

Automatic Code Compliance Checking in Designing Building Envelopes

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Abstract

Automatic Code Compliance Checking in Designing Building Envelopes

Xiangyang Tan

Automating the checking of building envelope design according to design regulations is a complex process because design regulations consist of complicated logic statements covering multiple functions. Existing mechanisms of building code computer-aided checking have some limitations dealing with design regulations. This thesis presents a new approach to automate code compliance checking for building envelope design based on simulation results and the building codes. In this approach, building codes and building performance simulation results are independent from the compliance checking software.

During the process, a hierarchical object-based representation of simulation results called EBIM (Extended Building Information Model) is proposed to describe the attributes of a building and its sub-systems. A new representation of building codes based on decision tables called EBC (Extended Building Codes) is also proposed so that users can check the building envelope design against building codes based on the standardized simulation results. A rules engine is applied for matching the data of the EBIM against the rules derived from the EBC.

This new approach integrates building information modeling, simulation applications, building codes, and decision tables together for automated code compliance checking in designing building envelopes. A prototype implementation system is developed based on the proposed approach. The case study gives two examples: the first one is the procedure

of evaluating the hygrothermal performance of an exterior wall of a house using this system, and the second one is an energy analysis comparison when an energy-efficient wall system is installed in a small building as a replacement.

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List of Acronyms

ACCBEP	Automated Code Checker of Building Envelope Performance
ACH	Air Changes per Hour
ADL	Agent Description Language
ADT	Autodesk Architectural Desktop
AEC	Architecture, Engineering and Construction
API	Application Programming Interface
BEPAT	Building Envelope Performance Assessment Tool
BIM	Building Information Modeling
BCA	Building Construction Authorities
BEPAC	Building Environmental Performance Assessment Criteria
BOCA	Building Officials and Code Administrators
BREEAM	Building Research Establishment Environmental Assessment Method
CAD	Computer-Aided Design
CASBEE	Comprehensive Assessment System for Building Environmental Efficiency
CORENET	Construction and Real Estate Network
CSV	Comma-Separated Values
EBC	Extended Building Codes
EBIM	Extended Building Information Model
EIFS	Exterior Insulation Finishing System
EJB	Enterprise Java Beans
ER	Energy Rating
ETAG	European Technical Approval Guideline
GBTool	Green Building Tool
GDL	Geometric Description Language

GUI	Graphical User Interface
HAM	Heat, Air, and Moisture
HQAL	Japanese Housing Quality Assurance Law
IAI	International Alliance for Interoperability
ICC	International Code Council
IFC	Industry Foundation Classes
IfcXML	Industry Foundation Classes in eXtensible Markup Language
IT	Information Technology
J2EE	Java 2 Platform, Enterprise Edition
jBPM	java Business Process Management
JDBC	Java Database Connectivity
JDOM	Java Document Object Model
JESS	Java Expert System Shell
LEED	Leadership in Energy and Environmental Design
MNECB	Model National Energy Code of Canada for Buildings
MNECH	Model National Energy Code of Canada for Houses
NBCC	National Building Code of Canada
NRCC	National Research Council Canada
ODBC	Open Database Connectivity
Rete OO	Rete algorithm for Object Oriented systems
SHGC	Solar Heating Gain Coefficient
SML	Standards Modeling Language
SPF	Standard Processing Framework
SPF-CL	SPF Communication Language
SRI	Sound Reduction Index
SUL	Standards Usage Language
W3C	World Wide Web Consortium
XML	eXtensible Markup Language

Chapter 1 Introduction

1.1 Problem statement

Sufficient examples exist illustrating the possibility that in the life span of a building some or all of the components of the building envelope may need to be replaced (Hassanain and Harkness 1998). One of the invariable “targets” in building envelope failure litigation is design professionals (Brindle 2007). Architects and engineers have to pay more attention to building envelope design from the preliminary stage.

Figure 1.1 is a photo taken in an apartment which is located in Urumqi, Xinjiang, China. This is a typical example that a minor mistake in designing the building envelope leads to a failure. A bay window is installed on the protruded wall for the architectural aesthetics. As shown in Figure 1.2, the architect forgot to add the insulation layer on the protruding sections of the wall encasing the window to protect against heat loss. The temperature of the interior surface along the window frame is lower than the dew-point, even lower than zero Celsius degree in cold winters. Therefore, ice builds up on the wall in the winter. In the spring, ice melts and water is absorbed in the porous construction material. Mold grows when the weather becomes warmer and then the wall is damaged. The cost to correct the problem would be high since it would require adding a new insulation layer to the 6-storey building which is already built. The situation worsens since the same design drawings were used in building three other residential buildings. All of them have the same problems.

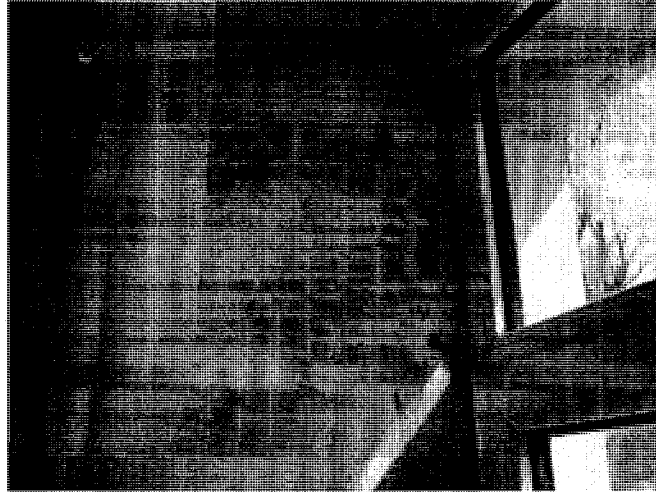


Figure 1.1: Mold growths on the wall¹

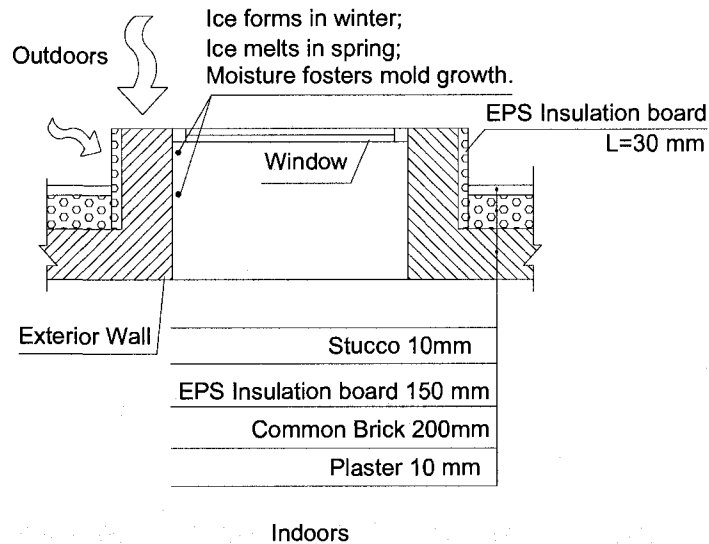


Figure 1.2: Diagram showing mistake in the design of an exterior wall²

Building code compliance checking of building envelope designs is one approach to reduce such design mistakes. A building code is a collection of regulations based on acceptable requirements that determine the design, construction, and materials used in buildings to ensure that buildings are structurally sound, safe from fire, free of health

¹ This photo was taken by the author in his apartment, Urumqi, Xinjiang, China

² The diagram was drawn by the author based on the design failure investigation.

hazards, and accessible (NBCC 2005). A conscientious design based on the building code can avoid the potential design fault. A conventional building code checking process in designing a house includes a series of actions. A cyclic period of checking a design needs many steps and efforts between the participants of the design team. A code compliance checking process takes time and efforts because of the complexity of building codes and gathering information from building components. An automated code compliance checking method to aid the design is considered a faster, error-prone, and more efficient solution than conventional code compliance checking procedure.

Building simulation is applied to calculate building characteristics such as energy, lighting, hygrothermal performance, and acoustics. It provides a cost-efficient and time-efficient way to evaluate the various performances of building subsystems according to design regulations. Based on building simulation tools, the conventional way for checking code compliance is analyzing the simulation results, searching references, and matching results against building codes by designers manually. Manual code checking increases the possibility of making mistakes during the procedure of code checking. Additionally, designers need a long-term trained skill to apply building simulation analysis into design practice. Therefore, automated code checking of the design based on simulation results becomes an ideal approach to avoid the time-consuming code checking process and potential mistakes. Several problems exist during the process from building simulation to checking compliance based on building codes. However, limitations are also found in the current automated design standards processing:

- Building simulation results are not integrated into the process of code compliance checking;

- Building codes, especially the energy code, is expected to update often as the concept of sustainable and green buildings is becoming a major concern. For example, after first published in 1983, the Model Energy Code (MEC) was edited in 1986, 1989, 1992, 1993, and 1995 (U.S Department of Energy 1999). As a successor of MEC, International Energy Conversation Code (IECC) was edited in 1998, 2000, 2003 and 2006 (DOE 2007).
- Regulations are different in different regions and code checking software for each region needs to be modified although the core algorithm does not change;
- Design regulations consist of complicated logical statements and conventional programming if-then-else logic statements are unable to describe design regulations efficiently; and
- Poor communication between building engineers and code checking software developers may result in low quality and low efficiency of the software code.

1.2 Objectives

The primary objective of this thesis is to explore a method for automated building code compliance checking for building envelope design. This objective is addressed from the perspectives of: (1) a standardized data model for code checking, (2) an applicable method for code compliance checking to a wide range in building engineering field, particularly in building envelope design, and (3) efficiency and ease of using the method.

Accordingly, the specific objectives are:

- Enhancing a building information model to improve building envelope design and creating a method to represent building codes explicitly;
- Establishing a framework of automated code compliance checking which separates software code and logical statements of building codes; and
- Developing prototype implementation software to assist architects and engineers in designing building envelopes.

1.3 Scope

The aim of this thesis is to propose an approach for automatic code compliance checking in building engineering and develop a computer tool based on the proposed approach. The framework of the proposed approach can be employed in checking building design, while focusing on the building envelope hygrothermal performance against design regulations and building codes.

A building envelope design process involves the knowledge in several domains including building physics, architecture, structures, mechanical engineering, building material properties, product manufacture, fire safety, maintenance and constructability. A building envelope design influences a building's quality during its life-cycle. Designers have to intentionally choose the proper materials or products among the numerous modern or traditional building materials or products depending on their functions and attributes. Meanwhile, the building envelope design should meet the relevant health, safety, and environmental requirements based on the building codes. Thus, developing a user-friendly computer tool for automated code compliance checking for building envelope

design is useful in carrying out the comprehensive procedure. To process the described procedure in automated building envelope design using the computer tool, the proposed approach should have independent modules with different functions. These modules include a building information model with simulation data, representation of building codes, and a rules engine for matching design facts and rules. Based on the proposed approach, the computer tool is developed including separated modules for designing building envelope assembly, visualizing building components, computing building envelope performance with simulation software, representing logics of building codes, and code compliance checking.

1.4 Contents

The structure of the thesis is as following contents:

Chapter 1 (*Introduction*) states the problems, complexities, and difficulties associated with the process of designing building envelopes, including code compliance checking and computer-aided design checking based on the codes and standards. Here, problems refer to shortcomings of manual code compliance checking; complexities refer to the complicated logics of rules and designing building envelopes; difficulties including integration of building information data and simulation, and separation of rules and programming code. Chapter 1 also outlines the research scope and defines the objectives.

Chapter 2 (*Literature Review*) reviews the current researches in automated code checking that include Singapore's Integrated Building Plan and Service (IBP/IBS) code checking system, Smart Codes project by ICC (International Code Council) and Model Checker by Solibri Inc. of Finland, online building code checking system developed at Stanford

University, U.S.A., Standard Processing Framework research at Carnegie Mellon University, U.S.A., and building envelope research at Concordia University, Canada. The second part of Chapter 2 briefly introduces the hygrothermal performances of building envelopes, the design effects on these performances, and the hygrothermal simulation for evaluating building envelopes. The third part of Chapter 2 introduces the building codes and regulations about building envelopes, which include the hygrothermal analysis for building envelopes in the *ASHRAE* handbook *Environmental Separation*- Part 5 of the *National Building Code of Canada* and its guide, *Building envelope* - Part 3 of *Model National Energy Code of Canada*, ASTM standard - *Guide for Limiting Water-Induced Damage to Buildings*, and Other evaluation standards and protocol for the evaluation of building envelopes. The common features of the building codes are summarized at the end of Chapter 2.

Chapter 3 (*Automatic Code Compliance Checking of Building Envelope Design*) systematically introduces a general framework of automated code compliance checking. In this framework, three major concepts are discussed including Extended Building Information Model (design facts), Extended Building Codes (rules package), and rules engine. Chapter 3 also describes the development of a prototype software implementation named ACCBEP applying the proposed approach, which has five modules: data integration module, building and component visualization module, building envelope performance computation module, Extended Building Codes (decision tables), and code compliance checking module.

Chapter 4 (*Case Study*) presents two case studies using the implementation application based on the proposed approach. Case study 1 introduces the procedure of the automatic

checking of an exterior wall system in a residential house using the proposed method and implemented application. Case study 2 presents an example in replacing an exterior wall system of a small building to compare the heating loads of different insulation walls.

Chapter 5 (*Conclusions and Future Work*) states the advantages and limitations of the proposed approach. Future work is also proposed.

Chapter 2 Literature Review

2.1 Introduction

2.1.1 Overview

Automated code compliance checking in architecture, engineering, and construction is considered a challenging task because multidisciplinary knowledge needs to be integrated to achieve the goal. Particularly, multidisciplinary knowledge is involved in designing building envelopes. Before developing a new system for automated code compliance checking for building envelope design, the following questions should be considered. What has been studied in automated code compliance checking recently? What are the developed systems' advantages and limitations? Why a new approach should be developed? How does a new system enhance the functions and avoid the limitations? When considering the automatic code compliance checking of a building envelope design, what performances have to be investigated for a proper design of building envelopes? What reference standards can be found and established for evaluating a building envelope design? After three parts of Chapter 2 are presented including current research in automated building code checking, building envelope performances, and the concerned building codes and regulations about building envelopes, the author attempts to find the answers through reviewing and synthesizing the existing research works and references.

2.2 Concepts about automated building code checking

The basic terms and concepts related to the automated building code compliance checking are defined and introduced in this section before reviewing literatures and proposing a new approach described in Chapter 2 and these essential concepts are integrated into the proposed approach described in Chapter 3.

2.2.1 Building Information Model (BIM) and Industrial Foundation

Classes (IFC)

Building Information Modeling (BIM) is a data model which describes a building and its sub-systems. The building lifecycle including the processes of construction and facility operation can be demonstrated using BIM.

The architectural CAD software allows architectural designers to draw 3D objects such as walls, doors and windows, integrating more architectural information data than simple geometry data. Architects and engineers design a building using CAD software such as ArchiCAD and ADT (Autodesk Architectural Desktop). ArchiCAD is an architectural CAD-software developed by the Hungarian company Graphisoft (2006). ADT is an architectural extension on the basis of AutoCAD developed by Autodesk Inc. Both ArchiCAD and ADT support the hierarchical Building Information Modeling (BIM). GDL (Geometric Description Language) (Graphisoft 2006) and IFC (Industry Foundation Classes) (IAI 2006) are common-use representatives of BIM (Fu et al. 2006). 2D, 3D geometry information and integrated building component specifications are containing in the GDL. IFC is a standard building data model developed by International Alliance for

Interoperability. IfcXML is a standard format to represent IFC building data model using XML schema specifications (IAI 2006).

A hierarchical BIM is a tree-like structure which describes a building and its sub-systems. GDL (Geometric Description Language) (Graphisoft 2006) and IFC (Industry Foundation Classes) (IAI 2006) are common-use representatives of BIM (Fu et al. 2006). BIM is a data source in and automated building code compliance checking system for obtaining building information.

IFC (Industrial Foundation Classes) is a data model developed by the IAI (International Alliance for Interoperability) to facilitate interoperability in the building industry. Traditional 2D and 3D modeling in CAD represent a building data using geometric entities such as points, lines, rectangles, planes. However, the traditional CAD data model does not represent building information for design, analysis, construction management, operation, and so on. IFC model is developed to exchange model-based data between model-based applications in the building industry, and it is now supported by many major CAD vendors such as ArchiCAD (Graphisoft 2006) and Autodesk Architecture (Autodesk Inc. 2007) as well as by many analysis applications such as the cost estimation software Timberline (Sage Software 2007).

The most important feature of IFC is its object-oriented approach. The IAI has specified the ‘things’ that could occur in a constructed facilities including physical objects such as doors, walls, fans, etc. and abstract objects such as space, organization, processes, etc. These specifications represent a data structure supporting an electronic project model useful in sharing data across applications. They are called classes which describe a range of components that have common characteristics. For instance, every door has a

characteristic of opening to allow entry to a space; every window has the characteristic of transparency so that it can be seen through. Door and Window are names of classes. These classes defined by the IAI are termed Industry Foundation Classes. As in computer science, when the concept of a class is applied, each instance of the class is called an object (IAI International 2006).

The information in IFC includes contents of different building domains, such as architectural domain, plumbing fire protection domain, structural elements domain, HVAC domain, electrical domain, construction management domain, facility management domain and other domains. Building envelopes' information is a portion of architectural domain. The information of IFC is expressed in a hierarchical format to represent a building component. IFC has become a world-wide recognized standard for exchanging, processing and representing building information data. IFC is selected as the data source of the BIM in our research.

2.2.2 XML and ifcXML

XML (eXtensible Markup Language) is a markup language for documents containing structured information. XML provides a text-based means to describe and apply a hierarchical structure to information. The XML specification defines a standard way to add markup to documents. XML is a simple and flexible text format language originally designed for publishing a large-scale electronic document. At its base level, all information manifests as text, interspersed with markup that indicates the information's separation into a hierarchy of character data, container-like elements, and attributes of those elements. Some features of XML that make it well-suited for data transfer are: (1)

simultaneously human- and machine-readable format; (2) the self-documenting format that describes structure and field names as well as specific values; (3) the strict syntax and parsing requirements that allows the necessary parsing algorithms to remain simple, efficient, and consistent; and (4) platform-independence (Refsnes Data 2006). Currently XML is becoming increasingly important in the exchange of a wide variety of data on the Web and elsewhere (Quin 2007). XML represents the data model of BIM and building codes described in Chapter 3 of this thesis.

IfcXML is a standard format to represent IFC building data model using XML schema specifications. The content of an ifcXML file follows the XML standard. The ifcXML2 methodology has now approved for the XML schema definitions for IFC2X edition 2. The first XML schema, ifcXML for IFC2x2 was published in January, 2004, in Paris. (IAI international 2006). IfcXML is used for the data source of BIM described in Chapter 3 of this thesis.

2.2.3 Building code, decision table and rules engine

Building code

A building code is a set of rules that specify the minimum acceptable level of safety for constructed objects such as buildings. The building code becomes law of a particular jurisdiction when formally enacted by the appropriate authority (ABCB 2006). The features of building codes are discussed in Section 2.5.6 in details.

Decision table

A decision table is a list of decisions and criteria and it is designed as a matrix (Parnas 1992). The decision table is a compact way to represent complex logic problems. The format of the decision table is also quickly readable and editable by users especially for people without programming background.

Rules engine

A rules engine is a software system that helps manage and automate processing rules (Proctor et al. 2005). The most rules engines were developed for business applications in the beginning. The rules for a rules engine can be business rules, public policy, environmental regulation, stock market rules, etc. Many rules engines are developed for different purposes by many organizations, i.e., JBoss Rules (Proctor et al. 2005), Workflow Magic (Sardi 2007), OpenRules(2007), OpenLexicon (2007) and many others are the non-commercial open source rules engines. JESS (Sandia National Laboratories 2007) and Microsoft Business Rules Engine (Microsoft Corp. 2007) are two famous representatives among the numerous commercial rules engines and expert systems. Proctor et al. (2005) states that JBoss jBPM (java Business Process Management) applies expressions and delegates in its decision nodes, which control the transitions in a workflow. At each node JBoss jBPM evaluates a rule set that dictates the transition to undertake, this is also a rules engine. A production rule system is a kind of rules engine and also an expert system. The brain of a production rules system is an inference engine that is able to scale to a large number of rules and facts. The inference engine matches facts and data, against production rules, also called productions or just rules, to infer

conclusions which result in actions. JBoss Rules is selected as the rules engine in the author's research.

2.3 Research in automated building code checking

Continuous research efforts have been made to improve automated code compliance checking. Examples include knowledge-based approach to design checking for conformance with standards (Elam 1988), and an E-rulemaking compliance assistance tool by representing logic sentences and control elements using XML (eXtensible Markup Language) structure (Lau et al. 2004). Standards Usage Language (SUL) is proposed for linking design systems and standards processors (Kiliccote and Garrett 2001). An Integrated Building Plan and Service (IBP/IBS) checking system established an object-based modeling approach for representing building designs and building codes (Yang and Xu 2004, Khemlani 2006). In addition to the previous research efforts, some practical automated code checking systems have been developed. For example, Solibri Inc. developed the Model Checker System to check IFC product models (Solibri Inc. 2007). Singapore government implemented CORENET system servicing for online integrated plan checking since 1995 (BCA 2006 and Khemlani 2005).

However, most of these works focus on a specific domain, such as fire safety, accessibility, architectural space and planning. Research of code compliance checking of the building envelope is less developed than the research in the previous domains. The possible reason is that the number of alternatives and performance attributes to be considered in building envelope design is very large (Fazio et al. 1989). Moreover, the standard criteria are hidden within the software and the building codes are combined with

the code checking systems. If building code changes, the software code needs to be re-programmed, compiled and tested again.

In recent years, the research group at Concordia University has proposed several approaches to tackle the above issues, such as a protocol and assessment tool based on Microsoft Excel for performance evaluation of light-frame building envelopes (Hovart 2005), application of IT and international standards to evaluate building envelope performance (He et al. 2005), an IFC (Industry Foundation Classes)-based framework for evaluating the overall performance of building envelopes (Fazio, He, Hammad and Horvat 2006) and automated code compliance checking of building envelope performance (Tan et al. 2007).

2.3.1 Singapore's Integrated Building Plan and Service (IBP/IBS) code checking system

Singapore's Ministry of National Development launched a major IT (Information Technology) project in 1995 by "re-engineering the business processes with state-of-the-art IT to achieve a quantum leap in turnaround time, productivity and quality" (Khemlani 2005). Singapore government developed an Integrated Building Plan and Service (IBP/IBS) code checking system to deliver a single plan-checking tool to check building plans submitted by Architects, and Mechanical and Electrical (M&E) Engineers for compliance of the various authorities' regulations (BCA 2006).

This project is named CORENET (Construction and Real Estate Network) e-Plan check system. The e-Plan check system is an expert application built on a client-server architecture that essentially allows architects and building service engineers to check

their design for regulatory compliance through an Internet gateway. Regulatory officers are also able to conduct audit checks on submission made by the building professionals through the same system (Cheng 2004).

The distributed code-checking prototype uses a J2EE (Java 2 Platform, Enterprise Edition) -based multi-tier architecture. Figure 2.1 is an architecture diagram of the prototype system. As shown in Figure 2.1, the system is implemented on the J2EE platform for delivery of online code-checking services.

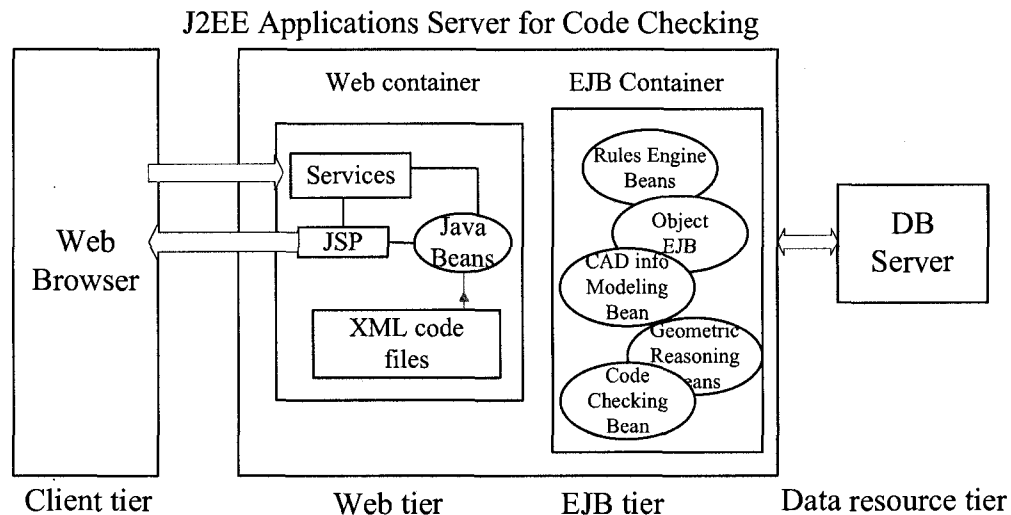


Figure 2.1: J2EE-based system architecture (Yang and Xu 2004)

This e-Plan checking system is composed of four tiers: (1) Client tier - Client users send their request and review checking results through web browsers; (2) Web tier - the Web tier delivers Web content to client; (3) EJB (Enterprise Java Beans) tier - this tier implements all application logic for building design support services including establishing checking rules based on the rule domain model, retrieving or reasoning design objects in the design domain model, applying checking rules to the design objects,

and reporting checking results; and (4) Data resources tier - It includes a database server used for the connection between the EJB tier and the database server.

This e-Plan Check system undertakes three major concepts:

- Object-based representation model for building code knowledge;
- IFC object model for representation of building design information; and
- An automated compliance-checking system application with Web-enabled, multi-tier-distributed, portable and scaleable features.

The limitations of the IBP/IBS checking system include:

- This e-Plan check system focuses only on architectural space especially fire safety code and structural safety. The design of building envelopes are not mentioned;
- It has no open standards for representation of the design regulations and building codes; and
- The rules of design standards are embedded into the code checking system. The users cannot edit the rules by themselves.

2.3.2 Smart Codes by ICC and Model Checker by Solibri Inc., Finland

The International Code Council (ICC) and Solibri Inc, Finland, collaboratively demonstrated *Smart Codes* project and the Model Checker System, which is the latest technique in code checking system in Washington, D.C., in November 2006 (ICC 2007).

Solibri Inc. was established in 1999 in Helsinki, Finland. Solibri Inc. (2007) team developed a system named Model Checker that is claimed as a “world leader in design spell checker”. It is used to review the Building Information Modeling (BIM) delivery and design coordination. It helps the user to extract information from the BIM to applications such as quantity and cost calculations.

Figure 2.2 shows an example of parameterized rule in the Model Checker system that beam dimensions must be within the allowable bounds. The nonconformity building components are marked red. ICC launches a project for intelligently processing building code called *Smart Codes* project. Smart codes describe codes, rules and regulations in IFC format so they can be applied to model checking system to identify the conflicts between the BIM and the codes, rules and regulations (Conover 2007).

Combining the Model Checker System and the *Smart Codes*, the building plan as represented by a BIM can be checked automatically, and the checking results can be output. An inspection checklist can be shown and the user can observe the study components of the building in 3D viewpoint developed based on Java 3D technique.

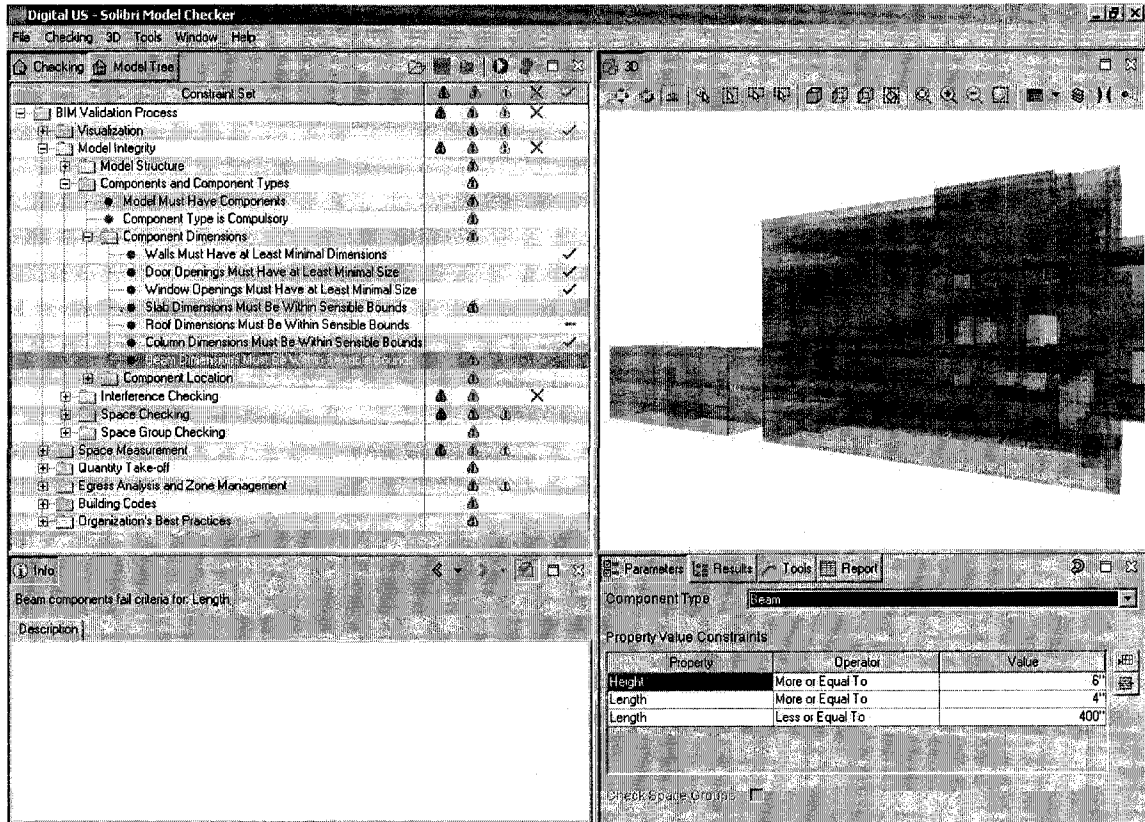


Figure 2.2: Parameterized rules: snapshot of Model Checker System³

The limitations of the Model Checker system include:

- The Model Checker system emphasizes “building model spellchecking” that means the checking process is a single if-then mode. For example, the Model Checker checks whether one parameter of the BIM is greater or less than a given value. Therefore, the complex logic of design regulations cannot be represented explicitly;
- The Smart Codes and Model Checker System are commercial projects and their technical details are not published because of the protection of patents.

³ Source from http://www.solibri.fi/images/stories/screenshots/big_jpg/parameterized_rules.jpg

- The rules of building codes has no open-standard and. The users cannot edit the rules by themselves.
- Simulation results are not facilitated within the Model Checker system.

2.3.3 Online building code checking system developed at Stanford University

A research group at Stanford University focuses on information management, and internet-based technologies to facilitate engineering analysis and design processes, and to coordinate concurrent engineering activities. For example, Han et al. (1998 and 1999) proposed an integrated client/server framework for an automated code-checking system; (Lau et al. 2004) proposed E-Government information architecture for regulation analysis and compliance assistance; and Lau and Law (2005) did a prototype study on Electronic-Rulemaking.

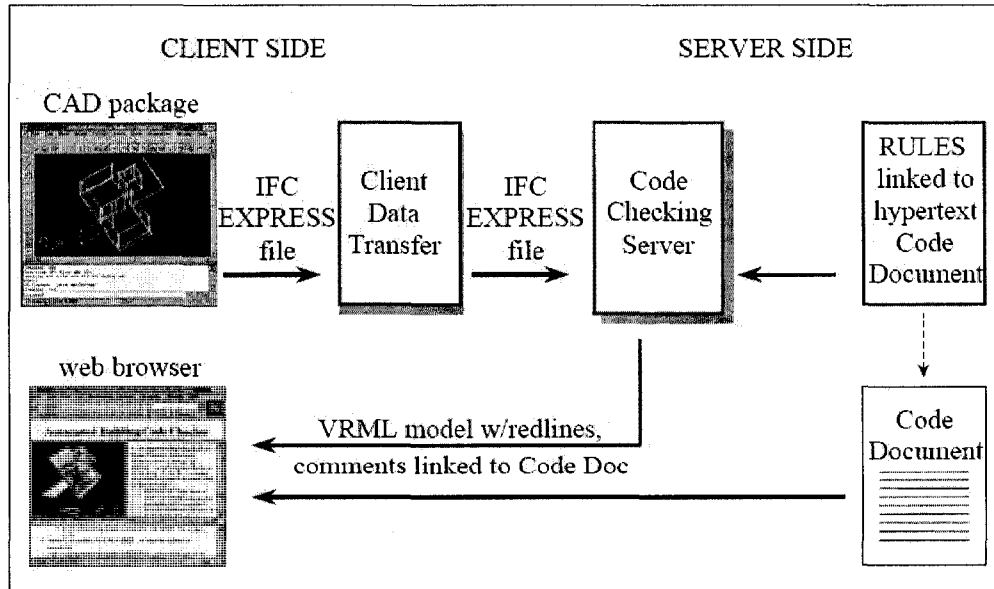


Figure 2.3: Mechanics of the prototype code-checking program (Han et al.1998)

Figure 2.3 shows the code-checking program residing on the server side of the system. The user (the client) sends an IFC model through the web or local network to the code-checking program. Once all the IFC building models containing a data structure with the relevant building components information have been received, the code-checking program can start analyzing the building model. The building code uses the same structure as the IFC project model hierarchy. Therefore, an individual component can be checked against all the applicable instances of the provisions for that class of building component.

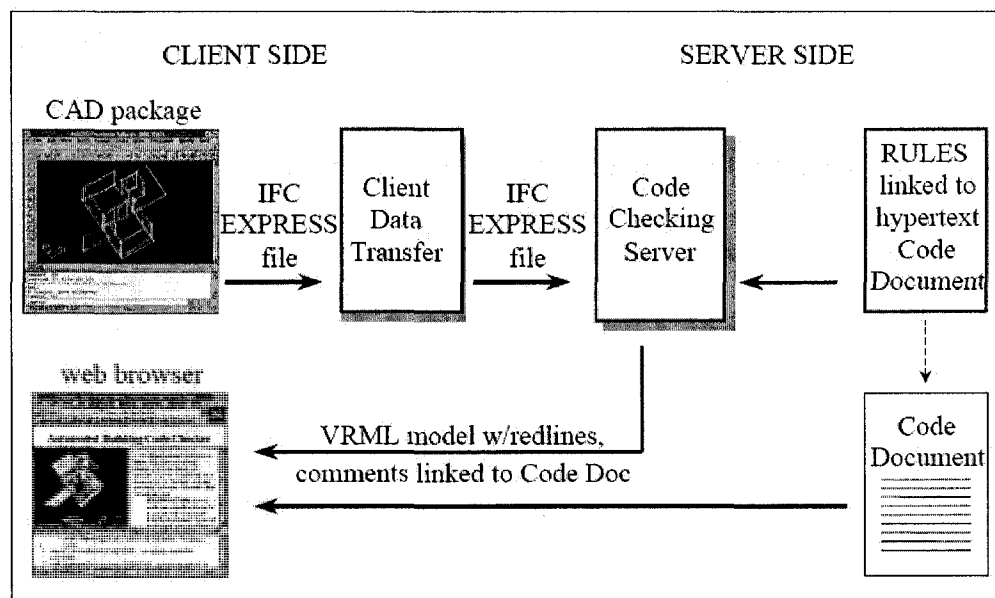


Figure 2.3: Mechanics of the prototype code-checking program (Han et al.1998)

Han et al. (1998) outlined the steps needed to solve a specific code-checking problem. Based on the approach, Han et al. (1998 and 1999) developed a code checking system for processing the design standards. The online code checking framework solves the design standards processing problem in one domain, handicapped accessibility. The principles

behind the solution gives can be applied into the general usage. However, this framework has limitations:

- The Han's code checking system cannot solve the generalized design standards processing issues because rules in this system cannot represent the complexity of the design standards.
- The model integrated building information and building code will be outdated when the building code changes because the rules are not separated from the checking system.

2.3.4 Standard Processing Framework: research at Carnegie Mellon University

Kiliccote and Garrett (1998 and 2001) at Carnegie Mellon University proposed a framework named Standard Processing Framework (SPF), for modeling, accessing, and evaluating standards with computer aids. SPF Communication Language (SPF-CL) is a common language to express SPF. SPF-CL has four aspects including interaction with other agents, knowledge base of design standards and computable forms, complying rules and compliance, and gateways to local reasoning methods. SPF-CL is composed of three languages:

- Agent Description Language (ADL) which is used to describe knowledge about agents and organizations. For example, ADL can define that an agent that can compute the maximum allowable height of a building, is within the framework application.

- Standards Modeling Language (SML) is used to describe the logical content of a standard to an agent. It defines requirements, including their applicability conditions, and data needs. The SML accommodates indeterminate provisions, exceptions and higher-order provision of the design standards.
- Standards Usage Language (SUL) was invented in order to generate a communication protocol between independent standards and standard processors. Generally, SUL is an application programming interface between design systems and generalized standards processing programs that check the conformance of a design against design standards.

SUL includes: (1) design information, (2) evaluation requests, (3) identifying feasible design space, which includes identifying insufficient data evaluation provision, collection of ranges and non-numerical values, (4) logical content of standards, and (5) details of evaluation, which includes self provision application status, transfer violation provision individual application status, transfer violation provision summary application status and single provision application status.

The major goal of the standards processing research is to completely separate standards processors from the design systems that use them. SUL acts as an abstraction boundary between standards processors and the design systems that use them. However, some limitations of this framework exist:

- The system runs slowly depending on the description in (Kiliccote and Garrett 2001), “the test system using SPF with only partial parts of BOCA93, a building with only few hundred parts took several hours to run on a DEC Alpha.” The

possible reason is that this implementation system did not apply an optimization algorithm in matching against the ADL and the SML.

- BIM, which becomes the international standard, are not applied in this system. The use of SPF is restricted to skilled people. The users must study the new languages that are not easy to understand.
- The SPF has no visual interface and not integrated with graphical 3D and 2D drawing.

2.3.5 Building envelope research at Concordia University

The cost of construction and maintenance of building envelopes occupies a considerable percentage of a building cost during its life cycles. Many researchers focus on this area because of the significant impact on the quality of life within the building. The research group lead by Dr. Paul Fazio at Concordia University focuses on the building envelopes research.

Gowri, Fazio and Seth (1993) developed a computer tool called HASES (Health and Safety Expert System). This computer tool integrates hypertext and knowledge-based system techniques to facilitate code compliance checking and provide access to case studies of problem scenarios. The software architecture of HASES consists of building database, objects database, code requirements and case studies database. This research established a basic architecture for code compliance checking in 1993. Using HASES system, field tester can obtain the feed back from the hypertext database which stores case studies information.

Gu, Bédard, and Zmeureanu (1999) developed a decision support system for compliance checking with the Model National Energy Code of Canada for Buildings (MNECCB). Based on MNECCB, the decision support system is designed to check if the early design of the exterior envelope complies with MNECCB requirements, to provide technical advice on how to improve the design according to the code, and to be a learning tool about the MNECCB. The system contains the code requirements for all building envelope subsystems such as wall, window, roof or exterior door. With improvement of information technologies, more opportunities appear and more advanced computer tools are developed.

BEPAT (Building Envelope Performance Assessment Tool)

Horvat and Fazio (2003) developed a protocol for evaluating the performance of full scale wood-frame building envelopes. The conceptual evaluation and assessment method is formed and outlined through this protocol. This protocol is intended to evaluate building envelopes as integrated systems with emphasis on durability characteristics according to performance-based systems. It lists the quantitative and/or qualitative functional requirements to mark and verify the design against the recommendation requirements. This protocol provides a well-formed knowledge base with quantitative requirements for evaluating the performance of a wall-frame building envelope.

DESIGN PHASE										
FUNCTIONAL REQUIREMENT	OPERATIVE or PERFORMANCE REQUIREMENT	ACTUAL DESIGN VALUES			CRITERIA	SCORE	EVALUATION METHOD(S)	COMMENTS		
Energy performance	Energy rating of windows and sliding glass doors	What is the energy level rating of the windows and sliding glass doors in your design?								
		Windows:	Rating							
		Type I	≥ 2	EL7	EL3	2	Frame 5.1 software			
		Type II	≥ 2	EL7	EL3	2				
		Type III	N/A	N/A	EL3	N/A				
		Type IV	N/A	N/A	EL3	N/A				
		Sliding glass doors	Rating							
		Type I	N/A	N/A	EL3	N/A				
		Type II	N/A	N/A	EL3	N/A				
		Type III	N/A	N/A	EL3	N/A				
	Estimated annual fuel consumption for heating and cooling		Default house from HOT2000, same layout, size and shape as your design	MJ	% difference of default	380 more 26% more 15% more to 15% less 15% -20% less 30% less		2	Calculation by HOT2000: default house for Quebec: heating and DHW by electricity, economised AAC	Comparison with reference house
			Evaluated house, HOT2000	MJ	-44.8					
	Emissions and embodied energy		Default house	Evaluated house	% difference of default			Calculation by EEE software (Contact Dr. Radu Zneureanu)		
			Emissions	N/A	N/A		N/A	If data not available, input N/A		
			Embodied energy	N/A	N/A		N/A			
		What type of structural system is used in your						In cases when innovative des		

Figure 2.4: Screen capture of BEPAT (Horvat 2005)

By comprehensively comparing the certification programs and evaluation tools, Horvat proposed a protocol for overall performance evaluation of light-frame building envelopes. The performance criteria, associated standards, and compliance evaluation methods are included in this protocol. Based on the proposed protocol, Horvat developed an assessment tool, which is named BEPAT (Building Envelope Performance Assessment Tool) as shown in Figure 2.4, using Excel to check building envelope system compliance against performance requirements. The performance evaluation protocol comprehensively integrates different aspects of building envelope performance up to date in Canada, by including the following aspects of evaluation: air tightness, thermal performance, moisture management performance, energy performance, acoustic

performance, and fire response. It establishes the performance requirements and their corresponding criteria for specific conditions of Montreal and it establishes a framework for the development of similar protocols for other regions.

The computer tool based on the protocol introduced the field for further computerization and points to further development opportunities: (1) the manual retrieval of information from design drawings could be done automatically; (2) the system would benefit from the integration of building simulation software for assessing building envelope performance; and (3) Compliance results could be correlated to the original standards automatically. Subsequent research by He, Hammad and Fazio carried out some of these developments.

IFC-based framework for the evaluation of building envelope performances

He, Fazio and Hammad developed an IFC-based framework for the evaluation of building envelope performances (He et al. 2005 and Fazio et al. 2007). The framework extracts geometry and material layer data of a house from CAD drawings in IFC model using IFC toolbox, links to performance evaluation applications, such as HOT2000 and MOIST3.0, and compares evaluation results against a set of criteria. A prototype system is developed including a preprocessor, an application integrator, and a postprocessor using Microsoft Visual Basic. This framework simplified the input and output data of the evaluation applications.

More applications can be integrated into the IFC-based framework when it is used as a basis. For further development of the IFC-based framework, the following questions may be considered to improve efficiency: (1) whether a simulation software can output according to a standardized format so that the programmer does not need to develop

software code for different evaluation software; (2) how to visualize a building information model with the building components so that the user can locate it quickly; (3) how a complex logic of a design regulation can be expressed in a precise way in a standard format so an expert without programming background can edit the rules to represent the design regulation; and (4) how to separate the rules from the evaluation software itself for code checking.

2.3.6 Comparison of the automated code checking systems

By reviewing the automated code checking systems in building engineering developed by the different organizations, there are several common limitations in these automated code checking systems. The building envelope research is less studied since most of the existing code compliance checking systems focus on the structure, architecture, fire-safety, accessibility, etc. Building information data is obtained from a data model like IFC that contains only geometric data, quantity, materials. Therefore, detailed data such as physical and chemical attributes, time factors, and the design details are not included. In addition, the rules that represent the building codes are not separated from the programming codes of some of these standards processing software. The mixture of programming code and rules may reduce the efficiency of software maintenance when the rules change.

Table 2.1 Comparison of automated code checking systems

Organization	Singapore Government	Solibri Inc. and ICC	Stanford University	Carnegie Mellon University	Concordia University
System Name	Integrated Building Plan and Service (IBP/IBS)	Model Checker and Smart Codes	Online Building Code Checking System	Standard Processing Framework:	BEPAT & IFC-based framework
Building info. model	IFC	IFC	IFC	SPF model	Manual input/ IFC
Simulation data	No	No	No	No	Yes
Building code logic statement	JESS	unknown	If-then	SML	If-then
Applied Domain	Spaces focusing on fire safety	Structure	Accessibility	Structure	Building envelopes
Possibility for general use	Yes	Yes	No	Yes	No
Open for editing rules	No	No	Yes	Yes	Yes
Visualization	Yes	Yes	Yes	No	No
Online application	Yes	No	Yes	No	No
Optimized algorithm	Rete algorithm	unknown	No	No	No
GUI	Yes	Yes	Yes	No	Yes
Correlation to original codes	Yes	No	Yes	Yes	No

As shown in Table 2.1, most of these systems select IFC as their building information model since IFC is becoming an international standard. None of them, except the system developed by He (2005), integrates the simulation data, although He's system has no function for automated code checking. Building code logics statements are represented

using different formats in the automated code checking systems. IBP/IBS select JESS (Java Expert System Shell) rules that represent the design regulations. JESS is not open-source software and it is not free for commercial use. JESS uses its own format to represent the rules. The Solibri Model Checker System is a commercial project. Users can only use the end-products of rules and have no right to edit the rules. SPF system uses SML to represent the rules. BEPAT and Stanford online code checking system use if-then-else logic statements to represent the rules that are not optimized for processing complicated rules. The selection of rules representations determines that the IBP/IBP, Model Checker, and SFP can be applied for general purpose. The online code checking system and BEPAT are only applied in handicapped accessibility and building envelopes but not general code checking purpose. Visualization is an important function for presenting the building models. IBP/IBS, Model checker system, and Online building code checking system support visualization. Online application through the Internet or local network for distributed access is developed within the IBP/IBS and online building code checking system that provide a web service for users. The optimization algorithm, Rete algorithm for matching rules against building data applied in JESS, is integrated within the IBP/IBS. Other code checking systems do not apply any optimized algorithm so that the processing time is slower than the IBP/IBS e-plan checking system. The optimization algorithm of the Model checker system is unknown since it is a commercial project. The IBS/IBP e-plan checking system and the online building code checking system have GUI (Graphical User Interface) that can help users easily use the automated code checking systems. SPF has language statements but it has no GUI. BEPAT uses Excel to develop the evaluation system. The IBS/IBP e-plan checking system, the online

code checking system, and SPF have the function that correlates the original design regulations. The users can conveniently look up the original building code. Searching the corresponding references manually requires a lot of time and efforts.

By discussing and comparing the automated code checking systems, a new automated code checking system focusing on building envelopes is proposed. This new system aims to integrate the advantages of the current existing systems and avoid their disadvantages.

2.4 Building envelope performance

Building envelope separates occupants in an interior environment from the exterior environment affected by outdoor conditions including heat, moisture, light, sound and other conditions. The criteria to assess the building envelope performance are functionality, durability and efficiency in protecting against thermal, moisture, solar and acoustic influences while considering the cost constraints. Much of building science is focusing on the thermal and moisture protection (Hutcheon and Handegord 1983). The success or failure of a building in terms of thermal and moisture control can be predictable from the behavior of physical effects and the properties of building materials and assembly.

2.4.1 Heat, air and moisture performance of wall and roof

Coupled heat, moisture and air transfer, which is also called hygrothermal influence, interactively impacts the durability of a building envelope system. Hygrothermal influence on wall/roofing is an essential factor during the life cycle of a building. Building envelope repairs account for a major portion of maintenance expenses of a building, especially in the harsh weather condition in Canada. The hygrothermal

phenomenon, which is effected by cyclic weather change, interior environment, and other factors, strongly impacts on the durability of a building envelop system.

A series of problems can happen due to the coupled heat, air and moisture transfer. For example, problems caused by the moisture may occur within wall and roofing components due to concealed water vapor condensation (Cammalleri and Lyon 2003). The wall and roofing are damaged by the unexpected moisture. Moisture in the insulation assembly significantly degrades thermal resistance of the porous insulation material. Moisture can cause the growth of molds that may harm the occupancies' health. Moisture can be transported through building envelope assemblies because of the air leakage.

The vapor diffusion is driven by the vapor pressure. The vapor pressure can be calculated from the relative humidity and air temperature. The air pressure drives the air leakage.

Overheating and cooling may damage building materials including changing the volume of masonry, wood and steel, causing cracks, or moving the building envelope system. During the process of freeze-thaw, precipitation, and condensation, water could leak into the building envelope potentially causing moisture damage.

The heat, moisture and air performances of walls and roofs described above form a knowledge base from which as set of criteria can be established for checking a building envelope design.

2.4.2 Impact of design on the hygrothermal performance of building envelopes

Improper design, interfacing or selection of building materials and assemblies may result in either inadequate separation of environments or premature deterioration (NBCC Guide

1999). According to a worldwide survey by 92 architects and engineers in practice (Hassanain and Harkness 1998), the first priority in designing a building envelope is placing the vapor barrier on the warm side of the insulation. This survey somewhat proves that the designers of building envelopes lack the integrated knowledge of hygrothermal transfer mechanism in designing a building envelope. In order to correctly design a building envelope, computation based on a hygrothermal numerical model is necessary.

Table 2.2: Typical building envelope defects and respective causes⁴

Category by defects	Possible reasons
Thermal Bridges	Structural elements
	Component connections
	Envelope penetrations
	Corner effects
Insulation System Defects	Discontinuity in insulation system design
	Voids and gaps
	Unsupported insulation
	Compression by fasteners and other elements
	Fibrous insulation exposed to air spaces
	Poor fitting insulation batt
Air Leakage Defects	Discontinuity of air barriers
	Inappropriate use of insulation or insulation adhesives as air barriers
	Punctured or displaced air barriers
	Polyethylene: inadequate support, lack of continuity
	Inappropriate selection of sealant materials
	Sealant failure due to differential movement
	Lack of interior finishing

In a hygrothermal simulation model, usually the initial conditions of pressure differentials, temperatures, moisture contents, relative humidity, and time factors are input values. The fluxes of the heat, air, and moisture are output results. The results may be used to evaluate the moisture tolerance of a building envelope systems subjected to various

⁴ Table 2.2 is based on Persily (1993).

interior and exterior loads. Heat fluxes may be used to determine thermal performance of the building envelope systems under the influence of moisture and airflow. Furthermore, the transient output results may be used for the assessment of the durability and indoor air quality of the building.

Table 2.3: Construction defects sorted by building elements due to poor design⁵

Category by building elements	Defects that often occur
Wall Assemblies	Airflow passages within the envelope
	Poor material selection or attachment
Roofing Systems	Thermal bridges: penetrations, structural elements
	Insulation defects: gaps
	Air leakage: penetrations, structural elements, flutes in corrugated steel decking, incomplete attachment of loose-laid membranes
Component Connections	Thermal bridge, discontinuity, and capillary at floor/wall
	Thermal bridge, discontinuity, and air leakage at window/wall
	Thermal bridge, discontinuity, and penetration at wall/roof
	Thermal bridge, discontinuity at column/wall
	Thermal bridge, discontinuity, and air leakage at wall/wall
Other Assemblies	Thermal bridge and discontinuity at wall/ceiling
	Air leakage, insulation defects and thermal bridging at overhangs
	Air leakage, and thermal bridging at soffits
	Air leakage through stairwells
	Air leakage through the interior partitions like a elevator shaft

Sufficient lessons have been learned from many cases that an improper design may result in serious and costly problems in building envelope systems. The possible defects induced by improper designs (Persily 1993) are summarized and listed in Tables 2.2 and 2.3.

Persily (1993) generalized six essential rules in designing building envelopes to prevent hygrothermal defects.

- (1) Vapor barrier and air barrier should be continuous to enclose the entire building;

⁵ Table 2.3 is based on Persily (1993).

- (2) Vapor barrier and air barrier must be strong enough and continuous to enclose the building against air pressure;
- (3) Vapor barrier and air barrier must be flexible at joints so the air movement may not effect enclosure;
- (4) Insulation layer must be continuous to protect the insulation defects and thermal bridging.
- (5) Copings, parapets, sills and other projections with drips should be designed to shed water from the facade.
- (6) Any water penetrating the facade should be drained backwards to the outside in design stage.

By understanding the impacts of design on the hygrothermal performance of building envelopes and the design principles of building envelopes, it can be realized that a good design of the building envelope must comply with building codes and design standards.

2.4.3 Hygrothermal simulation

To properly assess a building envelope design, the quantitative indicators about the performances of a building envelope become one of the important issues for code checking. Hygrothermal simulation is a feasible method to obtain the quantitative indicators.

To solve the problem of coupled heat, air and moisture through a wall or roof, researchers in building science have established numerical models to predict the hygrothermal

transfer process. Steady-state calculations and transient simulations are two analysis methods that have been validated by experiments and practice. By applying the weather data and material thermal and moisture attributes, the building envelope hygrothermal performance can be computed. The steady state method is also called the dew-point method or Glaser method. Its calculation details are given in the ASHARE (2005) and Appendices A1.1 and A1.2. The transient models are based on numerical simulations using finite difference or finite element techniques (Hagentoft 1992 and Li et al. 2006). Its computation details are given in Appendices A1.3 and A1.4.

To predict the long-term heat, air and moisture (hygrothermal) performance of building envelope systems, the hygrothermal simulation tool is a cost-efficient way. In order to analyze the hygrothermal performance of a building envelope, computer simulation programs have been developed based on the transient numerical models describing the hygrothermal transport through building envelopes, such as MOIST (Burch and Chi 1997), 1D-HAM (Hagentoft and Blomberg 2000), WUFI pro (Schmidt et al. 2005) and MOISTURE-EXPERT (Karagiozis 2001). At Concordia University, an integrated experimental approach is also presented applying a HAM model to the setup and conditions of lab tests (Li et al. 2005 and 2006).

2.4.4 Other performances of building envelopes: structural, aesthetics, fire safety, lighting and acoustic.

To design a proper building envelope system, controlling heat, air and moisture transfer is only a portion of the requirements. A building envelope design must address all of the variable requirements (Persily 1993 and Horvat 2005). The performances include:

- Structural performance is the ability to bear the gravity, wind and other loadings from dead load and live load. The structural part of a building envelope system is usually designed by structural engineers.
- Aesthetics' performance is often represented as an architecture facade to express an architectural style usually designed by architects.
- Fire safety performance is represented as a fire resistance index of building envelopes usually designed by architects. The detailed requirements are described in fire safety code (NFCC 2005).
- Lighting performance is mostly applied in fenestration system of building envelopes. Windows/Curtain wall/glass door admit daylight to reduce electric lights and can absorb heat from daylight. They will increase cooling load in summer and reduce heat load in winter. Solar energy systems can also be integrated with fenestration system to gain a sustainable energy source.
- Acoustic performance: According to the international standard BS EN ISO 140-3 (1995), noise and its control are important aspects of building design. Evaluation of acoustic performance focuses on the transmission of noise between separating wall and floor constructions. Acoustic performance parameters in buildings envelopes are usually represented as Sound Reduction Index (SRI) or equally known as the transmission loss.

These performances mentioned above are not included in the implementation framework that will be described in Chapter 3 since the research scope in this thesis focuses the hygrothermal performance. The other performances are only described in this section.

2.5 Building codes and regulations about building envelopes

Building codes and regulations are an aggregate of a series of requirements, criteria and descriptions in the field of AEC (Architecture, Engineering and Construction). Reading, understanding and implementing building codes need professional knowledge in AEC with considerable training and practice. Ash (1899) defined that a building code is generally considered as the minimum acceptable level of safety for a building in a jurisdiction. In the wide scope of building envelope, interaction of disciplines, which include heat and moisture transfer, fluid dynamic, acoustics, materials, and climate science, leads to building codes that are more complicated. This section will introduce the regulation and design standards about building envelopes in building codes and other design guidelines.

2.5.1 Hygrothermal analysis for building envelopes in ASHRAE handbook

The ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) handbook is a four-volume resource for HVAC&R technology. In Chapter 23, 24, and 25 of ASHARE handbook Fundamentals (ASHRAE 2005), fundamental knowledge and applications of thermal and moisture control in insulated assemblies of a building envelope are described. The theory and mechanics of heat transfer, moisture transfer, air flow and combined HAM (Heat, Air and Moisture) transfer through a building envelope are systematically discussed. Practical methods for installing insulation

and moisture control are also discussed. To design a proper wall/roofing assembly, material, position and thickness of each layer should be considered based on thermal and moisture properties of materials, other properties required by location of materials, space availability, compatibility of materials with adjacent materials, interior and exterior climate and performance expectations. ASHARE (2005) handbook lists several essential issues in designing building envelopes considering hygrothermal impacts. These issues are summarized:

- (1) During winter and fall in cold regions, occasional window condensation is common. Using multiple glazing, low-emittance glazing, low-conductivity spacers, appropriate selection of window frame, or gas-filled glazing can increase the interior surface temperature of the window to reduce the surface condensation.
- (2) Increasing thermal insulation or eliminating voids in the insulation can reduce the probability of condensation of walls and ceilings.
- (3) Eliminating the air leakage can reduce the condensation caused by infiltration of cold air.
- (4) To prevent excessive indoor humidity and most window condensation in cold climates, a ventilation level of 0.35 air changes per hour (ACH) (as recommended in ASHRAE Standard 62) is enough.
- (5) Vapor retarders must be installed and placed on the warm side of the insulation in cold regions.

- (6) Vapor and airflow retarder functions may be combined in one material.
- (7) Penetrations through the airflow/vapor retarder (such as electrical outlets, light fixtures, or plumbing stacks) should be minimized.
- (8) Ventilation is required to reduce the humidity in a crawlspace and attics which is mandated in all U.S. and Canadian model building codes.

2.5.2 Environmental separation- Part 5 of National Building Code of Canada and its guide

The National Building Code of Canada (NBCC 2005) is an objective-based code, also termed as performance-based code in US (Foliente 2000). In part 5, division B of NBCC, requirements of environmental separation are discussed. In the new version NBCC 2005, the definition “minimum requirements” is replaced by “acceptable solutions” to precisely match objective-based function in the building code. All acceptable solutions are linked to achieve one or more of the top-level objectives. For the regulations about building envelopes in part 5, most objectives are related to the safety and health. For better understanding and further technical description in part 5, NRCC (National Research Council Canada) organized expertise to edit a book NBCC User’s Guide. NBCC guides provide users with a more applicable and comprehensive compliance method and ensure that building envelope design and construction meet performance-level requirements (NBCC Guide 1995). Combining NBCC and its user’s guide, performance-based requirements of building envelopes are summarized and categorized:

- (1) Building envelopes shall be designed to resist all kinds of environmental loads primarily moisture.

- (2) Environmental loads including HAM, soil, and wind should be calculated and considered in design procedure. Structural loads including dead loads, precipitation pressure, earth pressure, earthquake effect, live load and load due to thermal or moisture-related should be calculated and considered in design procedure.
- (3) To resist heat loss, minimum thermal resistance of building envelopes shall comply with MNECB (Model National Energy Code of Canada for Buildings). Materials of building envelope should minimize moisture defects caused by condensation.
- (4) Thermal bridge and short-cut air flow passing by loose insulation should be avoided.
- (5) Air barrier system should be installed to prevent infiltration of the air. The air permeability of the material of air barrier should be less than $0.2 \text{ L/s}\cdot\text{m}^2$. Air barrier system should be continuous to enclose the entire building.
- (6) Vapor barrier should be installed to resist water vapor diffusion. Permeance of vapor barrier should be low enough to avoid condensation or moisture accumulation.
- (7) To protect precipitation, shakes or shingle should meet the relevant grade requirements. Junctions and joints should have sealing or drainage. Water accumulation caused by precipitation shall be drainage from building using downspout.

- (8) Building site should be graded so that surface water will not enter building and damage the building materials.
- (9) Foundation and floor drainage should be installed. Moisture protection from ground such as asphalt layer should be designed and installed.
- (10) Sound transmission class of separation of dwelling units should be less than 50 to protect noise.
- (11) Requirements of fire resistance of windows and skylights shall be complied with Fire Safety code.

2.5.3 Building envelope - Part 3 of Model National Energy Code of Canada

The Model National Energy Code of Canada for Houses (MNECH 1997) contains cost-effective minimum requirements for energy efficiency in new housing. The MNECH applies to single family houses of three stories or less, and to additions of more than 10 m². For all other buildings, The Model National Energy Code of Canada for Buildings 1997 (MNECB) must be complied with.

Minimum RSI levels for building envelope components per type of energy (oil, natural gas, electricity, wood, propane) for different regions of Canada are given in the MNECH. These levels were determined using regional construction and heating energy costs in a life-cycle cost analysis. Minimum energy ratings for windows, references energy-efficient equipment standards, and installation of heat recovery ventilator requirements are described in the MNECH. Similar to the MNECH, the MNECB provides maximum thermal transmittance (1/RSI or U) levels for building envelope components per type of

energy for different regions of Canada. In this section, the requirements of building envelope described in Part 3 of MNECH are summarized:

- (1) Insulation of building envelopes must be continuous and meet minimum effective thermal resistance requirement.
- (2) Overall thermal resistance of a building envelope must count the thermal bridge affects of structural members.
- (3) The cross-sectional structural members must be insulated tightly against their outline and the sum of cross-sectional area must be less than 2% of above-ground building envelopes.
- (4) Air barrier system should be installed and building envelopes should be well sealed in order to minimize the air leakage.
- (5) Walls, footings and floors in contact with the ground must be insulated.
- (6) The energy rating or overall thermal transmittance (U-value) of windows / doors must satisfy the minimum requirements.
- (7) Ratio of area of skylight to roof shall not exceed 2% or skylight must use double-glazing or thermal break so that U value of fenestration should not be greater than $3.4 \text{ W/m}^2 \cdot ^\circ\text{C}$. Area of windows must not exceed 20% of floor area.

2.5.4 ASTM standard: Guide for Limiting Water-Induced Damage to Buildings

ASTM (American Society for Testing and Materials) developed technical standards for materials, products, systems, and services. In volume 4, several articles present the methods and guides for testing, constructing, designing and maintaining building envelopes about hygrothermal performance. These articles include:

“E0241-04 Guide for Limiting Water-Induced Damage to Buildings”, “E0283-04 Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen”, “E0330-02 Test Method for Structural Performance of Exterior Windows, Doors, Skylights and Curtain Walls by Uniform Static Air Pressure Difference”, and “E0331-00 Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference”. The first article, “E0241-04 Guide for Limiting Water-Induced Damage to Buildings”, systematically describes the evaluation factors that can result in moisture-induced damage to building components. The latter three articles present test methods for evaluation existing building components. Since our research emphasizes the design stage of building envelopes, the first standard article is emphasized in this section.

In Section 8 of “E0241-04 Guide for Limiting Water-Induced Damage to Buildings” (ASTM 2000), practical recommendations are listed to direct designers, constructors and maintenance workers.

- (1) Surface grading must slope away from the wall. Ground level drainage must be away from ground. Below-grade drainage systems may be required when underground water level.
- (2) Flashings are always required for penetrations through the water-shedding membranes of roofs.
- (3) Building should be sheltered from wind driven rain on the site. Roof overhangs, gutter, and piped roof drainage should be installed to shelter wall from rain.
- (4) Balcony surface should be pitched away the door.
- (5) Joints of wall, windows and exterior mechanicals should be moisture-sealed.
- (6) Indoors RH in winter should not exceed 40%. For human comfort, dew point temperature should not be less than 2°C. Dry bulb temperature should be within the range 19-23°C.
- (7) Ventilation of a room should be at least 0.35 air changes per hour in cold weather.
- (8) Ventilation driving exhaust to outdoors is an effective way to control indoors humidity.
- (9) To prevent air leakage, the tape, caulk, gasket, expanding foam or sprayed foam are installed in / on the conjunctions. Air barrier should be installed on the walls / roofs.

- (10) Vapor retarders should be installed on the exposed earth in crawl space. Vapor retarders should be installed under the concrete slab. Vapor retarders should be installed on the perimeter of foundation walls.
- (11) Capillary breaks should be installed between slabs or concrete foundation walls and framings.
- (12) Continuous vapor retarders should be used in the wall side of building assemblies.
- (13) Flashings and curbs with an adequate height must be designed and they should be integrated roofing and cladding system properly.
- (14) Condensation occurred on windows or door and caused by thermal bridge should be avoided.

2.5.5 Other evaluation standards and protocol for evaluation of building envelopes

Horvat (2005) introduced several existing certification programs and performance assessment tools for residential buildings. These programs and tools include Swedish P-mark system (Anneling 1998), Japanese Housing Quality Assurance Law (HQAL 2007), European Technical Approval Guideline for Timber-frame Building Kits (ETAG 007), EnergyStar (2006) program in United States, LEED (2003) Green Building Rating System in U.S., R-2000 (2001) Program in Canada, DÄMMWERK evaluation software developed by Kern (2007), Building Research Establishment Environmental Assessment Method (BREEAM 1990) in UK, Building Environmental Performance Assessment Criteria (BEPAC 1993), GBTool (Green Building Tool) developed by an international

collaborative team (Cole and Larsson 2002) and Comprehensive Assessment System for Building Environmental Efficiency (CASBEE 2003).

Each of the certification programs or of the performance assessment tools presents an evaluation method for building a sustainable house. The requirements of the building envelope system are extracted from the above references and integrated with scoring and weighting systems. A protocol focusing on building envelopes of a light-frame residential building is developed by Horvat (2005). This protocol, organized on an excel spreadsheet, presents a comprehensive document for assessing the performances of building envelopes.

The design regulations described in Sections 2.5.1 to 2.5.4 and the protocol form a knowledge base for building decision tables that can represent more complex logics of building codes. The decision tables are described in details in Chapter 3 and in Appendix C.

2.5.6 Common features of building codes

Compliance methods of building codes are categorized into several approaches such as the prescriptive path, trade-off path, and performance path (MNECH 1997). In most countries, the performance-based approach is selected as the compliance method of building codes. The regulations embedded in the building codes using other compliance approaches can be converted or remodeled to performance-based approach. A key feature of a performance-based building code is that regulations contain the relevant performance requirements and the corresponding acceptable methods. The quantitative or qualitative provisions in performance-based building codes provide clear information to achieve the deem-to-satisfy goals (ABCB 2006). This feature provides a well-formed base for

representing a regulation in a definitive logic. This logical representation of building code can be transformed into a computer-readable format.

Moreover, multidisciplinary is an essential feature in the part of building envelopes of the building codes. The building envelope system is a separation between interior environment and exterior environment. Conditions from both sides affect the building envelope system. These conditions include heat, air, moisture, wind, solar radiance, snow, rain, hail, ice, chemical and biochemical, fire, surface water, ground water, and self-weight. In most circumstances, Impacts from these conditions interact with each other. Correspondingly, the provisions have to include the multidisciplinary functional requirements to describe how to resist these conditions or loadings to keep a healthy and safe indoor environment. Thus, the computer representation of building codes should be flexible to represent and define multidisciplinary terms.

A hierarchical logical structure is another common feature of building codes. The hierarchy is organized as book, chapter, section, provision, and sub-provision (Kiliccote and Garrett 2001). Like other technical documents, a building code uses a numbering system to represent the hierarchy of logic contents. The data structure of XML can represent the hierarchy. In logical levels, the hierarchy of regulations includes objectives, functional statements, performance requirements and building solutions (ABCB 2006). The feature of hierarchical logic set out a definitive mean for processing data using a computer tool. A data representation of regulations in computer-readable means, such as if-then-else statements, Boolean operator And/Or/Not, the logic rules or decision tables, creates the possibility to represent a building code completely.

2.6 Conclusions

By presenting and comparing the current research in automated code checking systems including Singapore's IBP/IBS checking system, Finland's Model Checker system with Smart Codes projects, Online Building Code Checking System by Stanford University, Standard Processing Framework by Carnegie Melon University, and Concordia University's BEPAT and IFC-based framework, we can see that the existing automated code checking systems have some unsolved problems and limitations, i.e., separation of rules and building information, lack of study of building envelopes, integration with building simulation data, etc.

By reviewing building envelope performance, hygrothermal simulation for building envelopes, and design regulations of building envelope in building codes, it has been possible to understand (i) what functions or characteristics of the building and of its sub-systems should be included into the ACCBEP framework described in Chapter 3; (ii) what rules including the building codes should be developed the decision tables in described in Chapter 3; And (iii) what simulation results can be integrated into the code-checking system.

For assessing the hygrothermal performance of building envelopes correctly, quickly and efficiently, while avoiding the limitations of the existing code checking systems, an integrated computer-aided system for automatic code compliance checking in designing building envelopes is desired.

Chapter 3

Automatic Code Compliance Checking of Building Envelope Design

3.1 Introduction

Based on the review of the literature, a series of questions are followed after finding the limitations of the existing automated code compliance checking systems. Which method is a proper automated solution for assessing a building envelope system according to the building codes? How can the automated system aid architects and engineers to solve the concerned problems quickly? During this process, how to use the existing simulation methods and develop a new implementation system? How to integrate the simulation results with a BIM (Building Information Model) into this system? Can this automated code checking system apply to a general purpose in building engineering? What can be applied to separate the building codes from the automated code checking system?

Therefore, a new approach of automated code compliance checking of building envelope design is proposed to answer the questions and solve the problems. In the proposed approach, simulation results are integrated into the BIM which is obtained from CAD, to form a new data model which can be used to evaluate the performances of building envelopes in a standardized framework. The new data model, named EBIM (Extended

Building Information Model), are matched against the building codes, which are represented using decision tables, named EBC (Extended Building Code). The EBIM and the EBC can be developed independently by the expertise in the different knowledge domains. The rules engine, which is integrated within the proposed code checking system based on a fast algorithm, called Rete algorithm, is applied to process the rules of EBC and the facts of EBIM. Based on the proposed approach, an implementation system named ACCBEP (Automated Code Checker of Building Envelope Performance) is developed. Chapter 3 introduces the proposed approach and the ACCBEP system.

3.2 Proposed approach

3.2.1 Framework of automated code compliance checking

This research proposes a framework which integrates a decision-table-based representation of building codes, building envelope performance simulation, and a BIM for automatic code compliance checking of building envelope design.

As shown in Figure 3.1, the framework of the proposed approach consists of facts, rules packages, rules engine and the assessment report. This approach is integrated within a software framework which includes:

- Hygrothermal performance simulation of building envelope;
- Extended Building Information Model (EBIM) of building simulation output in XML; and
- Automated code compliance checking using decision tables and a rules engine which is independant from design regulations.

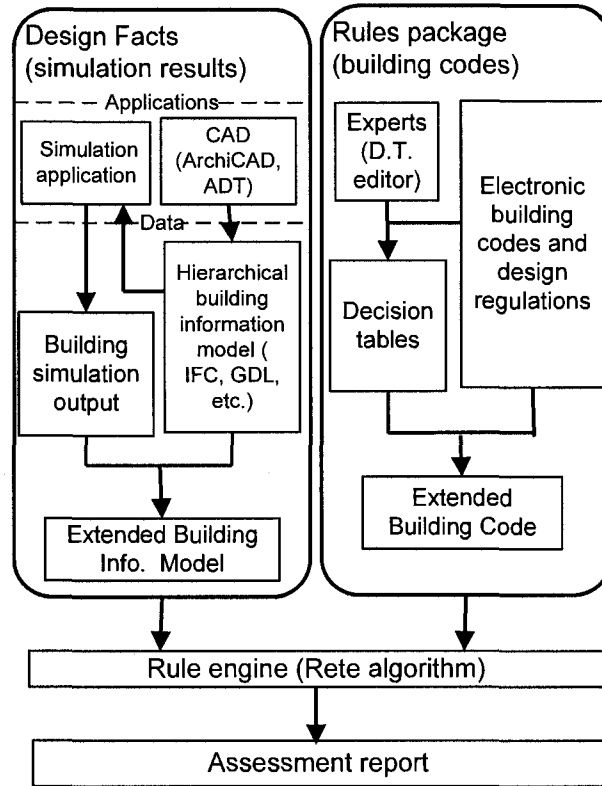


Figure 3.1: Framework of the proposed approach

In this framework, building codes (rules packages) and simulation results (facts) are separated from the programming code. This separation is important because the various parts of this framework can be processed by specialists in different domains. In addition, the core algorithm of programming does not have to be re-compiled when the building codes change.

3.2.2 Extended Building Information Model (design facts)

In a brief conceptual definition, EBIM is a data model that integrates BIM and results from building simulation or other applications. EBIM can be used for retrieving the detailed information for evaluation and analysis of a building system.

Building component properties are included in the BIM after attributes of the building and its sub-systems are defined in CAD-software. For example, in an IFC file, a specific entity `IfcMaterialLayerSetUsage` defines the usage of layer location, and orientation relative to the associated element geometry. `IfcMaterialLayerSet` defines the materials of a constructed element; a number of material layers are known, and the relative positioning of individual layers. `IfcMaterialLayerSet` is cited by `IfcMaterialLayerSetUsage` to define a hierarchical relationship (IAI 2006). As described in the example, these entities in an IFC file altogether represent the geometry of building envelopes, the layers of wall / roofing/ slab, the position, materials, and thickness of the layers and their heritage relationships. Unfortunately, only the basic information such as geometrics and material names are included in the IFC file. Building simulation is applied mostly to calculate energy, lighting, acoustic, and moisture movement. The essential information for analyzing the performances of building envelopes in the preliminary design stage is typically obtained from simulation tools or experiments. For example, the condensation within the wall and surface temperature of the wall cannot be obtained from the IFC model of the wall directly. Performance parameters obtained from simulations can be added into a BIM (IFC) to facilitate evaluation and code compliance checking. Therefore, a standard format that integrates IFC and simulation results for further and advanced analysis is a proper solution.

In order to analyze the hygrothermal performance of a building envelope, some computer simulation applications have been developed based on the transient numerical models describing the hygrothermal transport through building envelopes, such as MOIST (Burch and Chi 1997), 1D-HAM (Hagentoft and Blomberg 2000), WUFI pro (Schmidt et

al. 2005) and MOISTURE-EXPERT (Karagiozis 2001). The thermal performance of building envelopes affects the energy consumption of a building significantly. To analyze energy performance of a house, many applications are developed such as EnergPlus (2006), DOE-2 (2007), EE4, HOT2000 (Buildings Group/NRCan 2005) and other building energy simulation software (Hui 2003).

Most building simulation tools have their own output formats to represent the simulation results such as graphic chart, curves, and result files based on the text format files. Users can analyze the simulation results to evaluate the performance of a building envelope. The analysis of simulation output is a complicated process. Users evaluate the performance of building components according to the peak values, maximum/minimal values, curves trench, data distribution, simulation period, time interval, and many other factors. This analysis process requires the user to be skilled in both building engineering and building simulation software. Meanwhile, the standards for evaluation criteria for decision-making and values for code checking should be based on existing design regulations or previous experience. It is difficult to find critical factors from the complex simulation results manually for evaluation. It is also difficult to integrate the simulation results together with BIM for automatic code checking. Therefore, a standard simulation output file format for automated code checking becomes necessary to easily locate the critical factors for building code compliance checking and integrate BIM and simulation results. This standard of simulation output should be easy to integrate with the BIM, to quickly query, and to precisely describe objects and their attributes. Hereby XML is becoming a proper choice to represent those many attributes from simulation output. Simultaneously, BIM, which is represented as ifcXML, contains the semantic factors.

Non-numerical values can be retrieved from BIM. Even if the BIM does not define these non-numerical values, XML is a flexible language, so that the users can define the corresponding non-numerical values by themselves. The strength features of XML described in Section 2.2.2 provide an ideal approach to store the complex data.

Hence we define a new concept called EBIM (Extended Building Information Model) including building simulation output in XML. EBIM is characterized in terms of building objects and building sub-system objects, inheritance, and simulation data abstraction. As shown in the example in Figure 3.2, the EBIM has a hierarchical structure corresponding to building objects. Simulation results represent the attributes of building objects at the different levels.

EBIM can be used for analyzing building performance and automatic checking of the design according to building codes. EBIM can be used as a standard format to represent building simulation output. It provides a well-formed data model for subsequent analysis and decision-making for the hygrothermal performance assessment of a building. EBIM is an extension of ifcXML (IAI 2006) which has similar hierarchical structure. After defining an EBIM, a building information model with simulated attributes is obtained.

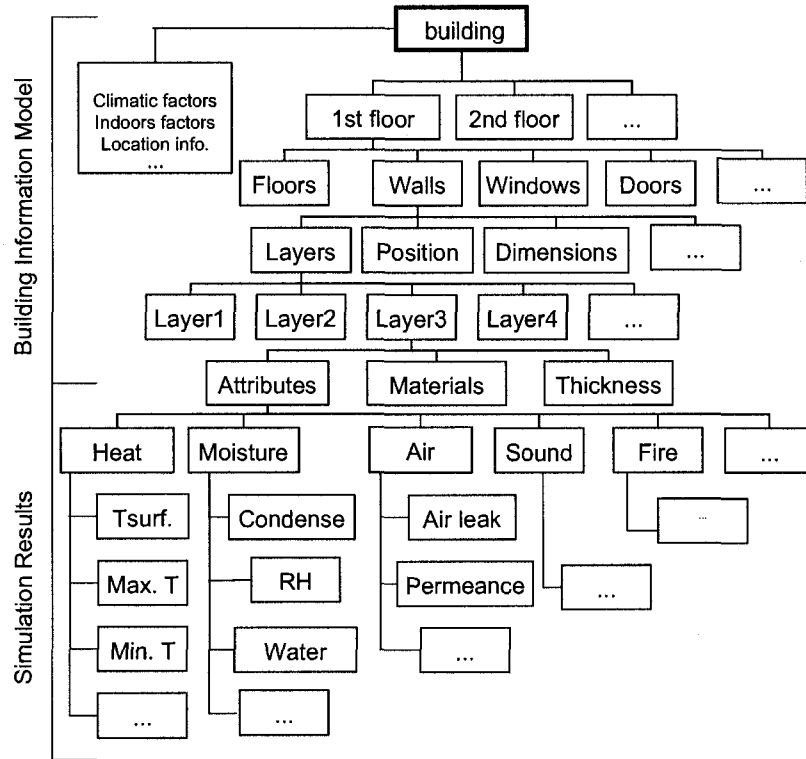


Figure 3.2: Hierarchical structure of EBIM

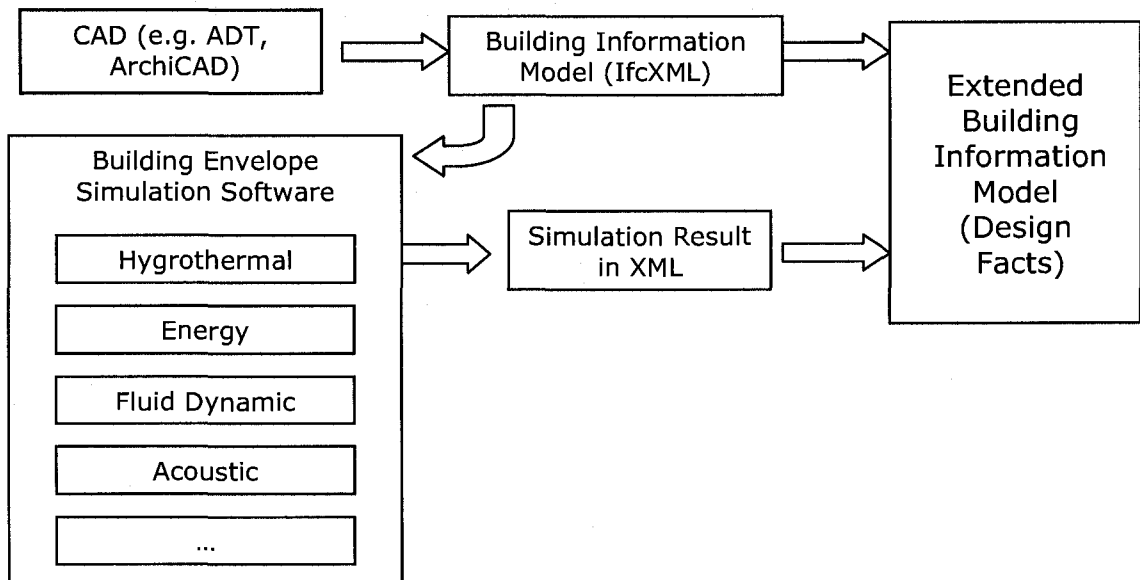


Figure 3.3: Conceptual workflow of creating of EBIM

Figure 3.3 shows the conceptual workflow of creating of an EBIM. The technical details of EBIM will be described in (3.4) of Section 3.3.2. Based on the EBIM, design facts are defined for processing by the rules engine as will be discussed in the Section 3.2.4. The EBIM is flexible to define terms of variable attributes, describe the meaning of the attributes, and store the related values. The characteristics of EBIM provide the possibility to integrate other building simulation software and other building design applications.

3.2.3 Extended Building Codes (rules package)

A rules package is a group of rules represented in decision tables which are derived from the building codes, design regulations and design guideline. A design regulation can be expressed using a decision table as the logic statements of the regulations. Building codes can be defined as a group of decision-tables. Decision tables express the logic of design regulations and their dependency. These provisions represented in decision tables can be appended in the relevant part of the building code. Since the building code has hierarchy structure, the content of a building code or design guideline can be published on the web and each clause or design regulation has its unique link, the decision tables include hyperlinks to the relevant regulations so that the designer can directly correlate the corresponding code contexts. Besides the straightforward rules within the building code, cross-reference rules which result from the exceptional descriptions in the regulations are also represented in decision tables. Figure 3.4 shows an example diagram of relationships of a building code including decision-tables with cross-referenced regulations. A building code is composed of chapters. A chapter is composed of sections. A section is composed

of clauses. Each clause or regulation is represented as the rules of a decision table. A clause containing an exceptional regulation can be represented in a decision table to state the basic relationships of the corresponding clauses.

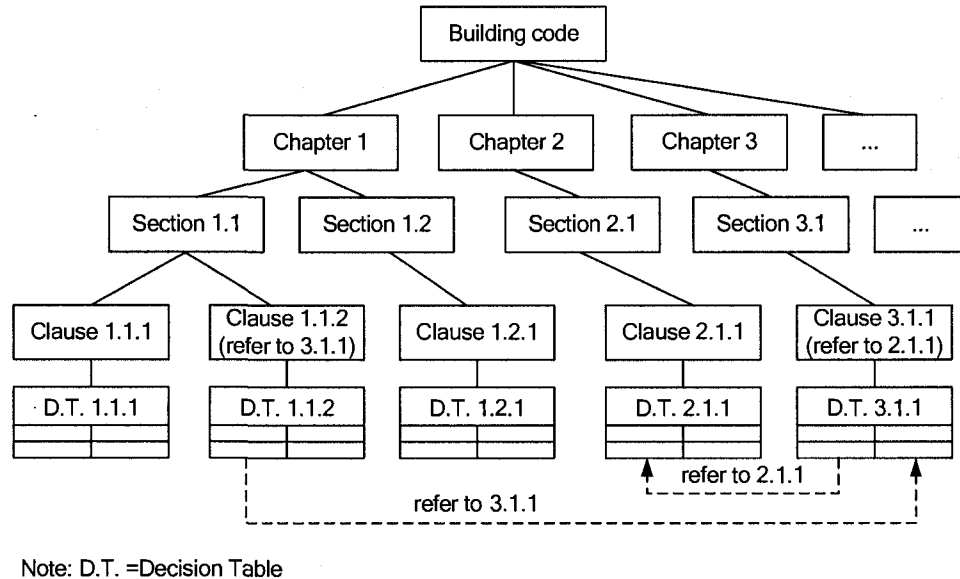


Figure 3.4: Diagram of structure of building code including decision tables with cross-reference regulations

A cross-referenced clause means a regulation within a building code referring to information elsewhere, either within the same document or in a different document. Cross-referenced clauses can be represented using decision tables. For example, Section 5.3 of NBCC Guide states that “materials and components installed as an environmental separator are required to provide an adequate resistance to heat transfer to minimize condensation with the component or assembly or on the surface of its warm side”. A decision table can be built up to describe this regulation. However, the specific requirements of R value, condensation rate, or surface temperature are not described in the NBCC Guide. Designers have to look up other references to obtain the corresponding information. Three rules of the decision table are added at the end of the decision table to

tell the system to find other references. Thus, the decision tables form a hierarchal structure as shown in Figure 3.4 to represent a design regulation explicitly.

As shown in the examples in Tables 3.1 and 3.2, a given decision table is composed of table headings, condition columns, and action columns. Each row of the decision table represents one rule. The rules of a decision table build a matrix to represent a regulation.

Table 3.1: An example of building conditions of a decision table

	Condition 1	Condition 2	Condition 3	Action 1
Headers	<i>Indoor RH (%)</i>	<i>Dewpoint Temperature (°C)</i>	<i>Dry Bulb Temperature (°C)</i>	<i>Result</i>
Rule 1	<= 40	>= 2	>= 19 and <= 23	Pass
Rule 2	> 40			Fail
Rule 3		< 2		Fail
Rule 4			< 19 or > 23	Fail

Table 3.2: An example of building actions of a decision table

	Condition 1	Condition 2	Action 1	Action 2	Action 3
Headers	<i>Window Type</i>	<i>Energy Rating⁶</i>	<i>Result</i>	<i>Comments/ Advice</i>	<i>Index</i>
Rule 1	fixed	>= -20	Pass	Good	CSA standard A440-2-04 (2004)
Rule 2	fixed	< -20	Fail	Install the window with a low-E (emission) glazing or double glazing or well-insulated frame or an entire well-insulated window	
Rule 3	Operable	n/a	Exceptional	n/a	Regulation for operable window

⁶ Energy Rating (ER) is calculated using $ER=72.20SHGC-21.90Uw-0.54(L_{75}/Aw)$ (CSA A440.2-04 2004).

A condition is a key criterion derived from a design regulation. The definition of conditions has four steps: (1) reading design regulations carefully; (2) identifying key words and key criteria which may affect the compliance result, (3) adding the determined names of key criteria into the headings of the decision table. The name of the EBIM should be defined the same way as the heading name in the decision table; and (4) determining the logical relationships of the criteria and filling into the decision table.

For example as shown in Table 3.1, a design guide in ASTM (2000) states “ASHRAE 55 recommended that for human comfort, dewpoint temperature of occupied spaces not fall below 2°C. Over the dry bulb temperature range of 19-23°C this corresponds to an indoor RH value of 32-25%. In contrast, experience and computer simulation models suggest that damaging moisture accumulation can be expected in many building of customary design in cold climates if winter indoor RH in heated buildings is maintained at levels in excess of 40%. These observations suggest that it is reasonable to expect buildings of customary design in cold climates to tolerate indoor RH levels above the minimum for human comfort, but not much above such levels.” After carefully reading this sentence, indoors RH, dew point temperature and dry bulb temperature are decided as the key criteria. These key words, indoors RH, dew point temperature and dry bulb temperature are added as the headers of a decision table. In order to satisfy the simplified requirement of human comfort, a rule is defined as “when indoor RH is less than 40% and dewpoint temperature is greater than 2°C and dry bulb Temperature is between 19°C and 23°C, this design requirement for human comfort is satisfied”. The format of a decision table representing this rule is shown in Table 3.1,

An action is an execution part of a decision table when the appropriate conditions are met. The definition of actions has three elements in the template for code compliance: (1) checking the result which has three options (failed, passed and exceptional); (2) advice or comments which may suggest a method to improve the design; and (3) relevant reference index which concerns this decision table and the hyperlink to the concerned regulation. For example as shown in Table 3.2, CSA (1998) says “the energy rating (ER) of a fixed window should be greater than -20”. To define the action part of a decision table representing this regulation, three rules for different situations are listed. Compliance results are “pass”, “fail” and “exceptional” respectively for each rule. An advice, “install the window with a low-E (Emission) glazing or double glazing or well-insulated frame.” to increase the energy performance of a window, is given in the cell of the rule 2 and action 2 of the decision table in Table 3.2. The related reference index CSA standard A440-2-98 and its web hyperlink are predefined in the decision table. These actions within the decision table are retrieved by the rules engine that will be described in the next section. The action which meets the appropriate conditions are matched and activated. After processing the incoming design data against the rules of the decision table, the corresponding action is executed and then the comment and the relevant reference index are written into a report file.

Extended Building Code (EBC) is defined here as an electronic version of the building code coupled with decision tables which logically define the rules derived from the building code (Tan et al. 2007). The decision tables of EBC constitute a great number of rules of the building code. Figure 3.5 shows the workflow in developing EBC based on decision tables for code checking:

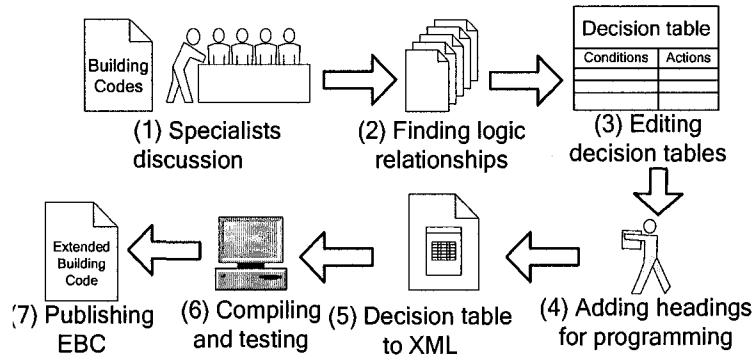


Figure 3.5: Workflow of creating an EBC

- (1) Specialists in building engineering meet, discuss and confirm the provisions of building codes;
- (2) Criteria, their logical relationships, compliance results and possible improvement advices are generated;
- (3) Conditions and actions are listed in a spreadsheet (e.g. Excel) according to a decision table template;
- (4) Programmers add table headings for programming. These table headings are the corresponding parameters in EBIM.;
- (5) Decision tables are generated based on step (1) to (5);
- (6) The code compliance checking software is compiled and tested for consistency of decision tables and design regulations; and
- (7) the EBC is published in an electronic version by combining the building code and the decision tables.

Using this proposed approach, only the values of criteria need to be revised or new decision tables need to be added when the building code is updated. On the other hand, when a design regulation is changed and if the rules of building codes are not separated

from the software, recompiling and revising the automated code compliance checking software requires much more time-consuming efforts than just changing the values in the decision table. The EBCs can be published in order that designers can use the compliance checking software to check their designs according to the current building codes.

These rules integrated in the decision tables of the EBC are called a rules package in IT field and will be used in the processing of the rules engine as discussed in the following section.

3.2.4 Rules engine and Assessment report

To process the rules and facts, an independent rules processing system is needed. A rules engine is a software system that helps manage and automate processing rules (Proctor et al. 2005). Most rules engines were developed for the business applications in the beginning. The rules for a rules engine can be business rules, public policy, environmental regulation, stock market rules, etc. In our research, the rules of building engineering are applied into the rules engine. The most important advantage using a rules engine is that it separates rules and programming codes. Moreover, a rules engine, which applies the advanced algorithm, processes rules and facts faster than conventional programs. Thus, the users of the code checking system are able to modify the rules without the need of the intervention of IT specialists and hence the application is more adaptable to changing rules.

Many rules engines are developed for different purposes by many organizations, i.e., JBoss Rules (Proctor et al. 2005), Workflow Magic (Sardi 2007), OpenRules(2007), OpenLexicon (2007) are non-commercial open source rules engines. JESS (Sandia National Laboratories 2007) and Microsoft Business Rules Engine (Microsoft Corp. 2007)

are two famous representatives among the numerous commercial rules engines and expert systems. In our research, JBoss Rules is selected as the rules engine in the implementation system, which is described in the next section.

Although a great number of rules engines are developed for processing rules, most of rules engines use the same core algorithm, i.e. the Rete algorithm. Rete algorithm was developed by Forgy (1982) at Carnegie Melon University. "Rete is the only algorithm for production systems whose efficiency is asymptotically independent of the number of rules." Haley Systems, Inc. (2007) compared and declared, "Rete is usually several times faster than other algorithm for small numbers of rules with Rete's performance becoming increasingly dominant as the number of rules increases". Rete algorithm is an efficient multi-objects matching algorithm, a non-numerical filter-optimization algorithm.

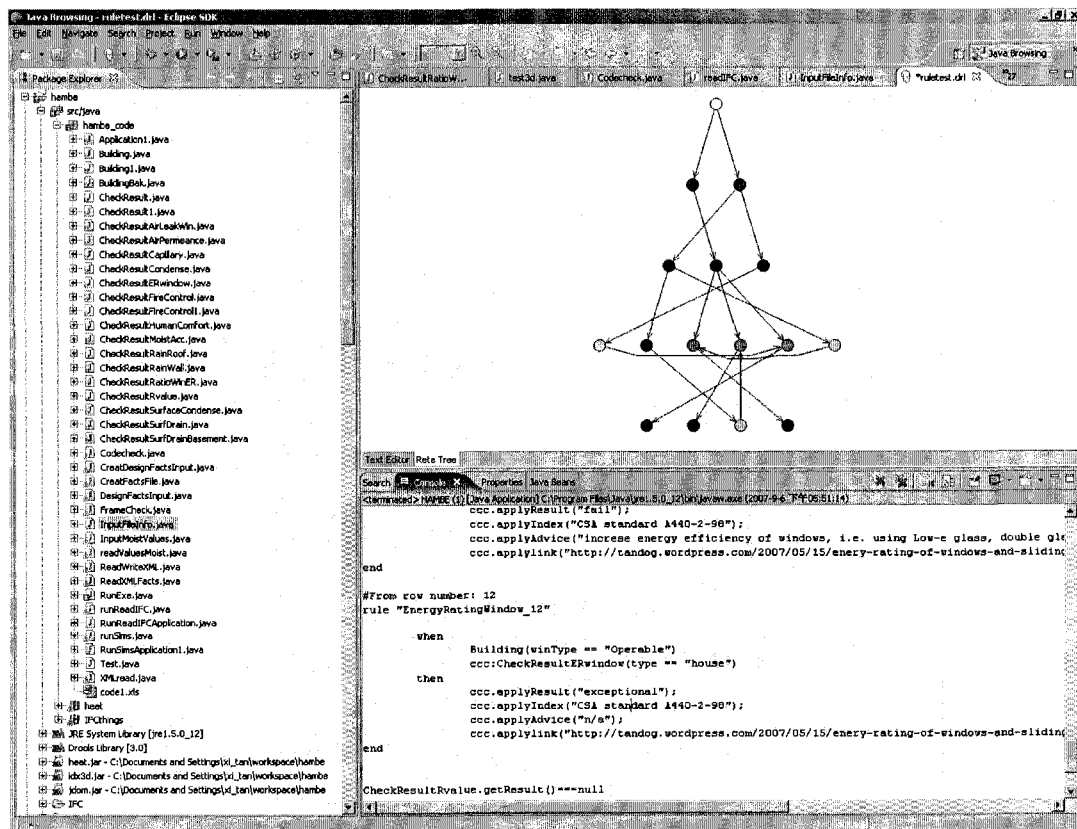


Figure 3.6: Screen capture of Rete tree of JBoss Rules for Table 3.2

Facts and rules are treated as nodes in the ACCBEP. These nodes are matched using the rules engine and then the matching results are obtained. The corresponding items in action parts of decision tables described in the previous section can be determined, selected, collected, and written into a code checking report. In the author's code compliance checking system, the assessment report contains the compliance checking results, the associated design regulations, reference indices, and advices to assist architects and designers.

The decision table, Table 3.2, is taken as an example to explain this procedure briefly. Each cell of Table 3.2 is treated as a node in the rules engine. Using Rete algorithm, the applied rules engine filters the repeated nodes during processing and matching these nodes. Figure 3.6 shows a screen capture of Rete tree of JBoss Rules for Table 3.2. Then the facts, e.g., the type of the study window, and the value of energy rating from EBIM are inserted into the rules engine. When the appropriate criteria are met, the execute system of the rules engine are "alarmed" and output the corresponding compliance result, index, and comment. The compliance result is output into a checking report file to assist the users.

3.3 Prototype implementation: ACCBEP

3.3.1 System framework

An application, named ACCBEP (Automated Code Checker of Building Envelope Performance) and focusing on the hygrothermal performance code checking, is developed. The system architecture of the application shown in Figure 3.7 is developed

based on the proposed approach described in Section 3.2. ACCBEP is developed using Java programming language under Eclipse environment (The Eclipse Foundation 2007). Java is selected because it is a platform-independent language and it is widely used for web applications. ACCBEP has five modules: (1) Data integration module, (2) Building and component visualization module, (3) Building envelope performance computation module, (4) Extended building codes, and (5) Code compliance checking module.

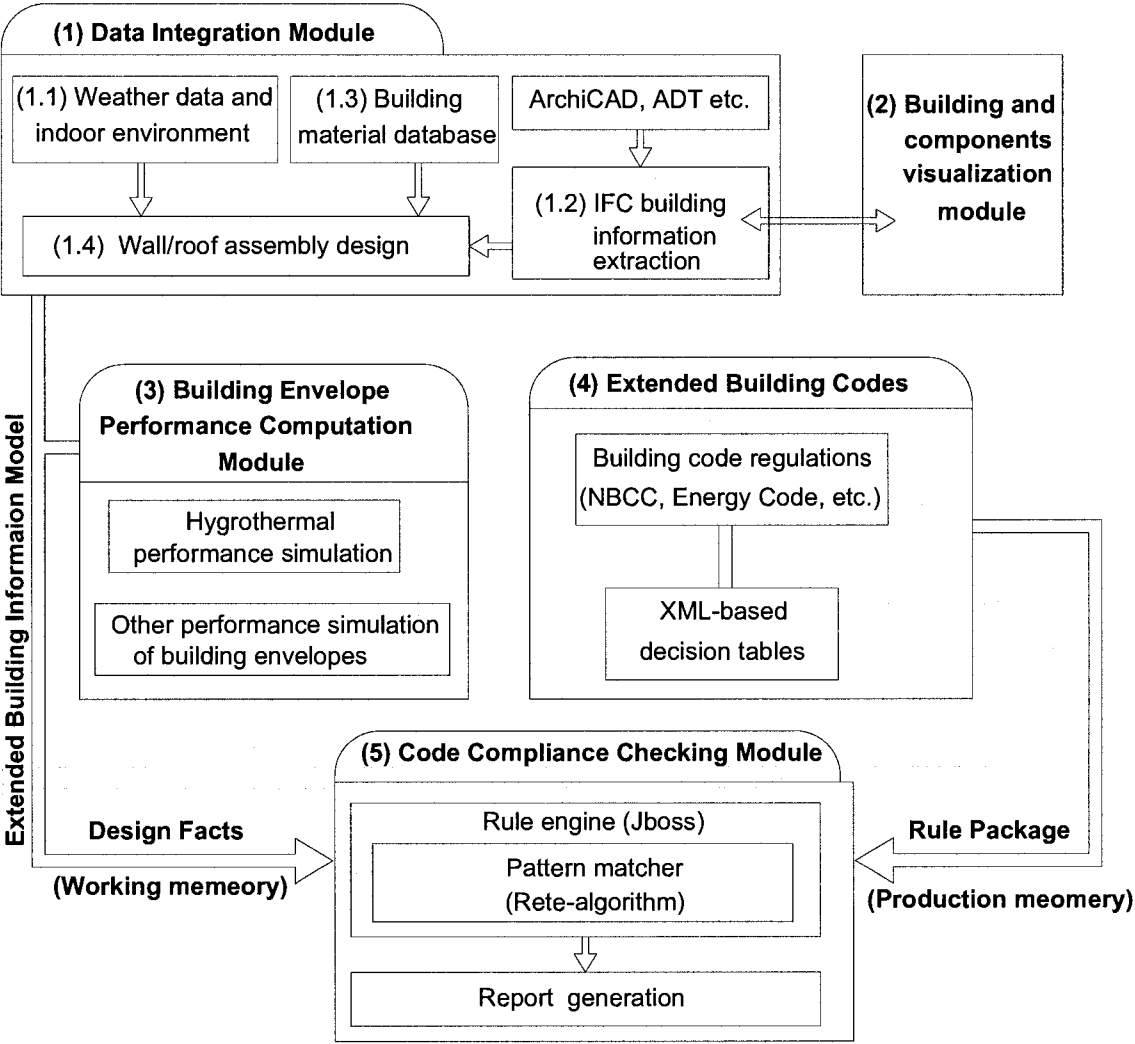


Figure 3.7: System architecture of ACCBEP

3.3.2 Functional modules of ACCBEP

(1) Data Integration Module

The function of data integration module is collecting environmental data, sequence, thickness, and material names of the assembly of a wall/roof, and attributes of the materials. The data integration module has four sub-modules:

(1.1) Weather data and indoor environment sub-module

In this module, the weather data are taken from EnergyPlus (2006). The weather data from EnergyPlus are hourly data from stations of many cities of the world. The weather data of the different cities and the corresponding climatic zones are collected and stored into a database. The daily temperature by month is visualized in a line chart using the Java2D technique in this program.

The hourly data can be applied into the transient hygrothermal, energy, solar, precipitation analysis in the coming update version, although only steady-state hygrothermal calculation is embedded within ACCBEP currently. The design conditions including outdoor dry-bulb temperature, outdoor relative humidity of a particular location, indoor dry-bulb temperature, and indoor relative humidity for steady-state calculation can be defined in the input interface of ACCBEP (Figure 3.8).

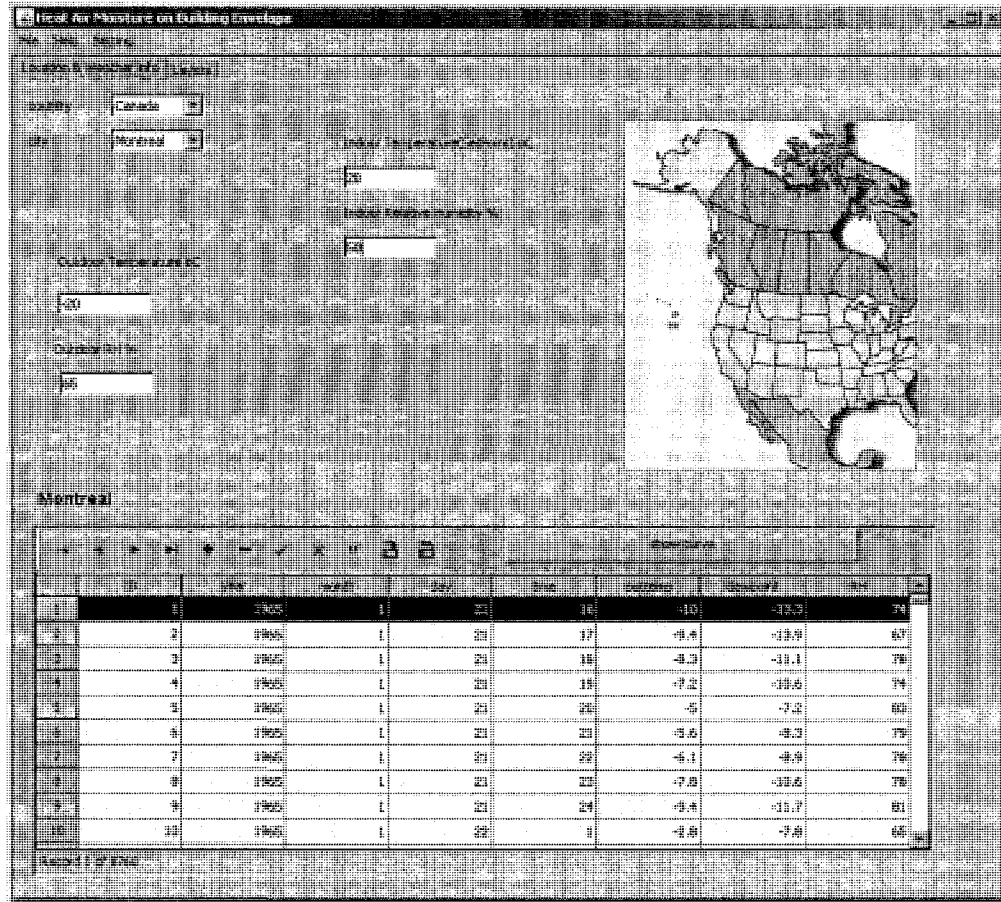


Figure 3.8: Screen capture of inputting outdoor and indoor environment data

(1.2) IFC information extraction sub-module

IFC building model is exported from CAD software such as ArchiCAD or Architectural Desktop (now AutoCAD architecture). Building envelope geometrical information is extracted from the IFC model. IfcXML is an XML representation using IAI IFC 2x2 schema and data developed in May 2005. IfcXML is implemented into the system because XML is broadly supported by utilities and databases.

In ACCBEP system, JDOM (Java Document Object Model) is selected for parsing the XML file because JDOM is an open source library for Java-optimized XML data manipulations (Hunter 2002). Ideally, a well-defined IfcXML is a BIM including all the

related information of a building. An IfcXML contains a huge amount of data expressing location, stories, building components, their dimensions, hierarchy and so on. For example, 610 lines IfcXML are used to describe a single isolated basement wall, which has only four layers: 100 mm concrete block and a 150 mm structure concrete with 30mm double-side plasters.

Since our research focuses on the building envelope, the objective of sub-module (1.2) is to extract the thickness, material names, order of assembly of a wall/roof from an IfcXML file. A Java class, which is named ReadIFC.java (please refer to Appendix E for the list of all Java Classes and files in the ACCBEP system), is developed for parsing the building envelopes' information using the API of JDOM. According to IFC schema and data structure, the mechanism of parsing an IFC for a building envelope is shown in Figure 3.9:

- (1) JDOM is initiated.
- (2) A blank database is created.
- (3) An IfcXML is loaded.
- (4) The database is distilled with the root elements and their children from the IfcXML file.
- (5) The element IfcRelAssociatesMaterial is queried.
- (6) Its child RelatedObejects, which has the name of the building component, is obtained.
- (7) The child element RelatingMaterial and its attribute "Ref" are obtained.
- (8) IfcMaterialLayerSetUsage is obtained by locating its ID according to the Ref from step (7).

- (9) The child element ForLayerSet and its attribute “Ref” are obtained.
- (10) IfcMaterialLayer is obtained by locating its ID according to the “Ref” from step (9).
- (11) LayerSetName, which has the composite name of the assembly, is obtained.
- (12) The child elements MaterialLayer List and their attributes “Ref” and position are obtained. In this step, the order and position of the assembly are obtained.

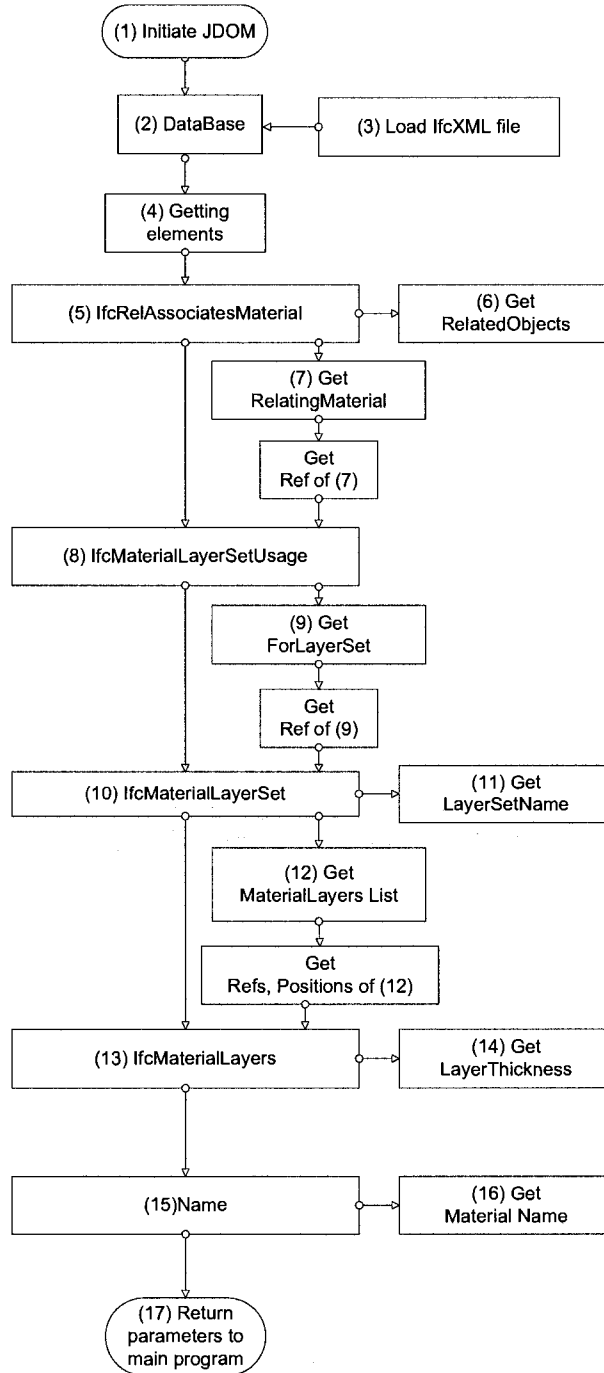


Figure 3.9: Mechanism of parsing an ifcXML for a building envelope

- (13) IfcMaterialLayers is obtained by locating its ID according to the “Ref” from step (12).
- (14) The child element LayerThickness is obtained.

- (15) The child element Name of (13) is obtained.
- (16) The MaterialName is obtained.
- (17) Returning the related parameters including object, layer set name, layer list, materials of layers, and the layers' position to main program for computation and visualization.

(1.3) Building material database

In ACCBEP, the database of building material hygrothermal properties are primarily developed in Access format based on the material data stored in the text-based file of MOIST (Burch and Chi 1997). A portion of building material properties is obtained from the reference ASHARE (2005). These material data are saved into a database using Microsoft Access. Access database is then connected to the program ACCBEP using a Java database connection driver, JDBC-ODBC (Sun Microsystems 2006). These building material data can be listed, selected, added, deleted, modified, and sorted in the building material database (Figure 3.10).

ID	sort	MaterialName	DefaultThic.	FirstSorpti.	SecondSorpt.	ThirdSorpti.	FirstDiffus.
1	AIR BARRIER	AIR BARRIER (PC2		5190E+02	2538E+04	9020E+00	0000E+00
2	SIDING	ALUMINUM SIDING	10	1009E+00	5358E+04	9312E+00	0000E+00
3	MANSORY	BRICK	13	7860E-02	3771E+01	8142E+00	4887E-04
4	MEMBRANE	BUILDING PAPER	1	5190E+02	2538E+04	9020E+00	9020E+00
5	ROOFING	BUILT-UP ROOFING	20	5190E+02	2538E+04	9020E+00	0000E+00
6	CONCRETE	CONCRETE	100	1253E+00	1432E+02	8279E+00	4917E-03
7	CONCRETE	CONCRETE BLOCK	100	1021E+00	1010E+02	7745E+00	4917E-03
8	INSULATION	FIBERBOARD_ AS	25	1140E+01	5060E+02	9230E+00	1356E-04
9	INSULATION	FIBERBOARD_ RD	25	2230E+00	6130E+01	9010E+00	6766E-05
10	INSULATION	FIBERBOARD_ SH	25	5305E+00	1246E+02	8750E+00	6766E-05
11	INSULATION	FOAM CORE SHEA	100	3640E+00	1460E+02	9020E+00	0000E+00

Figure 3.10: Screen capture of interface of building material database management sub-module

In order to accurately calculate the wall assembly, roof assembly, window or door performance, the accurate building material attributes are one of the critical issues in the system. A building material database of hygrothermal attributes include category, thermal conductivity, thermal specific heat, vapor permeability, density and other attributes. This building material database should be easily accessed and maintained online by various users such as architects, researchers, engineers, constructors and manufacturers. The designer can assign a wall/roof assembly efficiently by selecting different building materials from this database.

(1.4) Wall assembly design sub-module

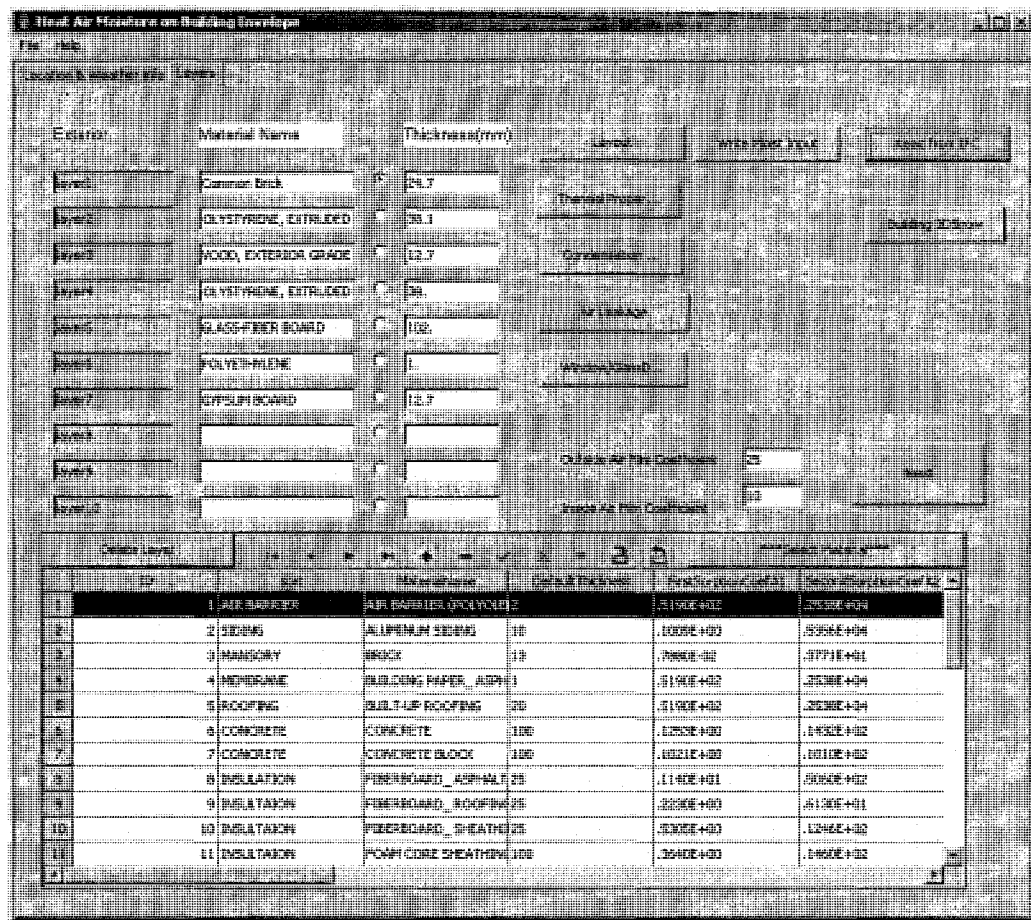


Figure 3.11: Screen capture of interface of wall assembly design sub-module

Building envelope design strongly influences the finished wall or roof performance. The data from sub-module (1.2) is displayed in the interface of this sub-module 4 (Figure 3.11). Users can modify, adjust and replace the layers of the existing assembly from the IfcXML file directly. Alternatively, user can design a new wall/roof assembly by choosing a building material from the database, and then assigning it to the layer position within the building envelope.

(2) Building and Component Visualization Module

This module assists the user to easily locate the building components and visually obtain the building envelope information. This module uses idx3D technique, which is a real time 3D engine in Java (Walter 2006), to represent the building model in 3D graphics.

Figure 3.12 shows the working flowchart of the visualization module. A designer draws a 3-D building using CAD software such as ArchiCAD and then both 3ds and ifcXML files of this building model are exported. The ifcXML is parsed to obtain the corresponding building envelope information using the utility described in sub-module (1.2). Meanwhile, the 3D objects of the building, which is containing in the 3ds file, are displayed using the integrated idx3D Java library. The visualization module links between building envelope information and the corresponding 3D objects. The assembly's information of a building envelope and its corresponding 3D model are displayed together.

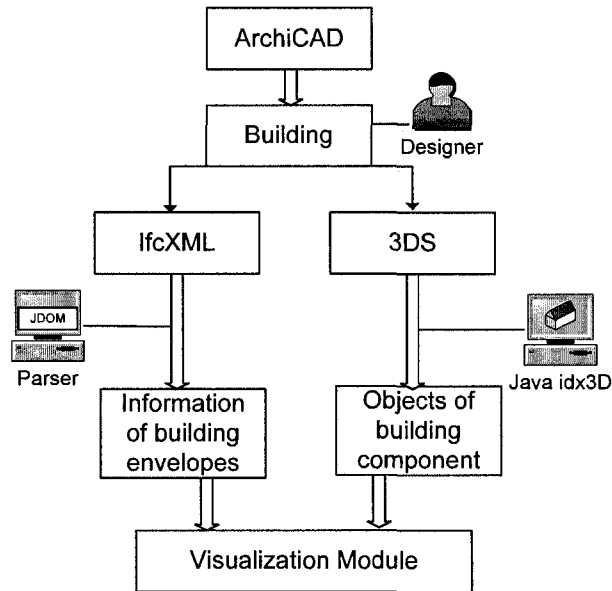


Figure 3.12: Flowchart of building components visualization

Actually several applications for viewing IFC model have been developed. But none of them are either open-source, Java-based, supporting reading building envelope information, and has open API. Therefore, it is difficult to integrate them into ACCBEP.

(3) Building envelope performance computation module

This module focuses on computing the building envelope hygrothermal performance using simulation. ACCBEP develops three methods including one integrated Java application and two third-party simulation software for computing the performance of the building envelope:

(3.1) Integration of the steady-state hygrothermal calculation using the Glaser method

The ACCBEP has a functional sub-module for steady-state numerical hygrothermal analysis for vapor diffusion through a wall assembly using the Glaser method, also called

dew-point method or steady-state hygrothermal calculation (ASHRAE 2005). The detailed programming method is described in Appendix A. In this sub-module, the related input data for calculation using the Glaser method, such as materials of a wall's assembly, thickness of each layer in the wall, the material's thermal conductivity, vapor linear permeability, indoor and outdoor temperature, relative humidity, film coefficient and local barometric pressure, are retrieved from module, i.e., (1) data integration module. The output values, including the temperature of each layer, vapor pressure of each layer, continuous pressure of each layer, condensation status, thermal resistance (R value), thermal conductance (U factor), and vapor permeability are obtained after calculation using Glaser method. These values are shown in the representation of line chart using the Java 2D technique (Figure 4.6).

(3.2) Integration of transient hygrothermal simulation using MOIST

The simulation software MOIST is utilized for transient hygrothermal analysis of building envelopes. The programming algorithm is described in Appendix A in detail. MOSIT is a free software for simulation of coupled heat and moisture diffusion through multi-layer assembly (Burch and Chi 1997). Its program core is an execution program under DOS environment using FORTRAN language. Its input and output files are ASCII data file. This computation module of ACCBEP converts the input data from module (1) to the input files of MOIST. This module also sets simulation parameters and stores them into the input files of MOIST. A Java class named InputMoistValues.java is applied to translate the input data from ACCBEP to MOIST:

- (1) With this Java class, the material names and thicknesses of each layer in a wall assembly are saved into the input file CONST.DAT in MOIST directory;

- (2) The units system is set to metric system and saved into the input file UNITS.DAT in MOIST directory;
- (3) The default simulation period is set to 2 years and interval time step is set to 24 hours and saved into the input file PERIOD.DAT in MOIST directory;
- (4) the weather data file is set into Montreal's weather data WYMONC and saved into the input file DEFSET.DAT in MOIST directory; and
- (5) The inside environment temperature and RH are set to 20°C and 40% respectively, and saved into the input file INDOOR.DAT in MOIST directory.
- (6) The other input data are using the default parameters defined in MOIST directory.

Then the core program ANALYZE.EXE for simulation computing is executed and the output files are generated. A Java class named readValuesMoist.java is developed for analyzing and processing the output files of MOIST:

- (1) The transient R values in the output file RESULTS.AR are summed up and the average R value of the wall during the latter year of the 2-year simulation period is obtained;
- (2) The transient surface temperatures of each layer in the output file RESULTS.AST is read and the average inside surface temperature is obtained; and
- (3) The transient relative humidity of each layer in the output file RESULTS.ARH is read and stored, and then the number of the days which RH value is over 80% at a particular layer is obtained.

These processed values are written into the EBIM file DesignFacts.xml (Appendix B) for the next step of code checking.

(3.3) Integration of energy simulation using EnergyPlus

EnergyPlus (2006) is an energy simulation software developed by the Department of Energy (DOE), United States. EnergyPlus is a powerful and complex simulation program designed for modeling buildings with all their associated heating, cooling, lighting, ventilating, and other energy flows. In this research, EnergyPlus is applied only for computing the heating loads of a building with an exterior wall system, which has a particular thermal resistance. EnergyPlus reads input and writes output as text files for simulating the energy performance of a building system. The integrated computation with ACCBEP using EnergyPlus has the following steps:

- (1) A building model is created using ArchiCAD and saved as an IFC model.
- (2) The IFC file is converted to an EnergyPlus input file in IDF format, using a utility IFC2IDF, which is included in the EnergyPlus installation package. Although IFC is a building information modeling standard, EnergyPlus does not identify IFC file as its input files for building information. EnergyPlus has its own input format IDF for defining a building's geometry information. A beta-version software IFC2IDF is developed for converting IFC to IDF. This IDF file has the default geometric information of a building model.
- (3) The parameters including weather data, thermostat, deadband, simulation period, time-step, output values, building envelope attributes and many other parameters are input into the IDF file manually. The user can also modify these parameters manually in this IDF file using a utility program IDFEditor within

the EnergyPlus package. This IDF file is treated as a basic template file for energy analysis.

- (4) A Java class named ChangeEPInput.java is developed for replacing the R value of exterior walls of the template building model.
- (5) The main program of EnergyPlus, EP-Launch.exe, is executed. The simulation output file is saved as a CSV (Comma Separated Values) file.
- (6) A Java class named ReadEPResult.java is developed for processing the output file. This java class searches and records the daily heating load of the study zone of the building. The sum of the daily heating load is obtained.
- (7) Thus the heating load during an entire year is obtained for calculating the heating load of a building.

Based on this data, users can compare the effects on sizing heating equipment and cost when applying the different insulation to an exterior wall system in cold areas.

(3.4) Integration of other simulation applications and EBIM

Additionally, besides the Glaser method, MOIST and EnergyPlus, the EBIM provides the possibility to integrate with other building simulation software if their input/output simulation results are using EBIM format. Hereby a simple example for calculating the ER (Energy Rating) of a window is given. A Java class named WindowFrame1.java is developed for the calculation of a window's energy rating using the equation below:

$$ER=72.20SHGC-21.90U_w-0.54 (L_{75}/A_w),$$

which is described in CSA A440.2-04 (2004).

After inputting the manufacture-controlled parameters including SGHC (Solar Gain Heating Coefficient), U factor, air leakage flow rate, glazing area and the type of a window, the ER of this window is obtained (Figure 3.13). This ER value of this window is stored into the EBIM file using the following format:

```
<energyRating desp="Energy rating of window">-11.36</energyRating>
```

This sentence in XML has three parts, an element “energyRating” as definition using a start-tag and a close-tag with angle brackets, an attribute (desp="Energy rating of window") describing the meaning of this element, and a value of the element. (Note: the element name MUST be the same as the corresponding header name defined in decision table described in Table 3.2 in Section 3.2.3) Therefore, the building information and simulation data are represented and stored into an XML file following the general format shown in this example (Appendix C).

In the ACCBEP system, the sources of EBIM are obtained from two parts. Majority part is from the computation module including the simulation results and IFC information. The rest part is from the manual inputs as the supplements which are not included either in the IFC or simulation data, especially design details, i.e., the seal conditions, weep holes, and the joints of components. In order to completely evaluate a building’s overall performance, the details of a building envelope design, and other performance simulation software, such as acoustic and fire resistance performance simulation can be integrated into ACCBEP to assess other aspects of building envelope performance in the future.

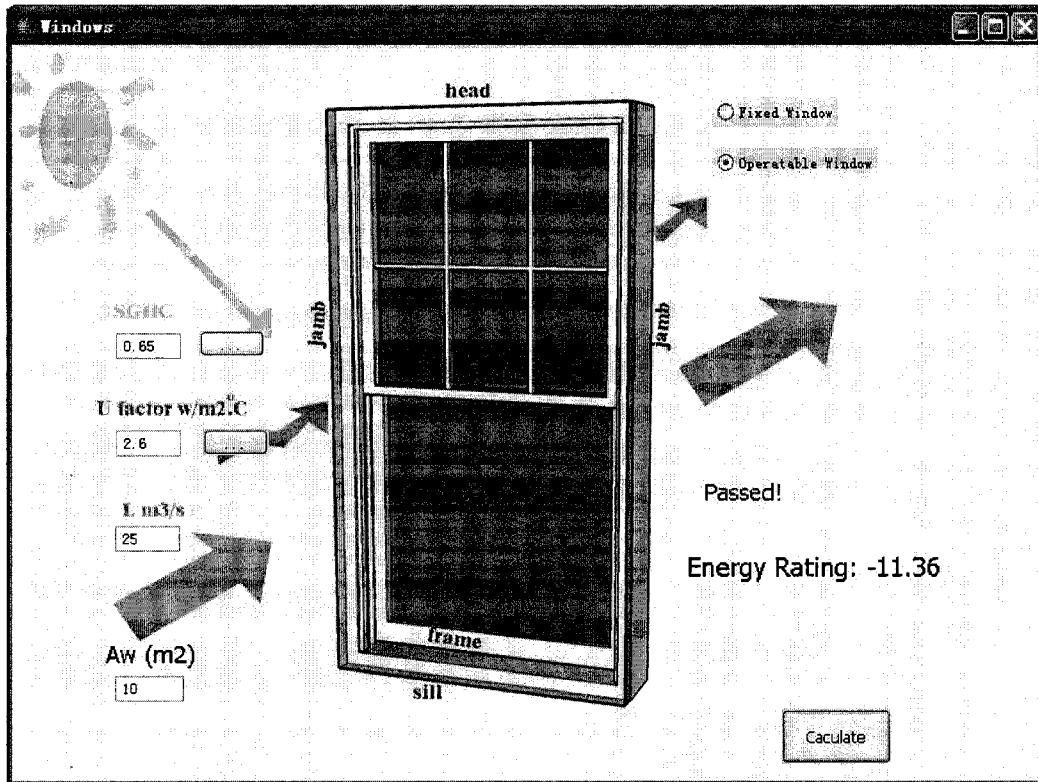


Figure 3.13: Screen capture of the program for calculating ER of a window

In summary, these important values, parameters, design details and other building information for code checking, which is called design facts in IT field, are retrieved from the EBIM by integrating the BIM data obtained from module (1) and the computed data from module (3).

Table 3.3(a): A decision table to check R-value of a house exterior wall in Toronto⁷

CONDITIONS					ACTIONS		
Location	Type	Wall Position with respect to Ground	Primary Heating Source	Thermal Resistance value: R-value (RSI)	Compliance Checking Result	Comments	Reference Index
Toronto (Region A, ON)	house	above	Electricity	R-value ≥ 4.4	pass	Good	MNECH 3.3.1.1 (Toronto)
			Propane, Oil, Heat Pump	R-value ≥ 3.0	pass	Good	
			Natural Gas	R-value ≥ 2.9	pass	Good	
			Electricity	R-value < 4.4	fail	Increase insulation layers so that R ≥ 4.4 RSI	
			Propane, Oil, Heat Pump	R-value < 3.0	fail	Increase insulation layers so that R ≥ 3.0 RSI	
			Natural Gas	R-value < 2.9	fail	Increase insulation layers so that R ≥ 2.9 RSI	
	house	below	Electricity	R-value ≥ 3.1	pass	Good	MNECH 3.3.2.1 (Toronto)
			Propane, Oil, Heat Pump	R-value ≥ 3.1	pass	Good	
			Natural Gas	R-value ≥ 2.1	pass	Good	
			Electricity	R-value < 3.1	fail	Increase insulation layers so that R ≥ 3.1 RSI	
			Propane	R-value < 3.1	fail	Increase insulation layers so that R ≥ 3.1 RSI	
			Natural Gas	R-value < 2.1	fail	Increase insulation layers so that R ≥ 2.1 RSI	
	building	any	any	any	exceptional	Go to	MNECB

⁷ Table 3.3 (a) and (b) is based on MNECH 1997.

Table 3.3(b): A decision table to check R-value of a house exterior wall in Montreal

CONDITIONS					ACTIONS					
Location	Type	Wall Position with respect to Ground	Primary Heating Resource	Thermal Resistance value: R-value (RSI)	Compliance Checking Result	Comments	Reference Index			
Montreal (Region A, QC)	house	above	Electricity	R-value ≥ 4.1	pass	Good	MNECH 3.3.1.1 (Montreal)			
			Propane, Oil, Heat Pump		pass	Good				
			Natural Gas		pass	Good				
			Electricity		fail	In Region A, Quebec, thermal resistance of a wall above the ground must be higher than 4.1 RSI				
			Propane, Oil, Heat Pump		fail					
		Natural Gas	fail							
		below	Electricity	R-value ≥ 3.1	pass			Good	MNECH 3.3.2.1 (Montreal)	
			Propane		pass			Good		
			Natural Gas		pass	Good				
			Electricity		fail	In Region A, Quebec, thermal resistance of a wall below the ground (basement) must be higher than 3.1 RSI				
	Propane		fail							
	Natural Gas	fail								
	building	any	any	any	any		exceptional	Go to		MNECB

Table 3.4: A decision table to check moisture accumulation of a house exterior wall

CONDITIONS		ACTIONS		
Type	Number of days for which RH>80% within the building envelope	Compliance Checking Result	Comments	Ref. index
house	Days ≤ 7	pass	good	Burch and TenWolde 1993
	Days > 7	fail	install vapor / moisture barrier with a high vapor resistance, e.g., polyethylene	

(4) EBC (decision tables)

The regulations extracted from building codes, which are relevant to the required performance of building envelopes, are converted to decision tables. EBC consists of an electronic version of the building codes and decision tables, which logically describe the statements in the building code. In the ACCBEP system, focusing on the hygrothermal performance of the wall, several reference regulations about hygrothermal performance requirements of an exterior wall have been implemented as decision tables using a spreadsheet:

- Thermal resistance of this wall, R value, must comply with the Energy Code (MNECH 1997, MNECB 1997) as shown in Tables 3.3 (a and b).
- Using hygrothermal transient simulation, when an interior vapor retarder is used in the construction, the weekly average RH at its outside surface should be less than 80% as shown in Table 3.4 (Burch and TenWolde 1993).

Besides the two regulations mentioned above, 16 decision tables including 159 rules are developed in this system (Appendix C). However, only the titles of the rest of other regulations are listed below since the details can be found from the references described in Chapter 1 (the references are also linked to the web contents): requirements of vapor barrier position and permeability (NBCC 2005), requirements of rate of condensation within building envelopes (Horvat 2005), requirements of drainage system installation for surface runoff and precipitation of building envelopes (ASTM 2000), interior surface temperature of building envelopes must be higher than dew-point to avoid condensation (BS EN ISO 13788 2002), simplified requirements of environmental occupant's comfort (ASHRAE 2005), requirements of air permeability of a wall's air barrier (Horvat 2005),

air leakage rate of windows (CSA A440.2-2004), energy rating of window system (CSA A440.2-2004), fire control requirements in building envelopes (NBCC 2005), requirements of basement drainage (ASTM 2000), requirements of limiting precipitation intrusion (ASTM 2000), requirements of rainfall management system (ASTM 2000), and capillary break and damp proofing requirements of basement wall (ASTM 2000). Thus, the regulations and rules expressed in the decision tables are used in the rules engine as the rules package in IT field.

(5) Code compliance checking module

The function of the code compliance checking module is to evaluate the building envelope performance based on EBIM against the rules derived from EBC. A code compliance report is generated to aid the user for building code checking. The rules are retrieved from the decision tables of EBC and stored into the rules package. The hygrothermal simulation results from module (3) are translated into XML format and read as design facts, which are integrated with the other related building envelope attributes derived from module (1).

Most rules engines are developed for business services. In our research, a business rules engine, JBoss-rule is integrated into this system for code checking in building engineering. The rules engine integrated in the ACCBEP solves the multi-objects pattern matching facts against rules. JBoss-rule implements Rete OO (Rete algorithm for Object Oriented systems).

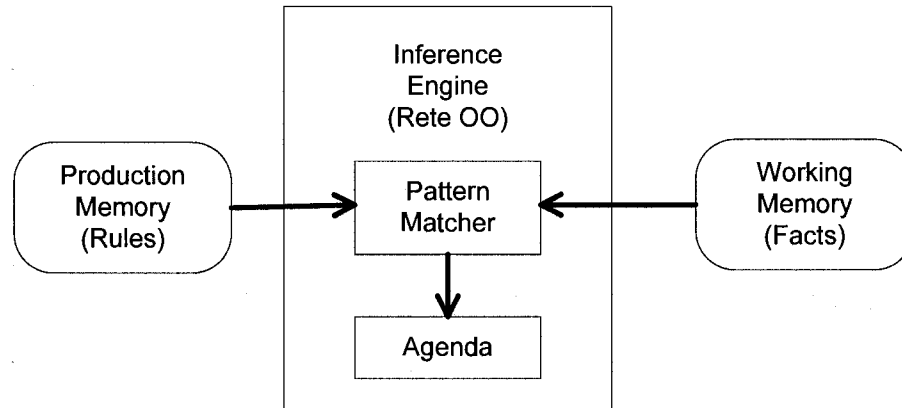


Figure 3.14: A basic Rete network (Proctor et al. 2005)

In a system applying the rules engine JBoss-rule, the rules are stored in the the production memory and the facts are stored in the working memory (Figure 3.14). The inference engine, which implements Rete OO, matches facts against rules using pattern matcher. The agenda manages the execution order of conflicting rules using a conflict resolution strategy (Proctor et al. 2005).

JBoss-rule can convert the decision tables among the different formats including Excel, CSV, rule language and XML rule. In the ACCBEP system, the JBoss-rule is used as a “black box” tool for processing code checking. The rules engine is applied to match the EBIM against the EBC. The Java library of JBoss-rule is integrated into module (5). Several Java classes are developed for manipulating the code checking process with the integration of JBoss-rule engine. As shown in Figure 3.15, in the code compliance checking module, the facts are stored in EBIM file. A Java class named ReadWriteXML.java is developed for converting EBIM to a data model (Building.java) for JBoss-rule. The rules of the decision tables and the facts are asserted into the pattern matcher, CodeCheck.java, which integrates the JBoss-rule.

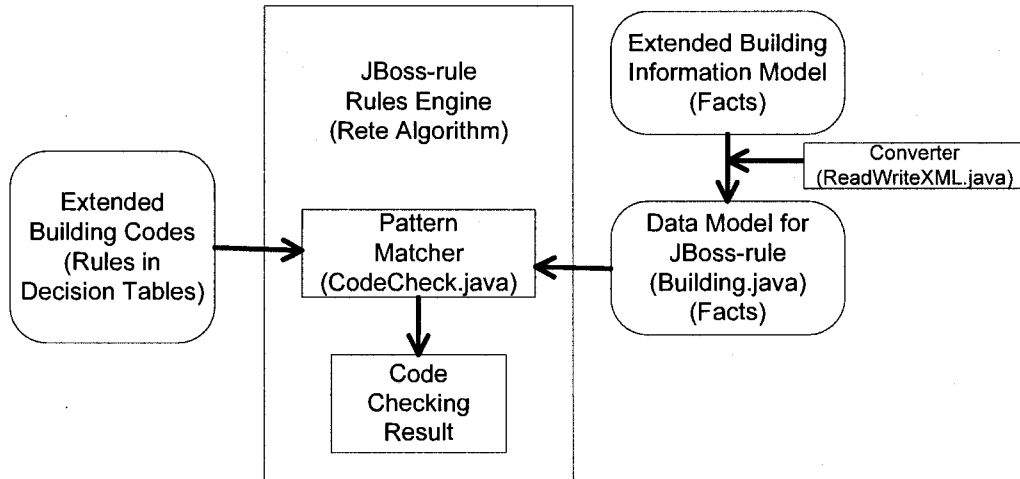


Figure 3.15: Flow chart of code compliance checking module

After running the rules engine, the corresponding checking results, which are predefined in the action parts of the decision tables, are obtained. The compliance checking results are displayed and written into a report file, which also includes reference indices, comments, and the reference standards to assist the building envelope designer (Appendix D).

3.4 Conclusions

The proposed approach integrating EBIM, EBC and rules engine successfully solves several difficult questions in code compliance checking system. The prototype implementation system ACCBEP based on the proposed approach is the first code compliance checking application focusing on the building envelope design in support of IFC, hygrothermal simulation applications, open standard of EBIM, 3D visualization, decision tables representing building codes, separation of rules and the software codes, and rules engine with a fast algorithm.

IFC is used as a data source to get the geometric building information as well as input data for simulations and for 3D visualization. The simulated results are analyzed and integrated with building information to generate an EBIM that can be inserted in an IfcXML file. EBIM provides an open standard format for not only code compliance checking but also for other analysis purposes. As a compact and efficient way, decision tables are used for representing the complex logical rules of building codes. In order to separate works of the experts in different technical domains such as building engineering and software programming, the rules engine is applied for matching design facts against rules based on Rete-algorithm. An assessment report is generated to assist the users.

Based on the framework of the proposed approach, more evaluation and analysis applications can be developed applying these new concepts EBIM, EBC and rules engine.

Chapter 4 Case Studies

4.1 Introduction

In this Chapter, two case studies are presented using our developed implementation system ACCBEP. The work flow of the system is introduced using the actual cases and the proposed approach is tested and validated.

In case study 1, a house is built using an EIFS exterior wall that is broadly applied in North American houses. ACCBEP is applied to check the hygrothermal performance of the building envelopes of the house according to the relevant design regulations. The entire process how to use ACCBEP is introduced in case study 1.

In case study 2, a small bank building is located in Montreal, Quebec. The R value of wall, and walls' geometric information for input and the hourly heating load of a specific zone for output of EnergyPlus are integrated within ACCBEP for assessing the energy performance of the building. A minimum R-value of the exterior wall system is replaced by the EIFS wall that is used in case study 1 for the small building. The heating loads are computed and compared when using two different exterior wall systems in the same building.

4.2 Case study 1: Code compliance checking of an EIFS wall in a residential house

4.2.1 Overview

In this case study, it is assumed that a residential house following the low-energy design criteria of the NOVTEC program (Gerbası 2000) is located in Montreal, Canada. The EIFS (Exterior Insulation and Finish Systems) are used for the exterior walls of this house. This case study is given to test the implementation of the proposed approach. This example shows the procedure of the automated checking of the hygrothermal performance of an EIFS exterior wall based on the hygrothermal simulation analysis during a two-year term.

4.2.2 Wall assembly design and IFC export

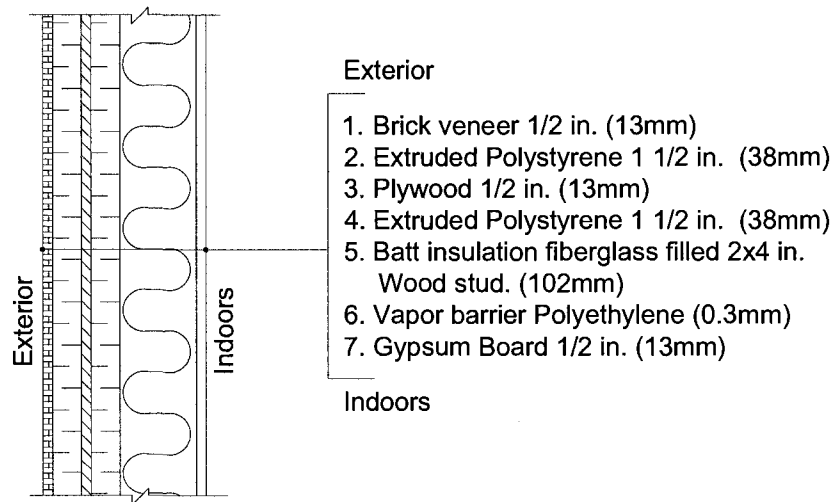


Figure 4.1: Layers of EIFS wall assembly

The CAD model of this house is modified using ArchiCAD based on the IFC file from He (2006)'s work. Figure 4.1 shows the materials of functional layers of the exterior wall assembly based on the reference EIFS wall of the NOVTEC house (Gerbasi 2000 and Lemieux 2006). The function, material and thickness of the layers of the wall assembly are listed from outdoors to indoors:

- (1) Rain screen: brick veneer 13mm;
- (2) Air barrier and rigid insulation: extruded polystyrene 38mm;
- (3) Sheathing panel: plywood 13mm;
- (4) Sheathing and rigid insulation: extruded polystyrene 38mm;
- (5) Wood-frame studs and filled insulation: fiberglass 102mm;
- (6) Vapor barrier: polyethylene 0.3mm; and
- (7) Finishing panel: gypsum board 13mm.

Firstly, an IFC building model which contains this EIFS wall's information shall be designed and defined. Graphisoft ArchiCAD v10.0 is selected for modeling the IFC as the working CAD software. The exterior wall system of a building model is defined as an EIFS in ArchiCAD following the steps below:

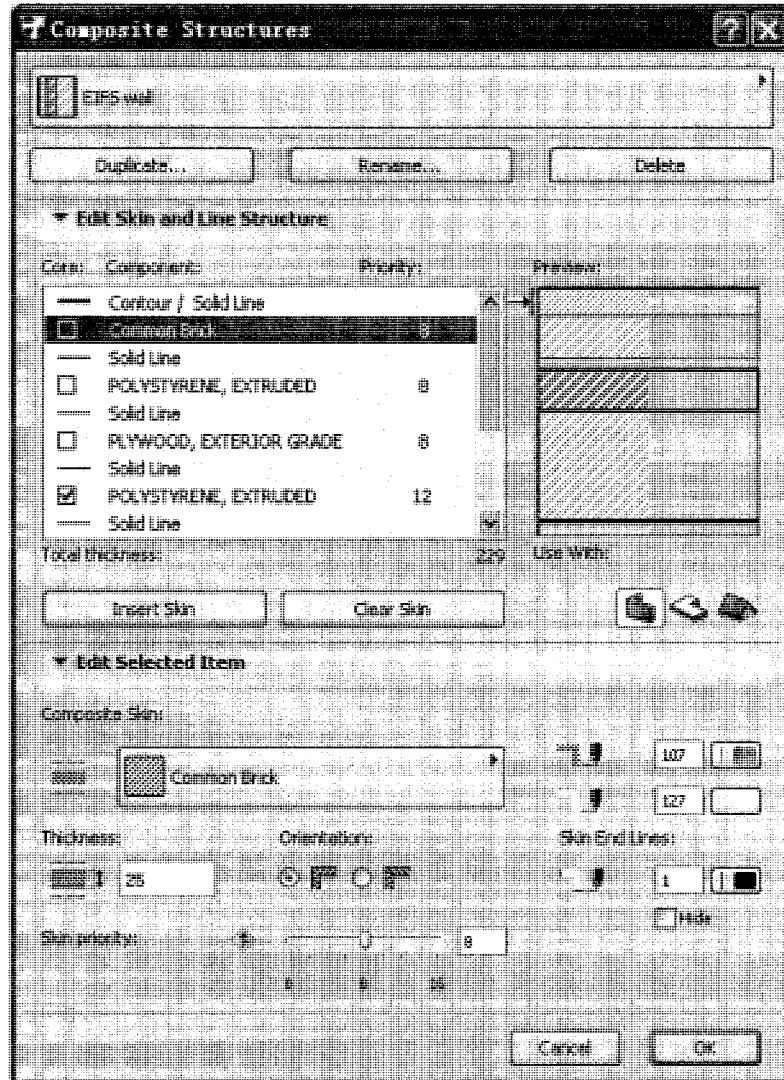


Figure 4.2: Defining an EIFS wall in ArchiCAD

(1) Definition of materials in ArchiCAD: After opening ArchiCAD, select Options / Element Attributes / Fill Types from the menu list. Click new button. Input the new material names including extruded polystyrene, polyethylene, and fiberglass and select the proper fill type patterns. The material names which are not included in the filling types of ArchiCAD are defined.

(2) Definition of the composite in ArchiCAD: Select Options / Element Attributes / Composite. Edit Component and Priority by adding the material of each layer and the thickness. Rename the composite structure as EIFS wall (Figure 4.2).

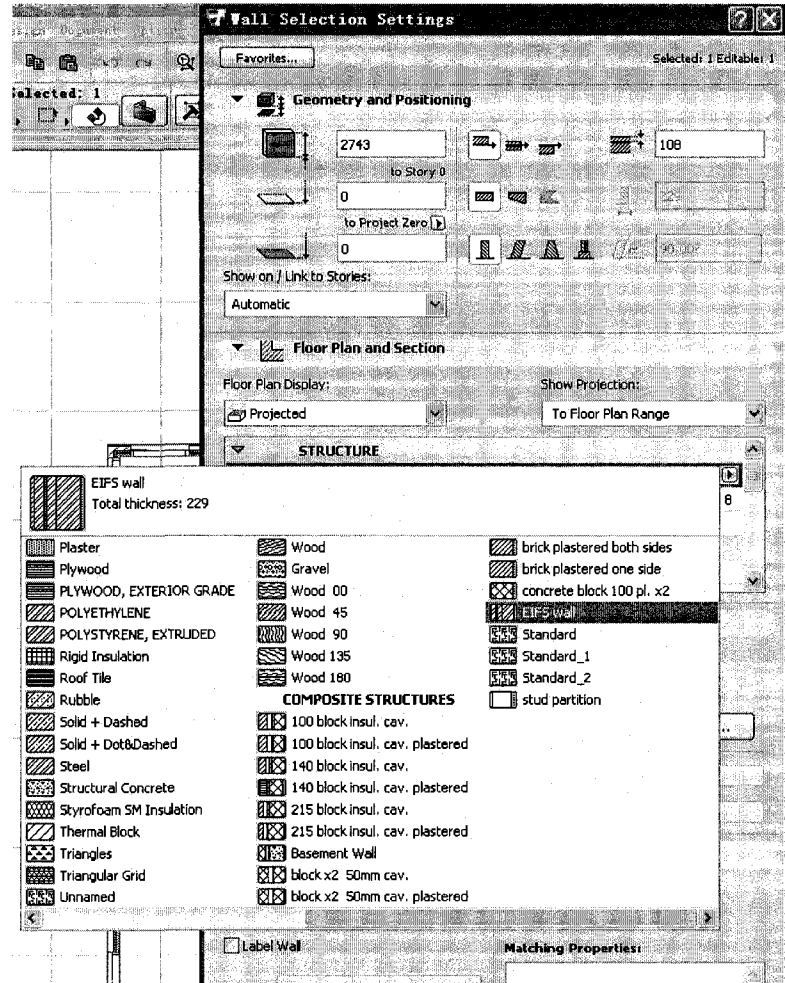


Figure 4.3: Assigning the EIFS wall to the exterior walls of the building model in ArchiCAD

(3) Loading or drawing building model: Open the IFC file of the NOVTEC house 3D model. This IFC building model was created by He (2005) using ADT. Both ADT and ArchiCAD are compatible with the IFC 2x 2 standards if the IFC add-on is installed. Any designed building model using ArchiCAD can be exported as IFC file.

(4) Assigning the EIFS wall to the house: Select and right-click an exterior wall component of the house. Select Wall Selection Settings from the pop-up menu. By clicking Structure / Cut Fill and selecting the EIFS wall from these wall assembly options, the selected wall is assigned with the EIFS wall (Figure 4.3). Repeat this step until all the exterior wall components are assigned.

(5) Exporting IFC: Click File / Save as. Set the file type as ifcxml. Type the filename “house.ifcxml” and click save.

Thus, a hierarchical BIM of this house in ifcXML (IAI 2006) is exported from ArchiCAD. The dimensions, materials, dependencies and other attributes of the exterior walls are contained in this file and will be used in the simulation of hygrothermal performance.

4.2.3 Attributes extraction of the wall

The wall information is retrieved from the ifcXML file. After running ACCBEP, a window pops up. Enter the layer tab. Click the button Read from IFC. Material name and thickness of each layer of the EIFS wall, which is read from the building information model “house.ifcxml”, are input into the program automatically (Figure 4.4).

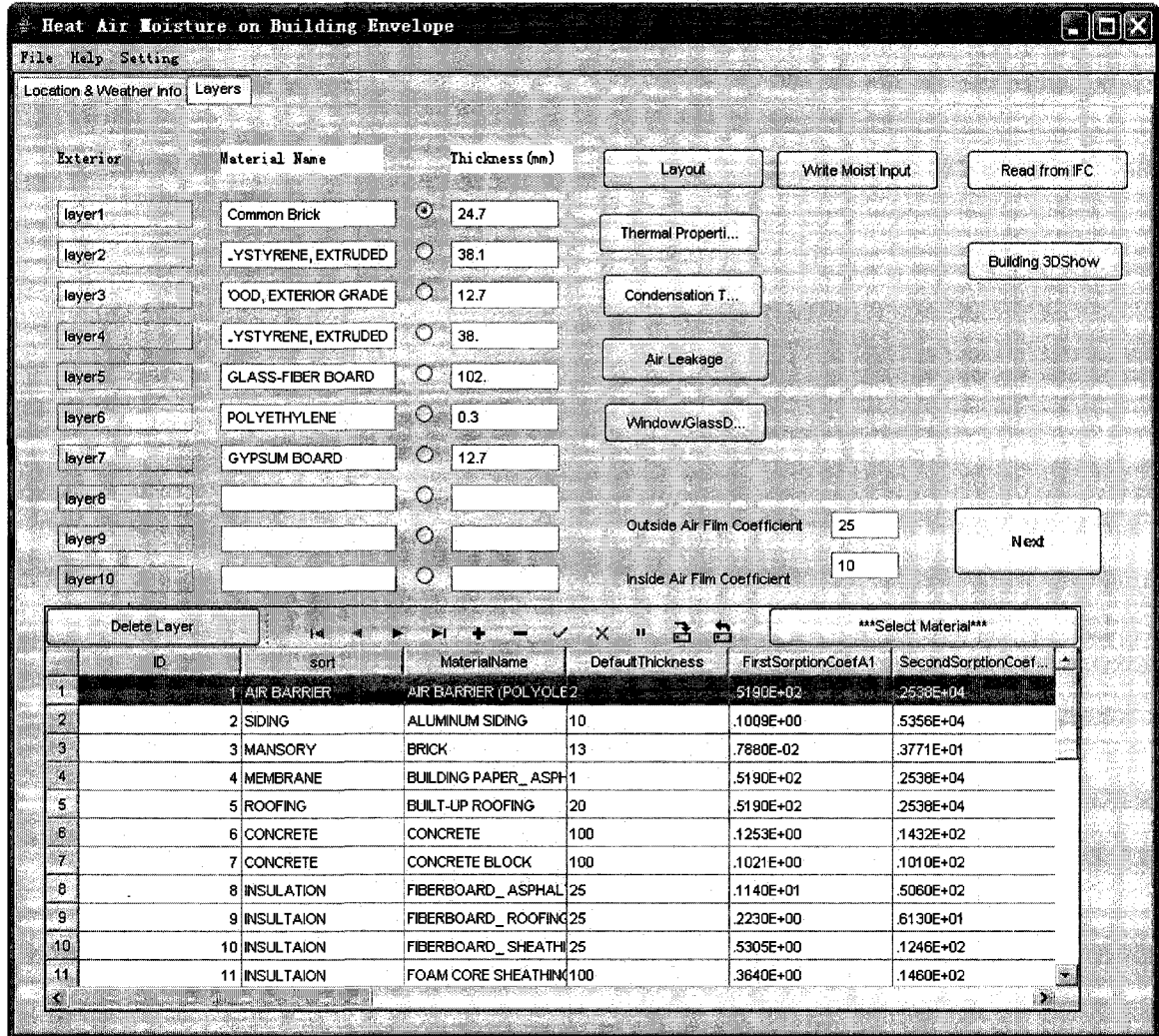


Figure 4.4: Snapshot of the layers' information of an EIFS wall obtained from ifcXML

Sometimes the designer wants to modify some parameter of the wall. For example, the designer wants to change the material of layer 7, gypsum board, to a wood sugar pine. Select radio-button of layer 7. Select the sugar pine from the materials database. Click the button Select Material. The material gypsum board is replaced by sugar pine. The designer also can edit the layer's dimension by inputting the thickness. Similarly, the layer is deleted by clicking the button Delete Layer. In this case study, the wall assembly is kept as the EIFS wall.

The materials and thickness information of the exterior wall assembly of the particular building component are displayed and the position of this wall is specified in 3D graphics by clicking the button Building3DShow. Figure 4.5 shows the screen capture of the house information display.

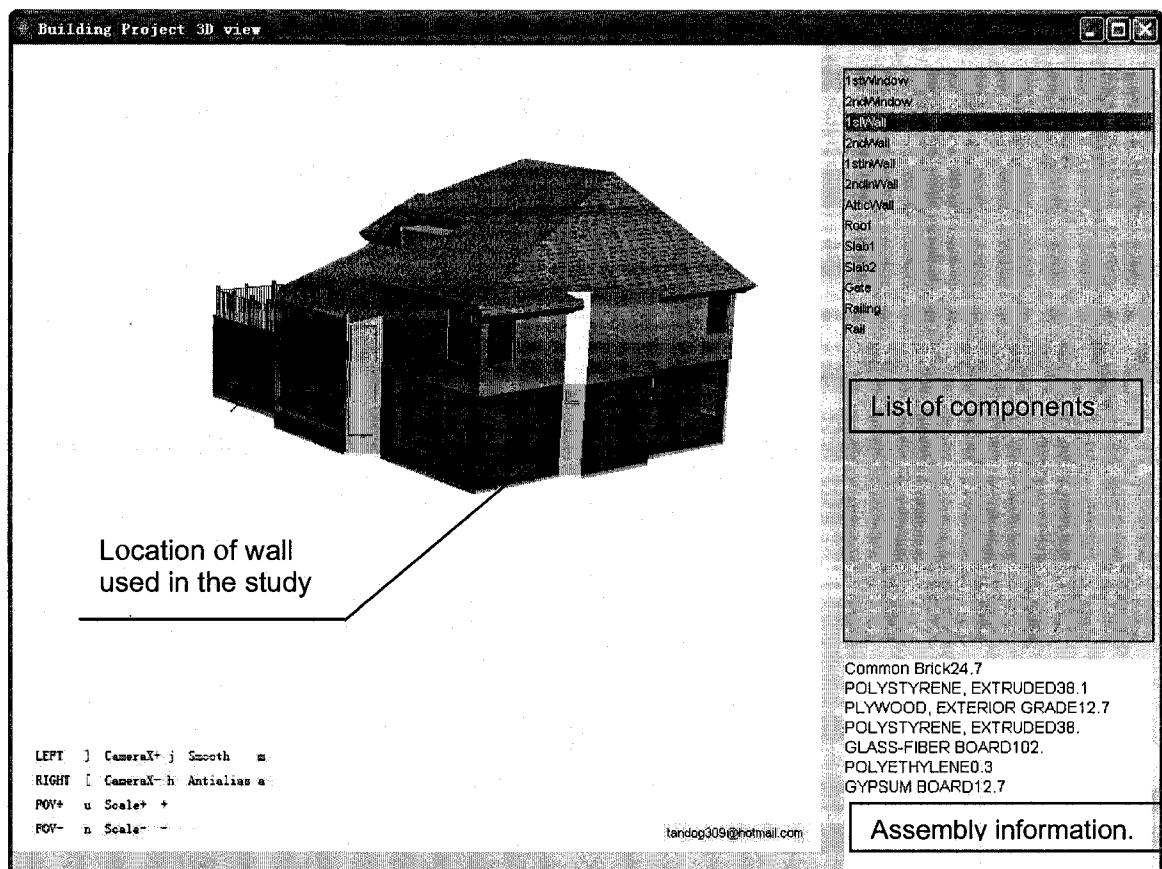


Figure 4.5: Screen capture of the display of wall location and assembly information

4.2.4 Hygrothermal simulation of exterior wall

(1) Steady-state hygrothermal analysis using Glaser method

Click the tab Location and Weather Info. Select Montreal as the city. Input outdoor temperature as -20°C , outdoor RH (Relative Humidity) as 65% according to the climatic data for heating design condition (ASHARE 2005). Input indoor temperature as $+20^{\circ}\text{C}$,

indoor RH as 50% to satisfy the basic human conformable requirement in winter. The steady-state calculation process using the conventional manual method is described in Appendix A.3 for the benefit of the reader. The input values of the Glaser method are inputted into the computation model of ACCBEP and the output values are integrated into the EBIM automatically.

By clicking the button Condensation, a profile chart including the curves of temperature, vapor pressure, and saturated vapor pressure of this EIFS wall is shown (Figure 4.6) after automated processing the relevant data of the exterior wall. The simulation results including R-value of the wall, condensation status, water permeability of the wall, interior surface temperature, and other parameters, are stored in the EBIM file and transferred to the code checking module automatically.

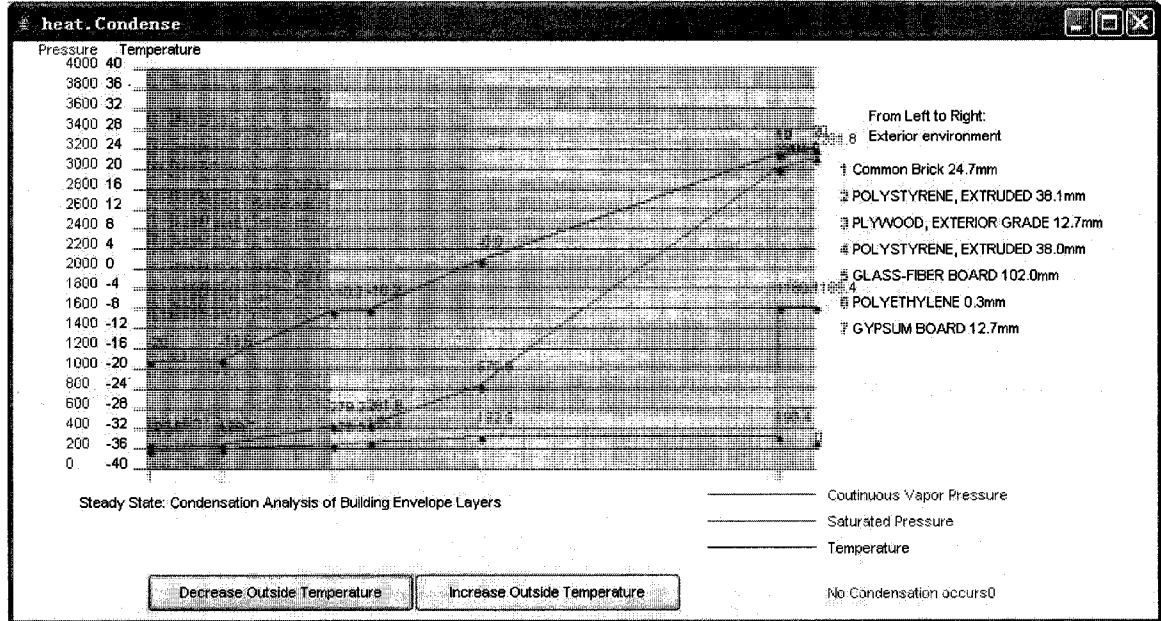


Figure 4.6: Screen capture of the profile chart of temperature, vapor pressure, and saturated vapor pressure of the EIFS wall

(2) Transient hygrothermal simulation using MOIST

The transient hygrothermal software MOIST is integrated into ACCBEP. MOIST allows calculation of the transient coupled one-dimensional heat and moisture transport in multi-layer building components exposed to natural weather. The long-term hygrothermal performance of the EIFS wall, which is described in Section 4.2.2, can be predicted using MOIST and the results are applied to check the design against the codes.

Under steady-state calculation, the RH within the wall assembly should not reach 100% otherwise liquid water would form within the wall in the form of condensation. Under transient simulation, the weekly average surface RH at a wall layer made of porous materials should not exceed 80 %. Otherwise, the mold may grow and the wall would be damaged. Burch and TenWolde (1993) stated “The International Energy Agency (1990) recently published Guidelines and Practices (Volume 2) for preventing mold and mildew growth at building surfaces. The consensus was that weekly mean surface relative humidity above 80% is conducive to mold and mildew growth”. A well-designed of a wall must comply with this criterion. In this example, the weekly average RH at the warm side of the insulation layer, fiber glass, should not exceed 80%. MOIST is applied to calculate the weekly average surface RH of the EIFS wall. In this example, the simulation conditions of MOIST include:

- The wall is the EIFS wall described in Section 4.2.2.
- Initial temperature of each layer is set 20°C.
- Initial moisture contents of layers “correspond to the equilibrium moisture content (EMC)⁸ at a relative humidity of 50%” (Burch and Chi 1997).
- Weather data is Montreal’s hourly weather data file from MOIST.

⁸ The definition, recommended values, and calculation equations of EMC refer to (Simpson and TenWolde 1999) and (Burch and Chi 1997).

- Material properties including heat transfer properties, vapor permeability properties, sorption coefficients, and capillary coefficients are taken from MOIST building material property database.
- Simulation time step is 1 hour. Simulation period is 2 years and plot interval is 168 hours (i.e. 7 days).
- Convection coefficient at inside surface ($\text{w/m}^2\cdot^\circ\text{C}$) is 2.61.
- Convection coefficient at outside surface ($\text{w/m}^2\cdot^\circ\text{C}$) is 11.36.
- Solar absorptance of exterior surface (Fraction) is 0.70. Surface tilt angle (Degrees) is 90.00. Surface azimuth orientation (Degrees) is 0.
- Indoor temperature ($^\circ\text{C}$) is 20.
- Indoor relative humidity is 50%.

The simulation conditions can be input using the graphic user interface provided by MOIST. This process of inputting these values is time-consuming. ACCBEP simplifies the manual time-consuming input procedure. The automated input process is automated as described in Section 3.3.2, subsection (3.2) *Integration of transient hygrothermal simulation using MOIST*. Using ACCBEP, the EIFS wall's information including thickness, material names, and simulation period, location is written into the MOIST-readable input files. Therefore, users can complete the simulation input procedure by clicking the button "Write into MOIST". Then the MOIST program runs. MOIST outputs simulation results (The diagrams of output files are given in Appendix A1.2). ACCBEP converts the results of MOIST into EBIM.

In this case, the output file Results.ARH, which includes the data of the weekly average surface RH of the exterior wall, is selected for analyzing the performance of the designed EIFS wall. Since the initial values of the simulation conditions are assumed, the data during the latter year of the two year is used to determine if the weekly average RH at the warm side of the fiber glass layer is over 80%. If so, then the design of the EIFS wall needs modification. If not, the design of EIFS wall complies with the design regulation.

As shown in Figure 4.7, weekly surface RH values at the warm side of the fiber glass layer are always below the critical 80% during the latter year of the two-year period. The design of the EIFS wall passed the criteria of the design regulation.

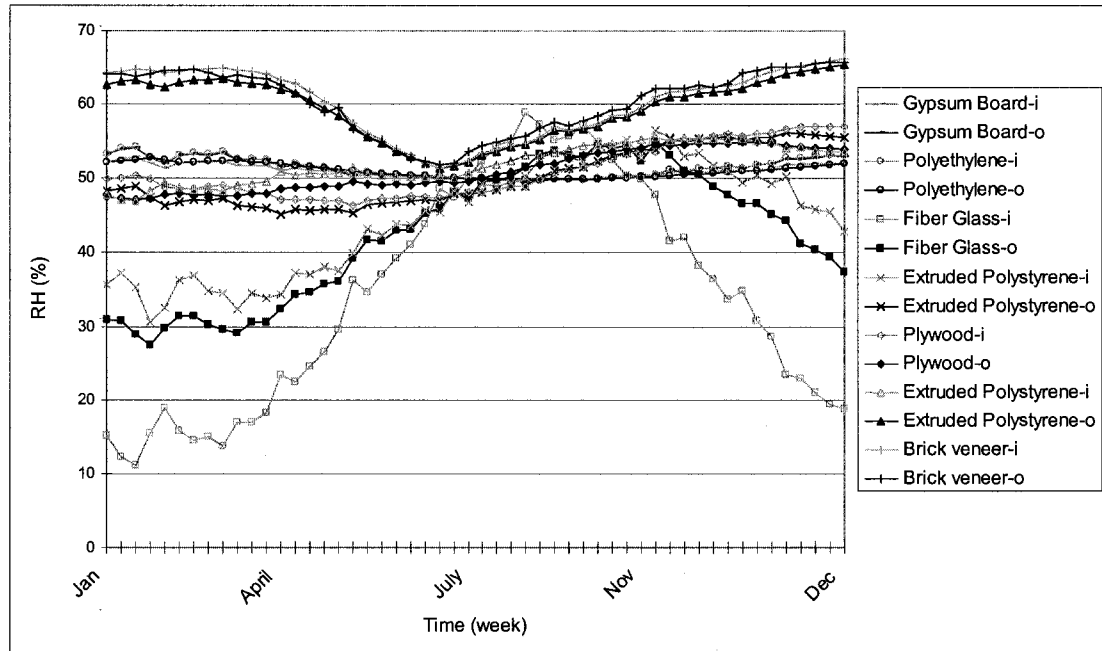


Figure 4.7: Weekly average surface relative humidity (RH) of the EIFS wall layers during the latter year of the two-year calculation period⁹

The procedure of applying the MOIST has the following steps:

By clicking the button “Write Moist Input” on the window shown in the Figure 4-4, the EIFS wall’s information derived from the file “house.ifcxml” is written into the file CONST.DAT according to MOIST format automatically.

Run the core computing program of MOIST, ANALYZE.exe for simulating the hygrothermal transfer through the EIFS wall.

After the simulation process of MOIST, the simulation results files are generated. These simulation outputs will be processed in the next code checking module.

⁹ “-o” means outside and “-i” means inside of the house relative to the EIFS wall.

4.2.5 Simulation result analysis and conversion

Simulation results are converted to the EBIM for automated code checking since the MOIST only outputs text files. EBIM is generated by integrating the BIM and converted hygrothermal data of the wall obtained from MOIST simulation result.

The automatic procedure of analyzing MOIST simulation results, converting analysis results to EBIM, and writing the EBIM to a file follows the steps below.

- (1) By clicking the button Next, a window pops up for inputting the design data of the study house and EIFS wall (Figure 4.8).
- (2) Click the button “Get from Steady”. The simulation results using Glaser method, including R-value, condensation status, water permeability, indoors RH, indoors air temperature, and interior surface temperature, are automatically filled into the text fields. The background color of the text fields is changed to red.

Design Facts Input		
Location	Montreal	
House Type	house	
Wall position to ground	above	Get From Steady...
Heat resource	Electricity	
R value m2.C/watt	9.67	
Vapor is installed on warm side?	yes	Get From Steady...
Is cladding with low permeability installed?	yes	
Installed Vapour Barrier?	yes	
Water Vapor Permeability Ng/m2.S.Pa	1.08	Energy+
Does Condensation occur within wall/roof?	no	
Condensation rate Ng/m2.s	0.00	
The days which RH>80% within the building envelope during one year	5.0	2
Interior Surface Temperature C	20.00	
Indoors RH %	50.00	
Indoors air temperature C	20.00	
Air Permeance of exterior wall L/s.m2	0.02	
Air Permeance of roof L/s.m2	0.02	
Joints Taping, Gasket, Sealed Penetrations, Ensure Continuity of Air Barrier?	yes	Check Constants
Window Type	type2	
Design air leakage rating of windows	a1	
Air leakage rate L/s.m2	2	
Fire control distance (meter) (the distance from an exposing building face to a p... if the exposing building cladding is combustible?	0.2	
Horizontal distance to the the window of adjoint wall (meter)	10	
the fire rating of that exposing building face cladding (mins)	60	
Installed skylight?	yes	
surface Grading from ex. Wall to ground?	yes	
External Drains installed?	yes	
Impermeable cap over backfill installed?	yes	
drain screen:(e.g. sand or gravel) adjacent to foundation walls?	yes	
Waterproofing of exterior side of basement wall?	yes	
Drainage pipes along the foundation perimeter installed?	yes	
Watertight control joints installed?	yes	
Flat roof or slope roof?	flat	
Slope grade of roof	0.02	
Slope grade of valley of roofs	0.02	
drainage area of 1 m2 roof (mm2)	100	
is air cavity designed behind the rainscreen wall?	yes	
width of air space (in.)	2	
Flashing installed on the bottom of rainscreen wall?	yes	
Drainage plane installed on the bottom of rainscreen wall?	yes	
Weep holes positioned on the bottom of bottom of rainscreen wall?	yes	
Crushed stone layer under slab installed?	yes	
Capillary break installed on the footing along the foundation wall?	yes	
damping proof is installed on the exterior side of basement wall?	yes	
capillary break between the sill plate and the top of foundation wall ?	yes	
Operable or Fixed Window	fixed	
Energy rating of window	100	
ratio of studs in 1 m of wall length	10	

Figure 4.8: Getting / inputting the design data of the house

- (3) Click the button “Get from Moist”. The simulation results from the MOIST program are analyzed. The weekly average RH, the average R value, and the average interior surface temperature of the exterior wall during the latter one year are obtained and automatically filled into the text fields. The background color of the text fields that are filled with MOIST results is changed to green.
- (4) The building envelope attributes that are not included in both of the simulation results and IFC need to be input manually because technical details information in design building envelopes are not supported by the current CAD software.
- (5) Click the button “Check Compliance”. The attributes of the building envelope of the house are exported into the format of EBIM shown in Figure 3.2 for checking the design of the wall assembly. Simultaneously, the code checking module is activated.

4.2.6 Developing decision tables

Sixteen decision tables including 159 rules are developed in this system based on Horvat(2005) and building codes and design guides described in Section 2.5.1 - 2.5.6. Microsoft Excel spreadsheet is applied as the developing tool of the decision tables. The details of developing decision tables are introduced in Section 3.2.3 and listed in Appendix C. Two regulations are highlighted for describing the working flow.

- Thermal resistance of this wall, R value, must comply with the Energy Code (MNECH 1997, MNECB 1997) as shown in Tables 3.3 (a and b).

- Using hygrothermal transient simulation, when an interior vapor retarder is used in the construction, the weekly average surface RH at the warm side of the insulation layer should be less than 80% as shown in Table 3.4 (Burch and TenWolde 1993).

In order to automatically determine if the wall assembly design satisfies the design regulations, the EBIM needs to be matched against the rules within the decision tables which represent these regulations.

4.2.7 Rules engine processing

ACCBEP is integrated with JBoss rules engine to process rules and facts, which are derived from EBC and EBIM, respectively. The facts (working memory) are obtained from the ifcXML model and simulation output data retrieved from dew-point method and MOIST simulation. The rules are obtained from the decision tables of an EBC. The JBoss rules engine processes the rules package and facts to check the exterior wall's design and an assessment report is generated. This rules engine is executed by clicking the button "Check Compliance" shown in Figure 4.8.

4.2.8 Report generation

A code compliance report is output as HTML format as shown in Appendix D. This evaluation report contains the checking results, reference indices, and advices based on the design facts and the decision tables. According to the assessment report, the designer can see that the wall assembly passed all the predefined rules because the wall is designed according to the reference low-energy NOVTEC house. In this case, the report shows that the assembly design of this EIFS wall satisfies all the concerned regulations

explained above. For the purpose of validation, when the vapor barrier layer was removed from the assembly of this wall, the assessment report gave the advice “install vapor / moisture barrier with a high vapor resistance, e.g., polyethylene” (Table 3.4). When the thickness of the wall’s insulation layer was reduced, an advice “in Region A, Quebec, thermal resistance of the wall above the ground must be higher than 4.1 RSI.” was given in the assessment report based on Table 3.3(b). Designers can find where the design error is and then revise the design to satisfy the requirements of the design regulations.

4.3 Case study 2: Comparison of heating load when replacing exterior wall system of a small building

4.3.1 Overview

It is assumed that a small bank building is located in Montreal, Quebec, Canada. This building information model, smallbank.ifc, is from an example file from EnergyPlus v2.0. Figure 4.9 is the perspective view of the small bank building in ArchiCAD. Figure 4.10 is the ground floor plan of the small bank building in ArchiCAD (Screen capture).

This case study is for comparing the heating loads of a room when two different insulation systems are applied to the same small building under the same design conditions. ACCBEP is applied for calculated the R value of the different exterior walls based on EnergyPlus. This R value is written into the EnergyPlus input file. After the simulation, the heating loads of the building with the alternative insulation systems are obtained using ACCBEP for comparison.

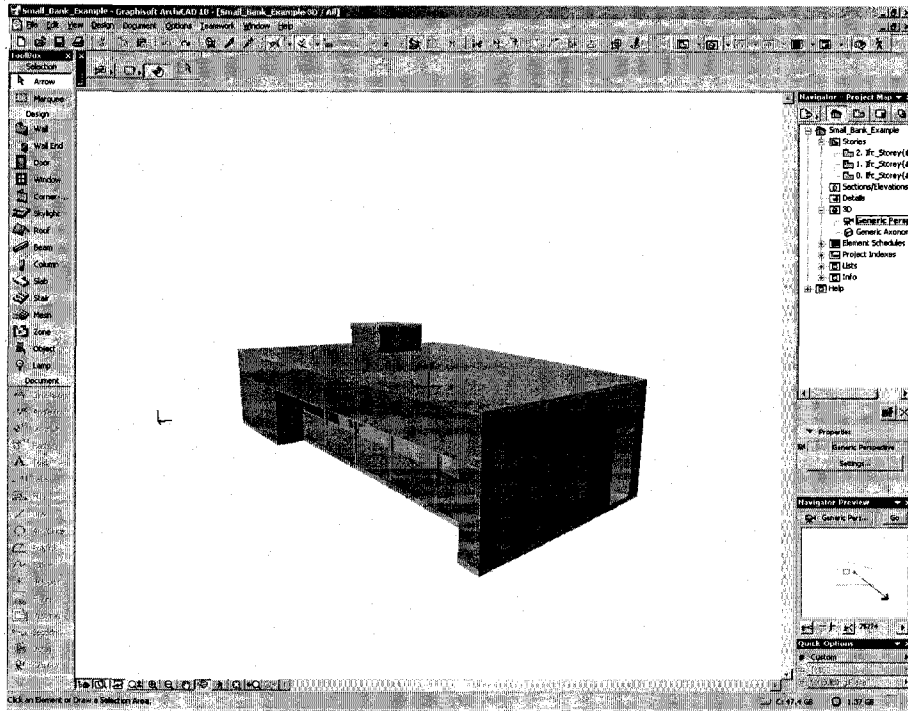


Figure 4.9: Perspective view of the small bank building in ArchiCAD (screen capture)

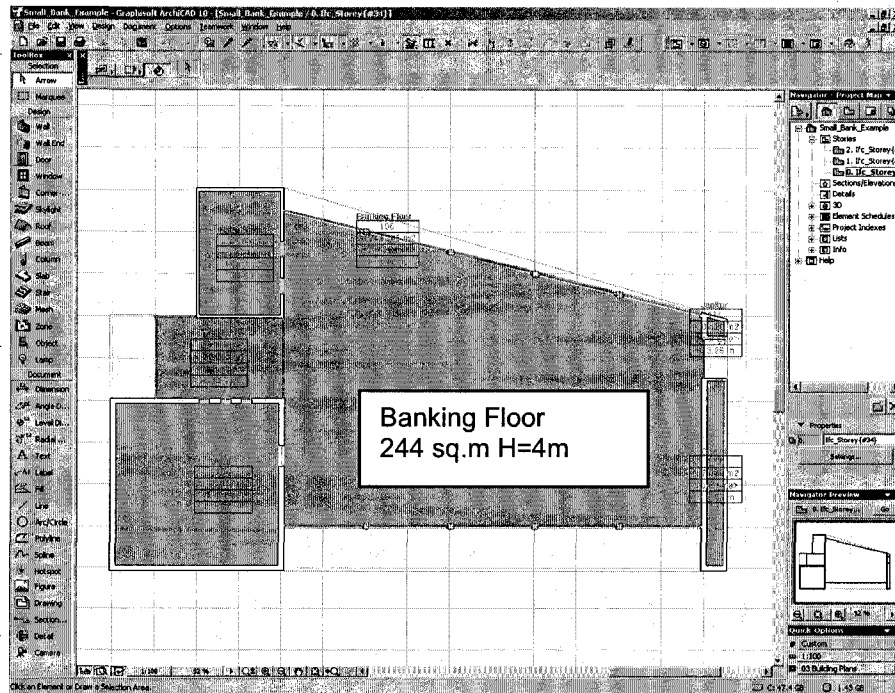


Figure 4.10: Ground floor plan of the small bank building in ArchiCAD (screen capture)

In the first case, the insulation systems of exterior walls of the small building just meet the minimum requirements of R-values according to the Quebec energy conservation regulation (Éditeur officiel du Québec 2007). The R value of the exterior wall is set to the minimum R-value 3.4 RSI for calculating heating load. The daily heating load is simulated using EnergyPlus based on the hourly weather data. In the second case, the exterior wall system of the building is replaced by the EIFS wall system (Figure 4.1), which has higher thermal resistance. The heating load results of the two cases are added to the EBIM of ACCBEP for comparison as discussed in the following sub-sections.

4.3.2 Converting the BIM to EnergyPlus format

In this case, the file `smallbank.ifc` is converted to `smallbank.idf`. In the IDF file, only the geometry information of the small building, such as the building envelopes' dimensions, positions, absolute and relative coordinate system, is included. Other energy simulation parameters for calculation the heating load of this building need be defined manually as the template building model for energy analysis.

4.3.3 Heating load calculation based on the minimum R value requirements

The design condition is defined for analyzing energy performance of the building. Heating load is a critical value for sizing the heating equipment and calculating the energy consumption. More precise simulation results can be obtained using EnergyPlus based on the hourly weather data rather than the conventional computation method based on a constant design degree day.

Assumptions of design conditions for simulation input:

- Heating status: the room Banking Floor is heated, other rooms are uncontrolled.
- Run period: one year (from 1 January to 31 December)
- Time step: one hour
- Thermostat setpoint: 20°C for heating, 24 °C for cooling
- Deadband of thermostat: 4°C
- Schedule: always (Heating equipment is always running.)
- Annual weather data: Montreal International Air Port data
- R value of exterior walls: 3.4 RSI
- R value of roof: 6.8 RSI
- R value of floor slab: 4.7 RSI

The thermal resistances of the building envelope meets the minimum requirements of Quebec energy conservation regulation (Éditeur officiel du Québec 2007). This building model is taken as a reference model for comparison.

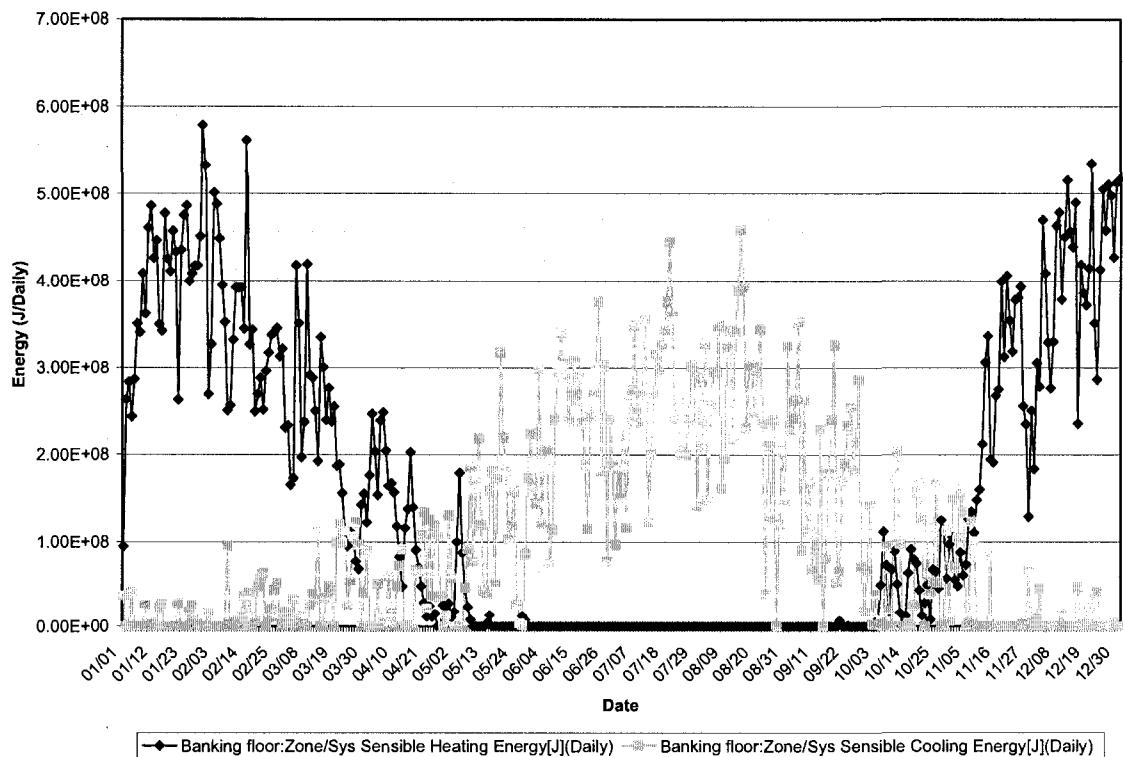


Figure 4.11: Chart of the heating / cooling load of the banking floor during one year ($R_{ex, wall}=3.4$ RSI)

The design conditions and output parameters are input into the EnergyPlus input file smallbank.idf (refer to the file names listed in Appendix E).

The program EP-launch is used to run simulation. The corresponding input file and weather file are selected (Figure 4.12).

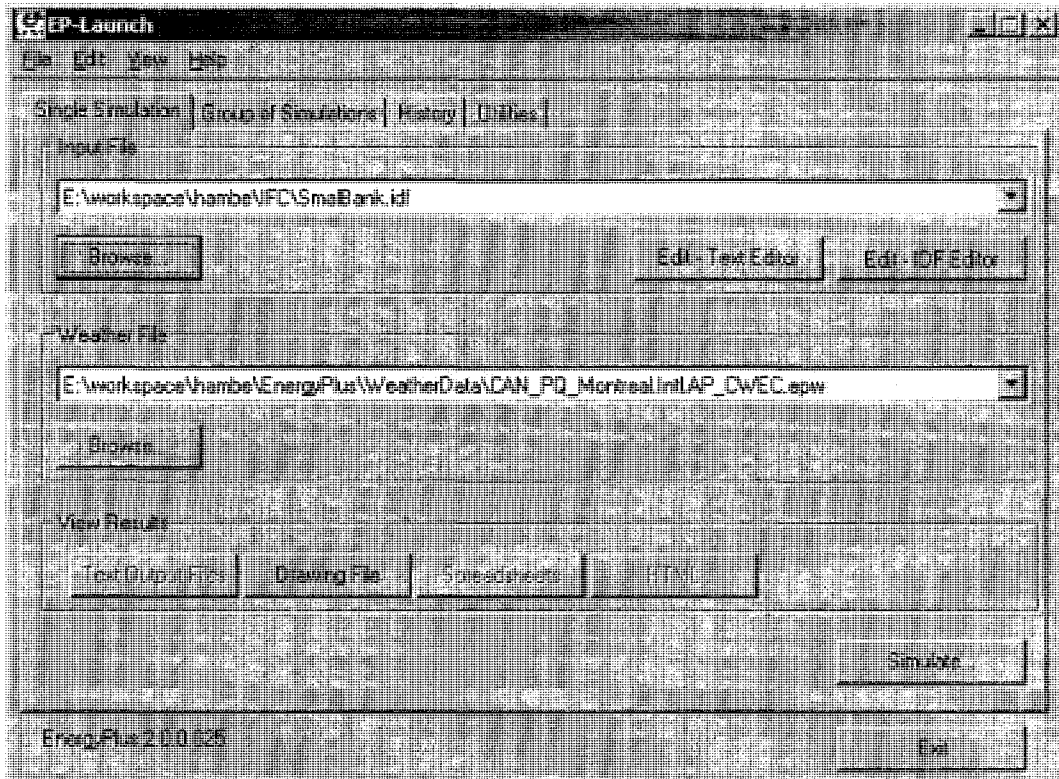


Figure 4.12: Screen capture of selecting input file and weather file in EnergyPlus

After running the simulation using EnergyPlus, a data file smallbank.csv is generated. The data of daily heating load and cooling load of the room banking floor during one year is contained in this file (Figure 4.11). By summing up the daily heating loads during one year period, the annual heating load is obtained. In this case, the annual heating load is 5.36×10^{10} J. Table 4.1 lists the simulated heating loads of the banking floor with exterior walls ($R_{ex, wall} = 3.4$ RSI).

**Table 4.1 Simulated heating loads of the banking floor with exterior walls
($R_{ex.wall}=3.4$ RSI)**

Annual Heating Load (J / year)	53,601,406,939
Maximum Daily Heating Load (J / day)	579,015,715
Peak Average Hourly Heating Load (J / hour)	24,125,654
Peak Average Hourly Heating Load (KW)	6.70
Unit heating load (W/m^2)	27.47

4.3.4 Apply R value of EIFS wall to the building

An EIFS wall as described in Section 4.2.2 is designed in ACCBEP. The steady-state R value is calculated using the method described in Section 4.2.3 and 4.2.4 of Case study 1. The same process explained in Case study 1 is repeated to calculate the R value of the EIFS wall. The new calculated R-value is applied to the small building automatically.

4.3.5 Heating load calculation based on a well-insulated exterior wall system

After the simulation using EnergyPlus, an output file, which contains the daily heating load and cooling load data, is generated. Figure 4.14 is the chart of the heating / cooling load of the banking floor with the exterior wall during one year ($R_{ex. wall}=9.68$ RSI). By summing up the daily heating load, the annual heating load is obtained as listed in Table 4.2.

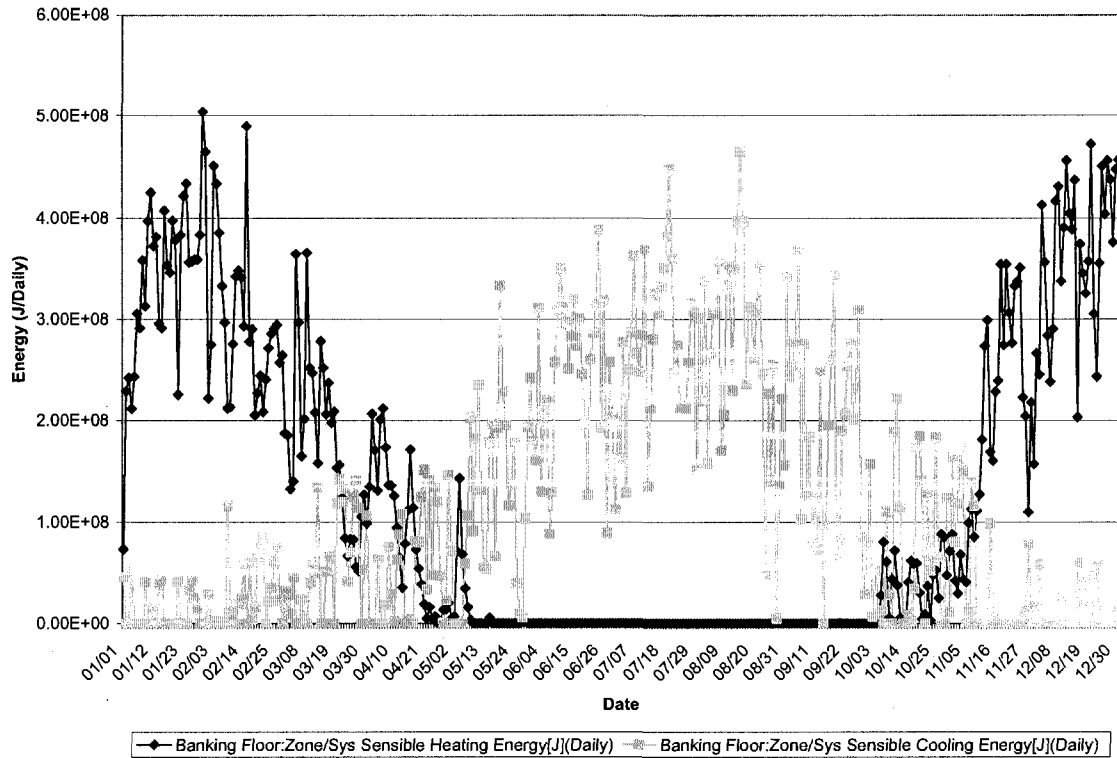


Figure 4.13: Chart of the heating / cooling load of the banking floor during one year ($R_{ex, wall}=9.68$ RSI)

Table 4.2 Simulated heating loads of the banking floor with exterior walls ($R_{ex, wall}=9.68$ RSI)

Annual Heating Load (J / year)	45,534,736,074
Maximum Daily Heating Load (J / day)	503,631,801
Peak Average Hourly Heating Load (J / hour)	20,984,658
Peak Hourly Heating Load (KW)	5.89
Unit heating load (W/m^2)	23.89

4.3.6 Processing EnergyPlus data in ACCBEP

The file of daily heating loads, smallbank.csv, contains a large amount of data. ACCBEP scans the file smallbank.csv, reads the simulation results, adds up the daily heating loads, writes into the EBIM, gets the annual heating load, and displays the result. This process is automated by clicking the button “Get Annual Heating Load”.

4.3.7 Comparison of heating loads of the building based on the different exterior wall systems

Table 4.3 Heating energy and cost comparison of the room banking floor with the different insulation wall systems

Wall Type	Annual Heating Load (J/year)	Energy (KWH)	Cost (\$)
R=9.68 RSI	45,534,736,074	12,648	885.40
R=3.40 RSI	53,601,406,939	14,889	1042.25

Note: the cost is calculated based on 7 cents / KWH.

As shown in Table 4.3, the banking floor with R-value of exterior walls of 3.4 RSI, which meets the minimum requirement of Quebec energy codes, consumes 12648.5 KWH during one year and the heating cost is \$885.40 based on the average unit price of 7 cents/ KWH (Hydro Quebec 2007). When the EIFS walls are used instead of the original exterior walls for the same building, the annual energy load is 14889.3 KWH, which costs \$1042.25. Comparing the heating energy and cost of the room Banking Floor in the small bank building, a conclusion is drawn that the heating energy saved is 17.7% after replacing the exterior walls as the EIFS walls.

4.4 Conclusions

By presenting the case studies, the ACCBEP system demonstrates advantages below:

- The complicated tasks are processed easily using automated application software integrated building simulation software, particularly in building envelopes design.
- The different aspects for assessing the performance of building envelopes are integrated into the ACCBEP software framework.
- The new concept EBIM, which integrates BIM and building simulation results together, shows an open platform that can apply the different analysis methods.

- The rules of building codes that contain complex logics are separated from the code compliance checking system.
- Users who are not experts in building engineering can easily use this computer tool to check the building envelope system based on the building codes.
- Users are freed from the time-consuming and repeated works in complying the building codes and designs.

Case study 1 gives an example of working flow of ACCBEP. Users can follow the same steps to evaluate the building envelope performances for variable designs based on the design regulations. Case study 2 demonstrates that ACCBEP can integrate the third-party simulation software for alternative purposes based on the proposed approach. The framework based on EBIM, EBC and rules engine can be a standardized framework for automated code compliance checking under an open and standard environment. A developer can easily add more building codes and more building simulation software into this framework and develop a new system for different purposes.

Chapter 5 Conclusions and Future work

5.1 Conclusions

In this thesis, a new approach has been presented for automated code compliance checking for evaluating building envelope systems. This approach starts by developing an Extended Building Information Model (EBIM) to integrate simulation results with the BIM, and an Extended Building Code (EBC) to represent design rules using decision tables. Then, a rules engine is used to check the compliance of the design facts in the EBIM with the rules packages of the EBC. The separation of the EBIM and EBC from the rules engine is important because the separated parts can be generated and modified independently by specialists in different domains. For example, new simulation tools can be used to analyze the performance of building envelopes and generate results which can be added to the EBIM as new design facts. Furthermore, the rules embedded in the decision tables of the EBC can be updated to reflect changes in building codes without the need to change the code compliance checking rules engine. This approach, when fully implemented in practice, would result in more efficient code compliance checking of building envelope designs with the added value of seamlessly incorporating the results of simulation tools.

The research presented in this thesis has implemented a prototype system based on the newly proposed approach for evaluating building envelope performance according to building codes. Moreover, by testing the prototype system in case studies, the proposed framework has been proven to be rational, achievable and extensible. The goal of

assisting building envelope designers to complete the building code compliance checking quickly, correctly, easily, and efficiently has been achieved.

5.2 Future work

The difficulties and limitations that we met during the research suggest possible directions for the following future work.

- Refining the EBIM and extending the proposed approach to other aspects of building envelope design need further study.
- It is still a challenging work to completely represent the contents and aspects of a building code in an automated code checking system.
- Developing decision tables is still a manual work. A decision table may be automatically derived from the original texts of a design regulation when applying advanced Artificial Intelligence (AI) techniques.
- Visualization module can be developed for viewing the internal structure of a building envelope and its relationships to the whole building and its sub-systems.
- More information of the design of building envelopes, such as junctions and crossing of building components shall be included in the BIM. This work needs cooperation with international organizations and vendors of building information standards.

This research established a solid milestone for helping the developers in the fields of building engineering and software programming.

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Appendix A: Hygrothermal Numerical Model

Section A.1 of this Appendix describes the transient hygrothermal numerical model (Hagentoft and Blomberg 2000 and Li et al. 2006) which is a basic numerical model of the hygrothermal simulation software such as MOIST, 1D-HAM and WUFI. Section A.2 describes the programming method of the simulation software that can be integrated into the proposed framework. MOIST is integrated into the ACCBEP system. Section A.3 describes the steady-state hygrothermal numerical model that is also named Glaser method or dew-point method. Section A.4 describes the programming method using the Glaser method that is applied in the ACCBEP framework.

A.1 Transient hygrothermal numerical model

Hagentoft and Blomberg (2000) state the governing equation for the temperature T is:

$$-\frac{\partial}{\partial x} \left(-\lambda \frac{\partial T}{\partial x} + q_a \rho c_a \cdot T \right) + r \frac{\partial W}{\partial t} = \rho c \frac{\partial T}{\partial t}$$

where

x : position of the x-axis along the vector of heat transfer (m);

T : temperature (K);

λ : thermal conductivity of the wall material (W/m·K);

q_a : air flow rate (m³/m²·s);

ρ : air density (kg/m³);

c_a : heat capacity of the air (J/m³·K);

r : latent heat of evaporation (J/kg);

W : water content (kg/m^3);

t : time (s);

c : heat capacity of the wall material ($\text{J}/\text{m}^3\cdot\text{K}$).

The governing equation for the humidity by volume is:

$$-\frac{\partial}{\partial x}(-\delta_v \frac{\partial v}{\partial x} + q_a \cdot v) = \frac{\partial w}{\partial t}$$

where

x : position of the x-axis along the vector of heat transfer (m);

δ_v : vapor diffusion coefficient (m^2/s);

v : humidity by volume (kg/m^3);

q_a : air flow rate ($\text{m}^3/(\text{m}^2\cdot\text{s})$);

w : water content (kg/m^3);

A.2 Programming method of transient hygrothermal computation

The simulation of the combined heat, air and moisture processes is performed using the following steps (Hagentoft and Blomberg 2000). The time step Δt is the stable time step.

- (1) Start ($t=t_{start}$)
- (2) Input of start values for temperatures and moisture (w, T)
- (3) Insert the actual boundary conditions (T, I, v, q_a)
- (4) Determine the conductance
- (5) Calculate the stable time step (Δt)
- (6) Calculate the relative humidity ($\phi(w)$)
- (7) Calculate the humidity by volume ($v = \phi \cdot v_{sat}$)

- (8) Calculate the change in moisture content (Δw)
- (9) Calculate the change in temperature (ΔT)
- (10) Update the time ($t_{new}=t_{old}+\Delta t$)
- (11) Update the moisture content ($w_{new}=w_{old}+\Delta w$)
- (12) Update the temperature ($T_{new}=T_{old}+\Delta T$)
- (13) Repeat step 3 to 12 until the stop time is reached
- (14) Stop

The EIFS wall described in case study 1 is used for simulation using MOIST. The input parameters including outside and inside loadings are described in Section 4.2.4-(2). The output data files are included in the CD-ROM with this thesis. Figures A.1 (a) to (d) are plots of the simulation output files of MOIST. Please note the data of the latter year of the two year period are more reliable since the initial values of temperature and moisture contents of the materials are assumed

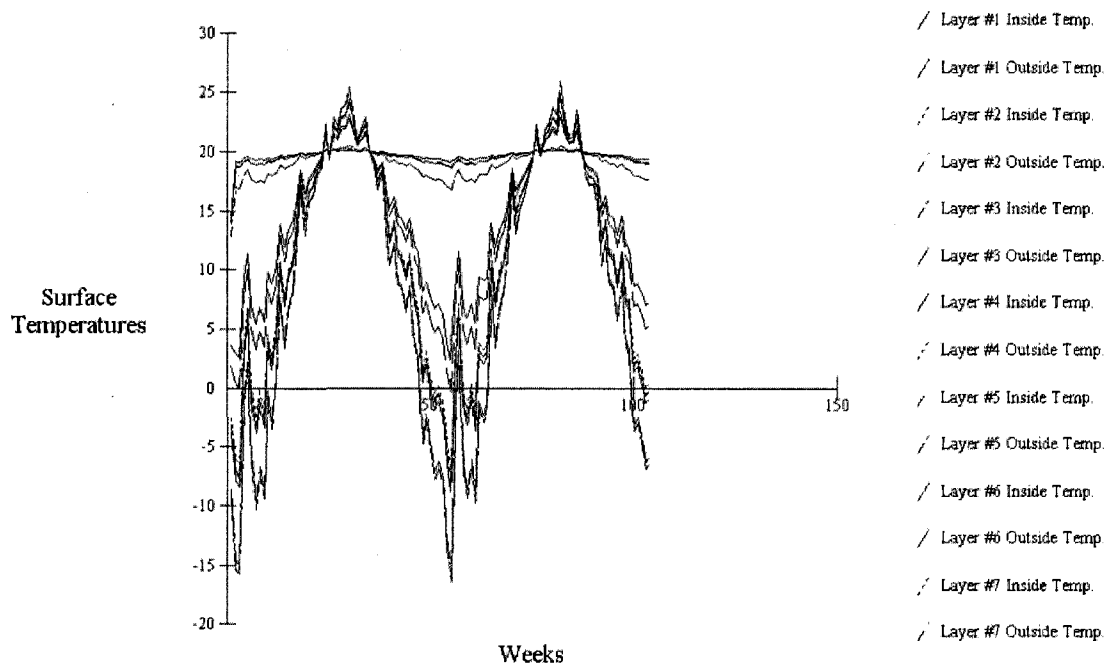


Figure A.1 (a): Weekly average surface temperatures of the EIFS wall in Montreal over 2 years (X axis represents time (week). Y axis represents surface temperature ($^{\circ}\text{C}$)).

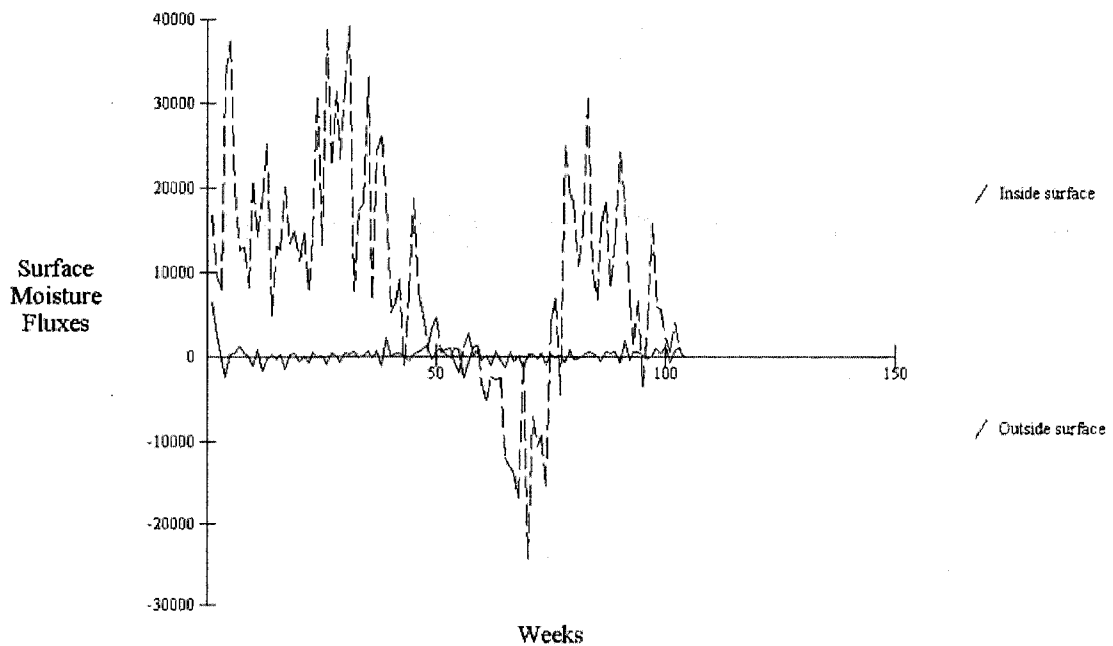


Figure A.1 (b): Surface moisture fluxes of the EIFS wall in Montreal over 2 years (X axis represents time (week). Y axis represents surface moisture flux ($\text{ng}/\text{Pa}\cdot\text{s}\cdot\text{m}^2$)).

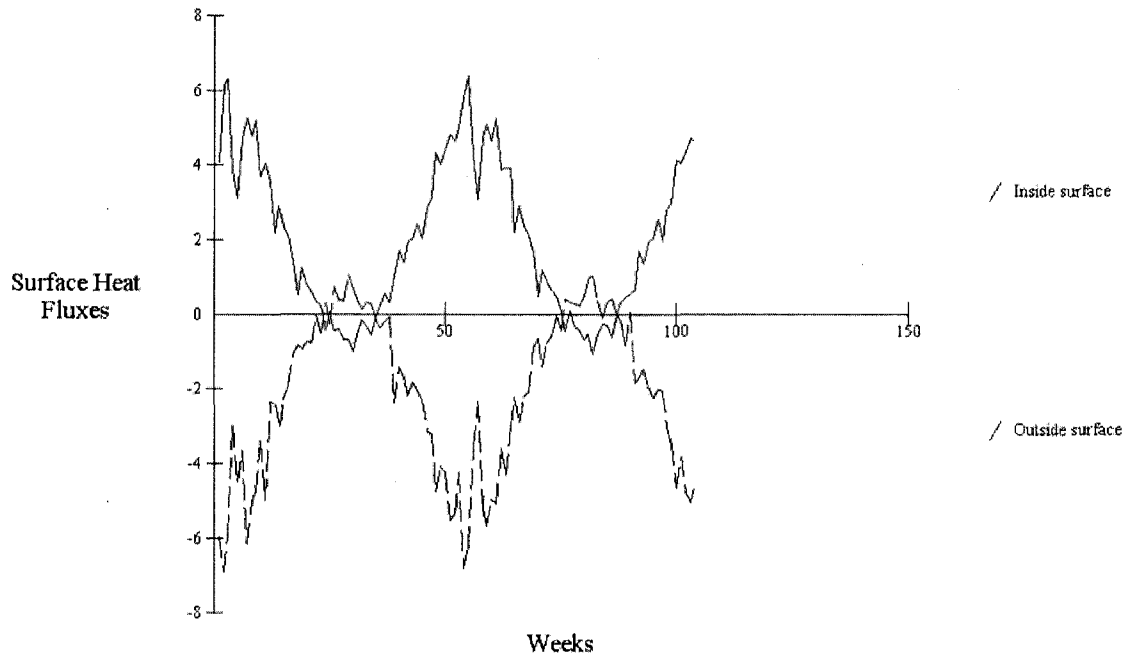


Figure A.1 (c): Surface heat fluxes of the EIFS wall in Montreal during 2 years (X axis represents time (week). Y axis represents surface heat flux (W/m^2)).

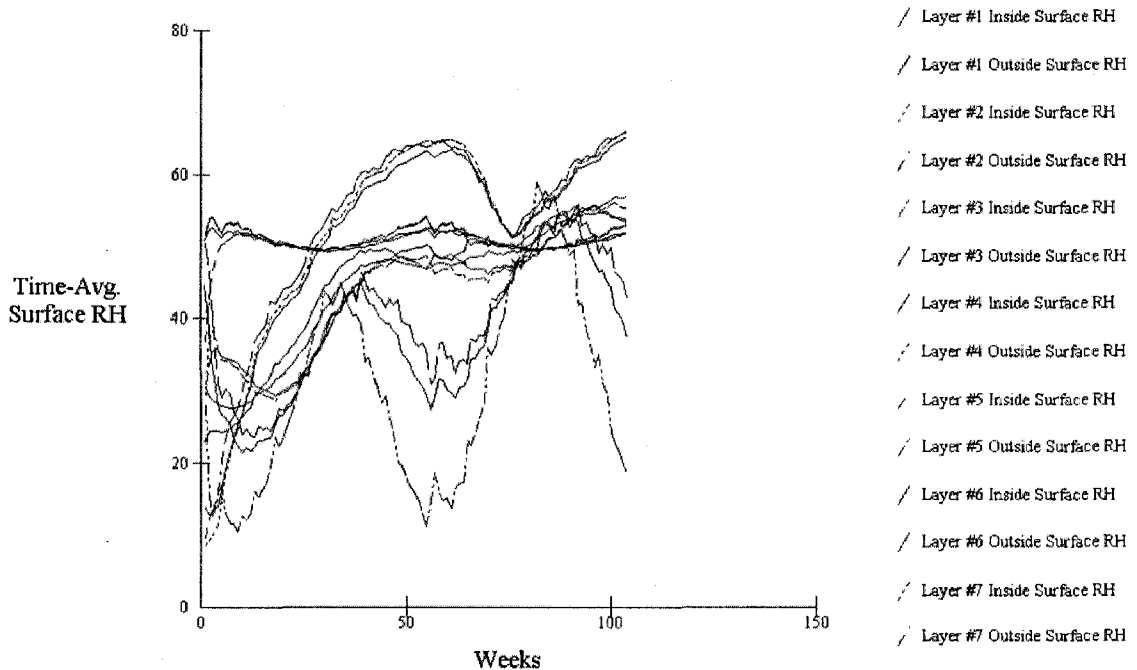


Figure A.1 (d): Weekly average surface RH of the EIFS wall in Montreal over 2 years (X axis represents time (week). Y axis represents surface RH (%))¹⁰

¹⁰ The layer order in MOIST (from inside to outside) is reversed in ACCBEP (from outside to inside).

A.3 Steady-state hygrothermal numerical model

In this section, steady-state hygrothermal calculation equations (Glaser method) are stated first, and example using the Glaser method is then presented to demonstrate the calculation procedure. As shown in Figure A.2, the EIFS wall, which is described in case study 1, is subjected to outside design temperature and relative humidity of -20°C and 65%, respectively and to typical residential interior design temperature and relative humidity of 20°C and 50% respectively. The temperature, RH, and vapor pressure profiles across the envelope are shown in Table A.1 and Figure A.3 (a and b).

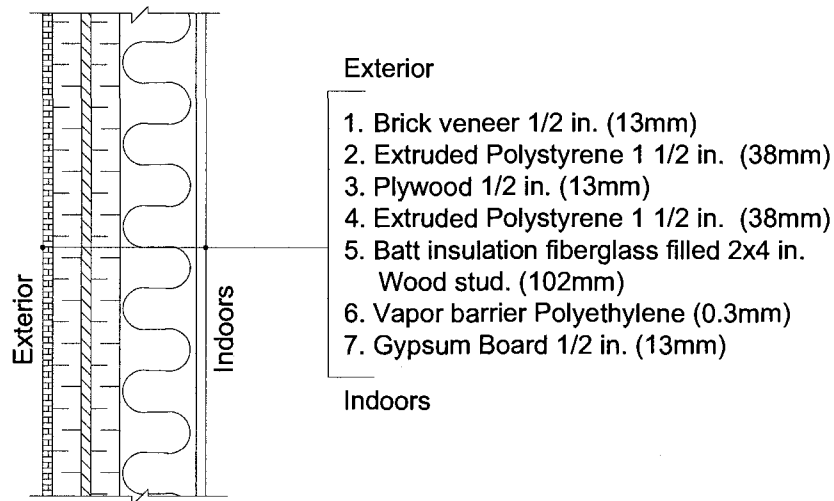


Figure A.2: Section of the EIFS wall

Glaser method equations:

For heat transfer

$$q = \frac{T_i - T_o}{1/\alpha_o + \sum R_x + 1/\alpha_i}$$

where

q : heat flux (W/m²);

T : temperature (K);

R : heat resistance ($\text{m}^2 \cdot \text{K}/\text{W}$);

α : surface heat transfer coefficient ($\text{W}/\text{m}^2 \cdot \text{K}$); and,

subscript o means outdoor and i means indoor.

For moisture transfer

$$m = \frac{P_i - P_o}{1/\beta_o + \sum Z_x + 1/\beta_i}$$

where

m : vapor flow rate ($\text{ng}/\text{m}^2 \cdot \text{s}$)

p : vapor pressure (Pa);

β : surface vapor transfer coefficient ($\text{ng}/\text{Pa} \cdot \text{m}^2 \cdot \text{s}$);

Z : vapor resistance of material layers ($\text{Pa} \cdot \text{m}^2 \cdot \text{s}/\text{ng}$), the subscripts denote different layers of the wall; and

subscript o means outdoor and i means indoor.

For saturated vapor pressure¹¹

$$P_s = aT^{-1} + b + cT^1 + d \cdot T^2 + eT^3 + f \cdot \log(T) \text{ (Pa)}$$

where

T : temperature (K);

$a = -5.8002206\text{E}3$; $b = 1.3914993$; $c = -4.8640239\text{E}-2$; $d = 4.1764768\text{E}-5$; $e = -$

$1.4452093\text{E}-8$; $f = 6.5459673$;

¹¹ The saturated vapor pressure is also listed in the Table 5.1 of (Hutcheon and Handegord 1983).

The Calculation procedure and an example:

EXCEL calculation for the EIFS wall described in case study 1 is carried out using Glaser method (the Excel spread sheet is shown in Table A.1). According to the method of Chapter 12 of Hutcheon (1983), the principle of excel calculation is listed:

- (1) Design condition: outdoor design temperature and relative humidity are set -20°C and 65%. For typical residential building in winter, interior design temperature and relative humidity are 20°C and 50%.

Saturation pressure $P_s = 103 \text{ Pa @ } -20^{\circ}\text{C}$, Vapor pressure $P_o = 103 \times 0.65 = 67.1 \text{ Pa}$

Saturation pressure $P_s = 2337 \text{ Pa @ } 20^{\circ}\text{C}$, Vapor pressure $P_i = 2337 \times 0.50 = 1168.5 \text{ Pa}$

$$\Delta P = P_i - P_o = 1101.4 \text{ Pa}$$

- (2) Temperature distribution

$$\text{Temperature drop across each element } \Delta T_n = \frac{R_n}{\sum R} \times (T_i - T_o)$$

$$\text{Interface temperature } T_{n+1} = T_n + \Delta T_n$$

- (3) Find the saturation pressure P_s for each interface based on interface temperature.

- (4) Water vapor pressure distribution

$$\text{Vapor pressure drop across each element } \Delta P_n = \frac{Z_n}{\sum Z} \times (P_i - P_o)$$

$$\text{Interface vapor pressure } P_{n+1} = P_n + \Delta P_n$$

- (5) Condensation will occur when $P_n > P_s$ at the interface of two layers. In this example, no condensation occurs within this wall.

Table A.1: the EIFS wall's condensation calculation

	Thickne ss	Ther mal condu ctivity	Thermal Conductivi ty	Therm al resista nce	Vapor permeabilit y	Vapor resistance	Temper ature	Saturate d vapor pressure	Calculat ed vapor pressure	Relative humidit y
Parameter ¹²	L_n	k	U_n	R_n	w	Z_n	T_n	P_{s_n}	P_n	RH_n
Unit	(mm)	(W/m·K)	(W/ m ² ·K)	(m ² ·K/ W)	(ng/Pa·m·s)	(Pa·m ² ·s/ ng)	(°C)	(Pa)	(Pa)	(%)
exterior film			25	0.04		0.00	-20.00	103.2		
									67.08	65.00
(1) brick veneer	13	0.517	39.77	0.025	3.00	0.0043				
							-19.73	108.2	72.23	66.76
(2) extruded polystyrene	38	0.017	0.45	2.24	1.20	0.03166				
							-10.49	226.0	109.91	48.63
(3) plywood	13	0.435	33.46	0.029	0.55	0.02354				
							-10.36	228.0	137.93	60.50
(4) extruded polystyrene	38	0.017	0.45	2.24	1.20	0.03167				
							-1.11	557.0	175.61	31.53
(5) fiberglass	102	0.021	0.205	4.86	125.00	0.00082				
							18.99	2183	176.58	8.09
(6) polyethylene	0.3	0.095	316.67	0.0031	0.00036	0.833				
							19.00	2196	1168.1	53.19
(7) gypsum board	13	0.092	7.08	0.14	43.73	0.00030				
							19.59	2309	1168.5	50.00
interior film			10	0.10		0.00				
							20.00	2337	1168.5	50.00
		R_{total}		9.67	W_{total}	0.926				

¹² L is thickness of the layer; k is the thermal conductivity; U is the thermal conductance; R is the thermal resistance; w is the vapor permeability; z is the vapor resistance of the layer; T is the temperature; P_s is the saturated vapor pressure; P_n is the calculated vapor pressure; and RH is the relative humidity.

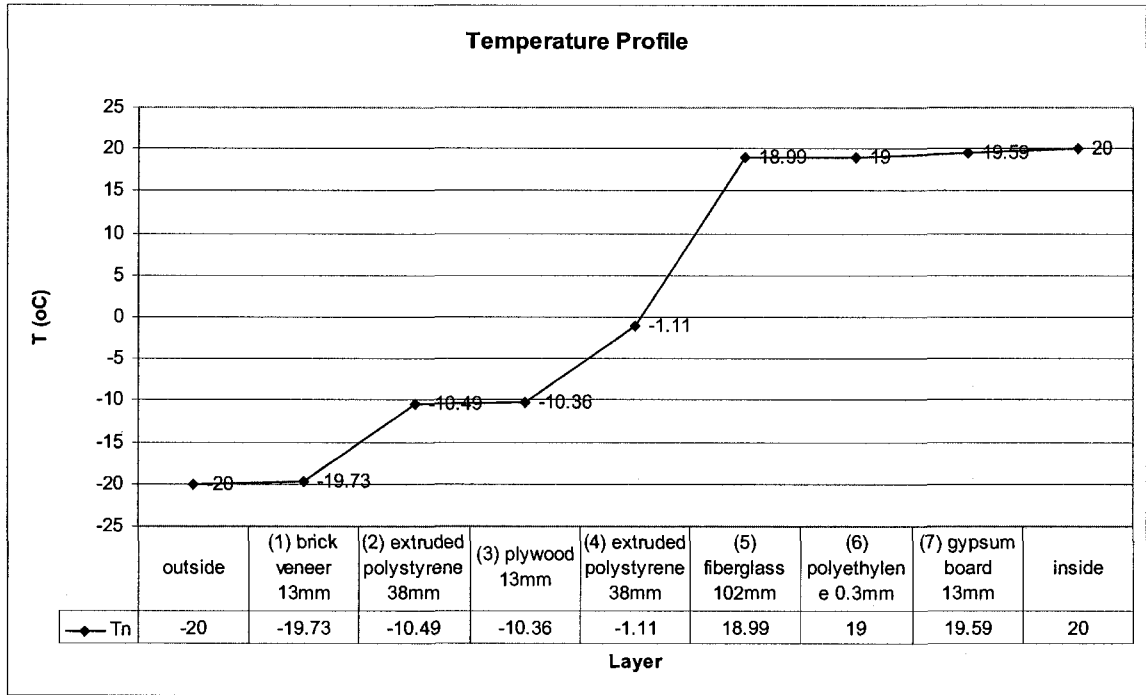


Figure A.3 (a): Profile of the temperature of the EIFS wall

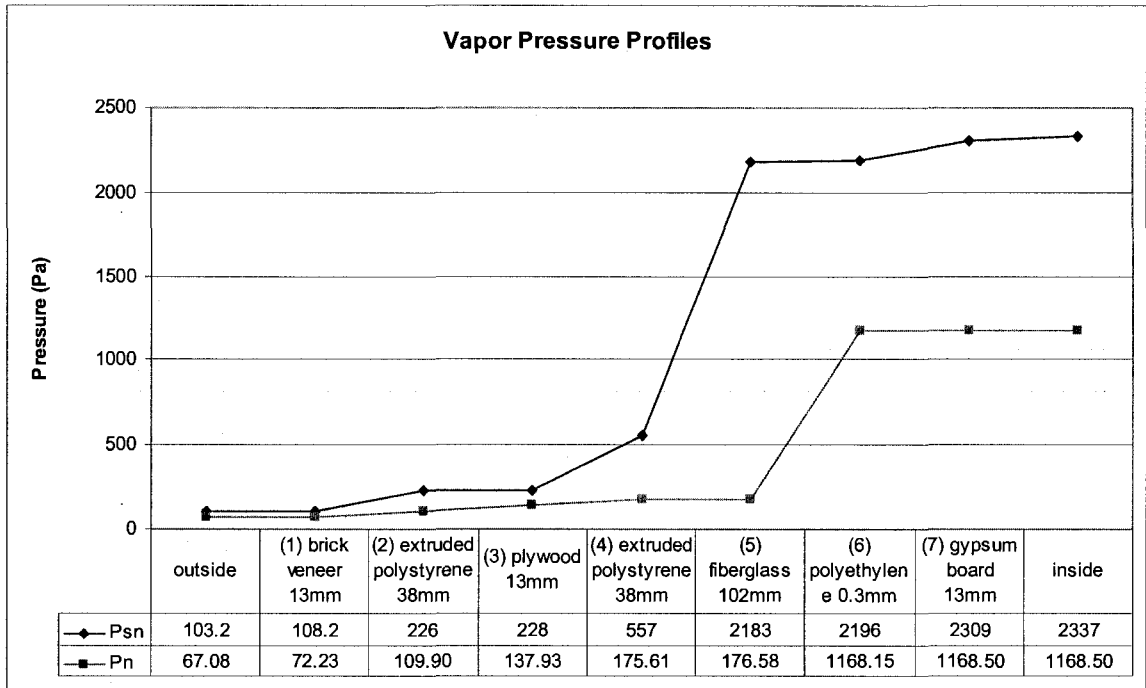


Figure A.3 (b): Profiles of saturated vapor pressure and calculated vapor pressure of the EIFS wall

A.4 Steady-state hygrothermal computing method

The flow chart of computing method of steady-state heat and moisture transfer through multilayer building envelope is shown in Figure A.1.

- (1) Main program start listening the interface action. The steady-state computing part initiates if the steady compute button is clicked. If the button is clicked, then the program reads and collects the relevant data from the interface. The input data are saved in the public data array including the selected material thermal and physical properties, layer thickness, outside air-film coefficient and inside air-film coefficient, outdoors and indoors temperature.
- (2) Calculate R-value of each layer $R=k/L$; Vapor diffusion resistance $W=\delta/L$;
- (3) Set a loop. The loop time is equal to the layer amount of the building envelope.
- (4) Calculate the inside and outside R values of each internal node in this loop;
- (5) Calculate the inside and outside W values of each internal node in this loop;
- (6) Save the R values and W values into data array for proceeding computing;
- (7) Set the second new loop. The loop time is equal to the layer amount of the building envelope. Each node temperature are calculated depending on the equation
- (8) Calculate temperature at node i, $T(i)=U_{out}(i)*T_{out}+U_{in}(i)*T_{in}/(U_{out}(i)+U_{in}(i))$

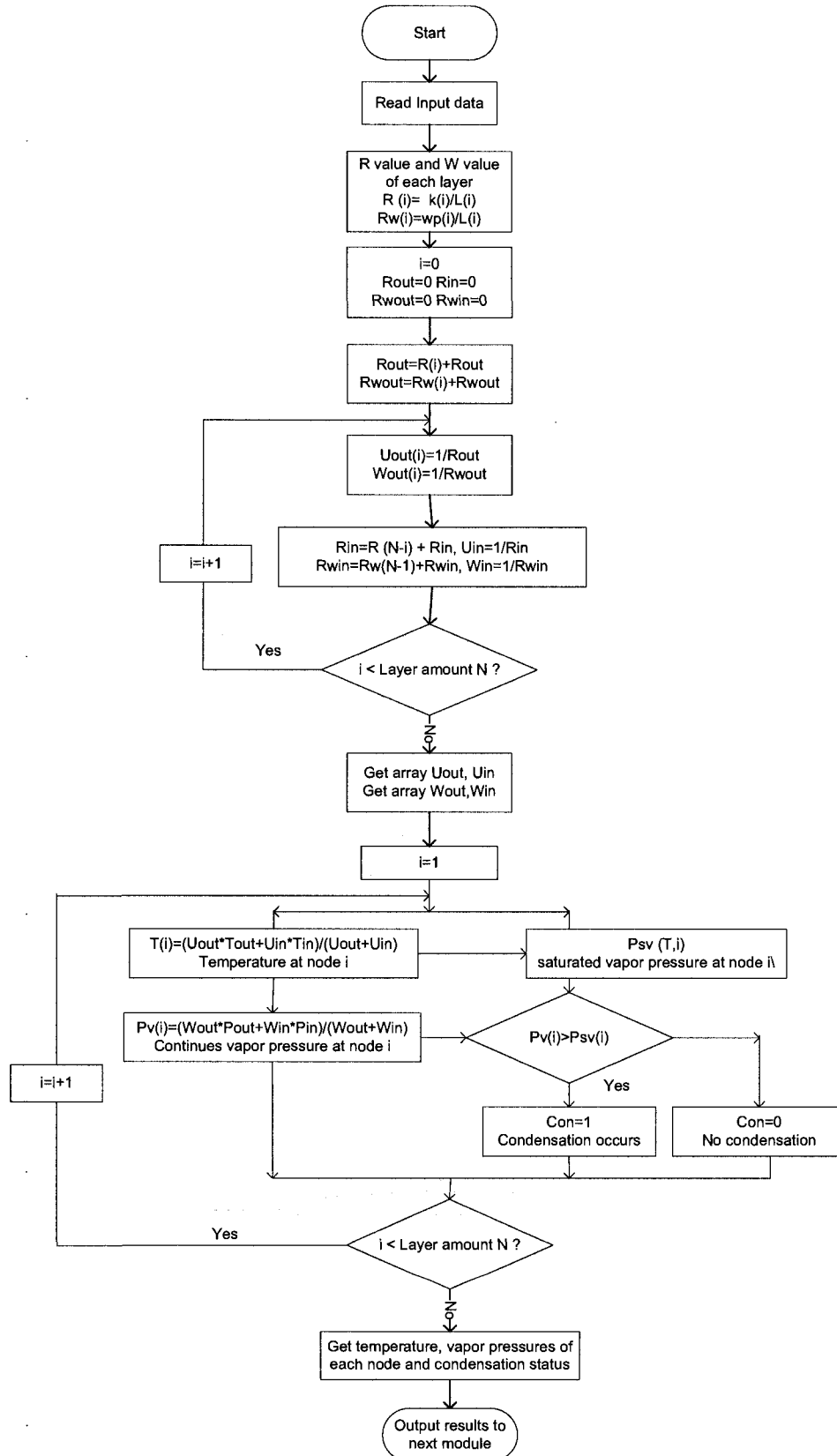


Figure A.4: Flow chart of computing method of steady heat transfer through a multi-layer building envelope

- (9) Calculate saturated vapor pressure $P_s(i) = \text{Math.exp}(a * \text{Math.pow}(T[i], -1) + b + c * T[i] + d * \text{Math.pow}(T[i], 2) + e * \text{Math.pow}(T[i], 3) + f * \text{Math.log}(T[i]));$
- (10) Get calculated vapor pressure at node i ,
- (11) $P(i) = W_{out}(i) * P_{out} + W_{in}(i) * P_{in} / (W_{out}(i) + W_{in}(i))$
- (12) Output $T(i)$, $P(i)$, $P_s(i)$ and draw the curves in the graphic chart using Java 2D.

Appendix B: A Design Facts File in EBIM

Filename: DesignFacts.XML

```
<?xml version="1.0" encoding="UTF-8" ?>
= <BuildingData>
  <location desp="Location">Montreal</location>
  <housetype desp="House Type">house</housetype>
  <wallposition desp="Wall position to ground">above</wallposition>
  <heatsource desp="Heat resource">Electricity</heatsource>
  <rValue desp="R value m2.C/watt">4.5</rValue>
  <vbPosition desp="Vapor is installed on warm side?">yes</vbPosition>
  <claddingPosition desp="Is cladding with low permeability
    installed?">yes</claddingPosition>
  <installedVB desp="Installed Vapour Barrier?">yes</installedVB>
  <vaporPermeability desp="Water Vapor Permeability
    Ng/m2.S.Pa">500.0</vaporPermeability>
  <condenseOccur desp="Does Condensation occur within
    wall/roof?">no</condenseOccur>
  <condenseRate desp="Condensation rate Ng/m2.s">5100.0</condenseRate>
  <moistaccDay desp="The days which RH>80% within the building envelope
    during one year">5</moistaccDay>
  <inSurTemp desp="Interior Surface Temperature C">8.9</inSurTemp>
  <inRH desp="Indoors RH %">90.0</inRH>
  <airTempin desp="Indoors air temperature C">20</airTempin>
  <wallAirPermenance desp="Air Permeance of exterior wall
    L/s.m2">0.02</wallAirPermenance>
  <roofAP desp="Air Permeance of roof L/s.m2">0.02</roofAP>
  <joints desp="Joints Taping, Gasket, Sealed Penetrations, Ensure
    Contiunity of Air Barrier?">yes</joints>
  <windowType desp="Window Type">type2</windowType>
  <airleakWin desp="Design air leakage rating of windows">a1</airleakWin>
  <airLeakRate desp="Air leakage rate L/s.m2">2</airLeakRate>
  <fireControlDistance desp="Fire control distance (meter) (the distance
    from an exposing building face to a property line or to imaginary line
    between two buildings)">0.2</fireControlDistance>
  <combust desp="if the exposing building cladding is
    combustible?">yes</combust>
  <hDistance desp="Horizontal distance to the the window of adjoint wall
    (meter)">10</hDistance>
  <fireRating desp="the fire rating of that exposing building face cladding
    (mins)">60</fireRating>
  <skyLight desp="Installed skylight?">yes</skyLight>
  <surfaceGrading desp="surface Grading from ex. Wall to
    ground?">yes</surfaceGrading>
  <exDrain desp="External Drains installed?">yes</exDrain>
  <backFillCap desp="Impermeable cap over backfill
    installed?">yes</backFillCap>
  <drainScreen desp="drain screen:(e.g. sand or gravel) adjacent to
    foundation walls?">yes</drainScreen>
```



```

<waterProofExBaseWall desp="Waterproofing of exterior side of basement
wall?">yes</waterProofExBaseWall>
<foundationDrainage desp="Drainage pipes along the foundation perimeter
installed?">yes</foundationDrainage>
<watertightJoints desp="Watertight control joints
installed?">yes</watertightJoints>
<flatOrSlopeRoof desp="Flat roof or slope roof?">flat</flatOrSlopeRoof>
<slopeRoofRatio desp="Slope grade of roof">0.02</slopeRoofRatio>
<roofValleySlope desp="Slope grade of valley of
roofs">0.02</roofValleySlope>
<drainAreaRoof desp="drainage area of 1 m2 roof
(mm2)">100</drainAreaRoof>
<airCavityofWall desp="is air cavity designed behind the rainscreen
wall?">yes</airCavityofWall>
<airCavityWidth desp="width of air space ( in.)">2</airCavityWidth>
<flashing desp="Flashing installed on the bottom of bottom of rainscreen
wall?">yes</flashing>
<drainPlane desp="Flashing installed on the bottom of bottom of
rainscreen wall?">yes</drainPlane>
<weephole desp="Weep holes positioned on the bottom of bottom of
rainscreen wall?">yes</weephole>
<stoneLayerunderSlab desp="Crushed stone layer under slab
installed?">yes</stoneLayerunderSlab>
<capBreakonFooting desp="Capillary break installed on the footing along
the foundation wall?">yes</capBreakonFooting>
<dampingProofBase desp="damping proof is installed on the exterior side
of basement wall?">yes</dampingProofBase>
<capBreakonFoundation desp="capillary break between the sill plate and
the top of foundation wall ?">yes</capBreakonFoundation>
<winType desp="Operable or Fixed Window">fixed</winType>
<energyRating desp="Energy rating of window">10</energyRating>
<studinWall desp="ratio of studs in 1 m of wall length">10</studinWall>
<winRatioofWall desp="ratio between fenestration vs. whole wall area (in
elevation) %">25</winRatioofWall>
<heatingLoad desp="Heating load during one year KWH">12648</heatingLoad>
</BuildingData>

```

Appendix C: Decision Tables for Implementation

The decision tables below are included in one Microsoft Excel spreadsheet file, code.xls.

Rule Table R value		CONDITION		CONDITION		CONDITION		CONDITION		ACTION		ACTION	
Decision Table 0	Location	wellposition	Wall Position to Ground	Resource	Heating Source	R value (RSI)	Value >=51	Type	Compliance Checking Result	Compliance Checking Result	Compliance Checking Result	Reference Index	Reference link
Thermal Resistance Performance	Toronto	above	above	Electricity	Electricity	4.4		house	pass	pass	good	MNECC 3.3.1.1	http://handog.wordpress.com/2007/05/07/r-value-requirements-in-ontario/
				Propane, Oil, Heat Pump	Propane, Oil, Heat Pump	3			fail	fail	Increase insulation layer		
				Natural Gas	Natural Gas	2.9			pass	pass	good	MNECC 3.3.2.1	http://handog.wordpress.com/2007/05/07/r-value-requirements-in-ontario/
				Electricity	Electricity	3.1			fail	fail	Increase insulation layer		
				Propane, Oil, Heat Pump	Propane, Oil, Heat Pump	3.1			pass	pass	good	MNECC 3.3.1.1	http://handog.wordpress.com/2007/05/07/r-value-requirements-in-ontario/
				Natural Gas	Natural Gas	2.1			fail	fail	Increase insulation layer		
				Electricity	Electricity				pass	pass	good		
				Propane, Oil, Heat Pump	Propane, Oil, Heat Pump				fail	fail	Increase insulation layer		
				Natural Gas	Natural Gas				pass	pass	good		
				Electricity	Electricity				fail	fail	Increase insulation layer		
Moisture Performance	Montreal	below	below	Electricity	Electricity	4.1		house	pass	pass	good	MNECC 3.3.1.1	http://handog.wordpress.com/2007/05/07/r-value-requirements-in-ontario/
				Propane, Oil, Heat Pump	Propane, Oil, Heat Pump				fail	fail	Increase insulation layer		
				Natural Gas	Natural Gas				pass	pass	good		
				Electricity	Electricity				fail	fail	Increase insulation layer		
				Propane, Oil, Heat Pump	Propane, Oil, Heat Pump				pass	pass	good		
				Natural Gas	Natural Gas				fail	fail	Increase insulation layer		
				Electricity	Electricity				pass	pass	good		
				Propane, Oil, Heat Pump	Propane, Oil, Heat Pump				fail	fail	Increase insulation layer		
				Natural Gas	Natural Gas				pass	pass	good		
				Electricity	Electricity				fail	fail	Increase insulation layer		
Rule Table Moisture		CONDITION		CONDITION		CONDITION		CONDITION		ACTION		ACTION	
Decision Table 1	Installed Vapor Barrier?	wellposition	Vapor is installed on warm side?	cladding Is cladding with low permeability installed?	Water Vapor Permeability Ng/m2.S.Pa	type	type	Compliance Checking Result	Compliance Checking Result	Compliance Checking Result	Reference Index	Reference link	
Moisture Performance	yes	no	no	yes	15	house	house	pass	pass	good	MNECC 5.3.1.1	http://handog.wordpress.com/2007/05/07/r-value-requirements-in-ontario/	
	no	yes	yes	no				fail	fail	fail			
	yes	no	no	yes				fail	fail	fail			
	yes	yes	yes	no				fail	fail	fail			
Rule Table Condense		CONDITION		CONDITION		CONDITION		CONDITION		ACTION		ACTION	
Decision table 2	Does Condensation occur?	condensateRate<=51	Condensation rate Ng/m2.S	type	type	Compliance Checking Result	Compliance Checking Result	Compliance Checking Result	Compliance Checking Result	Compliance Checking Result	Reference Index	Reference link	
Interstitial condensation (steady simulation)	yes	50000	50000	house	house	pass	pass	good	good	good	http://handog.wordpress.com/2007/05/22/thermal-and-moisture-control-in-insulated-assemblies-ashrae-handbook/		
	no					pass	pass	good	good	good			
	yes					fail	fail	Reduce condensation rate within building envelopes	Reduce condensation rate within building envelopes	Reduce condensation rate within building envelopes			

CONDITION	CONDITION	CONDITION	CONDITION	CONDITION	ACTION	ACTION	ACTION	ACTION	ACTION
Decision table 4	surfaceGrading from ex. Wall to ground?	exDrain	External Drains installed?	Impervious cap over backfill installed?	type	Compliance Checking Result	Reference index	Advice	Reference link
	yes	yes	yes	yes	type	pass		good	
	no	no	no	no	house	fail	ASTM E241-00 Standard Guide for Limiting Water-Induced Damage to Buildings	Ground should slope away from walls so that precipitation runoff from land areas does not pond near the foundation.	http://randocq.wordpress.com/2007/05/11/astm-e241-00-standard-guide-for-limiting-water-induced-damage-to-buildings/
	Drainage of precipitation and surface runoff					fail		Drains at ground level should be positioned so that the discharge from these drains is carried away from the foundation and flows away from it.	
						fail		Impermeable material (e.g. clay cap or sloping sidewalk) should be designed over the backfill to prevent surface water absorption and concentration at building perimeters.	
Ruile Table Surface Condensation									
Decision table 5	Interior Surface Temperature > 8.35	Building	Surface Condense	Surface Condense	type	Compliance Checking Result	Reference index	Advice	Reference link
	Interior Surface Temperature > 8.35	Building	Surface Condense	Surface Condense	type	pass		good	
	Surface condensation				house	fail	pr EN ISO 13788	8 C is calculated as minimum allowable internal surface temperature of building component below which mould growth is likely. The conditions are for Montreal, and given temperature is for the most critical month - January. hygroscopic materials	http://randocq.files.wordpress.com/2007/05/guide007.jpg

Rule Table Surface Condensation		ACTION		ACTION		ACTION	
CONDITION	CONDITION	CONDITION	CONDITION	CONDITION	CONDITION	CONDITION	CONDITION
Decision table 5	Building	type	Reference index	Advice	Reference link		
	$inSurTemp > 5$	house	pr EN ISO 13788	good	http://handson.files.wordpress.com/2007/05/20070524ed097_ID01		
	Interior Surface Temperature	Compliance Checking Result					
	8	pass					
Surface condensation	-80	house	fail	B C is calculated as minimum allowable internal surface temperature of building component, below which mould growth is likely. The conditions are for Montreal, and given temperature is for the most critical month - January. hygroscopic materials			
Rule Table Human comfort							
CONDITION	CONDITION	CONDITION	CONDITION	CONDITION	CONDITION	CONDITION	CONDITION
Decision table 6	Building	type	type	Compliance Checking Result	Reference index	Advice	Reference link
	$inRH = 5$	house	house	pass		good	
	Inside Air RH %	18.25	18.25	fail		Adjust indoors environment, the indoors RH value is not in the comfortable range.	
	40.60	18.25	18.25	fail		Thermal setpoint of indoors temperature is not in the comfortable range.	http://handson.wordpress.com/2007/05/22/thermal-comfort/
Human comfort (simplified)	40.60	18.25	18.25	fail	Chapter 8, ASHRAE 2005 ASHRAE Handbook—Fundamentals	The wall's interior surface temperature is not in the comfortable range. Thus the radiation of the wall will make occupant uncomfortable.	

Subtable Air Ingress		COMPLETION		CONDITION		ACTION	
CONDITION	COMPLETION	CONDITION	COMPLETION	ACTION	ACTION	ACTION	ACTION
Decision table 7	Roof Air permeance L/s.m2	Building wallAirPermeance>=S1, wallAirPermeance<=S2	Joints Taping, Gasket, Sealed Penetrations, Ensure Continuity of Air Barrier?	type	Code Compliance Result	Reference index	Advice
	0.0.02	0.0.02	YES		PASS		good
	0.02.000				fail		Install air barrier with high air-permeance resistance (i.e. aluminum foil, polyethylene, etc.);
	0.02.000	0.02.000		house	fail	CAN/CSA-A440.2-08	Install air barrier with high air-permeance resistance (i.e. aluminum foil, polyethylene, etc.); Air permeance of the opaque parts of building envelope
			No		fail		Make sure air-tight continuity, install air-tight joints (flashing, gasket, sealed penetration). The choice of air barrier component: Air permeance of the opaque parts of building envelope should not be lower than 0.02 L/m2.s
							http://handlog.wordpress.com/2007/05/21/nbc-guide-section-54-air-leakage/

Decision table 8		CONDITION		CONDITION		CONDITION		ACTION		ACTION		ACTION	
Window Type	Window Type	airLeakWin Design air leakage rating of windows	airLeakRate<=S1 Maximum air leakage rate	Building	airLeakWin Design air leakage rating of windows	airLeakRate<=S1 Maximum air leakage rate	type	Code Compliance Result	Reference Index	Advice	Reference link		
Air leakage of windows	type1	a1	2.78	Building	type1	a1	2.78	pass	CAN/CSA-A440-M80 Windows; ASTM E283-91	good			
		a2	1.60			a2	1.60						
		a3	0.55			a3	0.55						
		a4	0.25			a4	0.25						
	type2	a1	2.78		a1	2.78							
		a2	1.60		a2	1.60							
		a3	0.55		a3	0.55							
		a4	0.25		a4	0.25							
	type3	a1	2.78		a1	2.78							
		a2	1.60		a2	1.60							
		a3	0.55		a3	0.55							
		a4	0.25		a4	0.25							
	type4	a1	2.78		a1	2.78							
		a2	1.60		a2	1.60							
		a3	0.55		a3	0.55							
		a4	0.25		a4	0.25							
type1	a1	2.78	a1	2.78									
	a2	1.60	a2	1.60									
	a3	0.55	a3	0.55									
	a4	0.25	a4	0.25									
type2	a1	2.78	a1	2.78									
	a2	1.60	a2	1.60									
	a3	0.55	a3	0.55									
	a4	0.25	a4	0.25									
type3	a1	2.78	a1	2.78									
	a2	1.60	a2	1.60									
	a3	0.55	a3	0.55									
	a4	0.25	a4	0.25									
type4	a1	2.78	a1	2.78									
	a2	1.60	a2	1.60									
	a3	0.55	a3	0.55									
	a4	0.25	a4	0.25									

Table 9: Fire control of building envelope: Spatial separation of buildings		CONDITION	CONDITION	CONDITION	ACTION	ACTION	ACTION
Decision table 9	Fire control of building envelope: Spatial separation of buildings	fireControlDistance=1 fireControlDistance=2	Building fireRating=1, fireRating=2	combus: if the exposing building cladding is combustible?	type	codeComplianceResult	Advice Reference index Reference link
		Fire control distance (meter) (the distance from an exposing building face to a property line or to imaginary line between two buildings)					
		0.0.6		no		pass	Fire control distance should be greater than 1.2m when the cladding is combustible; the fire rating of the cladding should be greater than 45min; Fire control distance should be greater than 0.6 for the non combustible cladding.
		0.6.1.2	45.60		house	pass	NFCC 1068 http://irc.nrc-cnrc.gc.ca/pubs/bod/es/nrc042803_e.htm
		1.2.24	60.240			pass	
		1.2.24		yes		pass	
		0.0.6		yes		fail	
		0.6.1.2	0.45			fail	
		1.2.24	0.60			fail	
		1.2.24		yes		fail	
Table 10: Fire control of building envelope: Location of skylights							
Decision table 10	Fire control of building envelope: Location of skylights	skylight: Installed skylight?	Building Horizontal distance to the window of adjacent wall (meter)	type	codeComplianceResult	Advice	Reference index Reference link
		yes	5	house	fail	Does design of your house include skylights that are located less than 5 m of horizontal distance from the windows in adjoining exposed wall?	NFCC 1068 http://irc.nrc-cnrc.gc.ca/pubs/bod/es/nrc042803_e.html
		yes			pass		
		no			pass		

Rule table surface runoff		CONDITION	CONDITION	CONDITION	CONDITION	ACTION	ACTION	ACTION	ACTION
Decision table 11	rainScreen	waterProofExBaseWall	Building	waterTightJoints	type	pass	good	http://andbg.wordpress.com/2007/05/11/astm-e241-00-standard-guide-for-finding-water-in-toe-damage-to-buildings/	Reference link
	drainScreen (e.g. sand or gravel) adjacent to foundation walls?	Waterproofing of exterior side of basement wall?	Foundation/Drainage	waterTight control joints installed?	type	fail	placing free-draining backfill material (e.g. sand or gravel) or some other type of free-draining building material immediately should be adjacent to foundation walls.		
	YES	YES	drainage pipes along the foundation perimeter installed?	YES	house	fail	waterproofing barriers or membranes should be installed on exterior side of basement walls.		
	NO	NO	NO	NO		fail	Drainage pipes system should be installed along the perimeter of the foundation, placed below the basement floor level.		
						fail	In case of cast concrete foundation, does your design involves the use of control joints in order to make the foundation walls watertight?		

Rule table Moist/Accumulation		CONDITION		CONDITION		CONDITION		ACTION		ACTION	
CONDITION	CONSTRUCTION	Building	RoofValleySlopes=31	RoofValleySlopes=31	RoofValleySlopes=31	RoofValleySlopes=31	RoofValleySlopes=31	RoofValleySlopes=31	RoofValleySlopes=31	RoofValleySlopes=31	RoofValleySlopes=31
Decision table 12	Flat roof or slope roof?	min. slope of roof 0.1%	min. slope of valley of roofs 0.02	min. drainage area of 1 m2 roof (mm2)	type	Compliance Checking Result	Reference index	Advice	Reference link		
	slope		0.02	100	house	pass	ASTM E241-00 Standard Guide for Limiting Water-Induced Damage to Buildings	good			
	flat		0.005	100	house	fail		Please check the gradient of sloped roof, roof valleys, minimum gradient of sloped roof is 1% and minimum slope of roof valleys is 2%			
	flat		0.005			fail		Please check the gradient of the flat roof, roof valleys, minimum gradient of sloped roof is 2% and minimum slope of roof valleys is 0.6%	http://handog.wordpress.com/2007/06/11/astm-e241-00-standard-guide-for-limiting-water-induced-damage-to-buildings/		
	flat		0.005			fail		is the flat roof designed so that the drainage area corresponds with 1m2 of roof area?			
Rule table Rainwater											
DT 13	Rain water penetration management	airCavityWall is air cavity designed behind the rainscreen wall?	Flashing installed on the bottom of rainscreen wall?	Flashing installed on the bottom of rainscreen wall?	drainPlane drainage plane installed on the bottom of rainscreen wall?	Weep holes positioned on the bottom of bottom of rainscreen wall?	type	Compliance Checking Result	Reference index	Advice	Reference link
	yes	yes	yes	yes	yes	yes	house	pass	ASTM E241-00 Standard Guide for Limiting Water-Induced Damage to Buildings	good drainage space behind cladding or slope of min. 1% on the bottom of wall	http://handog.wordpress.com/2007/06/11/astm-e241-00-standard-guide-for-limiting-water-induced-damage-to-buildings/
	yes	yes	yes	yes	yes	yes	house	fail			
	yes	no	no	no	no	no	house	fail			
	yes	no	no	no	no	no	house	fail			

Rule Table Capillary		CONDITION		CONDITION		CONDITION		CONDITION		ACTION		ACTION	
CONDITION	CONDITION	Building	capBreakerFooting	capBreakerFoundation	capBreakerFoundation	capBreakerFoundation	capBreakerFoundation	capBreakerFoundation	capBreakerFoundation	capBreakerFoundation	capBreakerFoundation	capBreakerFoundation	capBreakerFoundation
DT 14	Crushed stone layer under slab installed?	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no
	Crushed stone layer under slab installed along the footing along the foundation wall?	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no
	Crushed stone layer under slab installed on the exterior side of basement wall?	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no
	Crushed stone layer under slab installed on the sill plate and the top of foundation wall?	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no
	Capillary suction of basement wall	pass	fail	pass	fail	pass	fail	pass	fail	pass	fail	pass	fail
	Advise	layer of min 3/4-inch crushed stone with fine removed, under the basement floor slab should be placed. should be placed prior to or surface of basement walls and the top of footings.											
	Reference Index	ASTM E241-00 Standard Guide for Limiting Water-Induced Damage to Buildings											
	Reference link	http://handog.wondershare.com/2007/06/11/astm-e241-00-standard-guide-for-limiting-water-induced-damage-to-buildings/											
Rule Table Energy Rating Window		CONDITION		CONDITION		CONDITION		CONDITION		ACTION		ACTION	
CONDITION	CONDITION	Building	energyRating<=1	energyRating<=2	energyRating<=3	energyRating<=4	energyRating<=5	energyRating<=6	energyRating<=7	energyRating<=8	energyRating<=9	energyRating<=10	energyRating<=11
DT 15	Energy Rating of Windows and Sliding glass doors (Simplified)	operable	-33										
	Energy Rating of Windows and Sliding glass doors (Simplified)	fixed	-33										
	Advise	increase energy efficiency of windows, i.e. using Low-e glass, double glazing, air-tight window and high thermal resistance window frame											
	Reference link	http://handog.wondershare.com/2007/06/15/e-241-00-standard-guide-for-limiting-water-induced-damage-to-buildings/											

Rule Table thermal performance		CONDITION		CONDITION		CONDITION		CONDITION		ACTION		ACTION	
CONDITION	CONDITION	Building	minRatioOfWall<=1	minRatioOfWall<=2	minRatioOfWall<=3	minRatioOfWall<=4	minRatioOfWall<=5	minRatioOfWall<=6	minRatioOfWall<=7	minRatioOfWall<=8	minRatioOfWall<=9	minRatioOfWall<=10	minRatioOfWall<=11
DT 16	Overall energy performance of house	house	max. ratio of studs in 1 m of wall length	max. ratio of studs in 1 m of wall length	max. ratio of studs in 1 m of wall length	max. ratio of studs in 1 m of wall length	max. ratio of studs in 1 m of wall length	max. ratio of studs in 1 m of wall length	max. ratio of studs in 1 m of wall length	max. ratio of studs in 1 m of wall length	max. ratio of studs in 1 m of wall length	max. ratio of studs in 1 m of wall length	max. ratio of studs in 1 m of wall length
	Overall energy performance of house	house	15	40	40	40	40	40	40	40	40	40	
	Advise	stud of the wall is too intensive, the ratio of stud to wall should be less than 15%. Too much glazing on the wall will reduce the energy efficiency of the house. The Maximum ratio of window to wall is 20%.											
	Reference link	http://www.aecounty.org/PA/CodesReg/Code.htm											

Appendix D: Evaluation Report File

Compliance Report:

File Name: **OutReport.htm**

(0) check R value

Check result: pass

Advice: good

Ref. Index: MNECC 3.3.1.1

Link: <http://tandog.wordpress.com/2007/05/07/r-value-requirement-in-ontario/>

(1) Check vapor barrier performance of walls/roofs

Check result: pass

Advice: good

Ref. Index: NBCC 5.3.1.1

Link: <http://tandog.wordpress.com/2007/05/21/42/>

(2) Check condensation of walls/roofs

Check result: pass

Advice: good

Ref. Index: NBCC 5.3.1.1

Link: <http://tandog.wordpress.com/2007/05/22/thermal-and-moisture-control-in-insulated-assemblies-ashrae-handbook/>

(3) Check moisture accumulation of walls/roofs

Check result: pass

Advice: The days which RH within the wall/roof exceeds 80% should not be more than 7 days.

The weekly average relative humidity at the warm side of the insulation layer may rise above a critical 80% level, which may be conducive to mold and mildew growth. Install VB or MB with high vapor resistance, i.e., polyethylene

Ref. Index: NBCC 5.3.1.1

Link: <http://tandog.wordpress.com/2007/05/21/39/>

(4) Check surface condensation of walls/roofs/windows/doors

Check result: pass

Advice: good

Ref. Index: pr EN ISO 13788

Link: <http://tandog.files.wordpress.com/2007/05/guide007.jpg>

(5) Human comfort index based on mean temperature and RH. (Simplified)

Check result: pass

Advice: good

Ref. Index: Chapter 8, ASHRAE 2005 ASHRAE Handbook Fundamentals

Link: <http://tandog.wordpress.com/2007/05/22/thermal-comfort/>

(6) Check air permeance of walls/roofs

Check result: pass

Advice: good

Ref. Index: CAN/CSA-A440.2-98

Link: <http://tandog.wordpress.com/2007/05/21/nbcc-guide-section-54-air-leakage/>

(7) Check air leakage rate of windows/glass doors

Check result: pass

Advice: good

Ref. Index: CAN/CSA-A440-M90 Windows; ASTM E283-91

Link: <http://tandog.wordpress.com/2007/05/21/nbcc-guide-section-54-air-leakage/>

(8) Check Fire control of building envelope: Spatial separation of buildings

Check result: fail

Advice: <1.2m: min.45min; <0.6: non combustible: Table 6.3.2.11.(1) National Housing Code of Canada 1998: Minimum construction Requirements for Exposing Building Faces

Ref. Index: NHCC 1998

Link: http://irc.nrc-cnrc.gc.ca/pubs/codes/nrcc42803_e.html

(9) Check Fire control of building envelope: skylight location

Check result: pass

Advice: Does design of your house include skylights that are located less than 5 m of horizontal distance from the windows in adjoining exposed wall?

Ref. Index: NHCC 1998

Link: http://irc.nrc-cnrc.gc.ca/pubs/codes/nrcc42803_e.html

(10) Check Drainage of precipitation and surface runoff

Check result: pass

Advice: good

Ref. Index: ASTM E241-00 Standard Guide for Limiting Water-Induced Damage to Buildings

Link: <http://tandog.wordpress.com/2007/05/11/astm-e241-00-standard-guide-for-limiting-water-induced-damage-to-buildings/>

(11) Check Drainage of precipitation and surface runoff of basement wall

Check result: pass

Advice: good

Ref. Index: ASTM E241-00 Standard Guide for Limiting Water-Induced Damage to Buildings

Link: <http://tandog.wordpress.com/2007/05/11/astm-e241-00-standard-guide-for-limiting-water-induced-damage-to-buildings/>

(12) Check Drainage of precipitation and surface runoff of basement wall

Check result: pass

Advice: good

Ref. Index: ASTM E241-00 Standard Guide for Limiting Water-Induced Damage to Buildings

Link: <http://tandog.wordpress.com/2007/05/11/astm-e241-00-standard-guide-for-limiting-water-induced-damage-to-buildings/>

(13) Check Rain water penetration management of wall

Check result: pass

Advice: good

Ref. Index: ASTM E241-00 Standard Guide for Limiting Water-Induced Damage to Buildings

Link: <http://tandog.wordpress.com/2007/05/11/astm-e241-00-standard-guide-for-limiting-water-induced-damage-to-buildings/>

(14) Check Capillary suction

Advice: null

Ref. Index: null

Link: null

(15) Check energy rating of windows or sliding glass doors

Check result: pass

Advice: increase energy efficiency of windows, i.e. using Low-e glass, double glazing, air-tight window and high thermal resistance window frame

Ref. Index: CSA standard A440-2-98

Link: <http://tandog.wordpress.com/2007/05/15/energy-rating-of-windows-and-sliding-glass-doors/>

(16) Check overall energy performance according to the ratio of stud and window to wall.

Check result: pass

Advice: good

Ref. Index: International Energy Conservation Code

Link: <http://www.aacounty.org/IP/PAC/CodeRequire.cfm>

Appendix E: Documentation of ACCBEP

E.1 Installation of development tools for the project ACCBEP

1. Install Java 5.0

- a. Select and download the file `jdk-1_5_0_12-windows-i586-p.exe` at the below link:

<https://sdlc1d.sun.com/ECom/EComActionServlet;jsessionid=07026B1D0C0DAEE40BA24C8829FD6120>

- b. Double-click on the previously downloaded file and following the installation instructions.

2. Install Eclipse 3.1 software (It does not includes Java 5.0)

- a. Download the file `eclipse-SDK-3.1-win32.zip` at the link

<http://www.eclipse.org/downloads/download.php?file=/eclipse/downloads/drops/R-3.3.1-200709211145/eclipse-SDK-3.3.1-win32.zip&r=1&protocol=http>.

- b. Double-click on the previously downloaded file and following the installation instructions.

3. Launch Eclipse

- a. Double-click the "eclipse.exe" file you installed OR the shortcut on the desktop you may have created.

4. Installing the GEF (Graphic Editing Framework) plug-in

- a. Go to the Help / Software Updates / Find and Install..."
- b. Choose the "Search for new features to install" option
- c. Add the update sites at the below link:

<http://download.eclipse.org/tools/gef/update-site/releases/site.xml>.

5. Installing the JBoss rules engine plug-in

- a. In Eclipse, click on **Help** -> **Software Update** -> Find and Install...
- b. Choose the **Search for new features to install** option, and click **Next**.

- c. Click **New Remote Site**.
 - d. Enter the following:
 - Name:** JBoss rules
 - URL:** <http://anonsvn.labs.jboss.com/labs/jbossrules/updates/drools-ide-update/>
 and click **OK**.
 - e. "**JBoss rules**" should appear under **Sites to include in search**. Click the checkbox next to it to select it, and click **Next**.
 - f. You should see the available features (**Drools IDE**) retrieved from the update site under **Select features to install**. Select the checkboxes next to them and click next.
 - g. Select the **I accept** option to accept the license and click **Next**.
 - h. Make sure the location is correct where you're installing it. The default (your workspace) should be fine.
 - i. Click **Yes** to make Eclipse restart itself.
- 6. Copy the project file folder of ACCBEP**
- a. Find the folder **hambe** enclosed in the CD-ROM with the thesis.
 - b. Copy the folder **hambe** into the workspace folder of Eclipse.
 - c. Select **File -> Import -> Existing project into the workspace -> Browse (select root directory)**. Find the previous copied folder **hambe**.
 - d. Select the project **hambe** and click the button **Finish**.
- 7. Assign the Java Library paths needed for ACCBEP**
- a. Assign 3d graphic Java engine **idx3d**
 - 1) Click the menu **project -> properties**
 - 2) Select the **Java Build Path** on the left panel. Click the tab **Libraries**. Click **Add Jar...** on the right panel.
 - 3) Find and select the **idx3d.jar** in the folder **hambe**. Note: this file also can be downloaded from its official website at the link <http://www.idx3d.ch/idx3d/idx3d.jar>.
 - b. Assign XML processing library **JDOM**

- 1) Select the **Java Build Path** on the left panel. Click the tab **Libraries**. Click **Add Jar...** on the right panel.
 - 2) Find and select the **JDOM.jar** in the folder **hambe**. Note: this file also can be downloaded from its official website at the link <http://www.jdom.org/dist/binary/jdom-1.0.zip>.
- c. Assign database, graphic interface, and other libraries **Heat**¹³.
- 1) Select the **Java Build Path** on the left panel. Click the tab **Libraries**. Click **Add Jar...** on the right panel.
 - 2) Find and select the **heat.jar** in the folder **hambe**. Note: this file is only saved under the enclosed CD-ROM.

8. Run the ACCBEP

- a. Click and select the main java program **HAMBE.java** under the package **heat** in the Eclipse IDE.
- b. Right-click on **HAMBE**. Select **Run as -> Java Application...**
- c. The program **ACCBEP** starts running.

¹³ Heat is a compressed file as a jar format. The file includes many libraries that are developed previously by the author Xiangyang Tan in the JBuilder 2005.

E.2 Files of the program ACCBEP

The ACCBEP system developed in Java is enclosed in the CD-ROM with the thesis. The names and functions of the files and directories are listed in Tables E.1 and E.2. Input and output files used in Case Studies are listed in Table E.3.

Table E.1 Functions of the files and folders in the development of ACCBEP

	File /Folder names	Functions
Folders	EnergyPlus	Energy Plus v 2.0 installed folder
	IFC	IFC, ifcXML files
	javacsv2.0	CSV file processing Java library using for processing Energyplus output
	matdata	Material database in access format
	MOIST	The transient simulation program MOIST folder
	projects	Projects description of Eclipse
Files	src	Source code of ACCBEP in Java
	*.3ds	Building model 3ds file using in idx3d Java
	*.drl	Rules package file
	*.idf	Energy Plus Input file
	*.jpg	Texture maps using in idx3d Java
	*.material	Material data for idx3d Java
	bin	Java classes
	code2.xls	Decision tables file in spreadsheet of excel format
	DesignFacts.xml	Design facts file in XML (EBIM)
	heat.jar	Database, graphic, and others Java Library
	idx3d.jar	3d graphic Java Library idx3d
	jdom.jar	XML development Java Library JDOM
	OutReport.htm	Code compliance checking output file

Table E.2 Functions of the Java Classes in the development of ACCBEP

Package	Java classes	Function of the program
hambe-code	Building.java	Design facts in Java translated from design facts XML file in EBIM format
	CheckResult*.java	Reading / Storing items of actions of decision tables for different regulations
	CodeCheck.java	Code compliance checking main program for matching facts against rules and writing the report
	CreatDesignFactInput.java	Automated creating the interface class for inputting the design facts
	CreatFacsFile.java	Writing a EBIM file
	FrameCheck.java	Window frame for code checking module
	InputFileInfo.java	Input file information that are the paths and names of the exterior input files
	InputMoistValues	Writing the values into the simulation software MOIST
	readValuesMoist.java	Reading the simulated values from the output file of MOIST
	ReadWriteXML.java	Reading / Writing XML file of EBIM
	RunExe.java	Running .exe file
	runReadIFC.java	Reading ifcXML file
	RunReadIFCApplication.java	Interface for running runReadIFC and display ifcXML
heat	AirLeak.java	Call AirLeakFrame
	AirLeakFrame.java	Calculation the air leakage of a house
	BP3dV.java	3d display
	Browser.java	Browser for viewing HTML file
	Condense.java	Calling CondenseCompute.java
	CondenseCompute.java	Steady state simulation program based on the Glaser method
	DrawC.java	Drawing the wall's profile using Java 2D
	drawlayers.java	Drawing the wall's assembly section using Java 2D
	drawWeather.java	Drawing the yearly outside temperatures graph using Java 2D
	F3d.java	3d display program for calling BP3dv.java
	graphresult.java	Drawing the wall's profile including temperatures and pressures using Java 2D
	HAMBE.java	Main program of the ACCBEP for calling HAMBEFrame.java
	HAMBEFrame.java	Main program of the ACCBEP including the data integration module, wall assembly design module, and the interface for calling the other modules.
	idx3dMaterialLab.java	Creating the materials for 3d object using idx3d in visualization module
	MoistureGain.java	Calling MoistureGainFrame.java

	MoistureGainFrame.java	Calculator for the moisture gain of a house
	test3d.java	3d display program
	TextureLab.java	Creating the textures for 3d object using idx3d in visualization module
	UnsteadyCal.java	Computing the temperature curve of a building envelope
	UnsteadyDraw.java	Drawing the results of UnsteadyCal.java
	Window.java	Calling WindowFrame.java
	WindowFrame.java	Calculation for the energy rating of a window
IFCthings	readIFCXML.java	Reading and processing IFCXML file
Process -EnergyPlus	ChangeEPInput.java	Finding and replacing the R value from the template EnergyPlus input file
	CsvReader.java	Reading CSV file
	CsvWriter.java	Writing CSV file
	NameofEPfile.java	Storing the paths and names of the EnergyPlus input / output files
	ProcessEnergyPlusFrame.java	Run EnergyPlus program Eplaunch.exe
	ProcessEP.java	Calling ProcessEnergyPlusFrame.java
	ReadEPResult.java	Reading the simulation results of EnergyPlus

Table E.3 Input and output files used in Case Studies

File function	File name and path	Output / Input in ACCBEP	Remark
NOVTEC house with EIFS walls file in ifcXML format	IFC/NOVTEC_House.ifcxml	Input file of ACCBEP (output of ArchiCAD)	ArchiCAD and Autodesk Architecture Desktop can import ifcxml after installing IFC 2x2 plug-in. The EIFS wall information is included in this file.
Building material database file in Microsoft Access format	matdata/matdata.mdb	Input file of ACCBEP	Building material database
Montreal weather data file in Microsoft Access format	weather.mdb	Input file of ACCBEP	Montreal hourly weather data during one year obtained from EnergyPlus website
House file for 3D visualization in 3ds format	NOVTEC_House.3ds	Input file of ACCBEP	This 3d model is created using ArchiCAD and the materials are added by the author.

Path setting file in txt format	filesetting.ini	Input file of ACCBEP	Setting file for storing the input file paths
Layers information of a wall in MOIST in text format	MOIST/CONST.DAT	Input file of MOIST (output of ACCBEP)	This file can be written by ACCBEP and also can be edited in MOIST
Montreal weather data in MOIST format	MOIST/WYMONC	Input file of MOIST	This is a default weather data for the simulation in MOIST
Unit for simulation file in text format	MOIST/UNITS.DAT	Input file of MOIST (output of ACCBEP)	1 is set to British unit system. 0 is set to ISO unit system. The default unit is ISO system.
Building material database file in text format	MOIST/PDATA.DAT	Input file of MOIST (output of ACCBEP)	The material name in this database must be exactly same as the building material database in ACCBEP. Otherwise, some error may occur.
Simulation period setting file in text format	MOIST/PEROD.DAT	Input file of MOIST (output of ACCBEP)	The default value is set to 2 years and the time step is set to one day.
Simulation results of R value of each layer in text format	MOIST/RESULTS.AR	Output file of MOIST (input of ACCBEP)	
Simulation results of RH value of each layer in text format	MOIST/RESULTS.ARH	Output file of MOIST (input of ACCBEP)	
Simulation results of moisture content of each layer in text format	MOIST/RESULTS.MC	Output file of MOIST (input of ACCBEP)	
The EnergyPlus input file of the small bank building in EnergyPlus format	./EnergyPlus/Small_Bank_Examplekkk.idf	Intermediate file of ACCBEP	This is a template file. The simulation parameters have been set. This file is the input file for EnergyPlus simulation and the output file from computation module of ACCBEP to get the R value.

The EnergyPlus simulation results of the small bank building in CSV format	./EnergyPlus/Small_Bank_Examplekkk.csv	Intermediate file of ACCBEP	The daily heating loads and cooling loads are saved in this file. This file is the output file of EnergyPlus and the input file for ACCBEP to get the annual heating loads.
Decision table file in Microsoft Excel format	../code2.xls	Intermediate file of ACCBEP	The entire table is listed in Appendix C.
EBIM file including the simulation results and building information in XML format	DesignFacts.xml	Intermediate file of ACCBEP	This file is input file for code checking and output file for simulation results.
Code checking result file in HTML format	OutReport.htm	Output file of ACCBEP	This file can be read using web browser. The hyperlink of the original code is included in this file.