. Knowledge related to interior finish:
   - Knowledge supporting the selection of interior finish based on the function of the space enclosed by the envelope system, e.g. wooden panels for theatres to dampen acoustical reverberation;
   - Knowledge aiding the selection of the interior finish material based on the aesthetic appeal;

- The options of paints and other finishes for the interior;

3.7 Chapter Summary

Chapter 3 discusses primarily the analysis of the building envelope design process through the literature review, described in Chapter 2, and the exercises on the building envelope section design documented in Appendix A and B. It discusses the designer's whole-to-part approach of the building envelope system design and the design of the core element (i.e. the building envelope section). It identifies and explains the three main stages of the design process: problem definition, design synthesis, and analysis and evaluation. The problem definition involves the extraction of information required for the building envelope system design, primarily the design conditions and performance requirements. The design synthesis stage is identified to have two approaches: design by intuition through experience and knowledge of the designer, and the assembly build-up either by step-by-step or case-based approach. The step-by-step approach is performed either by component-selection or function-satisfaction process. The function-satisfaction process is explained using tree-structured representation for each function, containing nodes with strategies and solutions. This chapter also discusses the sources and role of knowledge used in the building envelope design process at various stages. It is inferred from the study that the tool should focus on two aspects, the design methodology and intervention of knowledge. The following chapters present the design of a tool to support the building envelope design process incorporating the design methods and the knowledge.

Chapter 4

Analysis and Design of Building Envelope Design Tool

The design of a tool requires the analysis of the requirements for the tool and the possible methods of implementation. Based on the study of the building envelope design process, as discussed in chapter 2 and 3, this chapter establishes the requirements of the computer tool. To satisfy the requirements identified in the study, an integrated design tool is proposed. This chapter introduces the concept of the integrated building envelope design tool with a detailed explanation of its features.

4.1 Analysis of Requirements for the Building Envelope Design Tool

The requirements of the design tool are based on the characteristics of the design process, working trends of designers, and available knowledge. Each of the stages of the building envelope design process (problem definition, synthesis, and evaluation of design solutions) imposes different requirements for the design of the tool. The required features are presented in the following sub-sections.

4.1.1 Requirements of the Design Tool in the Problem Definition Stage

As discussed in Chapter 3, the problem definition stage handles project definition and performance specification. For project definition, the tool needs to support input of data for location and design conditions: mainly indoor and outdoor temperatures, indoor and outdoor relative humidities, and degree-days. Location is a primary data in the project definition that helps to retrieve other data and knowledge for performance specification and design synthesis. For example, the outdoor design conditions could be retrieved from data source such as NBCC, ASHRAE, CWEEDS, WYEC, and CWEC as discussed in Chapter 2. The following paragraphs contain the requirements with a reference number starting with the alphabet 'R'. They are later referred in the sections handling the features of an ideal tool and the prototype.

> R.1.1. Support to Input Project and Site Information: The tool needs to support input of data for the location and design conditions, where the location could be used as a key field to retrieve data and knowledge to support the input of other fields;

The specification of performance requirements is handled in two ways: using specific quantifying variables of various functions such as the required thermal resistance (in RSI) for control of heat flow, and vapor diffusion and condensation for control of moisture, and using binary variables with values 'yes' or 'no'. The benchmark values of the quantifying variables may be either a minimum allowable level or a maximum level. There are other standard levels prescribed by the industry and local authorities such as the R-2000 standards for Canada and NovoClimat for Quebec. For example, for a specification to achieve an envelope system of R-2000 standards in Montreal, the quantifying variable for the control of heat, the thermal resistance, in the wall sections is set as 4.1 RSI. As an example for the performance specification by binary variable, the presence or absence of an air barrier in the assembly can be quoted. On the basis of the location, type of building and type of section specified in the project definition, the design tool should be able to provide knowledge about standard levels to the designer. Also, the designer should be allowed to enter any arbitrary value for the variables to specify design objectives.

> R.1.2. Support to Specify Performance Requirements: The performance requirements are specified in terms of design objectives through quantifying variables or binary variables, specified either by the designer or with the support of system knowledge;

4.1.2 Requirements of the Design Tool in the Design Synthesis Stage

As discussed in Chapter 3, the design of the building envelope system is handled in two stages: design by experience and assembly build-up. Design by experience is a process of making design decisions that involves only the knowledge and experience of the designer. The information gathered in the problem definition stage acts as the reference for the design decisions, and hence the tool needs to display the information entered in the problem definition stage. The designer uses different mediums of representation for design decisions, such as, rough graphical sketches, scaled drawings, numerical notes and text.

R.2.1. Display of Problem Definition Data in Synthesis Stage: The data entered during the problem definition should be available for reference during the synthesis stage;

R.2.2. Support the Entry of Design Decisions in other Forms: An environment containing mediums to register the design decisions through rough sketches, texts, numbers, and scaled drawings is required;

Assembly build-up of an envelope section is the core of the design synthesis in the building envelope design process. As identified, the assembly build-up is bound to follow either a case-based approach or the two different step-by-step approaches: component-selection approach and function-satisfaction approach. In a case-based approach, proven design cases, classified based on the building type, type of envelope subsystems, location and design conditions, are used.

The component-selection approach involves selection and positioning of the material components that are hypothetically designated to handle one of the functions of the building envelope system, one-by-one until all the specified functions are achieved to the required levels. For the component-selection approach, the knowledge that classifies the materials in the database according to their functional properties is used. The designer requires to be informed with the component options retrieved by correlating the function under consideration with the functional properties of the materials in the database. In case a component has properties satisfying more than one function, the knowledge that it handles those functions should be integrated. For example, polyethylene film could be classified as an air barrier and a vapor barrier and could be selected for both to control air movement and vapor diffusion. Some of the existing tools support the component-selection approach (e.g., Condense 2.0). Up-to-date database about the building materials along with the functional properties has to be maintained (i.e. to add and delete records of the database). The tool could also attach knowledge about compatibility between materials and cost factors to build an assembly.

> R.2.3. Support the Component-selection Approach: For component-selection approach the design tool requires to maintain functional properties of various materials, and rules to display the appropriate component options in stages;

The function-satisfaction approach involves design decisions by focusing on the satisfaction of each specified function to required levels. Design by the function-satisfaction approach follows a model that represents the functions of the building envelope system. The trees of functions, as discussed in Chapter 3, could be used to select the design options in terms of strategies and solutions to achieve the functions of the envelope system to required levels. In some cases, the design solution to achieve a certain function may impact the performance of the assembly with respect to other functions. For instance, a design decision to provide solution for a certain function could provide a complete or partial solution to another function. Hence, the design tool should be able to crosscheck the performance of the assembly with the performance requirement specifications of all the functions and update the options based on the evaluation results. Thus, design options should be generated based on the functions to achieve, preceding design steps, design paths and evaluation of the assembly. Also, a knowledge support to make design decisions is required. A few examples of the suggestive knowledge would be traditionally followed solutions in the local industry and the repercussions of the selection of a generated design option. The other forms of knowledge are prescriptive rules and warnings, which aid to prevent the designer from making unfavourable decisions. The designer handles the functions in any order and also switches between the functions, thus supporting the holistic behaviour of the designer. For example, while selecting insulation for the control of heat function the designer may realize that there is a necessity to select a sheathing layer for its support. And hence, the designer even before defining the insulation may select a sheathing layer and come back to the selection of insulation layer later.

R.2.4. Support the Function-satisfaction Approach: For the function-satisfaction approach, the design tool should maintain a set of functions, e.g. a check list of functions of the building envelope system, and should have a functionality to check the performance requirement specifications with the actual performance of the assembly during the design synthesis stage;

R.2.5. Generate Design Options: The tool should generate design options in terms of strategies and solutions that would lead to achieve the functions of the envelope system to required levels. The design options generated should be based on the functions to achieve, the preceding design steps, and evaluation of the assembly;

R.2.6. Provide Knowledge Support: The tool should include a functionality to provide knowledge support, in terms of suggestive knowledge, prescriptive rules and warnings for decision making;

R.2.7. Provide Flexibility to Switch between Functions: The tool should provide flexibility to deal with the functions in any order and to switch between the functions thus supporting the holistic behaviour of the designer;

During the synthesis stage, the designer may realize that a particular performance requirement specification is misquoted, and hence may modify the required values. For instance, a designer working to achieve the NovoClimat standard may decide to accept the R-2000 standard considering the other functions such as cost and buildability, and hence would lower the specified RSI values (e.g. for wall from RSI 4.3 to RSI 4.1). Certain functions could be evaluated in parts and be projected for the whole assembly performance. For example, to evaluate the cost of the assembly, the overall cost could be determined by the calculation of cost per unit area of the components.

R.2.8. Allow Modification of the Problem Definition Information: The data entered during the problem definition stage should be available to the designer to modify during the synthesis and evaluation stages;

R.2.9. Provide Access to Analytical Models during the Synthesis Stage: The design tool should have functions that allows the designer to access the analytical methods, to evaluate the assembly in the mid of the design process;

At the end of the design path in selection of a component for a function, the designer needs to configure the component. The configuration of the component involves the selection of a material (suitable for the function) from the material database, and the definition of its dimensions and properties, such as thickness and color. The functional properties of the materials are attached so that suitable materials are picked and listed. The material properties pertinent to the function of the assembly should be displayed for the designer to make a selection by comparison.

R.2.10. Integrate a Material Database and List the Appropriate Material Properties: The design tool should integrate a material database along with the material properties pertinent to the functions of the envelope assembly. A list of materials suitable for the component in selection should be displayed;

R.2.11. Display the Properties of the Material during Configuration: The material properties of the materials in the database are required to be displayed to the designer during the configuration of the component selected.

4.1.3 Requirements of the Analysis and Evaluation Stage

Evaluation and interpretation of results of the design is the final stage that verifies the performance of the designed building envelope against the specified levels of performance. For evaluation, the tool needs to use logical methods that are derived primarily from the knowledge in the industry, and analytical methods that are developed scientifically. The knowledge support is required to evaluate results from the analytical methods.

R.3.1. Support to Check the Performance of the Assembly against the Requirement Specification: The design tool should be capable to verify the performance of the designed envelope section against the performance specification at any step;

R.3.2. Integrate Knowledge and Scientific Methods: The design tool should be integrated with the knowledge and scientific methods for analysis and evaluation.

4.1.4 Requirements due to the Characteristics of the Design Process

A designer with a background in architecture or engineering, handles the building envelope design process in co-ordination with the specialists or by referring to the knowledge and information of other related disciplines such as structural engineering, building science (HAM control, physics, chemistry, material science, thermodynamics, climatology), mechanical engineering, and construction management (time, cost and labour management). This multi-faceted characteristic of the building envelope design process imposes a requirement to accommodate the various working trends of the different specialities involved. Also, the knowledge from several disciplines has to be captured and integrated in the design tool.

The design process is subjective to the experience, knowledge and working trend of the designer. These attributes are complimentary to each other. Working trend depends primarily on the professional background of the designer, apart from the experience and knowledge. The design tool should consider the variations in the working trend of the designers to provide a suitable environment. For example, an architect during the synthesis activity (assembly build-up) may prefer graphical thinking to text-based approach. One of the prominent requirements of the design tool is to be able to represent design decisions in graphical format. The design decisions registered in graphical formats have two purposes, as discussed in Chapter 2, support for design thinking and to record the design decisions graphically thus maintaining the history of the design path. Another characteristic of the design process is its iterative quality. The tool is required to record and display the history of design paths, and provide a capability to revisit the decisions in later stages. Being able to modify the design decisions is a significant characteristic of the synthesis stage. Also, during the assembly build-up stage the designer maintains alternative design solutions for evaluation. Hence, a capability to record, modify and evaluate alternatives of design solutions is required. The design tool is to be used by designers with different levels of knowledge and experience, which influences the design approach. As far as the experience and knowledge is concerned the design tool should integrate the functions that would support an experienced and knowledgeable designer, as well as a novice. For example, an experienced designer may prefer a case-based approach in the synthesis stage over a step-by-step method, like the function-satisfaction approach. The design tool should support both the step-by-step approach and the case-based approach.

R.4.1. Support the Working Trends and Knowledge of the Disciplines Involved: The design tool should accommodate the working trends and knowledge of the associated various disciplines of the building envelope design process;

R.4.2. Support the Different Mediums of Representation: The design tool should support the different mediums of representation for the design decisions that the designer may want to use, such as, rough graphical sketches, scaled drawings, numerical notes and text based hints;

R.4.3. Maintain Alternatives: The tool should provide capability to store and maintain alternatives;

R.4.4. Maintain Design History: The tool requires a feature to maintain the history of design decisions and a capability to modify the design decisions to support the iterative nature of the design process;

4.1.5 Requirements of the Design Tool in Incorporating the Data and Knowledge

Knowledge plays a major role in the building envelope design process. Knowledge support is required in all the stages from various sources, as discussed in Chapter 3. The design tool thus needs to contain available key knowledge from the industry, and the capability to propose the relevant knowledge at appropriate junctions of the design process. Material data and weather data are the primary information required for the building envelope design process. Along with the general material properties, the functional properties are required to aid displaying the material list for functions.

R.5.1. Maintain Database: The design tool should have methods to maintain the database (i.e. to add and delete records, of building materials along with the functional properties);

R.5.2. Attach Knowledge to Database: In the material database, the tool could also attach knowledge about compatibility between materials and cost factors;

One of the roles of knowledge is to inform the designer about the available options at various stages of the design process along with the repercussions, (e.g., for insulation the designer knows cavity insulation is one of the options, and also the repercussion that it requires a layer to enclose the cavity outside as a protection against rainwater). Knowledge supports the designer to make design decisions logically where there is no appropriate analytical model available. The above-mentioned knowledge is referred as suggestive knowledge that helps the designer to make informed design decisions. Knowledge about traditionally used materials or components used for a particular function, building type and section type in a specified location is an example of suggestive knowledge. Regulatory bodies of local authorities and other institutes provide prescriptive knowledge (mandatory) to which the designer has to abide during the design process. In addition there are some rules, which handle the evaluation of design decisions and indicate the possible undesired effects and changes or additions, which could be referred as warnings. Thus, based on the role of knowledge influencing design decisions, knowledge could be classified as suggestive knowledge, prescriptive rules or warnings.

R.5.3. Provide Knowledge in Appropriate Form: The knowledge in the industry should be provided to the designer in three forms: suggestive knowledge, mandatory rules, and warnings, to make informed design decisions;

R.5.4. Provide Suggestive Knowledge: Along with the support to generate the design options for the designer, the design tool could also provide suggestive knowledge in terms of traditionally followed solutions in the local industry and the repercussions of the selection of a design option generated;

R.5.5. Provide Knowledge Support for Evaluation of Assembly: A knowledge support intertwined with analytical capabilities to interpret the results of analysis by sophisticated analytical models is required;

4.2 Integrated Building Envelope Design Tool

The requirements of the design process showed the need for a tool that radically differs from design tools currently available for the building envelope design process. In order to address this need an integrated computer tool to support the building envelope design is proposed. Unlike existing tools, which are primarily used for evaluation purposes, the proposed tool would support the design synthesis stage. It is based on the fact that envelope design is a sequence of decision-making steps to select and configure envelope subsystems.

4.2.1 Concept of the Design Tool

Based on the requirements for the design tool, three types of integration are identified to be included within the design tool: (i) integration of different working trends, mainly architectural design and engineering design; (ii) support for both logical and analytical methods; and (iii) inclusion of knowledge base obtained from several sources as identified in section 3.6. The commendable features of the proposed design tool are the intervention of knowledge, the support for design synthesis in every step, the handling of iteration and alternatives, and the flexibility to switch between functions while designing.

4.2.2 Scope of the Design Tool

The tool supports the identified three stages of the building envelope design process: (i) the problem definition stage; (ii) the synthesis stage; and (iii) the analysis and evaluation stage. During the problem definition stage the design tool supports the entry of information extracted from project definition and the performance specification, which would guide through the building envelope design process. The definition of components of the envelope section during the synthesis stage, integrated with analysis and evaluation functions, is supported. On completion of the assembly the design tool supports a complete evaluation with respect to efficiency and performance in the analysis and evaluation stage.

Of the subsystems of the envelope system, as discussed in Chapter 2, the design of envelope sections and connections are identified to be important in the building envelope design process. The scope of the research is confined to a tool that supports the design of one envelope section of the building envelope system at a time. Design of junctions and other subsystems are left for future work. The design tool considers only functions such as heat, air and moisture control, structural stability and aesthetics. The other functions could be addressed in the future based on the concept of the developed design tool. The core of the work is to identify a representation of the design process, to integrate the required level of knowledge, and to support the designer in the synthesis process. The research also concentrates on the interface design, which is important to provide a suitable environment for the designer. Of the different approaches presented for the assembly build-up process, as discussed, the research focuses on the step-by-step approach by function-satisfaction.

4.2.3 Design of the Tool

There are two aspects to handle in the design of the tool: issues of the building envelope design process and integration of knowledge to support the design process. This section discusses the planning and design of the tool that primarily involves the modelling of the user-system interaction, the system working and the knowledge intervention.

Four types of programming approaches exist: unstructured programming, procedural programming, modular programming, and object-oriented programming [Müller, 1997]. The object-oriented programming technique is used to design the tool out of the four identified programming techniques. Object-oriented programming is a technique that involves the definition of objects, through which the functions of the tool are achieved. Objects are reusable software components that model items in the real world, where data type and operations (function) are defined in the data structures. It also allows the creation of relationships between one object and another (e.g., objects can inherit characteristics from other objects). An important feature of object oriented programming technique is that it enables programmers to create modules without affecting the existing program. Since the building envelope design is a complex process involving multiple disciplines that consistently develops and redefines knowledge in the industry, an object oriented programming technique is used, which would allow additions and modifications. New objects could be created that inherits features from the existing objects, thus allowing reuse. Of the popular object-oriented programming languages (OOPL) such as Java, C++ and Smalltalk, Java was selected because of the availability of an extensive system in-built library support for the creation of user-friendly environment and the extensibility of the tool to the World Wide Web through applets. Applets are codes written in a programming language that can be included in a web page to perform required functions. It is widely written using the Java language and are transferred to a system and executed by the browser's Java Virtual Machine (JVM). The JVM is a program that runs under an operating system and interprets Java programs. By using applet programming using Java, the tool could be extended to a remote user with the help of World Wide Web, while maintaining the knowledge in a server.

The planning and design of the tool was handled using the concepts of the Unified Modelling Language (UML). UML is a visual modelling technique used to specify, visualize, and document the artefacts of an object-oriented system under development. The design of the software tool using UML is visualised through a series of stages such as identifying and creating use cases, identifying classes, establishing relationships between classes, and laying out sequential diagrams. The use cases model the dialogue between a user and the system. They represent the functions included in the system. A use case is a sequence of activities performed by a system with the actor participating from outside to yield a result [Quatrani, 2001]. This chapter presents the use cases to model the user-system interaction. Appendix C documents in detail the interaction of the user with the design tool.

The knowledge is handled with a knowledge based system or expert system, one of the artificial intelligence technique. An expert system as defined by

NRCan [2004] "is an information system that uses codified tacit knowledge in a knowledge base and an inference engine to solve problems that normally require significant human expertise".

The expert systems, as discussed in section 2.5.1 of Chapter 2, are used to emulate the human expertise in well-defined problem domains. C Language Integrated Production System (CLIPS) and Java Expert System Shell (JESS) are some of the popular tools used to define expert systems. JESS is an expert system shell for the JAVA platform that works similarly to the CLIPS system, where CLIPS is a C based expert system. The research uses JESS due to the following inherent advantages. JESS can be used in two overlapping ways. First, it can be a rule engine - a special kind of program that very efficiently applies rules to data. Secondly, it is a general-purpose programming language, which can directly access all Java classes and libraries [Friedman-Hill, 2000]. Though the knowledge handling in the prototype tool is primarily dealt using the object-oriented programming some exercises were tried during the course of the research.

4.2.4 Functions and Working of the Tool

The following sections elaborate on the working of the design tool. It elaborates the functions of the tool that supports all the three stages of the building envelope design process. The main focus of the discussion is the user-system interaction and the functions that support the building envelope design process.

4.2.4.1 Problem Definition Stage

The tool supports the problem definition stage, where the designer enters the required project and site conditions and performance requirement specifications. Considering the scope of the tool, (i.e. to support the design of one envelope section at a time that verifies only some functions such as control of heat, air and moisture, structural stability and aesthetics) the tool prompts for the following input information: (1) location details; (2) building details; (3) section type; (4) climatic and design conditions; and (5) performance specification (satisfies the requirement R.1.1 in section 4.1.1). The use case 'Enter Problem Definition' documented in Section C.3 of Appendix C elaborates the user-tool interaction of the problem definition stage.

The primary entry fields for the location are city/town and country. These are the first data that should be entered. The tool contains a database of location that is displayed, which supports the entry of location. Most of the data and knowledge could be stored and retrieved based on the entered city or town of the project. For example, the climatic conditions and design conditions in the building envelope design such as climatic type, degree-days, outdoor temperature, outdoor relative humidity, etc. are stored and retrieved in reference to the location of the project. Knowledge such as traditional materials and components of building envelope, standards and regulations of the local governing bodies etc. are also referred using location as a key field. Apart from the available list of location the tool also supports the entry of a new location. On an entry of a new location the designer could relate the data and knowledge of other fields to the closest location available in the database. Also the designer could include a new location with new additions to the data and knowledge pertaining to the problem definition stage. In the future, additional fields for longitude and latitude could be included to support the designer with an intelligent system to identify the type of climate based on the geographical location.

The building type and number of floors of the project are the required information about the building. Building type, whether it is residential, industrial, etc. influences the knowledge to be applied (certain prescriptive rules from governing organizations such as the allowable air exchange rate, thermal resistance value of the envelope assembly, and structural specifications are based on the building type). For example the choice of an exterior facing for a residential building (where the priority is on economising the costs of installation and maintenance) varies highly from that of a commercial building (where the priority is structural stability and protection of wind effects in case of high-rise buildings). Number of floors is similarly required to help the selection of structural systems (e.g., wood structural system is only for buildings lower than ground plus two floors). The design of the envelope assembly depends on the section type, whether it is roof, wall, foundation wall or junction. As stated in the scope, this research concentrates only on roof, wall and foundation wall.

Climatic condition is primarily defined by two fields, climatic type and degree days, which are used to instigate the appropriate knowledge during the design of the building envelope. Design conditions are primarily the exterior climatic conditions, referred as outdoor conditions, and the controlled indoor conditions. The fields prompted during the building envelope design are exterior and interior relative humidities, and exterior and interior temperatures. The tool contains a database that could provide the appropriate outdoor conditions based on the location entered. The indoor conditions could be retrieved based on the climatic type entered.

The functions could be evaluated by specifying design objectives either in quantifiable terms (evaluated using analytical methods) or in logical terms. Examples of the quantifiable functions are control of heat flow, control of vapor diffusion and economy. Values for minimum thermal resistance and condensation amount to achieve the control of heat and control of vapor diffusion functions, respectively, are considered as the performance requirements to be specified during the problem definition stage identified within the scope of this research. In case of quantifiable evaluations, functions of the building envelope are either achieved thoroughly or partly. This depends on the characteristics of the functions under consideration. For example, the level of thermal resistance can vary from the minimum allowable level specified by the regulations to the maximum comfort level (as discussed in Chapter 2). The proposed tool would maintain the different levels of thermal resistance as inbuilt system knowledge. As discussed, the specification of the performance requirements is either handled randomly by the designer through experience, or by the inbuilt standards coming from the regulatory bodies and research organizations (satisfies the requirement R.1.2 in section 4.1.1).

4.2.4.2 Design Synthesis Stage

Design synthesis is the core of the design process. As presented in the requirements, the design tool requires a user-friendly and flexible environment for different working trends. The interface envisioned for the tool is presented below, displayed in Figure 4.1, and explained through an example. Considering the identified characteristics and requirements of the design process, the proposed tool contains the following features: display of problem definition information (A); suggestive knowledge (B); design paths (C); design history (D); generation and evaluation of alternatives (E); layer configuration and material specification (F); graphical display (G); and evaluation display (H); material properties (I); analytical models (J); and prescriptive rules and warnings. The features are shown in Figure 4.1, which depicts the synthesis window of the design tool. Each of the above features is described in the following sections through an example.

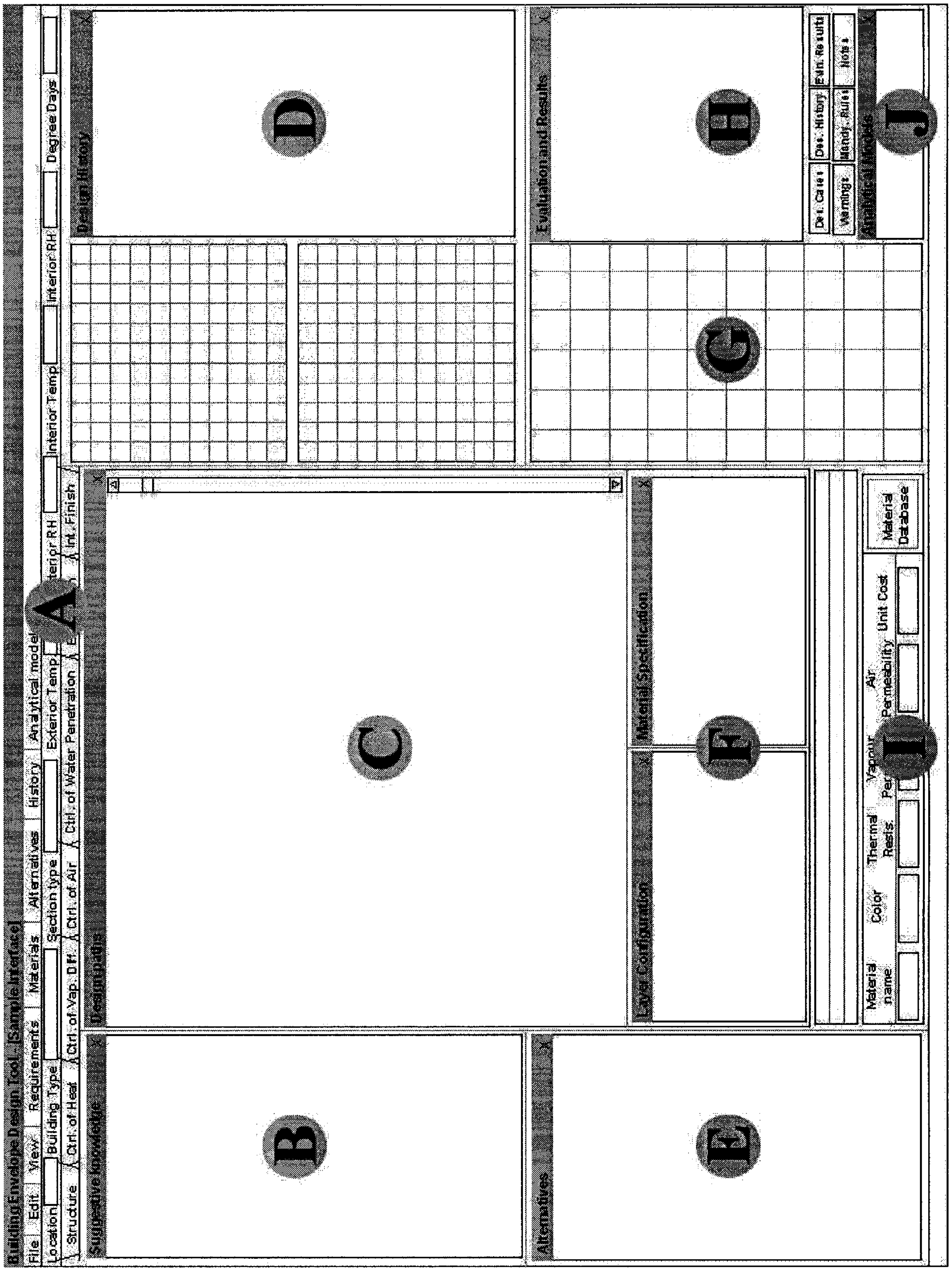

Figure 4.1: Representation of an Environment to support the Design Synthesis stage

Display of Problem Definition Information (A)

The information entered in the problem definition stage plays a significant role in both the synthesis and evaluation stages of the building envelope design process. During the synthesis stage the information is used to trigger appropriate knowledge to be displayed to the designer. Also, the designer requires it to make design decisions. The problem definition information appears in the top part of the design tool (this functionality satisfies the requirement, R.2.1 Display of Problem Definition Information in Synthesis Stage). Figure 4.2 shows an example of the display of the problem definition information (A) with values such as Montreal for location, residential and ground plus two for building type, wall aboveground for section type, -20°C for exterior temperature, 30% for exterior relative humidity, 23°C for interior temperature and 70% for interior relative humidity. The design tool also provides functionality to modify the values entered in the problem definition stage (this functionality satisfies the requirement, R.2.8: Allow Modification of the Problem Definition Information).

Design Paths (C) and Suggestive Knowledge (B)

The synthesis stage consists of a sequence of decision-making activities, either the selection of a strategy or solution, in order to achieve the required level of performance. The possible solution for each function is achieved by following a design path through a tree of design options (of the respective function) with strategies and solutions, as discussed in chapter 3. A design path is the sequence of

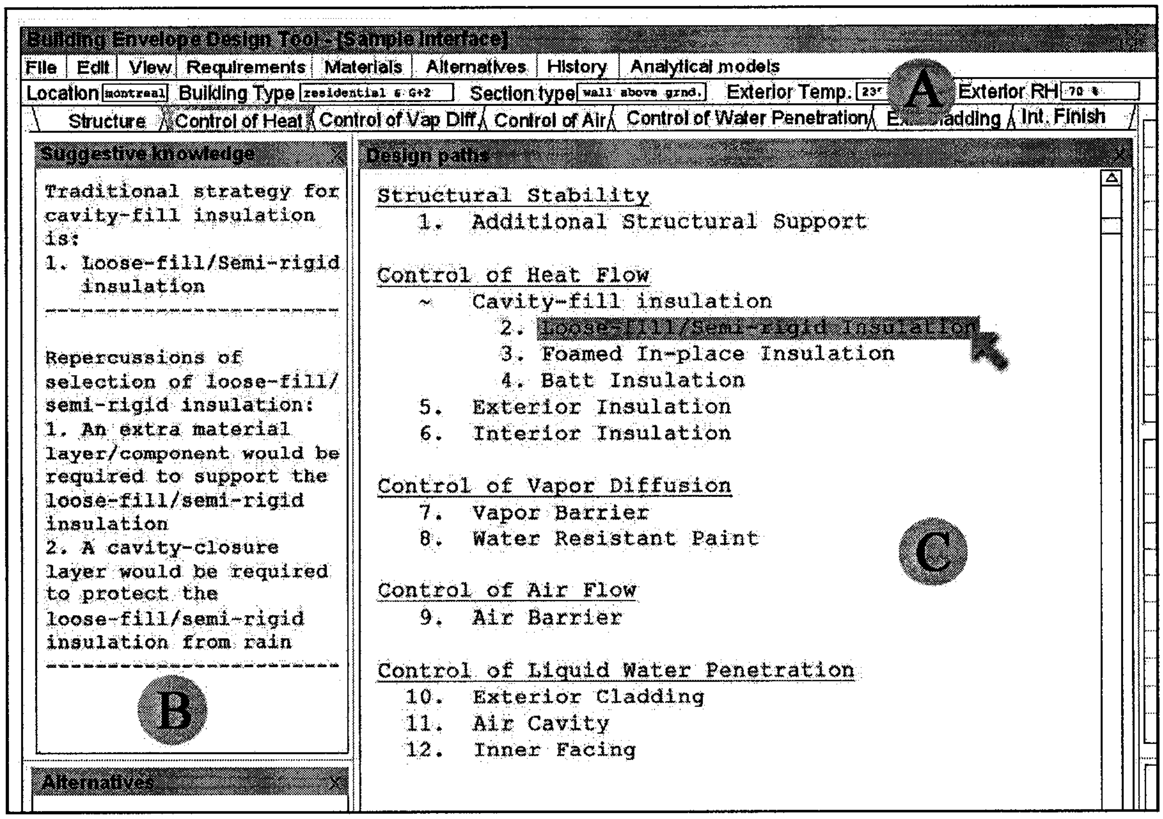

Figure 4.2: Sub-windows for the Design Paths and Suggestive Knowledge

decisions taken through each tree of possibilities to solve a function. In order to support this characteristic, the design tool is provided with the design paths sub-window where the strategies and solutions of the functions to be achieved are displayed as design options (this functionality satisfies the requirement, R.2.5: Generate Design Options). Figure 4.2 shows the Design Paths sub-window (C) with all the possible design options for a residential building (ground plus two floors) located in Montreal, after the structural system is selected (this is explained in detail in the following sections). The design options are dynamically proposed based on the project specification, performance requirements, previous design decisions and the functions to be achieved.

The suggestive knowledge sub-window displays knowledge such as the traditional systems and materials, and repercussions of the design options proposed in the design paths section (this functionality satisfies a part of the requirement R.2.6: Provide Knowledge Support). In this sub-window, knowledge is displayed to the user to support the selection of a strategy or solution and the configuration of a solution. This sub-window is activated when the designer selects a design option proposed in the design paths sub-window. The suggestive knowledge sub-window retrieves knowledge from the knowledge bases containing traditional strategies, functional performance and reminders by correlating with the specifications (this satisfies the requirement, R.5.4: Provide Suggestive Knowledge). In the example shown in Figure 4.2, the Suggestive Knowledge sub-window (B) displays the traditional strategy for cavity-fill insulation, the loose-fill/semi-rigid insulation. It also shows the following repercussions of the selection of loose-fill insulation: requirement of a support layer for the cavity-fill insulation and requirement of a cavity-closure layer to protect against the infiltration of rain.

At the start, the designer is required to select a structural system based on the building type and location. The design paths sub-window displays the design options for structural system. The suggestive knowledge sub-window displays the traditional structures being used in the location specified. The designer, wishing to learn more about the displayed structural systems, can see the repercussions of selection of a strategy or solution. For example, in the case of a residential building to be built in Montreal, the system would prompt wood stud, steel stud and concrete masonry units as design options. The suggestive knowledge window would propose the wood-stud structure as the traditionally followed design solution for the given conditions. On selection of a structural system, the options to satisfy other functions such as the HAM control and control of liquid water penetration are presented to the designer. HAM control is split further into three functions: control of heat conduction, control of vapor diffusion and control of air movement. Example in Figure 4.2 shows three strategies of control of heat flow function: cavity-fill insulation, exterior insulation and interior insulation, as proposed design options. The sub-strategies of one of the strategy, the cavity-fill insulation, are proposed as design options: loose-fill/semi-rigid insulation, foamed in-place insulation and batt insulation. The design options of other functions such as the control of airflow, control of vapor diffusion and control of liquid water penetration are also proposed, as shown. This provides the designer with the flexibility to move from one function to another thus satisfying the requirement, R.2.7: Provide Flexibility to Switch between Functions. For example, in the shown design paths, the designer could select the vapor barrier strategy of the control of vapor diffusion function after the selection of the cavity-fill insulation strategy of the control of heat flow function, instead of selecting the loose-fill/semi-rigid insulation as shown. The suggestion about the traditionally used cavity-fill insulation type for the given location is shown in the suggestive window, which is loose-fill/semi-rigid insulation. The repercussions of the loose-fill insulation/semi-rigid insulation, if selected, are shown in the suggestive knowledge window. Considering the suggestive knowledge, once the designer makes a decision to select a strategy of a function, the tool displays the next level of strategies or solutions towards achieving that function along with the already displayed options for the other functions. The tool correlates the project definition and performance specification, and the previous set of actions to guide the designer with succeeding levels of decision and suggestive knowledge. This has been discussed with the example shown in Figure 4.2. At the end of the design path is the selection of a material layer or component for the envelope assembly.

Prescriptive Rules (K) and Warnings (L)

Mandatory rules set forth by regulatory bodies and warnings to inform the user about illogical decisions in terms of performance are provided during the design process as and when encountered. The mandatory rules as discussed are extracted from codes and standards. The knowledge required for effective solutions are provided as warnings by manuals from institutions such as the Canadian Mortgage and Housing Corporation and the Institute of Research in Construction. The mandatory rules and warnings are prompted in separate dialog windows whenever required (this satisfies the requirement, R.5.3: Provide Knowledge in Appropriate Form). In the discussed examples of the above sections, after the designer selects loose-fill insulation/semi-rigid insulation as the insulation type

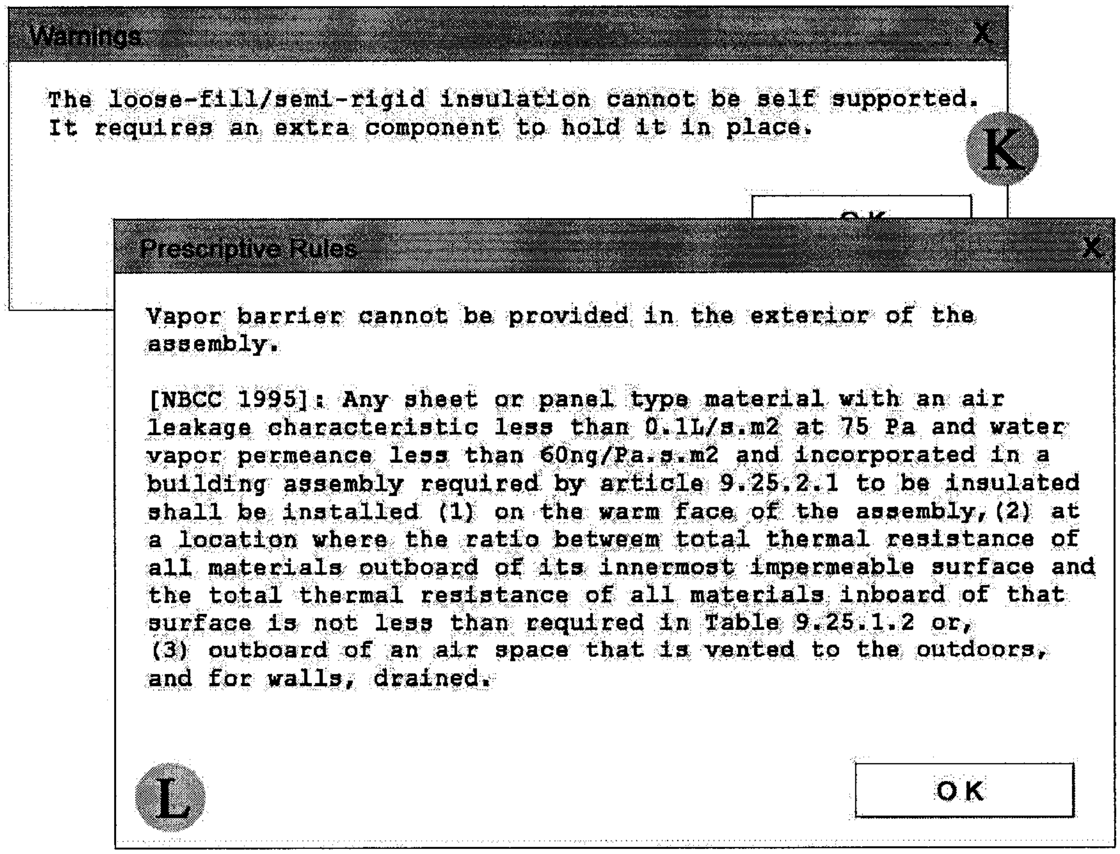

Figure 4.3: Sub-windows Illustrating the Display of Warnings and Prescriptive Rules

for the cavity-fill insulation the Warnings sub-window as shown in Figure 4.3 (K) displays a warning stating that the designer may require an extra component for the support of the insulation layer. While handling the control of vapor diffusion in a cold climatic situation, the designer may decide to provide a vapor barrier in the outside of the assembly, which would trigger the tool to display the prescriptive rule shown in the Prescriptive Rule sub-window (Figure 4.3-L).

Layer Configuration and Material Specification (F)

The Layer Configuration and Material Specification sub-window displays configuration fields with default values. The designer must input certain values

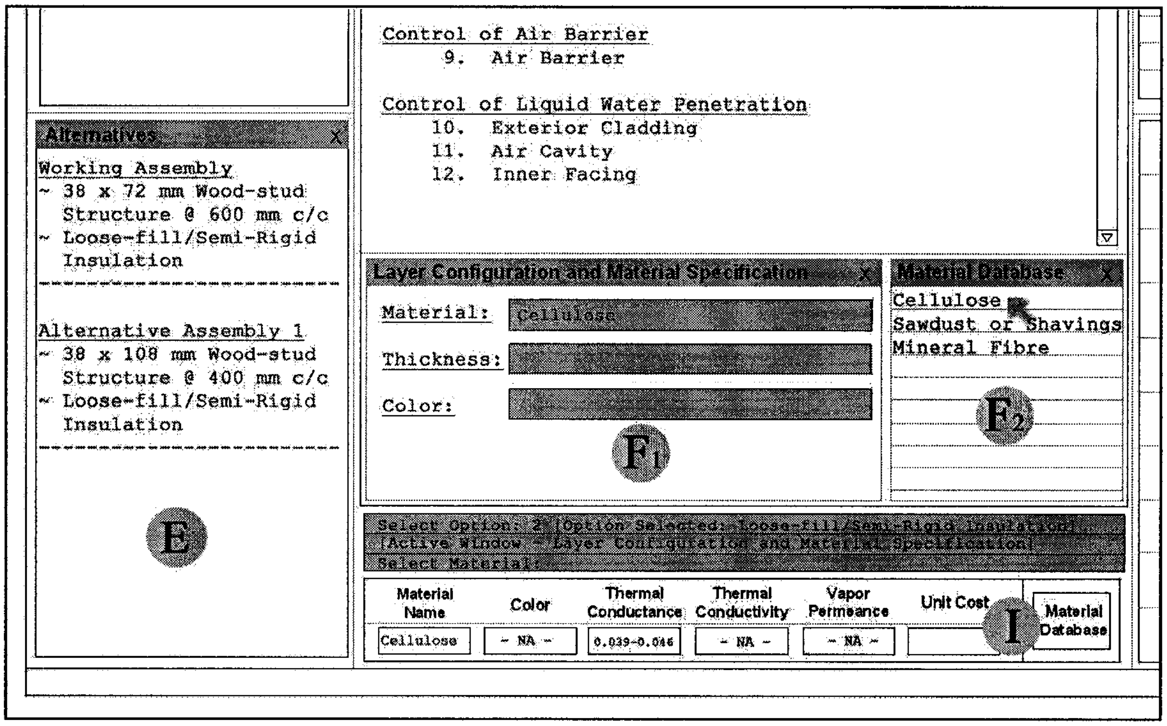

Figure 4.4: Sub-windows for the Alternatives and Layer Configuration and Material Specification

such as the material name, thickness and colour. The design tool has a Layer Configuration and Material Specification sub-window (F), as shown in Figure 4.4 that prompts appropriate attributes with default values when a layer or component is selected. The tool displays a list of materials suitable for the layer or component in the layer configuration and material specification sub-window, obtained from the material database. Figure 4.4 shows the Layer Configuration and Material Specification sub-window requesting information to be input to configure the loose-fill/semi-rigid layer as selected by the designer. A Material Database sub-window (F_2) displays a list of materials (cellulose, sawdust of shavings and mineral fibre) relevant to the strategy, loose-fill/semi-rigid insulation (this satisfies the requirement, R.2.10: Integrate the Material Database and List the Appropriate Materials). The material properties relevant to the functions of the building envelope of the material pointed in the database (the cellulose as shown in the figure) are displayed to aid the designer to make an informed design decision. On configuration of a solution, Evaluation sub-window, Design Path sub-window and Design History sub-window are updated.

Material Properties Display (I)

The properties of material under selection are displayed for reference to the user throughout the design process, as shown below the Layer Configuration and Material Specification sub-window (F_1) in Figure 4.4. The figure illustrates the material properties of the material pointed in the Material Database sub-window. The material properties illustrated correspond to the functions relevant to the building envelope design such as color, thermal conductance, thermal conductivity, vapor permeance and unit cost (this satisfies the requirement, R.2.11: Display the Properties of the Material during Configuration).

Generation and Evaluation of Alternatives (E)

One of the characteristics of the design synthesis stage is to maintain alternatives. The alternatives are generated at the time when the designer is uncertain about the selection from two or more options, during the design process. The right choice can eventually be made after an analysis and comparison of the performance. The tool supports the generation and storage of alternatives as per the designer's decision, as shown in the Alternatives sub-window (E) in Figure 4.4 (this satisfies the requirement, R.4.3: Maintain Alternatives). Example in Figure 4.4 shows two

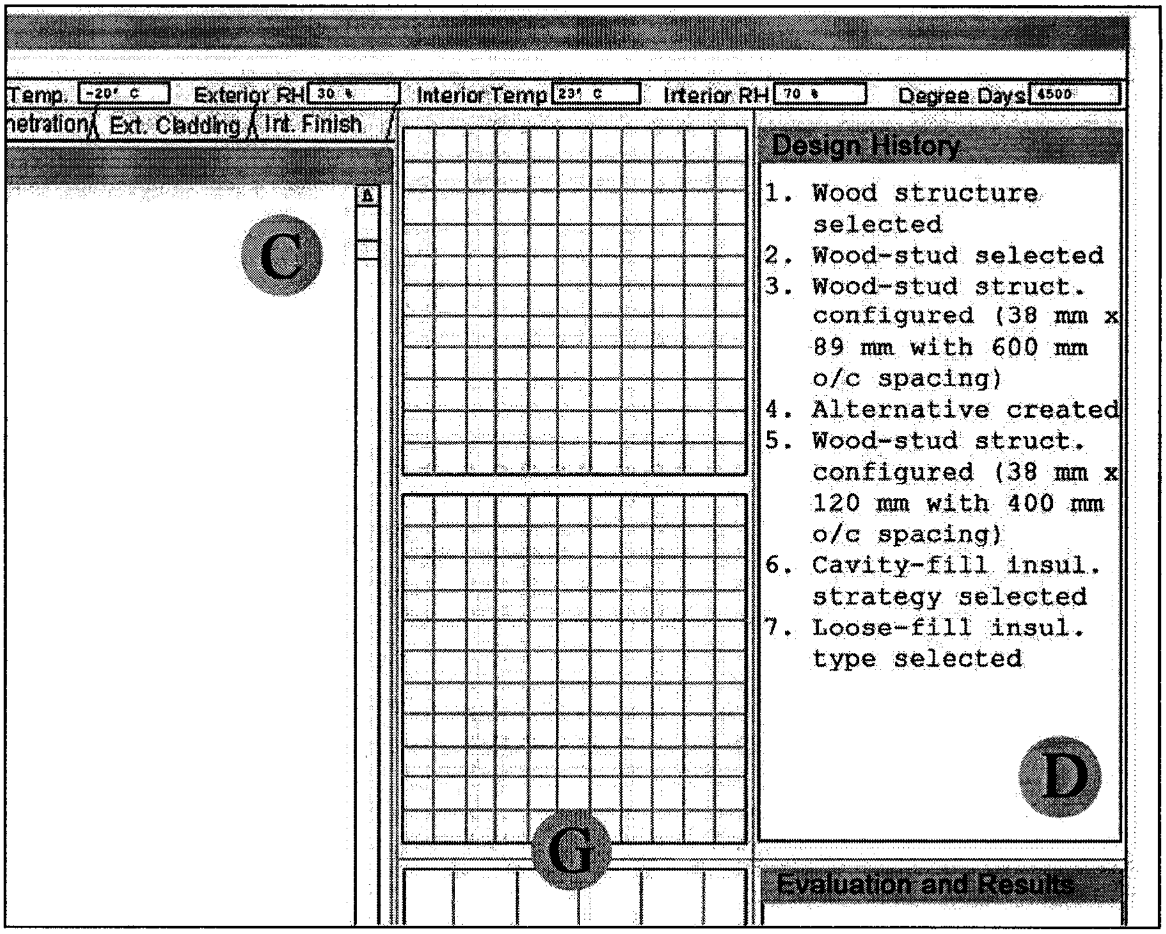

Figure 4.5: Sub-window for the Design History

alternatives where one of them is active and being worked upon and the other being kept for possible future use. It shows that the designer was uncertain about the options of the size of wood studs (either 38 mm x 72 mm or 38 mm x 108 mm) and the spacing between the studs (400 mm or 600 mm), and hence maintains two alternatives. The tool provides the flexibility to retrieve previous alternatives at any time of the design process for further elaboration or for analysis and evaluation. The stored alternatives can be simultaneously configured with the same layers as the current one if the designer wishes so.

Design History (D)

The steps of the design process are displayed in the Design History sub-window as shown in Figure 4.5. The Design History sub-window (D) in the figure illustrates design paths to select a structural system to satisfy the structural stability function and to satisfy the control of heat flow by selection of an insulation strategy. By maintaining design history the design tool provides flexibility to backtrack to any of the previous steps, thus supporting the iterative behaviour of the design process (this satisfies the requirement, R.4.4). In the illustrated example the designer may backtrack to the cavity-fill insulation selection and modify the selection to exterior insulation for the control of heat flow.

Graphical Representation (G) and Design Cases

The graphical section represented in grid format in Figure 4.6 (G), displays the section assembly with the selected materials. Apart from the recording of the design decisions, this feature helps the design thinking process, as discussed in Chapter 2 (this satisfies the requirements, R.2.2: Support the Entry of Design Decisions in Different Mediums and R.4.2: Support the Different Mediums of Representation). For example, the figure illustrates that cellulose is selected in between the studs as cavity-fill insulation for the control of heat function. From the graphical representation it is easy to observe that this layer requires a protection against the possible rainwater infiltration and a layer for its stability. Thus, it supports the design thinking process. The option to build up the assembly graphically using drawing tools and a support from design cases are considered as a future extension in the capabilities of the tool.

Evaluation Results Display

The evaluation of performance of the assembly against the specified level for each functions are displayed and updated in the Evaluation Results sub-window (Figure 4.6 - H). This helps to keep the designer informed and aware of the consequences of the choices. Figure 4.6 (H) illustrates an example of the Evaluation Results sub-window. The example illustrated indicates that the structural stability function is achieved through the wood-stud structure (38 x 89 mm with 400 mm

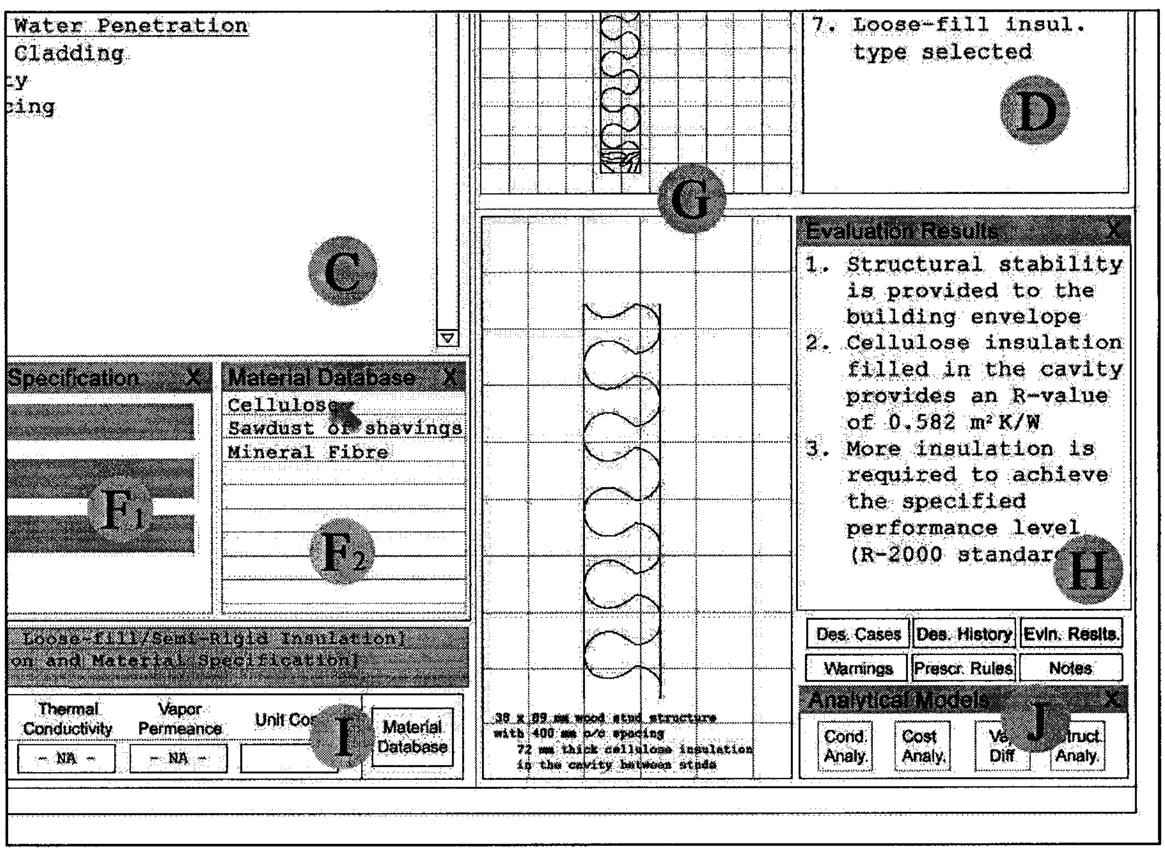

Figure 4.6: Sub-windows for the Alternatives and Layer Configuration and Material Specification

o/c spacing), whereas the insulation provided (89 mm thick cavity-fill insulation between studs using cellulose) does not completely satisfy the required performance level (R-2000 standards requiring an RSI of 4.1) for control of heat flow as entered by the user in the problem definition stage (this satisfies the requirement, R.3.1: Support to Check the Performance of the Assembly Against the Requirement Specification).

The Evaluation Results sub-window also displays the results when the designer evaluates an assembly section at will, using the access to analytical models in the Analytical Models sub-window. The figure illustrates an Analytical Models sub-window (Figure 4.6 – J) with four possible analyses: cost analysis, vapor diffusion and condensation analysis, and structural analysis (this satisfies the requirement, R.2.9: Provide Access to Analytical Models during the Synthesis Stage).

4.3 Other Requirements

The proposed design tool focuses on the function-satisfaction approach (satisfies the requirement, R.2.4: Support Function-Satisfaction Approach). The requirement to support the component-selection approach (R.2.4) is already dealt in the existing available tools for the building envelope design. A support for design synthesis by the case-based approach could also provide effective design solutions for the building envelope. Complete solutions of building envelope from the earlier designs cases and proven design cases in the industry could be stored and retrieved by the designer during the design process. This is a different field that requires an extensive research, which is left for future work.

The other requirements such as R.3.2: Integrate Knowledge and Scientific Methods, R.4.1: Support the Working Trends and Knowledge of the Disciplines Involved, R.5.1: Maintain Database, R.5.2: Attach Knowledge to Database, and R.5.5: Provide Knowledge Support for Evaluation of Assembly cannot be discussed using the interface. These requirements are handled in the design of the integrated tool.

4.4 Chapter Summary

This chapter specifies the requirements for an integrated design tool from the study of the building envelope design discussed in Chapter 3. It lists all possible requirements by analysing all the stages of the building envelope design process, the characteristics of the building envelope design process and the integration of the knowledge and data. Then, it elaborates the design of the tool developed on the basis of the identified requirements. It introduces the concept and scope of the tool, and presents an environment to support the user-system interaction in all the three stages: (i) the project definition and requirement specification stage; (ii) the assembly build-up stage; and (iii) analysis and evaluation stage. The functions of the design tool are discussed with examples using the developed user-interface.

Some of the functions identified: design paths and suggestive knowledge; mandatory rules and warnings; generation and evaluation of alternatives; design history and evaluation display; and display of problem definition information and material properties. Next chapter will demonstrate the implementation of some of the features discussed so far.

Chapter 5

Implementation and Evaluation of the Prototype Design Tool

Chapters 2 and 3 discuss the building envelope design process through a literature survey, hands-on exercises and an evaluation of existing computer tools. Chapter 4 discusses the level of computer support to be provided to the building envelope design process, outlining some significant characteristics and features that need to be included. This chapter deals with the analysis, design and evaluation of a prototype developed to test some of the characteristics identified and examined in Chapter 4.

5.1 Description and Working of the Prototype

The prototype is a text-based computer tool developed using the Java language and object oriented programming concepts. It has been developed to test some of the features that have been identified as unique and significant in relation to the building envelope design process. This includes providing suggestive knowledge, providing design options and providing the flexibility to handle functions in any

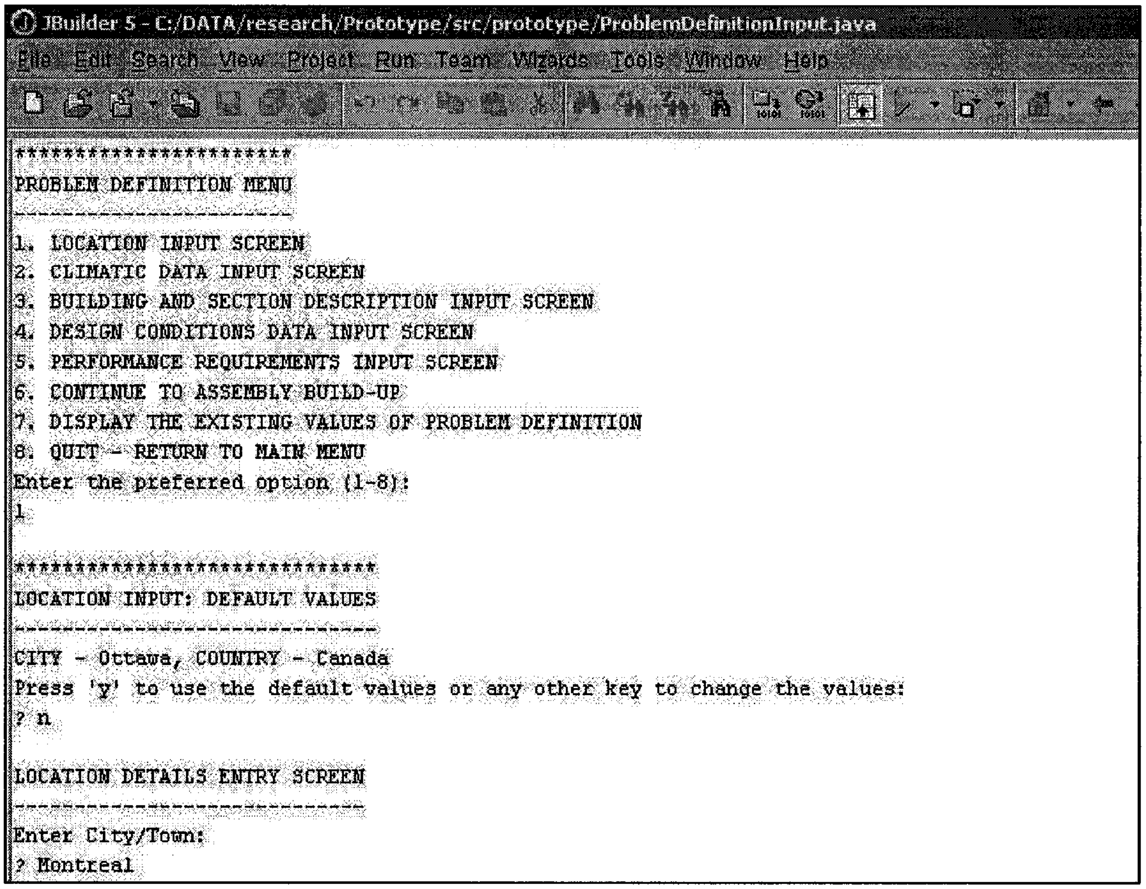

Figure 5.1: Screenshot of the Prototype showing Problem Definition Input

order (as well as to switch between the functions). The documentation of the use cases in Appendix C models the user-system interaction for the prototype.

The prototype handles the first two stages of the three stages of the building envelope design process: the problem definition and design synthesis. In the problem definition stage, the tool supports the input of information such as the location, design conditions, building details, section description, design conditions and the performance requirement specifications. The problem definition is handled using a *Problem Definition Menu* through which the designer enters relevant data (as shown in Figure 5.1). The first five options of the menu lead to the entry of information pertinent to the problem definition stage. As illustrated in

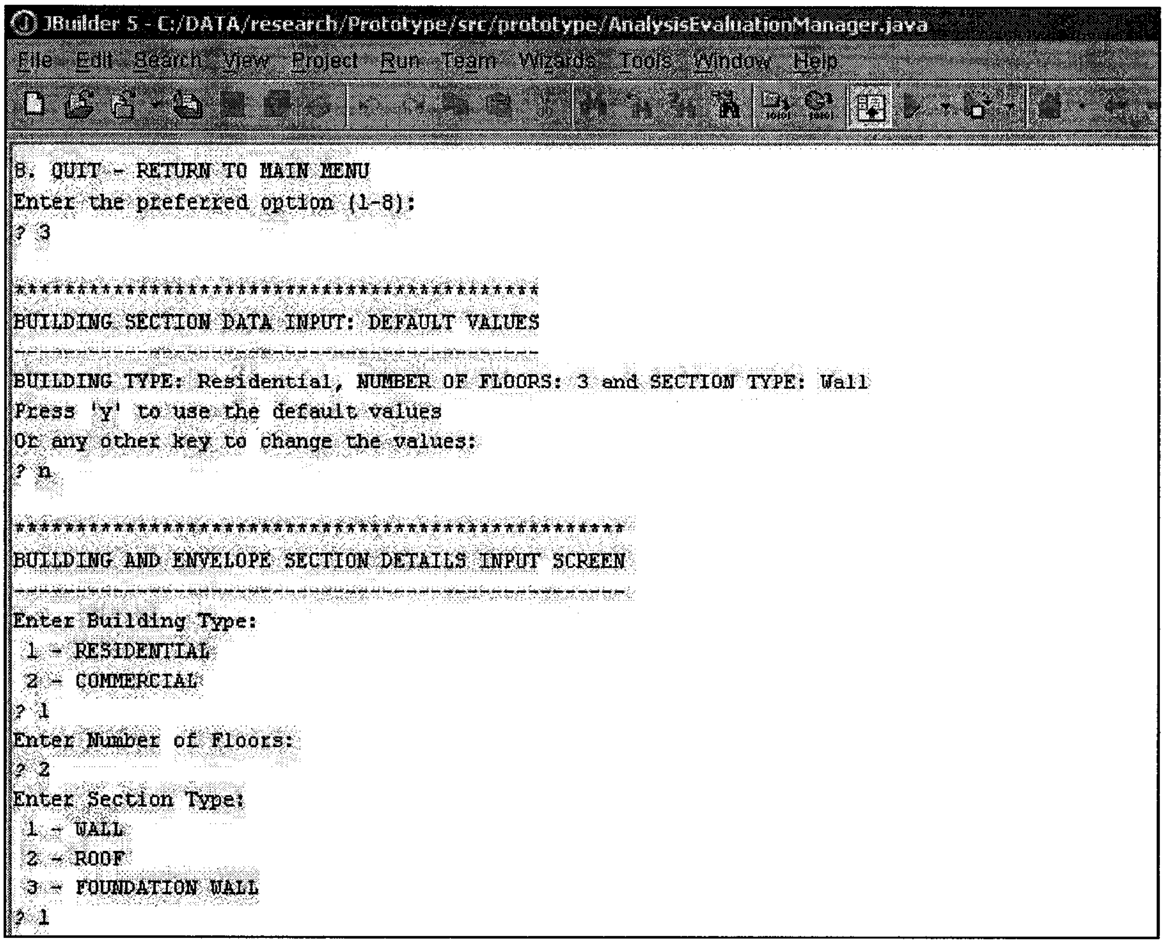

Figure 5.2: Screenshot of the Prototype showing Problem Definition Display Screen

the figure, on selection of option 1 the entry of location details such as city and country is handled. The tool is provided with the default values corresponding to Ottawa conditions. The designer is allowed to change the values (for example, from Ottawa to Montreal as shown in the figure). However, little validation is done to check the values entered in the current implementation. Similarly, the entry of values for the building type, section type and performance requirements are entered. Figure 5.2 shows the entry of building and section details. For building type, the options are residential and commercial. The default value is residential. For number of floors the designer can enter any number, the default

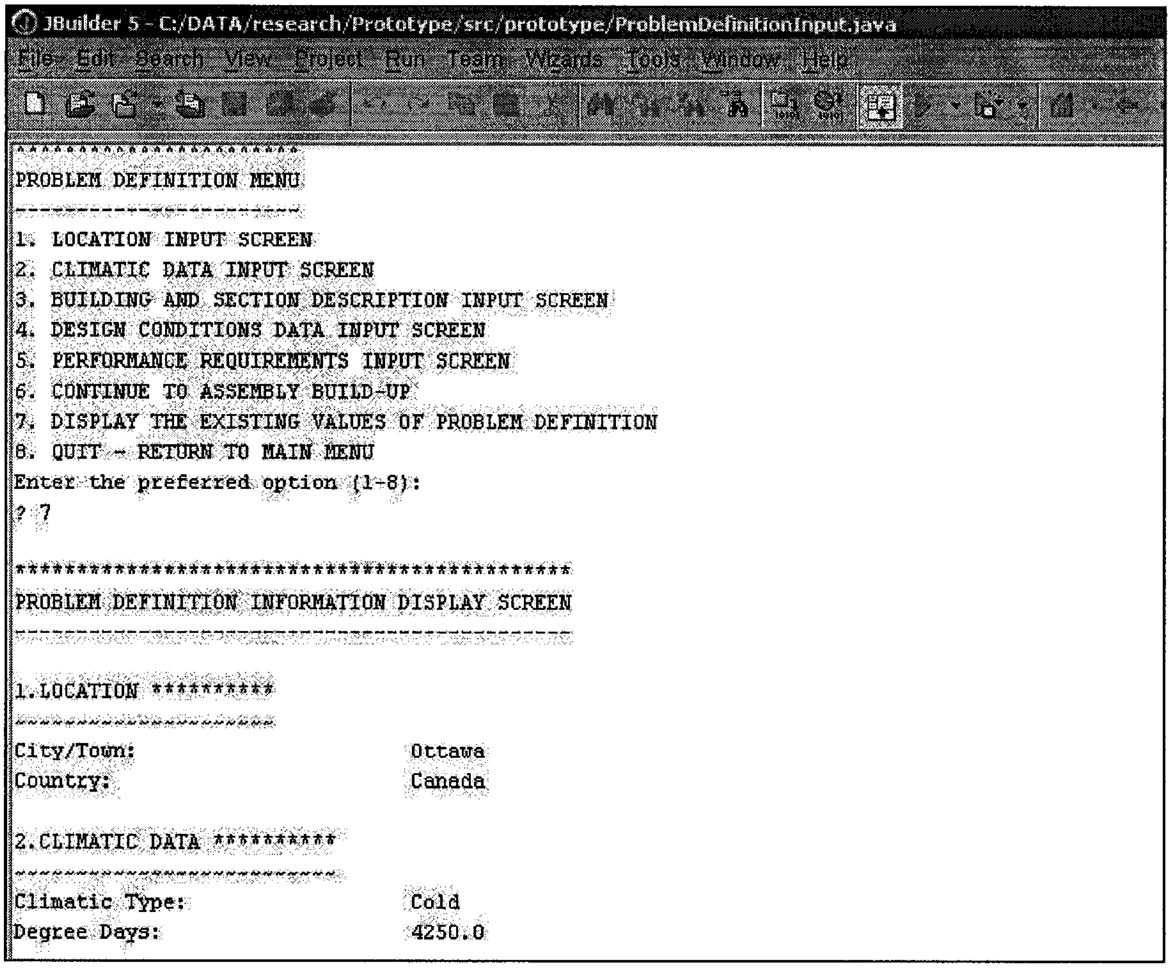

Figure 5.3: Screenshot of the Prototype showing Problem Definition Display Screen

value set at 3. For section type, the options are wall, roof and foundation wall with the default value being wall. With the selection of option 6, the designer continues with the next stage, Assembly Build-up, which is discussed in the following paragraphs. The design tool has option 7 to present the values entered in the problem definition stage using *Problem Definition Display Screen*, as shown in Figure 5.2. The figure demonstrates how the information is displayed (e.g. location and climatic data details) on selection of option 7, *'Display of the Existing Values of Problem Definition'*. The functions implemented above satisfy the requirements,

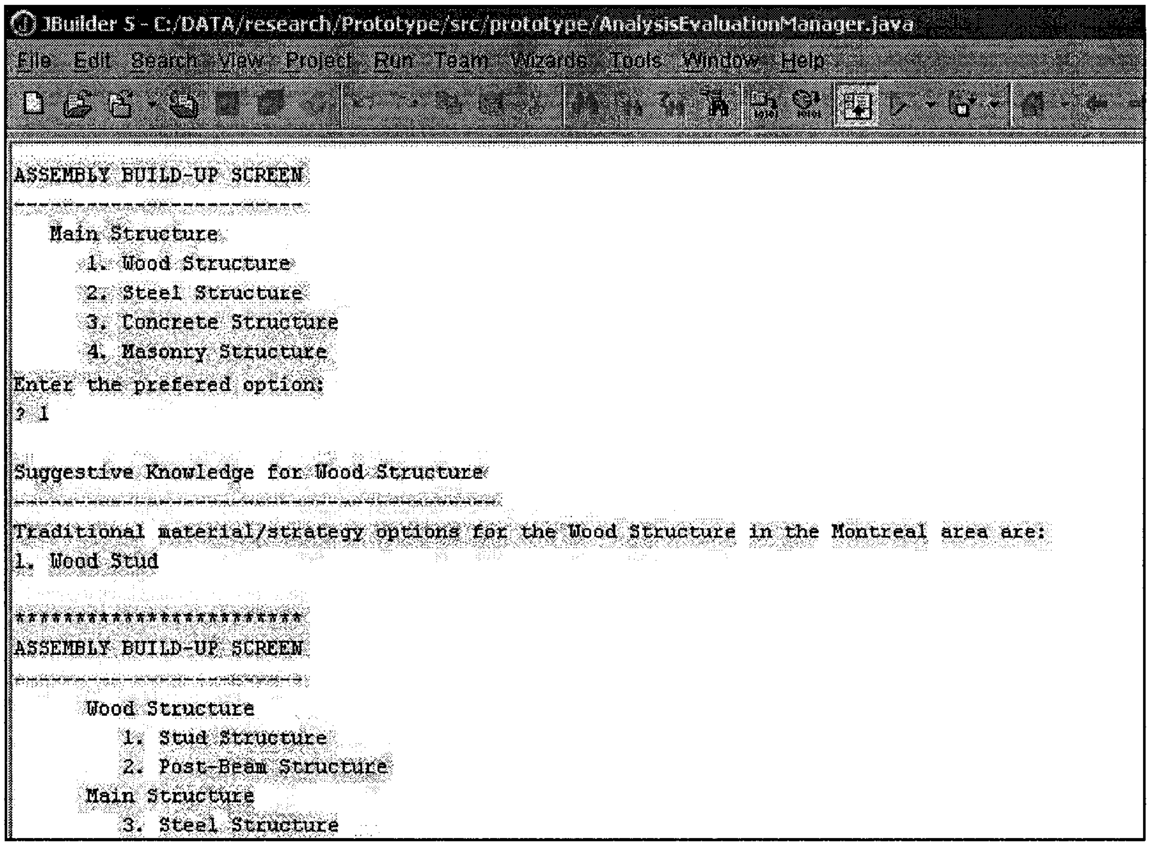

Figure 5.4: Screenshot of the Prototype showing Configuration of Structural Components

R.1.1: Support to Input Project and Site Information and R.1.2: Support to Specify Performance Requirements.

In the design synthesis stage, the tool starts with the structural stability function. It proposes the various structural system options such as wood structure, steel structure, masonry structure and concrete structure (as shown in Figure 5.4). This function proves that the design options for the functions could be generated and thus satisfies requirement R.2.5: Generate Design Options. As suggestive knowledge, the tool presents traditional strategies for the location and building type specified. In the example illustrated in figure 5.4, for a wall section design of a residential building located in Montreal, the suggestive knowledge indicates that

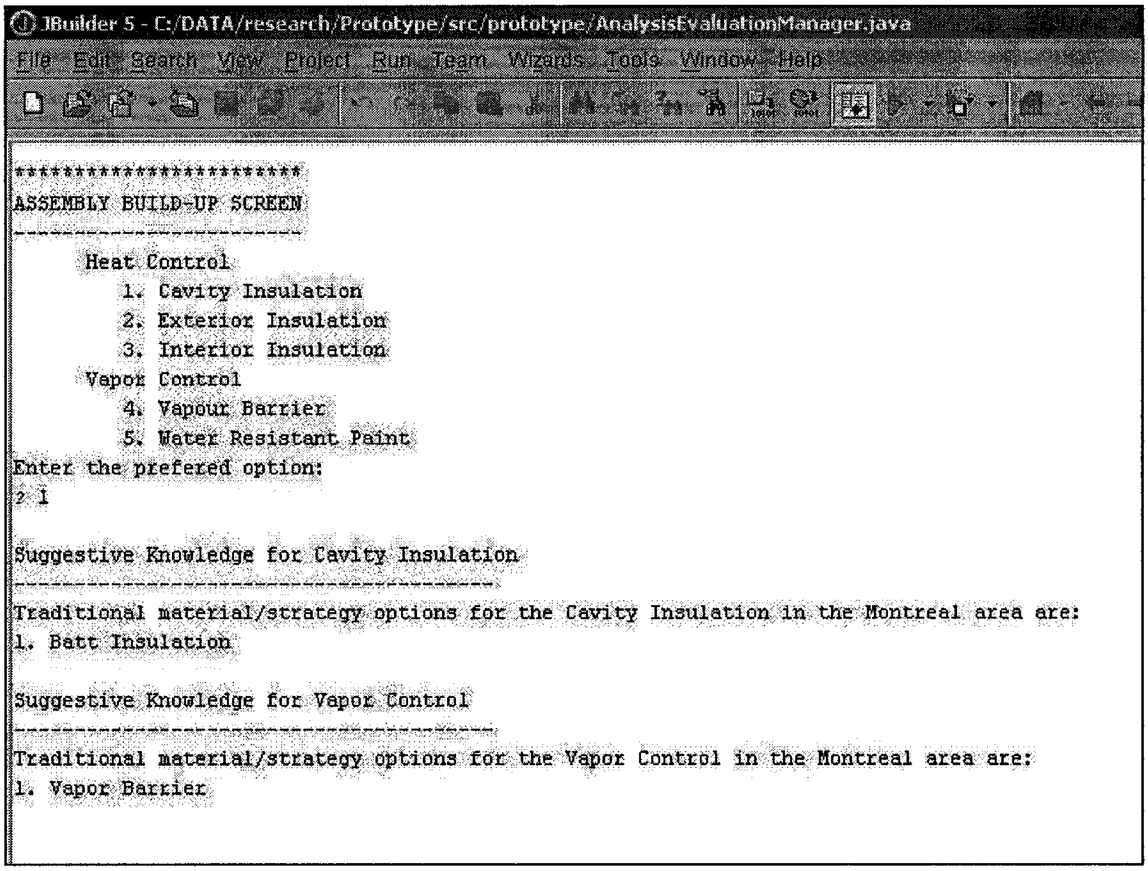

Figure 5.5: Screenshot of the Prototype showing the Assembly Build-up process

the wood stud is the traditional structural system. This function of displaying the suggestive knowledge proves the possibility of satisfying requirement R.2.6 Provide Knowledge Support, R.5.3: Provide Knowledge in Appropriate Form, and R.5.4 Provide Suggestive Knowledge. Upon selection of one of these strategies, the tool presents the next level of sub-strategies as design options. Let's say the user selects wood structure in the above example, the prototype provides two more sub-strategies, wood stud structure and post beam structure. If wood stud structure is selected, the following arrangement options are provided: 38 x 72 mm or 38 x 108 mm studs with a spacing of 400 mm or 600 mm.

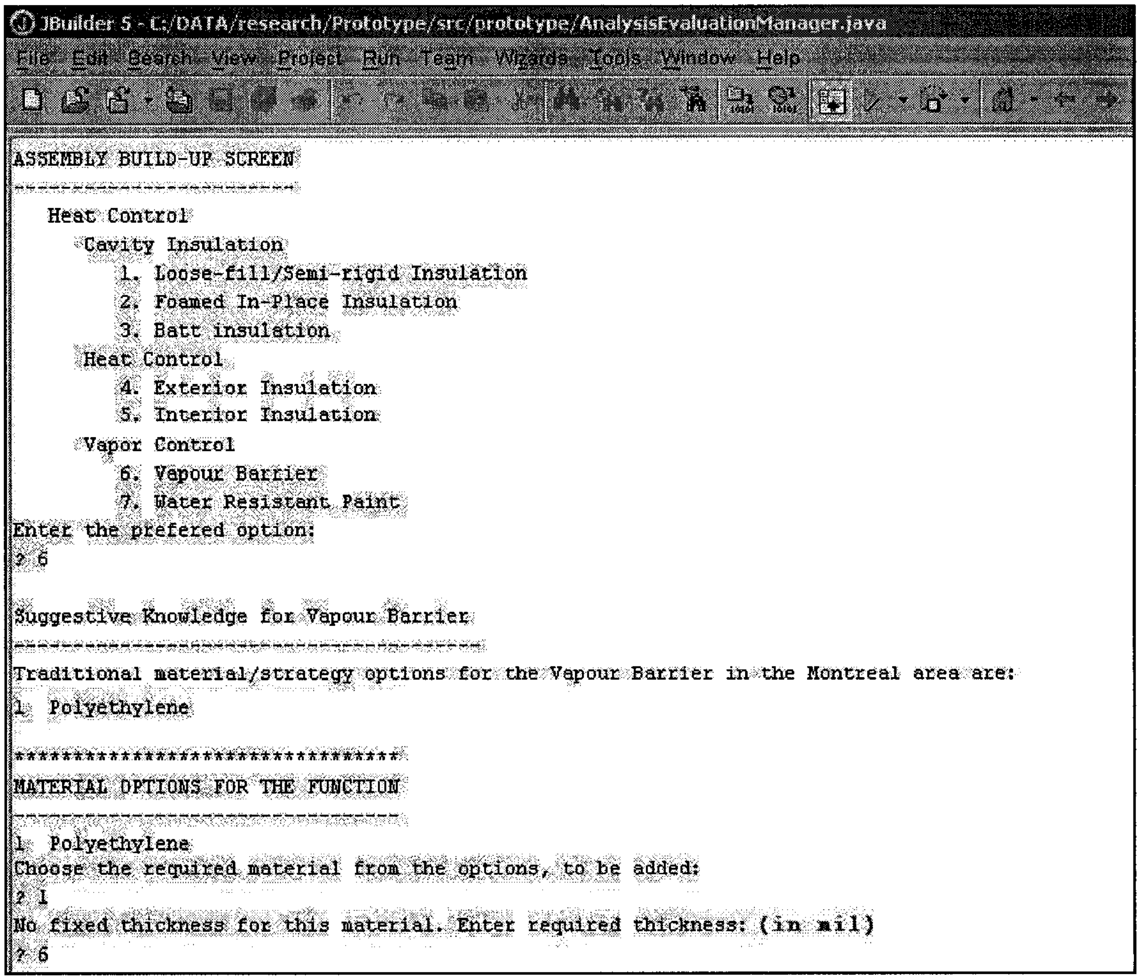

Figure 5.6: Screenshot of the Prototype showing Configuration of Components for Vapor Control

Once the structural component is selected, the tool prompts the options for other functions (see Figure 5.5 and Figure 5.6). The prototype currently handles only the control of heat flow and the control of vapor diffusion. On selection of one of the above two functions, the tool displays possible strategies as options through which the function could be achieved. In the example illustrated in Figure 5.5 and discussed in the above sections, when the designer selects the control of heat flow function, three main strategies are presented as design options: exterior insulation, interior insulation and cavity-fill insulation (after verifying the presence of a cavity). As suggestive knowledge, the cavity-fill insulation and exterior insulation strategies are presented as the traditional strategies, and are the preferred design options. For each strategy the design tool presents sub-strategies, wherever these sub-strategies apply. As in the example illustrated in Figure 5.6, if the designer selects cavity-fill insulation as the main strategy the tool displays loose-fill/semi-rigid insulation, foamed in-place insulation and batt insulation as sub-strategies. Batt insulation is suggested as the traditional strategy for the above example. If the designer selects loose-fill/semi-rigid insulation, the tool would suggest some of the loose-fill and semi-rigid insulation materials.

For the control of vapor diffusion, the tool displays 'vapor barrier in the inner wall' and 'water resistant paint on the interior finish of the assembly' as design strategies. If the tool identifies the existence of a layer other than the structural system in the assembly, a third design strategy 'increase the moisture storage capacity of the assembly' is displayed. If the designer selects either vapor barrier or water resistant paint as strategies, the tool displays the corresponding list of materials from the database. If the designer selects the strategy 'increase water storage capacity', the tool displays the components in the assembly asking the designer to choose the layer to be modified. The component selected is replaced with a high moisture storage capacity component. In the example illustrated in Figure 5.6, after the selection of loose-fill/semi-rigid insulation (a strategy for the control of heat flow function), the designer could select the vapor barrier (a strategy for the control of vapor function). It also allows the designer to move back return to the previous screen to select rigid insulation (a sub-strategy for the control of heat function). The designer has the flexibility to move back and forth between the control of heat flow and control of vapor diffusion functions. Thus the prototype proves that the flexibility is provided to the designer in switching between the functions during the assembly build-up stage, as was discussed as a requirement in chapter 4, R.2.7: Provide Flexibility to Switch between Functions.

At the end of a design path for a function, the designer obtains a final solution (i.e. a component). For instance, as shown in Figure 5.6, on the selection of the vapor barrier the component solution to support the control of vapor diffusion, the prototype lists gypsum in two varying thicknesses (9.5 mm and 12.5 mm) and polyethylene, as suggestions for the material to be used as a vapor diffusion component. This function in the prototype proves to satisfy the requirement, R.2.10: Integrate the Material Database and List the Appropriate Materials. It displays the properties of the materials in the list, thus satisfying the requirement R.2.11: Display the Properties of the Material during Configuration. Upon the selection of a material the tool prompts the designer to configure the component by choosing a thickness and selecting a position in the existing order of material components. In Figure 5.6, the example prompts the designer to enter a value for thickness for polyethylene, as there is no fixed thickness for this material. The prototype handles the evaluation during design synthesis by applying analytical and logical methods and by verifying the performance requirements. This function proves to satisfy the requirement, R.3.2: Provide Knowledge in Appropriate Form.

5.2 Design of the Prototype

The prototype uses the object-oriented programming approach and the Java language, as discussed in Chapter 4. The planning and design of the prototype was handled using the UML concepts. UML (Unified Modelling Technique), as discussed earlier in Chapter 4, is a visual modelling technique used to specify, visualize, and document artefacts of an object-oriented system under development. The modelling of the interaction between the user and the tool is done utilising use cases (one of the UML concepts), which are presented in Appendix C. The use cases provide a representation for the environment and functions of the design tool. The definition of the classes and the relationship between the classes are discussed using a class diagram.

The primary objective of the prototype is only to test some functions of the tool proposed in Chapter 4. Hence, limited knowledge is included in the prototype. To manage the knowledge attached to the building envelope design process, two approaches concerning computer programming were considered: the object-oriented approach (the approach that is used to design the environment and working of the non-knowledge part of the tool) and the rule based approach. The Java Expert System Shell (Jess) was identified for handling the rule-based approach. Jess combined with the Java language would be an effective development environment for the tool. However, this prototype is purely developed on object oriented programming concepts using Java. A number of tests were implemented to handle the knowledge using the rule-based approach with Jess. The integration of the knowledge worked out using the rule-based approach is left as future work.

5.2.1 Use Cases for the Tool

Four use cases are defined to specify the interaction of the designer with the computer tool: (i) *Enter Problem Definition* for the entry of project and site information and the performance requirements; (ii) *Structure Selection,* to support the selection of main structure to satisfy the structural stability function; (iii) *HAM control,* to support the selection of components to satisfy the control of heat flow and control of vapor diffusion functions; and (iv) *Analysis and Evaluation,* to support the evaluation of the assembly during the design synthesis and at the end of the assembly build-up. These use cases are explained in detail in Appendix C.

5.2.2 Description of the Class Diagrams

The class diagram, as shown in Figure 5.7 is developed using UML concepts. There are three types of classes: boundary, control and entity classes. Control classes handle the flow of events as defined in the use cases. Each control class models the sequence of one or more use cases. Boundary classes act as the interface facilitating the interaction between the actors and system. Entity classes hold information and associated behaviours of objects that are required to perform tasks internal to the system.

The prototype is designed with 22 classes. There are four control classes: 'MainControl', 'ProblemDefinitionManager', 'AssemblyBuildupManager' and 'AnalysisEvaluationManager'. The 'MainControl' class contains member functions that activate and control the other three control classes. As the name indicates, the three classes 'ProblemDefinitionManager', 'AssemblyBuildupManager', and 'AnalysisEvaluationManager' contain methods and variables to manage the problem definition input, design synthesis by satisfying functions through composition of assembly components and analysis and evaluation of the design solutions, respectively. These classes are greyed out in Figure 5.7 to indicate that they are control classes. The prototype uses eight boundary classes to model the user-system interaction: 'OptionInput', 'ProblemDefinition', 'StructureSelection', 'HeatControlInput', 'VaporControlInput', 'AirControlInput', 'LiqWatControlInput' and 'EvaluationDisplay'. The boundary classes are underlined in the figure. The 'OptionInput' boundary class is used to initiate the design process through the main menu. The 'ProblemDefinition' boundary class handles the entry of information during the problem definition stage. The next five classes are used in the synthesis process of the assembly, while the 'EvaluationDisplay' is for the analysis and evaluation stage.

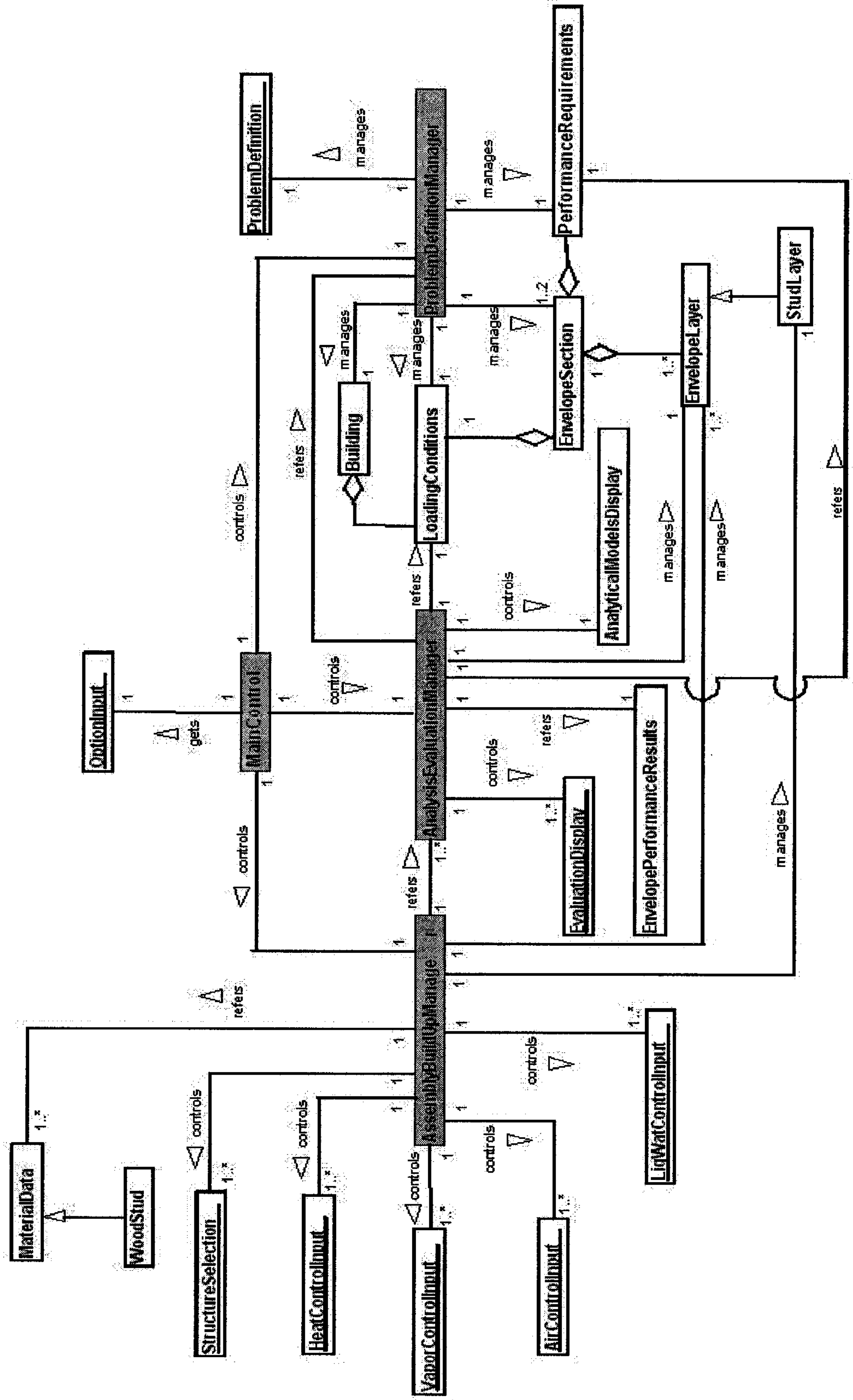

Figure 5.7: Class Diagram for the Prototype

The remaining 10 classes, 'Building', 'LoadingConditions', 'EnvelopeSection', 'EnvelopeLayer', 'StudLayer', 'PerformanceRequirements', 'MaterialData', 'WoodStud', 'EnvelopePerformanceResults', and 'AnalyticalModelDisplay' are used to model the entity classes to store and retrieve information.

Interactions between objects are facilitated through two types of relationships: association relationship and aggregation relationship. An association relationship provides a semantic connection between classes. An aggregation is a 'part-of' or containment relationship between the classes [Quatrani, 2001]. The following paragraphs discuss the classes through three design stages.

The 'ProblemDefinitionInput' boundary class is defined based on the sequence of events modelled in the use case, 'Enter Problem Definition'. This boundary class contains member functions to display entry screens and to allow the input of location, climatic conditions, design conditions, building details, section details and performance specifications. Each of the screens defined in the 'ProblemDefinitionInput' boundary class is controlled by the member functions in the control class, 'ProblemDefinitionManager'. The information entered in the displayed screen is appropriately stored in the member variables of the entity classes 'Building', 'LoadingConditions', 'EnvelopeSection', 'EnvelopeLayer', 'StudLayer', and 'PerformanceRequirements'. Figure 5.8 shows the relationship

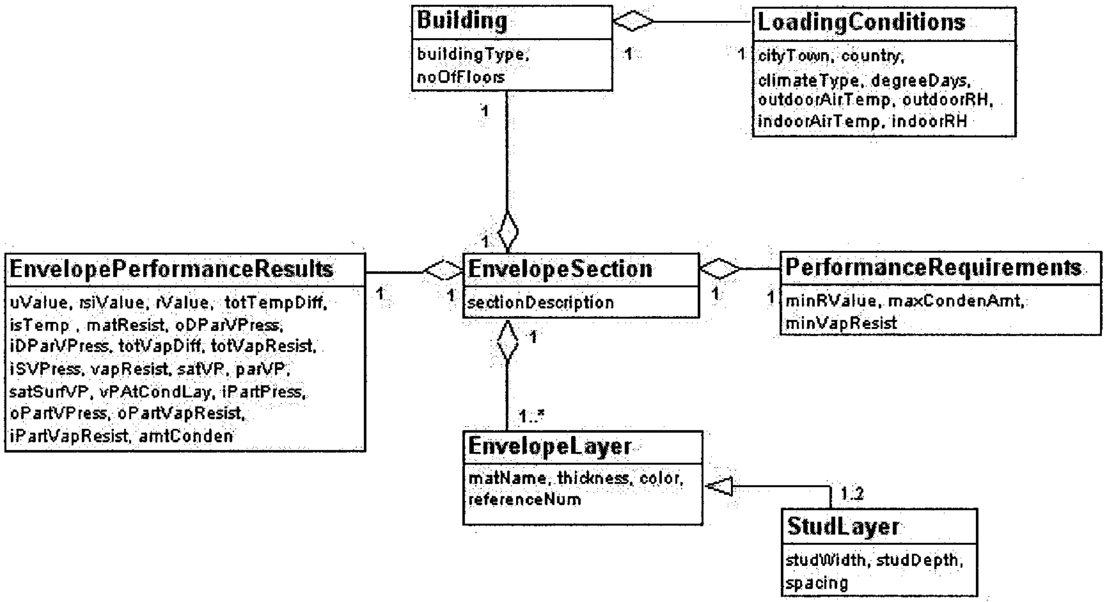

Figure 5.8: Entity Classes Defining the Envelope Section Assembly

between these classes. The 'LoadingConditions' class is conceived to be a part of the 'Building' class. The information such as the location and climatic conditions are accessed through the 'Building' class. The 'EnvelopeSection' class maintains an aggregate relationship with 'Building', 'EnvelopeLayer', and 'PerformanceRequirements' to access the information stored relevant to the problem definition. Apart from the classes used in the problem definition stage the 'EnvelopeSection' class also maintains an aggregate relationship with the 'EnvelopePerformanceResults'. Thus, 'EnvelopeSection' acts as a class through which the information in the other entity classes might be stored and retrieved. For example, the tool developed to store and retrieve the information about envelope assembly uses the 'EnvelopeSection' class, which in turn uses the 'EnvelopeLayer' and 'StudLayer' classes. An envelope section may have more than one envelope layer and so the relationship between the envelope section and envelope layer is one-to-many (i.e. each envelope section maintains as many instances as the number of layers in the envelope assembly). The 'StudLayer' class maintains an inheritance relationship with the 'EnvelopeLayer' class. Along with the information of a normal layer stored in the 'EnvelopeLayer' class, the 'StudLayer' includes some additional information to one instance, the stud layer instance. The prototype maintains the 'EnvelopeSection' class as a focus since it deals with only one section (e.g. wall section). The 'Building' class would be the focus in case the tool is extended with the capability to handle more than one section such as wall, roof and foundation wall. It would maintain a one-to-many relationship with the 'EnvelopeSection' class.

The design synthesis process as defined by the sequence of events detailed in the use cases Structure Selection and HAM Control are handled using the 'AssemblyBuildUpManager' control class and the related boundary classes, 'StructureSelection', 'HeatControlInput', 'VaporControlInput', 'AirControlInput', 'LiqWatControlInput' and 'AssemblyBuildUpInput'. The first five classes listed, handle the presentation of the tree nodes that are strategies or component solutions in sequence for the corresponding functions. The 'StructureSelection' boundary class contains member functions that display the options in each node of the design tree. For example, one of the nodes of the 'StructureSelection' class, the main structure selection, displays options such as wood structure, concrete structure, masonry structure and steel structure through a member function:

'showMainStructSelectScreen'. The prototype currently handles only the wood structural system and hence it includes the screens to display the options for the nodes, main structural systems, wood structure and wood stud structure. This boundary class validates and stores the option selected by the designer. Apart from the main structural system selection, this class also contains member functions for the selection of the support structure to achieve the structural stability function. The 'HeatControlInput' boundary class contains the member functions to display the strategies of the control of heat flow function, the sub-strategies for each strategy and ultimately the component solutions through the tree of the function, control of heat. Similarly, the 'VaporControlInput', 'AirControlInput', and 'LiqWatControlInput' boundary classes would handle the control of vapor diffusion, control of airflow and control of liquid water movement, respectively. The 'AssemblyBuildUpInput' is a generic boundary class that contains member functions to handle the configuration of components of the assembly. It serves to select and configure component layers for each of the functions. It handles the display of list of materials available, the selection of a material and the input of thickness, position and color of the component. It also contains member functions to display the suggestive knowledge such as traditional strategy/component and appropriate design strategy/component based on the given conditions and the history of the design path. The member functions handling the configuration of structural system components are different from those that handle the other components.

The flow of events of the 'Structure Selection' and 'HAM Control' use cases are controlled by the 'AssemblyBuildUpManager' control class. The display of design options, configuration of components and storage of information is managed by this control class. It contains member functions to evaluate the state of the assembly at the end of every design decision along the assembly build-up process. The validation and selection of the design options are handled by the member functions of this class. It refers to the 'AnalysisEvaluationManager' control class for analysis. Also, the suggestive knowledge to aid the selection of a design option is retrieved and passed on to the boundary class by the member functions of the 'AssemblyBuildUpManager' class. At the stage of selection of a component it obtains the components list from the 'Material' entity class. The 'AssemblyBuildUpManager' supports the configuration of the components. The 'WoodStud' entity class inherits from 'Material' entity class, which supports the wood stud structure configuration. After the selection of a component the configuration details of each of the component is passed on to the entity classes 'EnvelopeLayer' and 'StudLayer'.

The boundary class 'EvaluationDisplay' contains the member functions to display the final evaluation results of the envelope assembly. These member functions are called by the 'AnalysisEvaluationManager', which models the flow of events for the use case 'Analysis and Evaluation'. It contains the member functions to analyze and evaluate the assembly and to check the performance of the assembly with respect to each function. It refers to 'LoadingConditions', 'EnvelopeLayer' and 'StudLayer' entity classes to obtain the design conditions and details about the envelope assembly under design; to analyze and evaluate the performance of the assembly. The 'AnalysisEvaluationManager' contains member functions with the capability to evaluate each function. It also contains member functions to evaluate the assembly by comparing the specified performance requirements for each function with the results of analysis of the envelope assembly.

5.3 Evaluation of the Prototype

The implementation of the prototype acts as a proof of concept for the proposed integrated computer support discussed in Chapter 4. The implementation demonstrates that a computer tool based on the object oriented programming concepts would be able to handle the functions put forth as requirements. Section 5.1: Description and Working of the Prototype, discusses the functions that are implemented using the prototype to support the first two stages of the building envelope design process, problem definition and design synthesis. As discussed, the prototype proves to handle the two requirements put forth (in Chapter 4) for the problem definition stage, R.1.1: Support to Input Project and Site Information and R.1.2: Support to Specify Performance Requirements. The prototype proves to satisfy the requirements of the design synthesis stage, R.2.4: Support Function-Satisfaction Approach; R.2.5: Generate Design Options, R.2.6: Provide Knowledge Support; R.2.7: Provide Flexibility to Switch between Functions; R.2.10: Integrate the Material Database and List the Appropriate Materials; and R.2.11: Display the Properties of the Material during Configuration. The other requirements of the design synthesis stage: R.2.1: Display of Problem Definition Information in Synthesis Stage; R.2.2: Support the Entry of Design Decisions in Different Methods; R.2.3: Support Component-Selection Approach; R.2.8: Allow Modification of the Problem Definition Information; and R.2.9: Provide Access to Analytical Models during the Synthesis Stage, are difficult to implement using the text-based interface. Moreover, they are normal functions that are found in the existing tools. The prototype proves the two requirements identified for the analysis and evaluation stage, R.3.1: Support to Check the Performance of the Assembly against the Requirement Specification and R.3.2: Integrate Knowledge and Scientific Methods, however through the analysis and evaluation requirements of the design synthesis stage. The requirements imposed by the general characteristics of the building envelope design process, such as R.4.1: Support the Working Trends and Knowledge of the Disciplines Involved, R.4.2: Support the Different Mediums of Representation, R.4.3: Maintain Alternatives, and R.4.4: Maintain Design History, are left for future work while developing a graphical user interface for the tool. One of the requirements, R.5.1: Maintain Database, identified to integrate knowledge in the design tool is proved, whereas the other requirement R.5.2: Attach Knowledge to Database is left for Future Work.

The main functions that the prototype concentrates on are providing design options, suggestive knowledge and flexibility to handle functions in any order. The implementation integrates knowledge, evaluation methods and design paths for each function to provide design options during the assembly synthesis. The design options generated are based on the earlier design selections, evaluation of the thus far built-up assembly and design paths of each function tree. The implementation demonstrated that it can display suggestive knowledge at appropriate intervals to guide the designer through the selection of design options. It proves that it can handle the traditional strategies, sub-strategies and components used in the (local) industry. The prototype also proves the possibility that it may handle functions in any order during the synthesis of the assembly. It provides the flexibility to move back and forth between the control of heat flow and control of vapor diffusion functions. The current prototype does not provide the desired ideal design environment, because it lacks a graphical user interface. The other important requirements of the integrated tool, the repercussions of a selection of strategy or component, the design history and hence a support for the iterative nature of the design process were not tested and left for future work.

All the above functions are handled using object-oriented programming. The primary advantage of the object-oriented programming technique is found to be its re-usability, and thus its extensibility and possibility for modification. In particular, for the support of the building envelope design process where the knowledge and techniques constantly evolve, the object-oriented programming proves to be useful. In the future, expert systems, an artificial intelligence technique that follows a rule based programming; might be integrated into the tool to handle the knowledge part. Java Expert System Shell (JESS) could be the option that could be readily handled with the Java language that is used to program the prototype.

5.4 Chapter Summary

This chapter discusses the analysis, design, implementation and evaluation of a prototype as a proof of concept. It documents how a number of functions identified in previous chapters could be integrated as a tool to support the building envelope design process. Following are some of the functions considered: providing design options, providing suggestive knowledge and providing the flexibility to handle functions in any order. It discusses analysis and design of the prototype using the concepts of UML and elaborated the implementation of the prototype. Finally, the chapter evaluated the developed prototype.

Chapter 6

Conclusion

This chapter presents a summary of the research and discusses the contributions made and the future works foreseeable in this area.

6.1 Summary

The growing concern towards energy efficiency, especially after the energy crisis in the 1970s, has forced designers to consider building envelope performance as a main concern in cold climate countries such as Canada. Apart from energy efficiency, the building envelope design must consider other performance issues including durability, structural soundness and aesthetic values at the design stage. The building envelope design process has to reconcile two value systems: the qualitative aspects stemming from architectural design and the scientific and quantitative requirements of building science and engineering. This is a complex process involving a large number of scientific principles, analytical calculations and logical evaluations from multiple disciplines. To further complicate the process, there is a continual increase in the understanding of the building envelope behaviour through experimental and analytical research. Consistent growth of industry knowledge in terms of proven design practices is occurring. The support of computer tools for the building envelope design process would be helpful and hence a handful of computer tools for analysis and evaluation have been generated within the industry and by researchers. However, these tools focus only on a few specific issues. Most of these tools are highly sophisticated and primarily support research activities in labs rather than the design process in practice. Those tools developed to handle the design process provide support only for verification in the final stages, especially analysis. Hence, a need is identified for the development of an integrated computer tool that would provide design support for different methodologies, different working trends and as well as provide knowledge support.

The research presented here follows a three-stage process to define an appropriate design tool to support the building envelope design process: (i) literature review, exercises in building envelope design and evaluation of existing tools were carried out, to understand and represent the building envelope design process; (ii) based on this analysis, a generic model for the design process is first proposed. Then, requirements for an integrated tool are specified and an appropriate computer environment, with features supporting the identified requirements, is proposed; and (iii) as a proof of concept, a text-based prototype is developed to demonstrate some of the functions of the integrated computer tool for the building envelope design process.

Three stages are identified as essential to the building envelope design process: problem definition, synthesis, and analysis and evaluation. The required project and site analysis information and the design objectives in terms of performance requirements are specified in the problem definition stage. The synthesis stage involves the selection, composition, and configuration of assembly components of the various sub-systems of the envelope system. Two methods of synthesis are presented: (i) design decisions by experience and (ii) assembly build-up. Assembly build-up is the stage where most of the decisions about the selection and configuration of materials and components for envelope assembly are made. The assembly build-up usually takes place step-by-step through a component-selection or a function-satisfaction approach. The component-selection approach involves selection and positioning of the material components, hypothetically designated to handle one of the functions of the building envelope system, one-by-one until all the specified functions are fulfilled to the required levels. The function-satisfaction approach involves design solutions by focusing on the satisfaction of the specified functions to required levels. Each solution (i.e. selection and configuration of component) is achieved through a series of selection of strategies. The design paths through the options of strategies and solutions are represented in a tree form. The designer can switch back and forth through the design paths of more than one function in the building envelope design process. Also, the design decisions made during the process can be revisited. The building envelope design process is a complex and iterative process. Each choice of strategy or component selection is accompanied with evaluation using either analytical models or through the designer's experience and knowledge. There are two stages of analysis and evaluation in the building envelope design process handled using analytical models and logical evaluations: evaluation during synthesis and evaluation when the design is completed. The evaluation during the synthesis stage is fundamentally a first round of performance check for achieving the required results. The second round of analysis and evaluation is conducted upon the completion of configuration of the envelope assembly to verify the performance of the building envelope system.

Data and knowledge plays a significant role throughout the building envelope design process. Climatic data and material data are the primary data requirements for the building envelope design process. Regarding knowledge, the constructability, durability, and aesthetic appeal are significant. The various sources of knowledge required to support each stage of the design process are the rules and regulations of governing bodies, guidelines and manuals of scientific institutions, guidelines from standards, product manuals and catalogues, cost manuals and guides, construction techniques, proven design practices and rules of thumb.

For the design of the tool, several requirements for each of the stages of the building envelope design process are identified. Some of which are: generation of design options; capability to handle multiple functions simultaneously; capability to evaluate design decisions during the design process; capability to attach knowledge along with the properties of the materials; capability to provide suggestive knowledge, such as traditionally followed solutions or repercussions of a decision to the designer at the right time; maintain alternatives; maintain history of the design decisions during the design process; capability to provide mandatory rules and warnings; and evaluation of the design solution.

An ideal tool was conceptualized to support the design of one envelope section of a building envelope at a time, which considers the functions heat, air and moisture control, structural stability and aesthetics. It supports the step-by-step approach in the synthesis process. The significant features of the proposed design tool are the availability and intervention of knowledge, support for synthesis with features to handle iteration and alternatives, and the flexibility to switch between design paths in achieving the functions of the envelope system. The research also presents an interface for the design tool.

A prototype using Java and object-oriented programming concepts is developed with a text-based interface to test some of the significant features to support the building envelope design process, such as providing suggestive knowledge, providing design options and flexibility to handle multiple functions simultaneously. The prototype demonstrates that a computer tool based on object-oriented programming will be able to handle suggestive knowledge, provide design options and flexibility to handle multiple functions at a time.

6.2 Contributions

In general, this research contributes to a better understanding of the building envelope design process and proposes a model that could be adopted as a design tool. Below are the specific contributions of this research:

- Building envelope design is a relatively new discipline. Although there is sufficient information about building envelope systems and design methodologies in the industry, this information is not available ready-made to designers. This research reviews the scattered information about the building envelope design process, organizes and presents it in a way so that it may be used for future research. Along with information from literature sources, the research also presents inferences from exercises in the building envelope design process and the evaluation of existing design tools;

- The synthesis process to design a building envelope assembly is subject to the designer's knowledge and experience, and the subject case. Unlike other design disciplines there are too few design methodologies for the building envelope design. One of the main contributions of this research is the review of the various design methodologies and the definition of a comprehensive methodology to form a generic model. A model with three stages - problem definition, synthesis and evaluation - is presented, which could help achieve effective design solutions. The classification of different methods of design during the synthesis stage, such as synthesis by knowledge, and assembly build-up by component-selection and function-satisfaction approaches are significant contributions. The function-satisfaction approach is a comprehensive method through which informed design decisions could be made for effective design solutions;

- Knowledge plays a significant role in the building envelope design process. There are many sources of knowledge available from multiple disciplines that govern the design decisions. The knowledge and the information are not readily available for the designer. Of the available knowledge and their sources supporting the building envelope design process, those related to functions like control of heat flow, control of vapor diffusion, control of liquid water penetration and control of air flow, and those pertinent to the wall sections of residential buildings are reviewed, classified and documented;
- The research reviews the various characteristics of the design process from which a set of requirements are identified for an integrated design tool. The requirements presented, as such, could be used in the future to develop tools for the building envelope design process. Based on the requirements, several unique features are presented as follows: provide design options; the capability to handle many functions simultaneously and to provide support to switch between functions; the capability to revisit design

decisions; the capability to handle alternative design solutions; and the capability to handle the display of suggestive knowledge, mandatory rules and warnings. The features presented for the design tool deviate from the features of the conventional design tools and hence they should be addressed appropriately. An ideal environment for the synthesis stage with the features identified and a prototype as a proof of concept for various functions are presented. The requirements listed, the features identified to satisfy these requirements, and the ideal environment could all be used in the development of future design tools;

- The knowledge available in the industry from various sources is mostly in raw form, and thus requires the designer's discretion in order to use it appropriately. As per the identified requirements for an integrated tool, the available knowledge should be presented appropriately during the design process at the time of the need for use and in the required form. Through this research the extracted knowledge for synthesis is interpreted and classified according to the needs of the building envelope design process. A *support* in informing the designer about the various design options is identified to be a significant requirement for an integrated tool. In order to achieve this requirement, the design paths for assembly synthesis are modelled in the form of a tree of design decisions outlining strategies and components. Currently, trees of decisions are developed for the functions control of heat flow, control of vapor diffusion, control of liquid water penetration and control of airflow. The other forms of knowledge are suggestive knowledge (design options, repercussions of design decisions and traditional solutions), mandatory rules, and warnings. The role of knowledge in the evaluation of design decisions and solutions are also presented;

- One of the main reasons for the absence of good computer tools to support design is the difficulty in capturing and automating the process. Some of the requirements identified and functions evolved for an ideal tool are new and are not available in the present tools. This thesis tests some of these new functions, such as display of suggestive knowledge, capability to switch between functions, and listing of suitable materials for selection of components through a working prototype. The capability to implement such functions could be integrated in future design tools.

6.3 Future Works

The research has identified various requirements to provide an integrated computer support for the building envelope design process. It proposes various features for an integrated design tool that could satisfy the identified requirements. However, this research is only an initial step and requires further development. Below are avenues of future exploration that have been identified:

- The building envelope design process in this research is analyzed mostly through literature review, evaluation of existing computer tools and through personal exercises. Considering the versatility of the building envelope design process, research through survey and think-aloud techniques on a number of building envelope designers from the industry might reveal more requirements to be incorporated for the integrated design tool. A think-aloud technique is a methodology to study the way a user handles a task, in order to design a software tool to automate the task;
- The scope of the research considers only a limited number of functions such as heat, air and moisture control, structural stability and aesthetics. Considering additional functions such as acoustics, control of fire, and control of radiation, could lead to more requirements and hence more features. other functions could be addressed in the future on the grounds of the developed design tool;
- The research for this thesis deals only with the aboveground wall section design. Design of junctions and other subsystems have been left for future work;
- The scope of the research currently deals only with residential projects. In the future, the developed concept could be extended to industrial and commercial design projects;

- The various sources of knowledge are presented, however not all the knowledge in the industry is involved. Further effort to build a comprehensive knowledge base in the future is required to provide a complete tool;
- An 'ideal' environment with several features is presented to satisfy the requirements identified for the integrated computer tool. However, the prototype does not prove a number of features, such as maintaining alternatives, design history and graphical representations, which could be handled in the future;
- The prototype handles the knowledge supporting the building envelope design process through object-oriented programming techniques. Rule-based technique seems to be more appropriate to handle the knowledge part. In the future, more testing through implementation might be managed to identify the best approach.

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Appendix A

Building Envelope Design Exercise of a Typical Residential Building

Based on the design experience and established knowledge about the building envelope design process, a building envelope design exercise for a typical residential building was carried out. The objective of the exercise was to understand the design methods of the building envelope designers, particularly the main stages involved and the knowledge and data required in making effective design decisions. The following sections document the design process in stages.

A.1 Problem Definition for the Building Envelope Design

To start, the design problem was studied vis-à-vis the project analysis and site analysis of the building project. Based on the summary of the site and project analysis, the design conditions were fixed for the building envelope system design. The essential parameters required for the building envelope design process were extracted and referred for design synthesis, and analysis and evaluation.

A.1.1 Project Analysis

Client requirements for the project

- Spatial requirements by client - dimension, quality, etc... - Three bedrooms, one hall, one kitchen, two attached washrooms, attic space for storage and basement for mechanical systems
- Building type - Independent Residential Building (Bungalow type)
- Cost factor - cost effective (construction and operational cost)
- Aesthetic requirements - material type, shape etc... - No preference

Designer requirements for the project

- Spatial requirements by designer - zones, dimension, quality etc... - nothing specific

- Aesthetic requirements – material type, shape etc… - nothing specific

User requirements for the project

- Spatial requirements – dimension, quality etc… - same as client
- Aesthetic requirements – material type, shape etc… - same as client

Social requirements for the project

- Common people's requirements - NA
- Local government/governing body requirements – NA

A.1.2 Site Analysis

Physical characteristics of the site

- Location of the building – Montreal
- Climate – Cold climate
- Surrounding area – Residential buildings on three sides and a road on one side
- Soil conditions – Clayey
- Topography – Plain
- Accessibility – by the front road
- Landscape – a huge tree in front of the plot

Visual characteristics of the site – NA

Social Characteristics of the site

- Laws and regulations – the norms of the National Housing Code of Canada and regulations respecting energy conservation in new buildings for Quebec
- Standards – AHSRAE 2001 standards in defining the building envelope
- Social status - NA
- Available and unavailable materials – Wood abundantly available, Granite scarcely available

A.1.3 Summary of Results from the Problem Analysis:

- Design for cold climate;
- Design the structure for clayey soil;
- The presence of a tree should be noted in anticipation of future

problems such as the movement of soil. Foundation and structure of the building should be designed in order to take into account these potential problems;

- Use National Housing Code of Canada and regulations respecting energy conservation in new buildings of Quebec;
- Use ASHRAE 2001 standards;
- Use wood as much as possible due to its availability;
- The basement is required and it could be un-conditioned, as it is only used for storage and mechanical systems. Though the conditioning of the basement is followed by tradition, in this case it can be designed un-conditioned.

A.2 Design Synthesis

The design synthesis involved an intuitive approach, based on the problem definition primarily with the support of designer's knowledge, and then the step-by-step approach.

A.2.1 Design Decisions by Intuition

Intuitive design ideas for the building were generated (mainly influenced by the problem analysis):

- The building should be made simple in form
- Concrete foundation wall could be a solution
- Masonry structure could be used in basement to take the pressure from the soil
- Main structure could preferably be wood structure

A.2.2 Step-by-step Approach of the Building Envelope Design

1. Main structure of the building envelope above ground is decided to be of wood and below ground to be of concrete.

Foundation Design

2. Concrete foundation wall is used. The decision for selection of the type of foundation is done on the basis of two aspects, cost factor and performance of the structure against the pressure from ground. The designer's knowledge of traditionally used foundation walls in residential building aids to make the decision.

3. Use of concrete masonry wall foundation in the basement has huge a mass that would satisfy partially the other functions of a basement wall, such as HAM control.
4. The basement could be conditioned or un-conditioned. As one of the requirements state that the basement should be used as a space for mechanical systems, conditioning of the basement is logical and efficient. However, the option of un-conditioning the space is still open, as there are possibilities to contain mechanical systems in un-conditioned spaces.
5. Conditioning the space requires an addition of insulation on the foundation wall (either interior or exterior). Upon adding it to the exterior the installation and maintenance of the envelope becomes difficult (logical reasoning). Moreover, a layer of sheathing is required in order to protect the insulation. The three methods of conditioning the foundation wall are by adding insulation material: (i) that extends up to 1m in the floor; (ii) that extends to the floor; and (iii) only mid way of the wall (from ASHRAE standards). As the use of the basement is limited only for mechanical systems it is sufficient that the insulation could be either midway of the wall or till the floor.
6. Un-conditioning of spaces would be cost effective (by avoiding the cost of conditioning the space). However, the pipes and ducts of the mechanical systems must be insulated. If un-conditioned, the studs in the ceiling of the basement must be filled with insulation.
7. As suggested by the scientific community and logical reasoning, the conditioning of space would be preferred. It reduces the operation cost and helps the HAM control from entering above ground floors.
8. The interior facing of the basement could be gypsum board (conventional). In case the insulation is provided on the exterior, a layer of plaster is applied on the foundation wall.

Design of Wall Aboveground

9. On selecting a wood structure above ground the building envelope could be decided either to be a wood framed structure or beam-column structure.
10. Since, wood frame structures are found to be more prevalent in practice in Montreal, it is considered for the building envelope.
11. Structural design of the building (wood framed structure) is left to be designed using computer tools like WoodSizer and manuals of CMHC (guidelines of public organizations). Structural design primarily comprises the specification of dimensions of wood studs (whether 2x4,

2x6, 2x8 etc) and the spacing of the studs (like 12", 16" or 24") to be used in wall and other places.

12. About the framed structure, provision of other layers like cladding, thermal barrier, moisture barrier and air barrier are to be decided.
13. From the conditions prevailing and the knowledge about materials, a rough idea of the probable materials for each of these layers and a rough order are considered.
    - Cladding - probably wood siding or a brick layer without paint coating
    - Thermal barrier - cavity fill insulation with semi-rigid or flexible insulation material (to effectively use the space between the studs). A layer of surface insulation may be added to avoid thermal bridge by the studs.
    - Wind barrier/Sheathing - a layer of plywood sheathing and a gap of few centimetres between siding and sheathing (method suggested by ASHRAE standard).
    - Vapor retarder - a layer of tight polyethylene (a widely used material) could be stapled to the wood studs. It may also act as an air barrier with appropriate detailing.
14. Considering the framework, a rough section of the building envelope is sketched mentioning all the above layers with the discussed materials
15. An analysis of the thermal gradient, moisture gradient and condensation is made by using the simple steady state method prescribed by ASHRAE or by using the CONDENSE computer tool. An iterative approach may be applied in the selection of the layers until an optimum solution is attained with respect to performance and cost.

Design of Windows

16. The design of windows is more related with space design (one of the building systems). The position and size of windows is a function of the user requirements, aesthetic requirements, market availability and control of environmental performance.
17. The material for the frame of the window glazing could be wood, aluminium or steel. Steel is not a convention. The cost factor and the ease of maintenance, considering the market trend and availability, favour the use of aluminium.
18. Analytical models could be used to optimize the size of the windows with respect to space.

19. The standards could be consulted to provide the ratio of openings with solid walls.

20. The materials to be used and the number of glazings could be decided on the basis of installation cost and operation cost (using the cost factor requirement of the client). The options for number of glazings are single-glazed, double-glazed or triple glazed and the type of window pane includes whether to provide plain glass, etched glass or corrugated glass. Provision of a microfilm on the glass pane for the control of heat function may be decided through calculation of cost differences (optimization between the installation and operational cost could give a clear solution) and the wish of the client.

21. The size factor depends more on the industry standards (information from catalogue and brochures of manufacturers)

22. The performance with respect to environment control could be analyzed using the computer tools

Design of Roof

23. One of the requirements by the client is the attic, which leads to a sloped roof. The structure is wood as decided in the previous stages.

24. Structural design of the building is done using computer tools like WoodSizer and manuals of CMHC (guidelines of social organizations). It comprises the dimensioning of wood studs (whether 2x4, 2x6, 2x8) as joists and the spacing of the studs (12", 16", 24" etc).

25. The primary functions of the roof such as protection against rain, snow, wind and other external agents, along with the control of HAM are considered. The layers decided are either shingles or roofing membrane for protection against air and liquid water, insulation for prevention of heat loss and vapor barrier for prevention of vapor permeability.

26. Since insulation needs to fill in the cavity of the wood rafters or joists, it should be flexible and semi-rigid. Providing a layer of rigid insulation as a surface mounted insulation to avoid thermal bridge is also considered.

27. Two options are available for positioning of the thermal barrier: insulation placed along the roof rafters or on the floor frame of the attic. Some sketches on the pattern of heat transfer support design for positioning of the insulation. The insulation is positioned among the roof rafters and thus the attic turns out to be a conditioned space, while in the case it is added to the attic floor frame and ventilation is provided (ventilation is necessary as otherwise there is a probability of condensation) the attic becomes an un-conditioned space. In line with the client's requirements, it is preferred that the attic be conditioned and

hence the layer of insulation is placed on the roof rafters.

28. The membrane layer, normally felt sheets or one/two layers of bitumen is usually thin and needs support. Hence, a layer of plywood sheathing as support could be mounted on joists. However, this is applied only in the flat roofs. In this case, shingles instead of membrane and sheathing is used, as it is a slope roof.

Design of Details

29. In the detailing stage of each section the compatibility and buildability factors are considered. Continuity of the air barrier, thermal insulation and vapor retarder are also considered
30. The design is handled by perceiving the section from two points: overall view for compatibility and an in depth view for buildability, stability and support of layers.
31. Each section is checked for support and stability of the layers they enclose. In some instances the trend defines the fixing of layers in the structure. However, in some cases the designer could define an unconventional fixing system for layers, in order to fulfill some aesthetic requirements (designer's requirements). The case for a standard building is to reduce the production cost and hence is more influenced by the industry trend.
32. The wall-window/door junctions, wall-roof junctions and corners are to be logically approached in detailing. The precautions that the designer may need to take are towards the continuity of barriers, thermal bridges and application of appropriate sealants.
33. Dimensioning is one of the important items to be checked by the designer at the detailing stage, which was approximated during the early design stage. The dimensions of the materials that were considered during the early selection stages may have corrections depending on the compatibility of the materials with each other and with the main structure. Hence, a readjustment of dimensions could happen.
34. An analysis followed by an evaluation at the end of detailing is required to gauge the performance and cost factors.

A.3 Summary and Conclusion

The design exercise discussed above is very much a brainstorming of the options of various design solutions for the design of the building envelope. It discusses the design of foundation wall, wall, roof, and window sections. The design exercise demonstrates that the design of the building envelope is an integral part of the building design. The design of other systems such as the spatial systems, service systems and structural systems influence the building envelope design process.

At the start of the envelope design process, the designer focuses on defining the problem by extracting information from the project and site analysis of the building design problem. Based on the information gathered during the problem definition, the designer makes intuitive design decisions through experience and knowledge. The decisions made during this stage provide a base for further design, where the designer follows a step-by-step approach. Also, during this stage the designer focuses on each of the envelope sections starting with the foundation wall, wall, roof and then window. Based on the industry practices various components to be selected are identified. Several options for each of the component are considered and decided based upon the efficiency of performance and cost. Most of the decisions made in the exercise are based on the experience and knowledge of the designer. Some of the decisions are fixed, while many of them are tentative and retained for the future to be decided through analysis and evaluation.

The main characteristics of the exercise are selection of components among many design options, iterative behavior of the designer and maintenance of alternatives. The analysis and evaluation of the design solutions are in two parts: the analysis and evaluation during the design synthesis through experience, knowledge and simple logical methods, and the analysis and evaluation after the assembly build-up, using analytical models and computer tools.

Appendix B

Exercise on Design of Building Envelope Wall Section

The building envelope design process involves the design of independent envelope sections. This appendix discusses the exercise that focused only on the assembly build-up stage. In most of the cases, the design of the envelope system starts with the design of the envelope section of the exterior wall. Based on the design decisions about the components of the envelope section of the exterior wall, the other envelope elements such as, roof, foundation wall, windows, joints, and connections are determined. The design synthesis process of each element is inter-related and influences the design of other elements. This design exercise primarily focuses on the design of the exterior wall element for a residential building.

Section B.1 discusses the step-by-step approach of the building envelope section design for the same conditions discussed in the previous exercise. Section B.2 discusses the design options that were considered during the design synthesis stage. Section B.3 discusses the knowledge from industry and reference manuals used for making design decision during the exercise. And section B.4 discusses the knowledge classified based on the functions.

B.1 Step-by-step Methodology of the Exercise on the Envelope Section Design

The following section discusses the design path taken by the designer, while composing a wall assembly section for a residential building (of 3 floors) in Montreal.

1. The decision was made to start from the basement and move upwards. But, as the thickness of the foundation wall could be effectively optimized using the thickness of the above ground wall, design of section above ground was considered first.

2. In the above ground wall section design, the process started with the design

of the main structure (as there is no apparent decision made about any of the components of the wall, especially the exterior finish).

3. The wood structure was selected as the main structure considering the tradition of residential constructions and the availability of wood in the local area.

4. Of the two options, wood stud structure was considered over the post and beam construction as followed in tradition.

5. An indication for wood stud with a dimension of 38 mm x 108 mm (2x6) was drawn. The decision to select 2x6 for wood studs is based on the knowledge from the industry, as it would be an optimum solution.

6. The insulation being the next prominent component of a building envelope, it is selected to fit the stud space. Of the three main options, the loose fill insulation using fibreglass was considered. However, a comparative study could be held between the other materials of loose fill insulation. The selection could be made prioritizing either the performance or cost. *Condense* was decided to be used for this analysis, at a later stage.

7. The wood studs may act as a type of sheathing in order to hold the studs together and to provide a support to the loose fill insulation. The other option is 12.5 mm sheathing of Plywood or OSB. The final decision on the sheathing material could be made by comparing the materials cost, buildability, and efficiency criteria.

8. On the exterior of the sheathing, a layer of Rigid Insulation was considered. However, since the stud-fill insulation is 6″ thick, the assembly without exterior insulation could also be sufficient and cost effective, and hence an alternative for the existing section design was considered. An alternative (section 2) without the rigid insulation was developed along with the original section (section 1).

9. A vapor barrier for the envelope was considered on the warmer side of the envelope. Through the knowledge from industry, it is decided to apply the Polyethylene film over the inner side of the studs. Above the Polyethylene, a gypsum layer as interior sheathing was decided to be applied. A layer of paint above the Gypsum board was then decided.

10. On the exterior of the back wall, it was decided to have 25 mm air-cavity and a rain screen.

11. The rain screen could either be brick wall or wooden siding. For the time being both of the above, sections 1 and 2 were considered with wooden siding and brick veneer. Thus, four sections were considered as alternatives to be evaluated using *Condense* for cost and efficiency, and to decide upon the section to be used.

12. The four sections were then evaluated, using *Condense*, and compared to decide upon the section to proceed with.

13. The four section analyzed were (layers presented from exterior to interior), as shown in figure B.1 and figure B.2:

    a. Section 1 (brick facade with rigid insulation) – 100mm brick layer, 25mm air space, 50mm extruded polystyrene, 13mm plywood (sheathing),

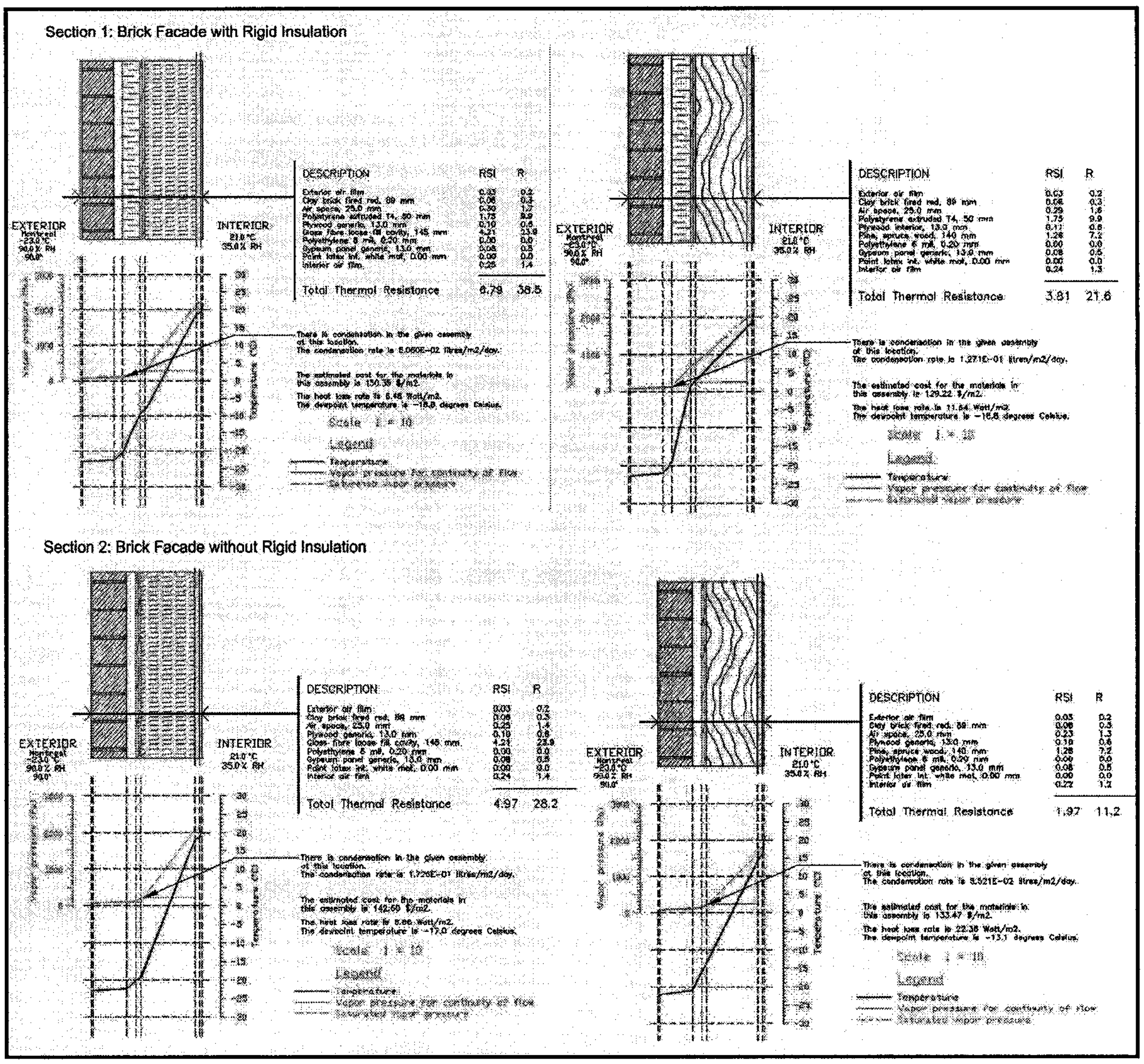

Figure B.1: Condense Analysis of Section 1 and Section 2

145mm glass fibre loose fill insulation / 2x6 wood studs, 6mil polyethylene, 13mm gypsum panel generic, paint latex int. white mat

b. Section 2 (brick facade without rigid insulation) - 100mm brick layer, 25mm air space, 13mm plywood (sheathing), 145mm Glass fibre loose fill insulation / 2x6 wood studs, 6mil polyethylene, 13mm gypsum panel generic, paint latex int. white mat

c. Section 3 (wood siding facade with rigid insulation) - 12mm wood siding, 25mm air space, 50mm extruded polystyrene, 13mm plywood (sheathing), 145mm Glass fibre loose fill insulation / 2x6 wood studs, 6mil polyethylene, 13mm gypsum panel generic, paint latex int. white mat

d. Section 4 (wood siding facade without rigid insulation) - 12mm wood

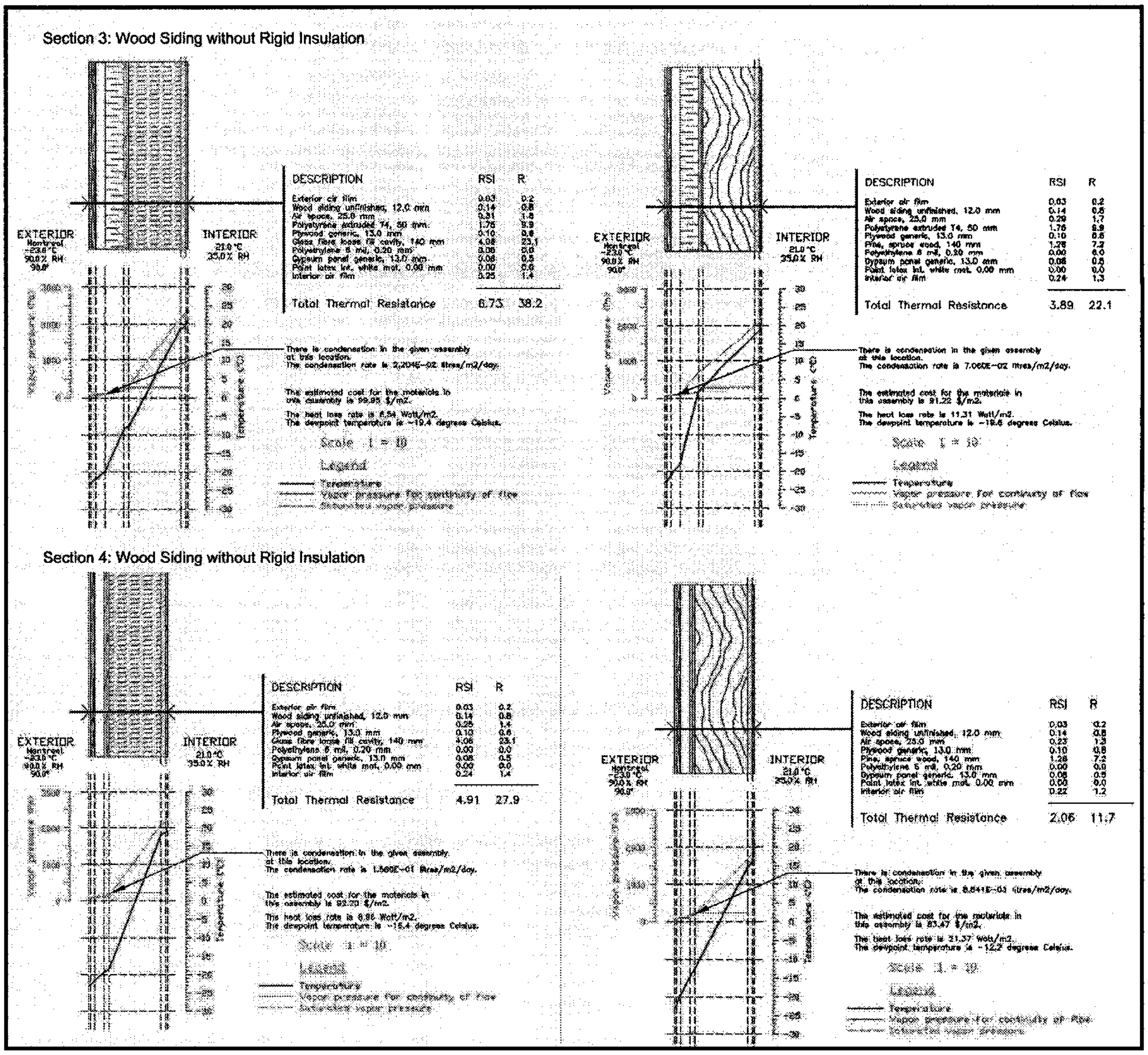

Figure B.2: Condense Analysis of Section 3 and Section 4

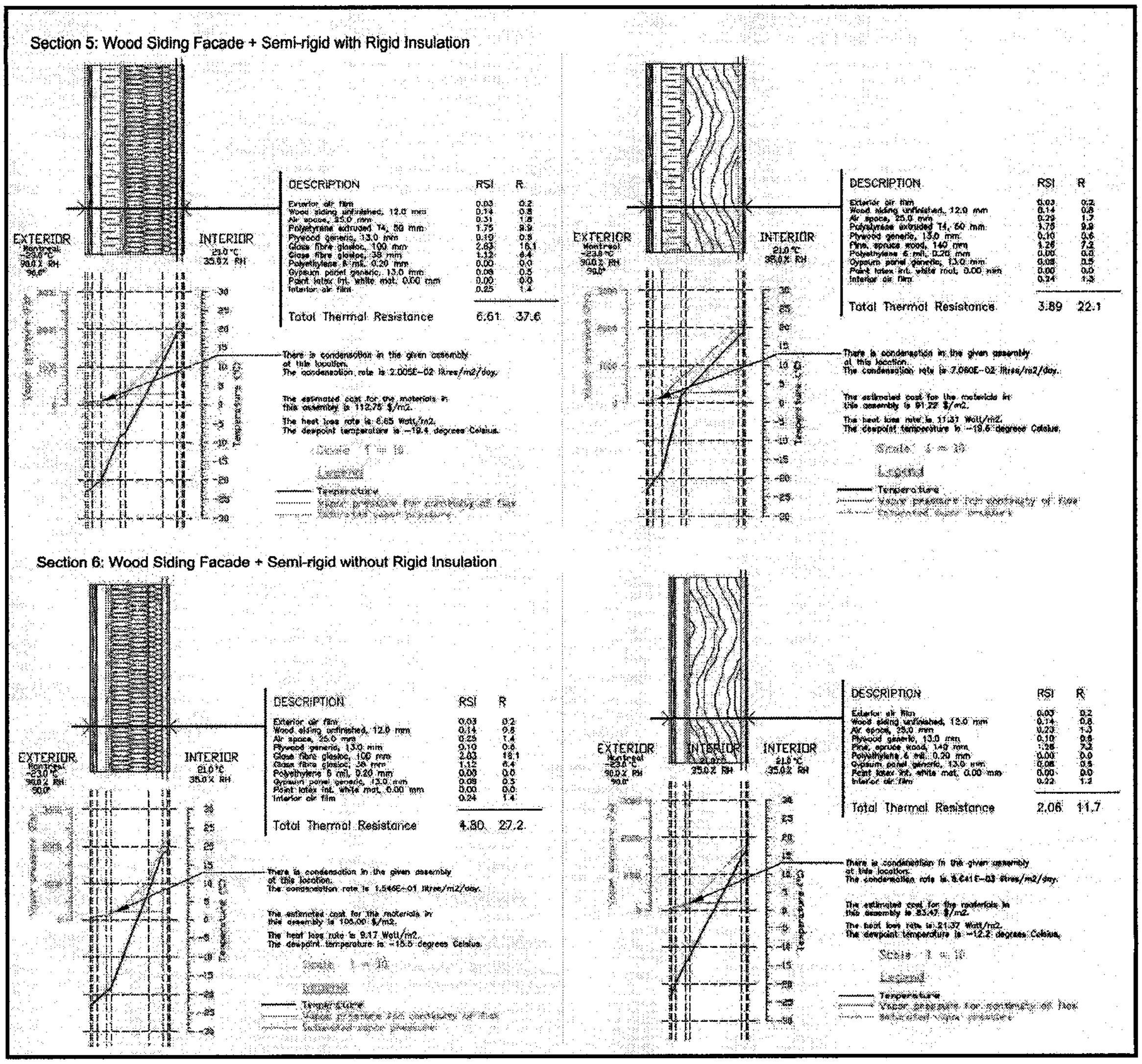

Figure B.3: Condense Analysis of Section 5 and Section 6

siding, 25mm air space, 13mm plywood (sheathing), 145mm Glass fibre loose fill insulation / 2x6 wood studs, 6mil polyethylene, 13mm gypsum panel generic, paint latex interior white mat

14. On analysis, the sections without rigid insulation display a possibility of condensation in the loose fill insulation.

15. Upon comparison of the brick facing and wood siding sections, the brick facing sections are found to be 1.5 times higher in cost factor than the wood siding sections.

16. The wood siding section with rigid insulation is found to be more appropriate than the other sections.

17. However, trying other components such as the thickness of the polyethylene, the insulation type in between the studs and other similar factors could offer optimal results.

18. A second set of analyses were carried out using different options, as shown in figure B.3, figure B.4 and figure B.5.

    a. Section 5 (wood siding facade + semi-rigid insulation with rigid insulation) - 12mm wood siding, 25mm air space, 50mm extruded polystyrene, 13mm plywood (sheathing), 145mm Fibre glass semi-rigid insulation / 2x6 wood studs, 6mil polyethylene, 13mm gypsum panel generic, paint latex int. white mat

    b. Section 6 (wood siding facade + semi-rigid insulation without rigid insulation) - 12mm wood siding, 25mm air space, 13mm plywood

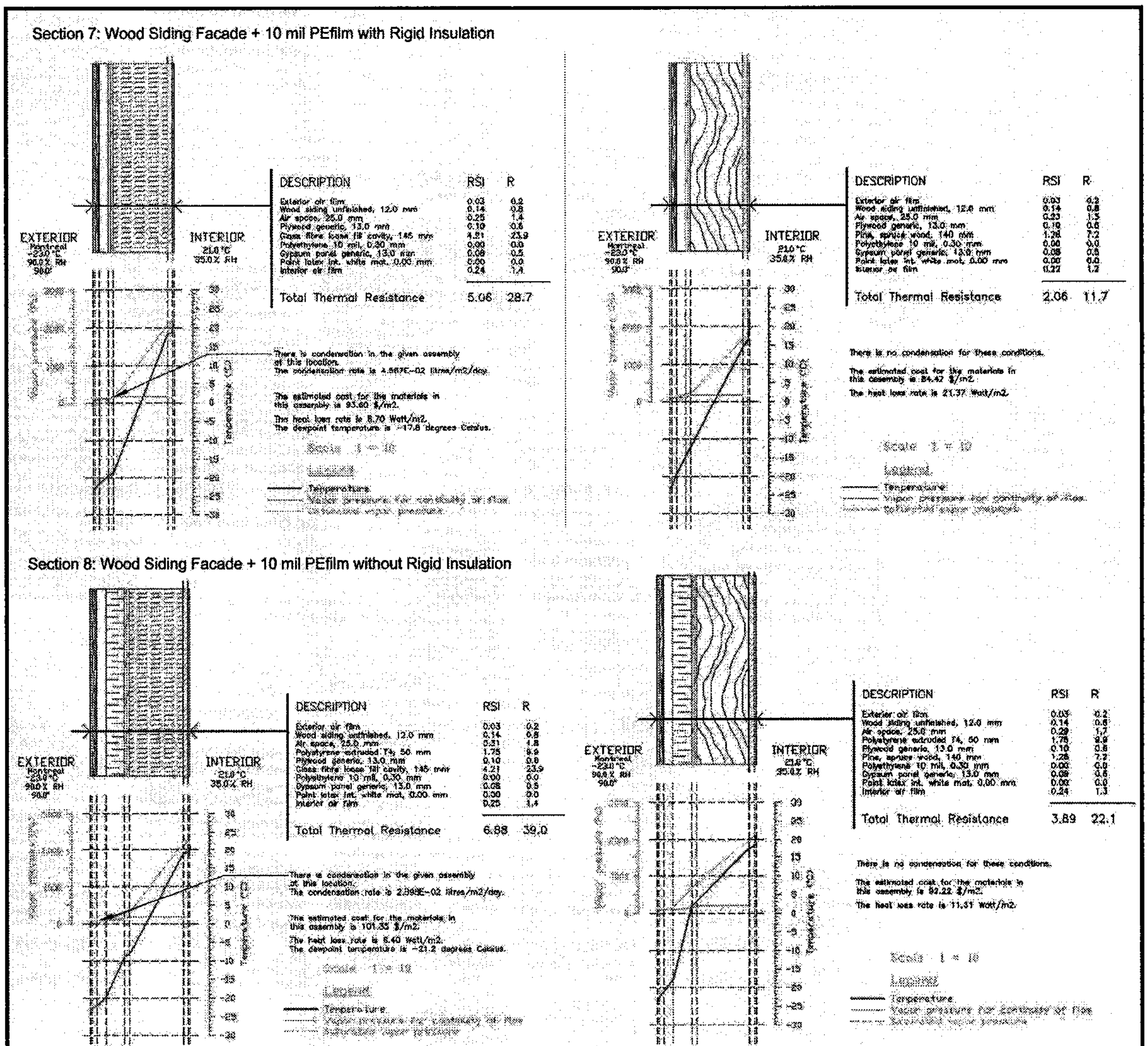

Figure B.4: Condense Analysis of Section 7 and Section 8 (sheathing), 145mm Fibre glass semi-rigid insulation / 2x6 wood studs, 6mil polyethylene, 13mm gypsum panel generic, paint latex int. white mat

c. Section 7 (wood siding facade + 10mil PE with rigid insulation) - 12mm wood siding, 25mm air space, 50mm extruded polystyrene, 13mm plywood (sheathing), 145mm Glass fibre loose fill insulation / 2x6 wood studs, 6mil polyethylene, 13mm gypsum panel generic, paint latex int. white mat

d. Section 8 (wood siding facade + 10mil PE without rigid insulation) - 12mm wood siding, 25mm air space, 13mm plywood (sheathing), 145mm Glass fibre loose fill insulation / 2x6 wood studs, 6mil polyethylene, 13mm gypsum panel generic, paint latex interior white mat

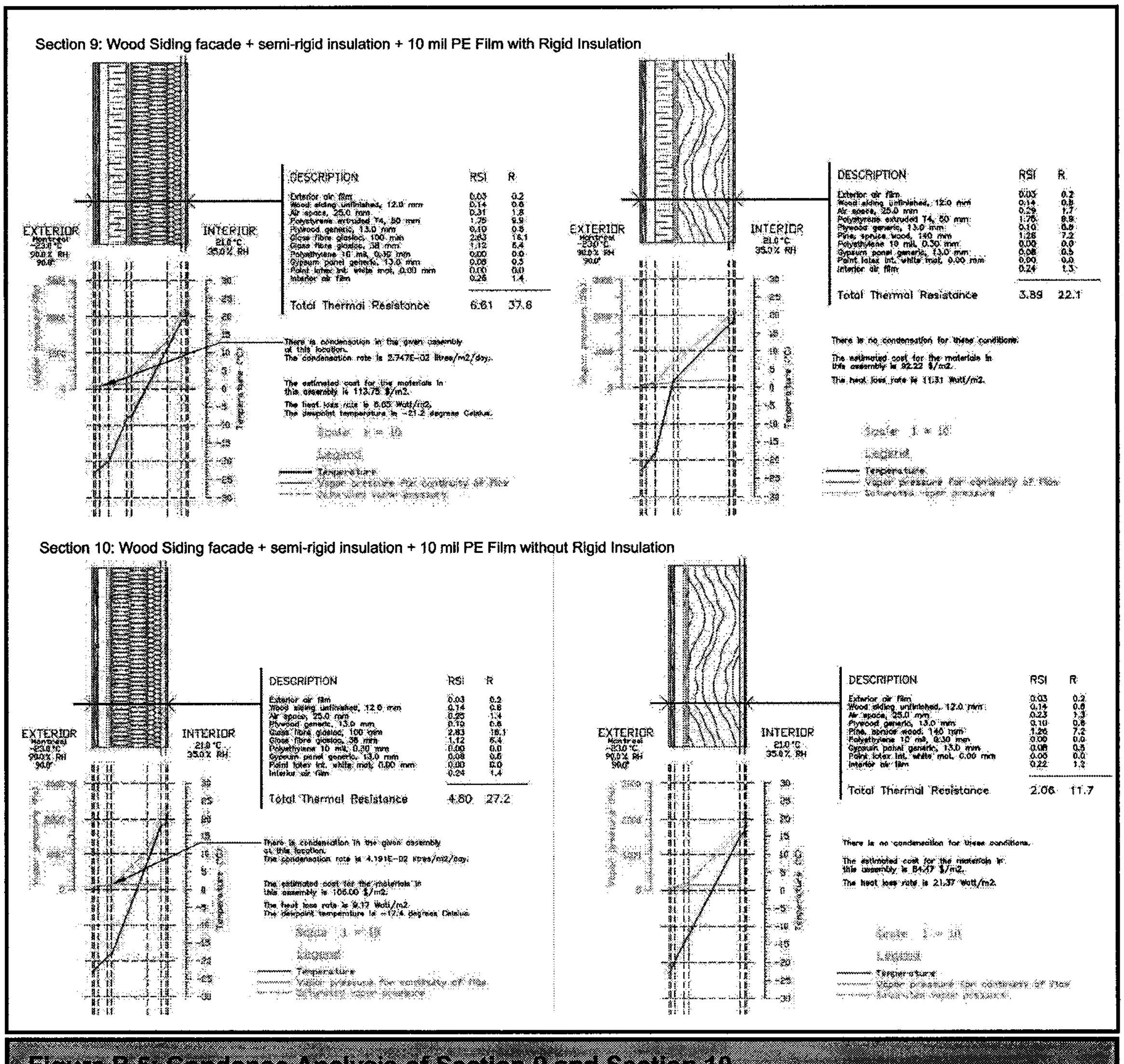

Figure B.5: Condense Analysis of Section 9 and Section 10

e. Section 9 (wood siding facade + semi-rigid insulation + 10mil PE with rigid insulation) – 12mm wood siding, 25mm air space, 13mm plywood (sheathing), 145mm Fibre glass semi-rigid insulation / 2x6 wood studs, 10mil polyethylene, 13mm gypsum panel generic, paint latex int. white mat

f. Section 10 (wood siding facade + semi-rigid insulation + 10mil PE without rigid insulation) – 12mm wood siding, 25mm air space, 13mm plywood (sheathing), 145mm Fibre glass semi-rigid insulation / 2x6 wood studs, 10mil polyethylene, 13mm gypsum panel generic, paint latex int. white mat

19. Of the six sections, three sections without rigid insulation were ruled out as they exhibited the presence of Condensation

20. The presence of 10 mil PE film instead of 6 mil PE film didn't show any improvement in performance (with higher cost)

21. Based on the above observations, the section 5 with 12mm wood siding, 25mm air space, 50mm extruded polystyrene, 13mm plywood (sheathing), 145mm Fibre glass semi-rigid insulation / 2x6 wood studs, 6mil polyethylene, 13mm gypsum panel generic, paint latex int. white mat was selected and compared with the already analyzed section 3, where there is only a change in the insulation material.

22. Due to the workability factor and tradition (practice), Section 5 with semi-rigid insulation as Section 3 against the loose fill insulation was selected, though there is a +10% margin in the cost

23. The total thickness of the wall section was calculated by adding the thickness of the layers of the section

Section 5:

a. Wood siding -12 mm

b. Air space - 25 mm

c. Extruded Polystyrene - 50 mm

d. Plywood sheathing - 13 mm

e. Fibreglass semi-rigid insulation/wood studs - 145mm

f. 6 mil Polyethylene - negligible (0.18 mm)

g. Gypsum panel generic - 13 mm

h. Paint latex int. white mat - negligible

Total - 258 mm

24. Considering the workability of the section and the consistency of the thickness of the layer materials, the thickness of the assembly is rounded up and assumed to vary between 260 - 300 mm

25. The foundation wall is then decided to have a thickness of 350 mm. This may be the overall thickness of the foundation wall as the layers to be supported are only 145 mm (wood studs), 13 mm (plywood sheathing) and 13 mm (gypsum board panel). + concrete wall (8")

26. Of the available types of foundation walls, the masonry and concrete structures were considered for further analysis as is practised in the industry. The selection could be made on comparison of the cost, functionality and performance of the foundation wall derived.

B.2 Design Options considered for selection of each component of the Building Envelope Section Design Process

The design of the building envelope wall section is usually influenced by the traditional methods and the designer's experience and knowledge. The following section discusses the design options considered during the building envelope section design exercise.

B.2.1 Structural stability:

Normally, the design process starts from two points: selection of structural system or selection of exterior cladding. In this case the design process started with the selection of the structural system. The designer has four main types of structural systems: wood structure, steel structure, masonry structure and concrete structure. In case of a residential building in Canada, on the basis of the traditional knowledge, the designer normally selects wood structure. The designer has two options for wood structure based on the type of construction: wood stud and post-beam structure. The choice of type of wood construction and the layout to be used in the building are done using analytical methods by verifying the standards. On deciding the type of structure, the designer selects material for other functions like exterior facing (for aesthetics, shelter and prevention of external agencies), thermal barrier, air barrier and moisture barrier (vapor and liquid water). The order of selection of the layers varies depending on the designer's experience and intuition. However, the design is handled through iteration and modification. The compatibility of the layers plays a major role in selecting the whole system. Normally, the cases of proven design practices help the designer in choosing. In most cases the designer may even prefer to select a complete system in one go.

B.2.2 Exterior Cladding:

For exterior cladding, normally the designer has wood siding, brick tile cladding and a layer of brick wall as a double skin for wood structures. While deciding the exterior facing the designer has to question specifically the properties of material selected for its resistance against all the external forces such as snow, rain, dust, impacts etc. Stability, buildability, material availability, compatibility with the existing and the forth-coming layers are the common reviews that the designer has to ponder upon while deciding all the layers.

B.2.3 Barriers:

The predominant attitude of the designer with barriers is to iteratively try various types of materials, positions of the barrier layer and thickness of the barrier layer in order to achieve the specified environmental performance. This attitude measures well with all three barriers: thermal, moisture and air barrier. As a secondary element, the choice of this barrier could be a function of installation cost. Normally, the verification is done on completion of the assembly. A common rule in providing the barriers is continuity. The continuity of the air barrier is considered during the detailing stage of the assembly construction, using logical methods. Though the continuity of barriers is essential they are logically verified by the user at the detailing stage.

B.2.3.1 Thermal Barrier:

For the thermal barrier, normally the designer chooses a layer of insulation, which could be cavity insulation or surface applied insulation. The materials for the cavity insulation are glass fibre, mineral fibre, cellulose, and spray-applied foams. The material used could be of a type flexible and semi-rigid insulations (blanket, batt, or felt insulation, available as either sheets or rolls which are usually used in cavity insulation) or rigid insulation (available in rectangular blocks, boards or sheets, which are usually used in surface applied insulation). The other types are, loose fill insulation (made of fibres, powders, granules or nodules that are usually poured or blown into walls or other spaces); insulating cement (loose material that is mixed with water or a suitable binder); reflective materials (available in sheets and rolls of single layer or multiplayer construction); and formed in-place insulations (available as liquid components or expandable pellets that can be poured, frothed or sprayed in place to form rigid or semi rigid foam insulation). The type of structure could influence the selection of the type of insulation, e.g. the designer would select a flexible type of insulation, such as loose fill insulation or semi-rigid insulation, rather than the rigid insulation type for an irregular shape. Further down, the exact type of material can be specified on verifying the performance and cost factors.

B.2.3.2 Moisture Barrier:

The moisture barrier has to control two types of moisture ingress: moisture diffusion and liquid water ingress. The moisture diffusion can take place either by air infiltration or through pores of materials.

Provision of vapor barrier provides a resistance to the moisture ingress and prevents moisture ingress due to diffusion. The purpose of vapor barrier is to prevent the accumulation of moisture in the structure, which can be verified using analytical models, however at the end of the design of assembly. The material options for vapor barrier are plywood sheathing, metal cladding (not used in wood structure), polyethylene etc... The type and thickness (for performance) of the vapor barrier is relative to the climatic condition of the site as the moisture accumulation on the materials (structural components depends on the location) with respect to vapor barrier.

- Vancouver - practically no accumulation of moisture in winter
- Windsor - slight increase of moisture accumulation during winter period
- Toronto - significant increase of moisture, yet during the spring season the drying is complete
- Montreal - borderline
- Winnipeg - beyond the safety zone - may cause premature deformation

Though there is an impact in the moisture accumulation due to geographic location, the continuity of air barriers is more important than the level of 'perfect' materials.

The moisture flow into a building by air is more significant than the diffusion. Hence, the main purpose of providing an air barrier, which is to prevent the air leakage, is to reduce the moisture accumulation in the structural components as well as to prevent the disruption of indoor air quality. For an air barrier, the conventional material used is Polyethylene film.

Liquid water penetration is the direct ingress of moisture as liquid through holes, orifices, cracks, bridges and gaps in joints, directed by the forces due to gravity, capillary action, kinetic energy, and air pressure differentials. This can be tackled and verified by the designer through experience and logical reasoning. Overlapping panels, sloping joints as in concrete panels, wide joints sloping down and out (in intentional joints), ties and anchors that slope down and out, and pressure equalization are some of the logical methods followed by the designer to prevent rainwater ingress. The other solutions are providing proper flashing, proper sealants and proper drains (such as the gutter and down spouts). The pressure equalization technique using the rain screen wall construction is one of the effective techniques.

B.2.3.3 Air barrier:

Air control represents a critical factor in environmental control. It underscores virtually all facets of environmental control as it conducts heat and moisture through the building envelope.

Design aspects of air barrier performance:

- Details of joints
- Differential movements of construction
- Installed performance of different air barrier systems - Trowel applied, torch applied, adhesive back or mechanically fastened materials
- Details involving steel columns, roof/wall junctions, or brick ties in masonry walls
- Differential movements in the structure also affect the continuity of air barriers – these develop due to thermal expansion and contraction of the building elements, deflection of beams and mortar shrinkage. In addition, air-barrier materials differ in crack-bridging ability (rigid parging materials usually do not offer protection from cracks developing in masonry walls). However, reinforced flexible membranes

with adequate thickness may perform well.

- While some structural movements can be predicted, in many cases, designers must rely on experience and judgment to anticipate the impact of differential movements on the specific design

B.2.4 Interior Finish:

Interior facing is the layer normally influenced by the design of other layers, which plays a minor role. The selection of this layer is mostly to satisfy the aesthetics function. Normally, gypsum board, plasterboards, plastic sheets, plywood sheathings etc. are used as interior facing materials. The interior layer in certain cases are used for acoustics (noise damping and sound absorption)

B.3 Summary of Knowledge used in the Envelope Section Design Exercise

The following section summarizes the knowledge used for each design decision of the building envelope section design exercise. It also provides the source/basis of knowledge:

B.3.1 Intuitive stage:

Step	Basis	Description
1	Industry knowledge	Wood, steel, concrete and masonry walls are the possible types in terms of primary material for construction
2	Industry knowledge	Wood is abundantly available in the local market - Montreal
3	Industry knowledge	Wood is traditionally used as a structural material for residential buildings
4	Basic knowledge	High level of insulation of walls is required in Montreal due to the type of climate

	Reference from National Building Code (NBC)	Degree days value of Montreal falls in the less than 4999 category (of Appendix C of NBC)
5	Industry knowledge	Whenever wood structure is used, some part of insulation (either loose-fill or semi-rigid) is normally provided in the cavity between wood studs
6	Basic knowledge	Being a cold climate, a layer of vapor barrier must be provided on the warmer side to avoid moisture permeance by diffusion
	Reference from NBC	Any sheet or panel type material with an air leakage characteristic less than 0.1L/s.m2 at 75 Pa and water vapor permeance less than 60ng/Pa.s.m2 and incorporated in a building assembly required by article 9.25.2.1 to be insulated shall be installed (1) on the warm face of the assembly, (2) at a location where the ratio between total thermal resistance of all materials outside of its innermost impermeable surface and the total thermal resistance of all materials inboard of that surface is not less than required in Table 9.25.1.2 or, (3) outboard of an air space that is vented to the outdoors, and for walls, drained
7	Industry knowledge	Rain screen walls are preferred against the face-sealed walls. A layer of air cavity next to the exterior facing is a common practice

B.3.2 Structural System:

Step	Basis	Description
1	Industry Knowledge	Wood structure could be either stud-wall type or post-beam construction
2	Industry knowledge	The platform construction is traditionally used

	Reference from National Housing Code (NHC) illustrated guide	Stud-wall has two types of construction methods - balloon and platform construction methods.
3	Industry Knowledge	Post-beam type of construction mostly needs wood-studs to support the partition walls and layers of the wall.
	Reference from NBC	Post-beam type of wall should be designed in accordance with NBC, Part 4
4	Reference from Canadian Mortgage Housing Corporation (CMHC) manuals	2x4, 2x6 and 2x8 are the standard size of wood studs available for construction
5	Industry Knowledge	2x4 and 2x6 are the commonly used studs for wall construction in residential buildings
	Reference from NHC illustrated guide	The size and spacing of the wood studs are determined considering the loads that are supported, the unsupported height of the studs and the location of the wall (interior and exterior)
6	Reference from NHC illustrated guide	The minimum stud size of the wall system could be 2x3 or 2x4 with a maximum stud spacing of 400mm and 600 mm and a maximum unsupported height of 2.4 m and 3 m respectively, in case of the wall below roof with or without attic space
7	Reference from NHC illustrated guide	The minimum stud size of the wall system could be 2x4 or 2x6 with a maximum stud spacing of 400mm and 600mm respectively, and a maximum unsupported height of 3 m (for both) in case of the wall below roof with or without attic space plus 1 floor

	Analytical verification	Analysis for the structural stability of the specified wall with varying spacing specifications are required either using the WoodSizer or the manuals. However, a structural plan of the building envelope is required before doing this analysis
8	Industry knowledge	2x4 studs with 600 mm o/c spacing would be sufficient and is found efficient for an envelope (wall below roof with or without attic space) - from a previous design case handled in an assignment
9	Logical evaluation	When 2x4 studs are used there is only 89 mm gap for the cavity insulation, which may not be sufficient for efficient RSI value
	Analytical verification	Analysis for condensation and the total RSI value of a 2x4 built up assembly is required as the decision would be against the tradition (as per Knowledge 6)

B.3.3 Cavity-fill Insulation:

Step	Basis	Description
1	Industry knowledge	Loose fill and semi-rigid insulation are the widely used types for cavity insulation
	Reference from manuals of CMHC	Types of insulation include: (i) Loose fill insulation (fibres, powders, granules or nodules) e.g. glass fibre; (ii) Flexible and semi-rigid insulations (blanket, batt, or felt insulation in either sheets or rolls form) e.g. glass fibre and fibre glass; (iii) Rigid insulation (rectangular blocks, boards or sheets) e.g. extruded and expanded polystyrene, Insulating cement (loose material mixed with water or a suitable binder); (iv) Reflective materials (sheets and rolls of single layer or multiple-layer); and (v) Formed in-place insulations (liquid components or expandable pellets that are poured, frothed or sprayed) e.g. Polyurethane

	Analytical verification	Verify more types from *Condense*
2	Reference from NBC	Insulation shall be installed so that there is reasonably uniform insulating value over the entire face of the insulated area (from NBC 9.25.2.3)
3	Reference from NBC	Thermal insulation shall be installed so that at least one face is in full and continuous contact with an element with low air permeance (from NBC 9.25.2.3)
4	Industry Knowledge	Whenever wood studs are used as the type of structure, some part of insulation (either loose-fill or semi-rigid) is normally provided in the cavity between wood studs
5	Logical evaluation	The thickness of insulation in terms of cavity fill depends on the dimension of wood studs
	Logical evaluation	The thickness of cavity fill insulation is decided upon by the dimension of the wood stud - 2x4 and 2x6 are the two probable alternatives considered
6	Reference from database	*Condense* has a rich database of insulation materials, which could be verified
7	Industry Knowledge	Glass fibre is a widely used loose fill insulation
8	Industry Knowledge	Fibre glass and glass fibre semi-rigid insulation are the traditionally used insulation material

B.3.4 Sheathing Layer:

Step	Basis	Description
1	Reference from NBC	The addition of insulation into exterior walls of existing wood frame buildings increases the likelihood of damage to framing and cladding components as a result of moisture accumulation (from NBC A-

		9.25.2.2.(4)
2	Reference from NBC	Where insulation is exposed to the weather and subject to mechanical damage, it shall be protected with not less than, (i) 6 mm asbestos-cement board, (ii) 6 mm preservative treated plywood or (iii) 12 mm cement parging on wire lath applied to the exposed face and edge (from NBC 9.25.2.3.(6))
3	Reference from NBC	Insulation located in areas where it may be subject to mechanical damage shall be protected by a covering such as gypsum board, plywood, particleboard, OSB, wafer board or hardboard (from NBC 9.25.2.3.(7))
4	Industry Knowledge	Plywood, OSB and hardboard are the traditionally used materials that could be used as sheathing on the exterior
5	Industry Knowledge	The sheathing layer used in the wood stud wall also acts as an additional structural support
6	Logical evaluation	Plywood on comparison to the other traditionally used materials acts better in terms of structural support
7	Information from Database	Data about the thickness of plywoods are available in *Condense*
	Analytical verification	Requires calculation of cost and performance (using *Condense*)
8	Reference from NBC	The thickness of sheathing also depends on the Minimum RSI ratio as indicated in Table A - 9.25.1.2. A
	Analytical verification	Analysis of the minimum RSI ratio is required in order to decide upon the thickness

B.3.5 Exterior Insulation:

Step	Basis	Description
1	Industry Knowledge	Rigid insulation exterior to the sheathing layer provides extra resistance for the heat flow
2	Industry Knowledge	Rigid insulation could help maintain the uniformity of the heat flow (RSI value) through the wall assembly
	Analytical verification	Calculation of the RSI values of the section with and without exterior insulation is required, using *Condense*

B.3.6 Vapor Barrier:

Step	Basis	Description
1	Industry knowledge	Vapor barrier for a cold climate should be provided on the warmer side of the building envelope cross section
	Reference from NBC	Any sheet or panel type material with an air leakage characteristic less than 0.1L/s.m2 at 75 Pa and water vapor permeance less than 60ng/Pa.s.m2 and incorporated in a building assembly required by article 9.25.2.1 to be insulated shall be installed (1) on the warm face of the assembly, (2) at a location where the ratio between total thermal resistance of all materials outboard of its innermost impermeable surface and the total thermal resistance of all materials inboard of that surface is not less than required in Table 9.25.1.2 or, (3) outboard of an air space that is vented to the outdoors, and for walls, drained
2	Reference from NBC	Vapor barrier shall have an initial permeance not greater than 45 ng/(Pa.s.m2) (from 9.25.4.2. (1) of NBC)
3	Reference from NBC	When used where a high resistance to vapor movement is required, such as in wall constructions that incorporate exterior cladding or sheathing having a low water vapor permeance, vapor barriers shall have a permeance not greater than 15 ng/Pa.s.m2

		(from 9.25.4.2. (2) of NBC)
4	Industry Knowledge	Polyethylene film is the traditionally and widely used effective vapor barrier
	Reference of Database	Verify the materials to act as vapor barrier in *Condense*

Interior Sheathing:

Step	Basis	Description
1	Industry knowledge	All the materials listed under exterior materials could act as interior sheathing as well.
2	Industry knowledge	Interior sheathing materials traditionally employed are Gypsum board, Particle board and OSB
3	Industry knowledge	Interior sheathing could vary depending upon the function of the space enclosed by the building envelope, e.g. acoustic panels for auditoriums
4	Industry knowledge	Gypsum board is traditionally used as the interior sheathing material
	Analytical verification	Verification using the Means Building Construction Cost Data, Section: Finishes may also be carried out

B.3.7 Interior Coating:

Step	Basis	Description
1	Industry knowledge	A layer of paint over the Gypsum board is a practice in residential walls (for aesthetics)
2	Analytical verification	The list of paints that could be applied on the interior face of the wall could be verified using the Means Building Construction Cost Data, Section: Finishes and

		Condense database
3	Subjective decision	Based on the preference of the designer, white colour was chosen

B.3.8 Air Cavity:

Step	Basis	Description
1	Industry knowledge	Air cavity is an essential ingredient of the wall assembly created with the rain screen principle
2	Industry knowledge	Air cavity acts as the first layer of defence against water penetration
3	Industry knowledge	The minimum thickness of the air cavity should be 12.5 mm
4	Industry knowledge	Though there is not much prescribed about the maximum allowed thickness, an effective thickness would be 25 mm (with respect to buildability and to maintain the overall thickness)

B.4 Classification of Knowledge on the Basis of Functions

The building envelope section from an assembly-of-components point of view could aid to summarize the knowledge. The following knowledge is gathered and compiled from the exercises conducted on the building envelope section design. They are limited to the residential building type and wall section type.

7. Generic knowledge involved in the building envelope design process:
    - Knowledge of primary materials and construction types for each component of the assembly envelope;
    - Knowledge of traditional materials and construction types for each component of the assembly envelope;
    - Design cases from literature, manuals, and previous design cases for each component in reference with the design conditions;

- Knowledge to evaluate the results of scientific analysis;
- Knowledge of the unit price of the components;

8. Knowledge related to the structural stability function:
    - Classification of structure and all the options available, based on the building type;
    - Classification of wood structure based on the construction type;
    - Options available for wood stud sizes in case of wood-stud structure;
    - Regulations for wood stud structure, minimum stud size, maximum spacing, and maximum unsupported height from governing bodies such as National Building Code;
9. Knowledge related to the control of heat flow:
    - Options of strategies for insulation components, primarily the classification of the insulation, based on the insulation material type;
    - Knowledge specifying the thickness of the material used as exterior or interior insulation, usually provided by the manufacturer;
    - Knowledge indicating the use of loose-fill or semi-rigid insulation in the cavity between studs;
    - Analytical capability and knowledge to evaluate the results of heat resistance;
    - Knowledge indicating the positioning of vapour barrier adjacent to the insulation layer;
    - Material options on the basis of type of insulation selected;
    - Knowledge handling the thickness of the insulation to be less than the thickness of the stud depth;
10. Knowledge related to the control of vapour diffusion:
    - The strategies of the various methods of vapour diffusion control;
    - Knowledge indicating the possibility of vapour diffusion control by other means, basically by using a material layer with high moisture storage capacity and by using vapour resistant paints;
    - Knowledge indicating the positioning of the vapour barrier depending on the design conditions, especially the climatic type;
    - The material options that comply to the regulation of the National Building Code;

- Knowledge indicating the use of low-permeance material layers for other components such as sheathing, and exterior cladding;
- Knowledge about the allowable vapour permeance, based on the building type and section type;

11. Knowledge related to rain-water control:

    - Knowledge specifying the thickness of the material used as an exterior cladding, usually provided by the manufacturer;
    - The necessity of the rain screen, from the proven design practices;
    - Knowledge indicating the need of presence of air cavity and its position, and the minimum thickness to be at least 12.5 mm and the effective thickness to be 25 mm (considering the buildability aspects);
    - Knowledge as to the weather resistance capability of the inner wall, and to indicate the requirement of a weather resistant sheathing layer;

12. Knowledge related to interior finish:

    - Knowledge supporting the selection of interior finish based on the function of the space enclosed by the envelope system, e.g. wooden panels for theatres to dampen acoustical reverberation;
    - Knowledge aiding the selection of the interior finish material based on the aesthetic appeal;
    - The options of paints and other finishes for the interior;

B.5 Summary

The building envelope section design exercise discussed in this appendix follows the same design conditions as in the design case discussed in Appendix A, residential building with three floors in Montreal. The exercise followed a component-selection approach where the designer was equipped with industry knowledge and reference materials for making design decisions. The analytical tool primarily used in this exercise is Condense, primarily used for the analytical verification of condensation, thermal gradient and vapor gradient. It was also used for material database and cost analysis. Some of the significant characteristics of the envelope section design process identified are designer's knowledge of various design options; iterative nature of the design process; analytical verifications in the middle of the design process; prescriptive knowledge; knowledge from manuals and knowledge of materials.

Appendix C

Documentation of the Use Cases for the Prototype

The planning and design of the tool was handled using the concepts of the Unified Modelling Language (UML). UML is a visual modelling technique used to specify, visualize, and document the artefacts of an object-oriented system under development. The design of the software tool using UML is visualised through a series of stages such as identifying and creating use cases, identifying classes, establishing relationships between classes, and laying out sequential diagrams. The use cases model the dialogue between a user and the system. They represent the functionality provided by the system. A use case is a sequence of transactions performed by a system that yields a measurable result of values for a particular actor [Quatrani, 2001]. This appendix presents the use cases to model the user-system interaction of the prototype. However, the implemented prototype does not follow exactly the way the use cases are documented in the following sections. There are few modifications incorporated in the prototype.

Documentation of Actors

- *Building Envelope Designer:* A person who is responsible to design, analyze and evaluate the building envelope.

Documentation of Use Cases

1. *Enter Problem Definition*

    The Building Envelope Designer activates this use case. It provides the capability to enter the problem definition information relevant to the building envelope under design

2. *Structure Selection*

The Building Envelope Designer activates this use case. It provides the capability to satisfy the structural stability function in the envelope assembly build-up.

3. *HAM Control*

   The Building Envelope Designer activates this use case. It provides the capability to make design decisions to satisfy the control heat, air and moisture functions of the building envelope.

4. *Analysis and evaluation*

   The Building Envelope Designer or the Assembly Build-Up use case activates this use case. It provides the capability to analyze and evaluate, if all the functions and performance specifications are satisfied.

Flow of events

1. *Flow of events for the **Enter Problem Definition** use case*

1.1 Preconditions

There are no preconditions for this use case.

1.2 Main flow

The use case displays the **Problem Definition Screen** to prompt the Building Envelope Designer to select the section for data entry from the following options: **LOCATION, CLIMATIC CONDITIONS, DESIGN CONDITIONS, BUILDING DETAILS, SECTION DETAILS, PERFORMANCE SPECIFICATION, CONTINUE and QUIT.**

If the option selected is **LOCATION,** the ***S-1: Enter the Location*** Sub flow is performed.

If the option selected is **CLIMATIC CONDITION,** the ***S-3: Enter the Climatic Condition*** Sub flow is performed.

If the option selected is **DESIGN CONDITION,** the ***S-4: Enter the Design Condition*** Sub flow is performed.

If the option selected is **BUILDING DETAILS,** the ***S-5: Enter the Building Details*** Sub flow is performed.

If the option selected is **SECTION DETAILS,** the *S-6: Enter the Section Details* Sub flow is performed.

If the option selected is **PERFORMANCE SPECIFICATION,** the *S-7: Enter the Performance Specification* Sub flow is performed.

If the option selected is **CONTINUE** the use case checks if all the required Data are entered **(E7)**. The use case **Structure Selection** is activated.

If the option selected is **QUIT,** the use case ends.

1.3 Sub flows

S-1: ***Enter the Location***
The system displays the **Location Data Input Screen** with entry fields for **CITY/TOWN and COUNTRY, and** a list of cities and their corresponding countries retrieved from the database (as suggestive knowledge).

The Building Envelope Designer enters the value. The system checks the database for the city/town. If found *(E-1),* and if it corresponds to only one country *(E-2),* the system prompts the Building Envelope Designer whether to continue with the identified city and its corresponding country. The Building Envelope Designer accepts the City and the Country **(E-3)**. The system stores the value (city and country), retrieves the corresponding values of other variables (variables of design condition and climatic condition) in preliminary information input as defaults and returns to the **Problem Definition Screen.**

S-2: ***New Location Input***
The system prompts the Building Envelope Designer whether to use the information of the closest city in the database or to enter new information about the location. The designer selects to use the information of the closest city in the database **(E-4)** and the sub flow ***(S-3): Enter the Closest Location*** is performed.

S-3: Enter the Closest Location

The system displays the **Closest Location Data Input Screen** with entry fields for **CITY/TOWN and COUNTRY, and** a list of cities and their corresponding country retrieved from the database. The Building Envelope Designer enters the value.

The Building Envelope Designer enters the City/Town. The system checks the database for the City/Town If found ***(E-5)*** and if it corresponds to only one country ***(E-6),*** the system prompts the Building Envelope Designer whether to continue with the identified city and its correlating country as the closest city from the database. The designer opts to continue. The system stores the value (city and country) retrieves the corresponding values of other variables (variables of design condition and climatic condition) in preliminary information input as defaults and returns to the **Performance Specification Entry Screen.**

S-3: ***Enter the Climatic Condition:***

The system displays the **Climatic Condition Data Input screen** with the fields for **CLIMATIC TYPE and DEGREE DAY.** The fields display the retrieved values by correlating the information entered for location from the database, as default values. The Building Envelope Designer accepts the value or enters a new value. The system checks if the Building Envelope Designer enters the acceptable values for **CLIMATIC TYPE and DEGREE DAY *(E-7).*** The system stores the value, retrieves the corresponding values of other variables (variables of design conditions) in preliminary information input as defaults and returns to **Performance Specification Entry Screen.**

S-4: ***Enter the Design Condition:***

The system displays the **Design Condition Input screen** with the fields for **EXTERIOR TEMPERATURE, EXTERIOR RELATIVE HUMIDITY, INTERIOR TEMPERATURE** and **INTERIOR RELATIVE HUMIDITY,** with the default values (example: -23, 40, 21 and 75 for cold climate). The Building Envelope Designer accepts the value or enters a new value. The system checks if the Building Envelope Designer enters the values for the fields **EXTERIOR TEMPERATURE, EXTERIOR RELATIVE HUMIDITY, INTERIOR TEMPERATURE** and **INTERIOR RELATIVE HUMIDITY *(E-8).*** The system stores the value and returns to **Performance Specification Entry Screen.**

S-5: ***Enter the Building Details:***

The system displays the **Building Details Input screen** with the fields for **BUILDING TYPE** and **NUMBER OF FLOORS**, with the default values, 'Residential' and '2' respectively. The Building Envelope Designer accepts the value or enters a new value **(E-9).** The system stores the value and returns to **Performance Specification Entry Screen.**

S-6: ***Enter the Section Details:***
The system displays the **Section Details Input screen**, which prompts with a field for **SECTION TYPE,** with the default value, Wall. The options for the section type are wall, roof and foundation wall. The Building Envelope Designer enters one of the options **[E-10].** The system stores the value and returns to **Performance Specification Entry Screen.**

S-7: ***Enter the Performance Specification for Assembly:***
The system displays the **Performance Specification of Assembly Input screen**, with options **STANDARD and CUSTOM** for **SPECIFICATION TYPE.**

If the option selected is **STANDARD,** the sub-flow ***S-8: Select Standard Specification*** is performed.

If the option selected is **CUSTOM,** the sub-flow ***S-9: Select Custom Specification*** is performed.

S-8: Select Standard Specification
The system displays the various standard performance specifications, correlating with the location, prompting the building envelope designer to verify/select one among them. The building envelope designer chooses to verify one performance specification. The system displays the performance level to be achieved in terms of functions, and prompts the designer to accept or deny the option. The designer chooses to accept the specification standard **[E-11].**

S-9: Select Custom Specification
The system displays the **Custom Specification Input screen**, with suggestions and entry fields for **R-VALUE** and **CONDENSATION LEVEL.** The designer enters valid values **[E-12].**

1.4 Alternative flows

E-1: The system could not identify any **CITY/TOWN** correlating in the database to the one entered by the Building Envelope Designer. If the entered value doesn't correlate with the information available in the database the sub flow ***New Location Input (S-2)*** is performed.

E-2: The system identifies more than one country matching with the city. The system lists all the countries to the user and prompts the Building Envelope Designer to enter one of them. The designer enters one country value. The system retrieves corresponding information for other variables as defaults and returns to the **Performance Specification Entry Screen**.

E-3: The Building Envelope Designer doesn't accept the prompted **CITY/TOWN**. The system prompts the Building Envelope Designer that 'Do you want to continue with the entered city as a new location or go back to the Location Data Input Screen?' If the designer selects new location the sub flow ***New Location Input (S-2)*** is performed, or else ***Enter the Location (S-1)*** is performed.

E-4: The building envelope designer doesn't accept to use the closest location. The system does not carry any default value for further steps.

E-5: The system could not identify any **CITY/TOWN** correlating in the database to the one entered by the Building Envelope Designer. The system prompts the designer to re-enter or opts to go back to the Location Data Input Screen.

E-6: The system identifies more than one country matching with the city. The system lists all the countries to the user and prompts the Building Envelope Designer to enter one of them. The designer enters one country value. The system retrieves corresponding information for other variables as defaults and returns to the **Performance Specification Entry Screen**.

E-7: The Building Envelope Designer didn't enter values or enters invalid value for **CLIMATIC TYPE** and/or **DEGREE DAY**. The system prompts to enter the value or opts to continue without the value.

E-8: The Building Envelope Designer didn't enter values for any of the variables **EXTERIOR TEMPERATURE, EXTERIOR RELATIVE HUMIDITY, INTERIOR TEMPERATURE and INTERIOR RELATIVE HUMIDITY**. The system prompts to enter the value or opts to return to the **Performance Specification Entry Screen.**

E-9: The Building Envelope Designer didn't enter values for any of the variables **BUILDING TYPE and NUMBER OF FLOORS**. The system prompts to enter the value or opts to return to the **Performance Specification Entry Screen**.

E-10: The Building Envelope Designer didn't enter values for the variable **SECTION TYPE**. The system prompts to enter the value or opts to return to the **Performance Specification Entry Screen.**

E-11: The Building Envelope Designer denies the standard option. The system returns to the **Performance Specification of Assembly Input Screen.**

E-12: The Building Envelope Designer didn't enter values or valid values. The system returns to the **Performance Specification of Assembly Input Screen.**

2. *Flow of events for the **Structure Selection** use case*

*2.1 **Preconditions***

The use case ***Enter preliminary Information Input*** must be executed before this use case begins.

*2.2 **Main flow***

The use case displays the **Structure Selection Screen** with few suggestions and options for selection of a structure to provide structural stability. The options displayed are **WOOD STRUCTURE, MASONRY STRUCTURE, RCC STRUCTURE, STEEL STRUCTURE, CONTINUE, BACK or QUIT.**

If the Building Envelope Designer selects the **WOOD STRUCTURE** option, the ***S-1: Select Wood Structure*** sub-flow is performed.

If the Building Envelope Designer selects the **CONTINUE** option, the system checks, if the type of structure is selected and continues to the ***HAM Control*** *use case.*

If the Building Envelope Designer selects the **BACK** option, the system returns to the ***Enter Preliminary Information of Project*** *use case.*

If the Building Envelope Designer selects the **QUIT** option, the use case terminates.

2.3 Sub flows

S-1: Select Wood Structure

The system displays the **Wood Structure Selection Screen** with suggestions and options for the selection of a wood structure to provide structural stability. The options displayed are **POST BEAM, WOOD STUD, CONTINUE, BACK or QUIT.** The designer enters an option.

If the Building Envelope Designer selects the **POST BEAM** option, the **Post Beam Configuration Screen** is displayed with suggestions and entry fields for **BEAM WIDTH, BEAM DEPTH, COLUMN WIDTH, COLUMN DEPTH and COLUMN-COLUMN SPACING.**

If the Building Envelope Designer selects the **WOOD STUD** option, the *S-2:* ***Select Wood Stud Structure*** sub-flow is performed.

S-2: Select Wood Stud Structure

The system displays the **Wood Stud Structure Selection Screen** with suggestions and options for the selection of a wood structure to provide the structural stability. The options displayed are **SINGLE STUD, DOUBLE STUD, CONTINUE, BACK or QUIT.** The designer selects an option.

If the Building Envelope Designer selects the **SINGLE STUD** option, the sub flow *S-3:* ***Configuration of Single Stud*** is performed.

If the Building Envelope Designer selects the **DOUBLE STUD** option, the sub flow *S-5:* ***Configuration of Double Stud*** is performed.

S-3: Configuration of Single Stud

The system displays the **Single Stud Configuration Screen** with suggestions and entry fields for **STUD SIZE and STUD SPACING.** The designer enters the preferred valid values **[E-1].** The system prompts if the designer wants to add extra support. The designer requests extra support **[E-2]**. The sub-flow ***S-4 Select Extra Support,*** is performed.

S-4 Select Extra Support

The system displays the **Extra Structural Support Selection Screen** with suggestions and options, **PLYWOOD LAYER and BRACING.** The Designer enters the option.

If the Building Envelope Designer selects the **PLYWOOD LAYER** option, the ***S-5: Configuration of Plywood Layer*** sub-flow is performed.

If the Building Envelope Designer selects the **BRACING** option, the ***S-6: Configuration of Bracing*** sub-flow is performed.

S-5: Configuration of Plywood Layer

The system displays the **Plywood Layer Configuration Screen** with suggestions and entry field for **THICKNESS**. The designer enters the preferred valid values **[E-3].** The system performs ***S-6: Position the layer*** sub flow.

S-6: Position the layer

The system displays the **Layer Positioning Screen** with the already selected and positioned layers as reference layers and the entry fields for **REFERENCE LAYER and POSITION** (POSITION variable carries Exterior, Interior or In-between as value**).** The designer enters the preferred valid values **[E-4].** The system continues to ***HAM Control*** *use case.*

S-7: Configuration of Bracing

The system displays the **Bracing Configuration Screen** with suggestions and entry field for **BRACES DIMENSION and SPACING**. The designer enters the preferred valid values **[E-5].** The system performs ***S-6: Position the Layer*** sub flow.

S-8: Configuration of Double Stud

If the Building Envelope Designer selects **DOUBLE STUD,** the **Double Stud Configuration Screen** is displayed with entry fields for **STUD SIZE1, STUD SIZE2, SPACING BETWEEN DOUBLE STUDS and STUD SPACING.** The designer enters the preferred valid values **[E-6].** The system continues with the ***HAM Control*** use case.

2.4 *Alternative flows*

E-1: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or returns to the **Wood Stud Structure Selection Screen.**

E-2: The designer doesn't request extra support. The system continues to the ***HAM Control*** *use case.*

E-3: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or returns to the **Extra Structural Support Selection Screen.**

E-4: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or opts to return to the **Structure Selection Screen.**

E-5: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or returns to the **Extra Structural Support Selection Screen.**

E-6: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or returns to the **Wood Stud Structure Selection Screen.**

3. *Flow of events for the HAM Control use case*

3.1 *Preconditions*

The use case ***Enter Preliminary Information of Project*** and ***Structure Selection*** must be executed before this use case begins.

3.2 *Main flow*

The use case displays the **HAM Control Screen** with functions as options that are yet to be satisfied, which is/are **CONTROL OF HEAT FLOW, CONTROL OF VAPOR DIFFUSION, CONTROL OF AIR MOVEMENT, CONTROL OF LIQUID WATER INGRESS, CONTINUE, BACK and QUIT.** The assembly section designed so far is also displayed.

If the Building Envelope Designer selects **the CONTROL OF HEAT FLOW** option, the ***S-1: Control of Heat Flow*** sub flow is performed.

If the Building Envelope Designer selects the **CONTROL OF VAPOR DIFFUSION** option, the ***S-15: Control of Vapor Diffusion*** sub flow is performed.

If the Building Envelope Designer selects the **CONTROL OF AIR MOVEMENT** option, the ***S-21: Control of Air Movement*** sub flow is performed.

If the Building Envelope Designer selects the **CONTROL OF LIQUID WATER INGRESS** option, the ***S-23: Control of Liquid Water Ingress*** sub flow is performed.

If the Building Envelope Designer selects the **CONTINUE,** the system checks if the structure, control of heat, vapor and air functions are satisfied **[E-1]** and continues to ***Analysis and Evaluation*** *use case.*

If the Building Envelope Designer selects the **BACK,** the system returns to the ***Structure Selection*** *use case.*

If the Building Envelope Designer selects the **QUIT,** the use case terminates.

3.3 Sub flows

S-1: Control of Heat Flow

The system displays the **Control of Heat Flow Screen** with suggestions and options for selection of a type of insulation to provide the control of heat. The options displayed are **CAVITY INSULATION, EXTERIOR INSULATION, INTERIOR INSULATION, CONTINUE, BACK or QUIT.**

If the Building Envelope Designer selects the **CAVITY INSULATION** option, the ***S-2: Selection of Cavity Insulation*** sub flow is performed.

If the Building Envelope Designer selects the **EXTERIOR INSULATION** option, the ***S-7: Selection of Exterior Insulation*** sub flow is performed.

If the Building Envelope Designer selects the **INTERIOR INSULATION** option, the ***S-9: Selection of Interior Insulation*** sub flow is performed.

If the Building Envelope Designer selects the **CONTINUE** option, the system continues to the main flow of ***HAM Control** use case.*

If the Building Envelope Designer selects the **BACK** option, the system returns to the preceding main flow, sub-flow or alternative flow.

If the Building Envelope Designer selects the **QUIT** option, the use case terminates

S-2: Selection of Cavity Insulation

The system displays the **Cavity Insulation Screen** with suggestions and options for the selection of insulation to provide the heat control. The options displayed are **LOOSE-FILL or SEMI-RIGID INSULATION, FOAMED IN-PLACE, BATT, CONTINUE, BACK or QUIT.**

If the Building Envelope Designer selects the **LOOSE-FILL or SEMI-RIGID INSULATION** option, the ***S-3: Configuration of Loose-fill/Semi-rigid Insulation*** sub-flow is performed.

If the Building Envelope Designer selects the **FOAMED IN PLACE INSULATION** option, the ***S-11: Configuration of Foamed-In Place Insulation*** sub-flow is performed.

If the Building Envelope Designer selects the **BATT INSULATION** option, the ***S-12: Configuration of Batt Insulation*** sub-flow is performed.

If the Building Envelope Designer selects the **CONTINUE** option, the system continues to ***Control of Heat Flow*** sub flow.

If the Building Envelope Designer selects the **BACK** option, the system returns to the preceding main flow, sub-flow or alternative flow.

If the Building Envelope Designer selects the **QUIT** option, the use case terminates.

S-3: Configuration of Loose-fill/Semi-rigid Insulation

The system displays the **Loose-fill/Semi-rigid Insulation Configuration Screen** with suggestions and entry fields for the **MATERIAL NAME and THICKNESS.** The designer enters the preferred valid values **[E-2].** The system checks the assembly for an exterior cavity-closure layer. The system does not find a cavity-closure layer **[E-3]**. The system prompts the designer to provide a layer to close the cavity. The designer requests to add a layer to close the cavity **[E-4]**. The system performs ***S-5: Select a Base/Cavity Closure Layer*** sub flow.

S-4: Position the layer

The system displays the **Layer Positioning Screen** with the already selected and positioned layers as reference layers and the entry fields for **REFERENCE LAYER and POSITION** (POSITION variable carries Exterior, Interior or In-between as value). The designer enters the preferred valid values **[E-5].** The system returns to the previous Sub-flow or Alternative Flow.

S-5: Select a Base/Cavity Closure Layer

The system displays the **Base/Close-Cavity Layer Screen** with the suggestions and options, **BASE/CAVITY-CLOSURE LAYER ON EXTERIOR and BASE/CAVITY-CLOSURE LAYER ON INTERIOR.** The designer enters an option.

If the Building Envelope Designer selects the **BASE/CAVITY-CLOSURE LAYER ON EXTERIOR,** the system performs ***S-6: Base/Cavity-Closure Layer on Exterior*** sub flow.

If the Building Envelope Designer selects **BASE/ CAVITY-CLOSURE LAYER ON INTERIOR** option, the system performs ***S-7: Base/Cavity-Closure Layer on Interior*** sub flow.

S-6: Base/Cavity-Closure Layer on Exterior

The system displays the **Base/Cavity-Closure Layer on Exterior Screen** with the suggestions and options **PLYWOOD LAYER** and **RIGID INSULATION.** The designer enters an option.

If the Building Envelope Designer selects **PLYWOOD LAYER,** the system performs *S-7: Configuration of Plywood Layer* sub flow.

If the Building Envelope Designer selects **RIGID INSULATION,** the system performs *S-8: Configuration of Rigid Insulation* sub flow.

S-7: Configuration of Plywood Layer

The system displays the **Plywood Layer Configuration Screen** with suggestions and entry field for **THICKNESS**. The designer enters the preferred valid values **[E-6].** The system checks if the position is already defined. It is defined **[E-7].** The system returns to HAM Control Screen.

S-8: Configuration of Rigid Insulation

The system displays the **Rigid Insulation Configuration Screen** with suggestions and entry fields for **MATERIAL NAME and THICKNESS.** The designer enters the preferred valid values **[E-8].** The system checks if the position is already defined. It is already defined **[E-9]**. The system returns to HAM Control Screen.

S-9: Base/Cavity-Closure Layer on Interior

The system displays the **Base/Cavity-Closure Layer on Interior Screen** with the suggestions and options, **PLYWOOD LAYER, DRYWALL and RIGID INSULATION.**

If the Building Envelope Designer selects the **PLYWOOD LAYER** option, the system performs *S-7: Configuration of Plywood Layer* sub flow.

If the Building Envelope Designer selects the **DRYWALL** option, the system performs *S-10: Configuration of Drywall Layer* sub flow.

If the Building Envelope Designer selects the **RIGID INSULATION** option, the system performs *S-8: Configuration of Rigid Insulation* sub flow.

S-10: Configuration of Drywall Layer

The system displays the **Drywall Layer Configuration Screen** with suggestions and entry field for **THICKNESS.** The designer enters the preferred valid values **[E-10].** The system performs *S-4: **Position the layer*** sub flow.

S-11: Configuration of Foamed In-place Insulation

The system displays the **Foamed In-place Insulation Configuration Screen** with suggestions and entry fields for **MATERIAL NAME and THICKNESS.** The designer enters the preferred valid values **[E-11].** The system performs *S-4: **Position the layer*** sub flow. The system checks for a base layer to provide the foamed in-place insulation. The system finds a base layer **[E-12].**

S-12: Configuration of Batt Insulation

The system displays the **Batt Insulation Configuration Screen** with suggestions and entry fields for **MATERIAL NAME and THICKNESS.** The Designer enters the preferred valid values **[E-13].** The system performs *S-4: **Position the layer*** sub flow.

S-13: Selection of Exterior Insulation

The system displays the **Exterior Insulation Screen** with suggestions and options for selection of a wood structure to provide structural stability. The options displayed are **RIGID INSULATION, FOAMED IN PLACE INSULATION, BATT INSULATION, CONTINUE, BACK or QUIT.**

If the Building Envelope Designer selects the **RIGID INSULATION** option, the *S-7: **Configuration of Rigid Insulation*** sub flow is performed.

If the Building Envelope Designer selects the **FOAMED IN PLACE INSULATION** option, the ***S-11: Configuration of Foamed In-place Insulation*** sub flow is performed.

If the Building Envelope Designer selects the **BATT INSULATION** option, the *S-12: **Configuration of Batt Insulation*** sub flow is performed.

If the Building Envelope Designer selects the **CONTINUE** option, the system continues to the ***Control of Heat Flow*** sub flow.

If the Building Envelope Designer selects the **BACK** option, the system returns to the preceding main flow, sub-flow or alternative flow.

If the Building Envelope Designer selects the **QUIT** option, the use case terminates and returns to the Enter Preliminary Information Input use case.

S-14: Selection of Interior Insulation

The system displays the **Interior Insulation Screen** with suggestions and options for selection of a wood structure to provide structural stability. The options displayed are **RIGID INSULATION, FOAMED IN-PLACE INSULATION, BATT INSULATION, CONTINUE, BACK or QUIT.**

If the Building Envelope Designer selects the **RIGID INSULATION** option, the ***S-8: Configuration of Rigid Insulation,*** sub flow is performed.

If the Building Envelope Designer selects the **FOAMED IN PLACE INSULATION** option, the ***S-11: Configuration of Foamed In-Place Insulation*** sub flow is performed.

If the Building Envelope Designer selects the **BATT INSULATION** option, the ***S-12: Configuration of Batt Insulation*** sub flow is performed.

If the Building Envelope Designer selects the **CONTINUE** option, the system continues to the ***Control of Heat Flow*** sub flow.

If the Building Envelope Designer selects the **BACK** option, the system returns to the preceding main flow, sub-flow or alternative flow.

If the Building Envelope Designer selects the **QUIT** option, the use case terminates

S-15: Control of Vapor Diffusion

The system displays the **Control of Vapor Diffusion Screen** with suggestions and options for the selection of a system to provide the vapor diffusion control. The options displayed are **POLYETHYLENE FILM, MOISTURE STORAGE LAYER, VAPOR RESISTANT PAINT, CONTINUE, BACK or QUIT.**

If the Building Envelope Designer selects the **POLYETHYELE FILM** option, the ***S-16: Configuration of Polyethylene Film*** sub flow is performed.

If the Building Envelope Designer selects the **INCREASE MOISTURE STORAGE CAPACITY** option, the ***S-17: Increase Moisture Storage Capacity of the Assembly*** sub flow is performed.

If the Building Envelope Designer selects the **VAPOR RESISTANT PAINT** option, the ***S-18: Configuration of Vapor Resistant Paint*** sub flow is performed.

If the Building Envelope Designer selects the **CONTINUE** option, the system continues to the main flow of ***HAM Control** use case.*

If the Building Envelope Designer selects the **BACK** option, the system returns to the preceding main flow, sub-flow or alternative flow.

If the Building Envelope Designer selects the **QUIT** option, the use case terminates.

S-16: Configuration of Polyethylene Film

The system displays the **Polyethylene Configuration Screen** with suggestions and entry fields for **THICKNESS.** The Designer enters the preferred valid values **[E-14].** The system performs ***S-4: Position the Layer*** sub flow.

S-17: Increase Moisture Storage Capacity of the Assembly

The system displays the **Increase Moisture Storage Capacity of Assembly Screen** with options to **ADD LAYER and CHANGE CONFIGURATION OF A LAYER.** The system displays the already selected assembly and prompts to select an option to change the configuration. The designer enters an option.

If the designer selects the **ADD LAYER** option, the ***S-18: Add a New Layer*** sub flow is performed.

If the designer selects the **CHANGE CONFIGURATION OF A LAYER** option, the ***S-19: Change the Configuration of a Layer*** sub flow is performed.

S-18: Add a New Layer

The system displays the **Add a New Layer Screen** with suggestions and entry fields for **MATERIAL NAME and THICKNESS.** The designer enters the preferred valid values **[E-15].** The system performs ***S-4: Position the layer*** sub flow.

S-19: Change the Configuration of a Layer

The system displays the **Change Configuration of a Layer Screen** with the already selected layers as options to change the configuration, with suggestions. The designer selects an option, and the system displays the entry field for **MATERIAL NAME and THICKNESS** with the already entered values. The designer changes the one/both the values **[E-16].**

S-20: Configuration of Vapor Resistant Paint

The system displays the **Vapor Resistant Paint Configuration Screen** with suggestions and entry fields for **PAINT NAME and COLOR.** The designer enters the preferred valid values **[E-17].** The system performs ***S-4: Position the layer*** sub flow.

S-21: Control of Air Movement

The system displays the **Control of Air Movement Screen** with suggestions and options for selection of systems to provide control of air movement. The options displayed are **TYVEK LAYER, DRY WALL LAYER, CONTINUE, BACK or QUIT.**

If the Building Envelope Designer selects the **TYVEK LAYER** option, the ***S-22: Configuration of Tyvek Layer,*** sub flow is performed.

If the Building Envelope Designer selects the **DRY WALL LAYER** option, the ***S-10: Configuration of Dry Wall Layer,*** sub flow is performed.

If the Building Envelope Designer selects the **CONTINUE** option, the system continues to the main flow of ***HAM Control*** *use case.*

If the Building Envelope Designer selects the **BACK** option, the system performs **BACK** option the system returns to the preceding main flow, sub-flow or alternative flow.

If the Building Envelope Designer selects the **QUIT** option, the use case terminates.

S-22: Configuration of Tyvek Layer

The system displays the **Tyvek Layer Configuration Screen** with suggestions and entry fields for **THICKNESS.** The designer enters the preferred valid values **[E-18].** The system performs the *S-4: **Position the layer*** sub flow.

S-23: Control of Liquid Water Ingress

The system displays the **Control of Liquid Water Ingress Screen** with the suggestions and options for selection of systems. The options displayed are **FACE SEALED CLADDING, RAIN SCREEN CLADDING, CONTINUE, BACK or QUIT.**

If the Building Envelope Designer selects the **FACE SEALED CLADDING** option, the *S-24: Exterior Cladding* sub flow is performed.

If the Building Envelope Designer selects the **RAIN SCREEN CLADDING** option, the *S-29: Rain Screen Cladding* sub flow is performed.

S-24: Exterior Cladding

The system displays the **Exterior Cladding Screen** with options **SIDING, BRICK VENEER, and CONCRETE BLOCK.** The Designer enters an option.

If the designer selects the **SIDING** option, the *S-25: **Configuration of a wood siding*** sub flow is performed.

If the designer selects the **BRICK VENEER** option, the *S-26: **Configuration of a Brick Veneer*** sub flow is performed.

If the designer selects the **CONCRETE BLOCK** option, the *S-27: **Configuration of a Concrete Block*** sub flow is performed.

S-25: Configuration of a Siding

The system displays the **Siding Configuration Screen** with suggestions and entry fields for **MATERIAL NAME and THICKNESS.** The designer enters the preferred valid values **[E-19].** The system requests if the designer wants to add an exterior coating. The designer requests to add a layer of exterior coating **[E-20]**, and the system performs, ***S-26: Configuration of Exterior Coating*** sub flow performs.

S-26: Configuration of Exterior Coating

The system displays the **Exterior Coating Configuration Screen** with suggestions and entry fields for **COATING NAME and COLOR.** The designer enters the preferred valid values **[E-21].** The system returns to the HAM control use case.

S-27: Configuration of a Concrete Block

The system displays the **Siding Configuration Screen** with suggestions and entry fields for **MATERIAL NAME and THICKNESS.** The designer enters the preferred valid values **[E-22].** The system enquires if the designer wants to add an exterior coating. The designer requests to add a layer of exterior coating **[E-23]**, and the system performs, ***S-26: Configuration of Exterior Coating*** sub flow performs.

S-28: Configuration of a Brick Veneer

The system displays the **Siding Configuration Screen** with suggestions and entry fields for **MATERIAL NAME and THICKNESS.** The designer enters the preferred valid values **[E-24].** The system enquires if the designer wants to add an exterior coating. The designer requests to add a layer of exterior coating **[E-25]**, and the system performs, ***S-26: Configuration of Exterior Coating*** sub flow performs.

S-29: Rain Screen Cladding

The system displays the **Rain-Screen Cladding Screen** with suggestions for the selection of systems to provide control of liquid water ingress, by providing two layers of defence. The system checks the assembly for a rain protective cover layer of the inner wall. The system finds a cover layer **[E-26]**.

The system then performs **S-24: Exterior Cladding** *sub flow.*

3.4 *Alternative flows*

E-1: On evaluation, the functions control of heat flow, vapor diffusion and air movement are found not satisfied. The system displays the results and prompts the user to return to assembly build-up or continue with the analysis and evaluation.

E-2: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or opts to return to the **Control of Heat Flow Screen.**

E-3: The system finds a cavity closure layer. The system returns to the **HAM Control Screen.**

E-4: The designer does not request to add a new layer to close the cavity. The sub flow ***S-5: Position the Layer*** is performed.

E-5: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or opts to return to the previous sub-flow or alternative flow.

E-6: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or opts to return to the previous sub-flow or alternative flow.

E-7: The position is not yet defined. The system performs ***S-4: Position the Layer*** sub flow.

E-8: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or opts to return to the previous sub-flow or alternative flow

E-9: The position is not yet defined. The system performs ***S-4: Position the Layer*** sub flow.

E-10: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or opts to return to the previous sub-flow or alternative flow.

E-11: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or opts to return to the **Control of Heat Flow Screen.**

E-12: The system doesn't find a base layer. The system prompts the designer to provide a layer as base to spray foamed in-place insulation. The designer requests to add a layer to close the cavity. The system performs ***S-5: Select a Layer as Base/Cavity Closure*** sub flow.

E-13: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or opts to return to the **Control of Heat Flow Screen.**

E-14: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or opts to return to the **Control of Vapor Diffusion Screen.**

E-15: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or opts to return to the **Control of Vapor Diffusion Screen.**

E-16: Value is not changed. The system saves the old value and returns to the **Control of Vapor Diffusion Screen.**

E-17: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or opts to return to the **Control of Vapor Diffusion Screen.**

E-18: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or opts to return to the **Control of Air Movement Screen.**

E-19: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or opts to return to the **Control of Liquid Water Ingress Screen.**

E-20: The designer doesn't request to add a layer of exterior coating. The system returns to the HAM Control use case.

E-21: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or opts to return to the **Control of Liquid Water Ingress Screen.**

E-22: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or opts to return to the **Control of Liquid Water Ingress Screen.**

E-23: The designer doesn't request to add a layer of exterior coating. The system returns to the HAM Control use case.

E-24: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or opts to return to the **Control of Liquid Water Ingress Screen.**

E-25: The designer doesn't request to add a layer of exterior coating. The system returns to the HAM Control use case.

E-26: The system doesn't find a cover layer. The system displays entry fields for configuration of a system to provide rain protection to the inner wall. The system displays the entry field for **MATERIAL NAME and THICKNESS.**

E-27: Value is not entered or non-valid value is entered. The system prompts the designer to re-enter the value or opts to return to the **Control of Liquid Water Ingress Screen.**

4. *Flow of events for the **Analysis and evaluation** use case*

*4.1 **Preconditions***
The use cases ***Enter Preliminary Information of Project*** and ***Structure Selection*** must be executed before this use case begins.

*4.2 **Main flow***
The use case displays the **Analysis and Evaluation Screen** with access to the analytical models and evaluation of functions as options, **ANALYTICAL MODELS, EVALUATION, COMPLETE ANALYSIS AND EVALUATION, BACK and QUIT.**

If the Building Envelope Designer selects the **ANALYTICAL MODELS** option, the ***S-1: Select Analytical Model*** sub flow is performed.

If the Building Envelope Designer selects the **EVALUATION** option, the ***S-2: Select Evaluation*** sub flow is performed.

If the Building Envelope Designer selects the **COMPLETE** option, **ANALYSIS AND EVALUATION** sub flow is performed.

If the Building Envelope Designer selects the **BACK** option, the system returns to ***HAM Control*** *use case.*

If the Building Envelope Designer selects the **QUIT** option, the use case terminates and returns to the ***Enter Performance Specification Entry Screen.***

4.3 Sub flows

S-1: Select Analytical Model
The system displays the **Analytical Models Screen** with options for the selection of the analysis that the designer wants to perform. The options are **R-VALUE, VAPOR DIFFUSION, CONDENSATION, CONTINUE, BACK or QUIT.**

The building envelope designer selects any of the options, and the system performs an analysis using the input data entered in the preceding stages and inbuilt material database. The system returns to the ***Analysis and Evaluation Screen.***

S-2: Select Evaluation
The system displays the **Evaluation Screen** with options for selection of the evaluation of function that the designer wants to perform. The options are **STRUCTURAL STABILITY, CONTROL OF HEAT, CONTROL OF VAPOR, CONTROL OF AIR and CONTROL OF LIQUID WATER PENETRATION, CONTINUE, BACK or QUIT.**

The building envelope designer selects any of the options, and the system performs an analysis using the input data entered in the preceding stages and inbuilt material database, and correlates the knowledge base to trigger evaluation. The system returns to the ***Analysis and Evaluation Screen.***

S-3: Select Complete Analysis and Evaluation
The system checks heat flow, vapor diffusion and condensation, along with the evaluation of the performance by comparing with the designer's custom and designer's specification. The system conducts a comprehensive evaluation of the assembly for all the functions. The system displays the **Complete Analysis and Evaluation Screen** with the results.