

IFC-Based Framework for Evaluating Total Performance of Building Envelopes

P. Fazio¹, H. S. He¹, A. Hammad², M. Horvat³

Abstract

Evaluating the overall performance of buildings has emerged as a trend in building engineering in recent years. Several programs that evaluate building performance have been developed or are being developed in different regions of the world. The Building Envelope Performance Assessment Tool (BEPAT) was initiated at Concordia University based on the feedback received from manufacturers. After briefly introducing the development of the tool, this paper presents an integrated framework which applies Information Technology (IT) and the international standard *Industry Foundation Classes* (IFC) to ensure that the building envelope satisfies energy requirements as well as other requirements such as moisture and thermal performance, concurrently. The framework is designed to extract geometric and material layers' data of a house from CAD drawings in IFC data model, link to performance evaluation applications, such as HOT2000 and MOIST3.0, and compare evaluation results with a set of criteria. To demonstrate the functionalities of this framework, a prototype system has been developed including a preprocessor that imports the building model from an IFC-compatible CAD application, an application integrator, and a postprocessor. Finally, a case study, which aims to validate this prototype system, is discussed in detail.

CE Database subject headings: framework, building envelope, performance evaluation, Industry Foundation Classes (IFC).

¹ Building Envelope Performance Laboratory; Centre for Building Studies; Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Quebec, Canada

² Concordia Institute for Information Systems Engineering, Concordia University, Montreal, Quebec, Canada

³ Ryerson University, previously at Building Envelope Performance Laboratory; Centre for Building Studies; Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Quebec, Canada

Introduction

There is a global trend in understanding and evaluating the overall performance of buildings. In several countries (Sweden, EU, Japan, US, etc.) such programs have been or are being developed in an attempt to assess the issues that influence the performance of the building itself and, in some cases, to assess the impact of the building on its surrounding. Examples of these programs are: P-mark (Sweden) (Anneling,1998), Housing Quality Assurance Law – HQAL (Japan) (Ministry of Construction Japan, 2000), ETAG 007—European Technical Approval Guideline for Timber-frame Building Kits (European Community) (EOTA , 2001), R-2000 Program (Canada) (NRCan, 2005), Novoclimat (Quebec, Canada) (Quebec Agency for Energy Efficiency, 2005), LEED™ (US) (U. S. Green Building Council, 2003), etc. A comparative review of these existing certification programs that deal with evaluation and assessment of housing presented advantages and shortcomings of such programs and identified issues specific for Canada (Horvat and Fazio, 2005). In addition, the need for developing a similar kind of evaluation program was voiced by Canadian manufacturers and exporters of prefabricated houses. This resulted in two studies done jointly by Concordia University and Forintek Canada Corp.: Assessment of the Prefabricated Building Industry (Fazio at al., 2000; Horvat et al., 2001) and Durability in Housing: A Review of Quality Certification Programs and Recommendations (Horvat et al., 2002). The studies showed that recognition of superior quality would be an asset in marketing the products for domestic as well as export markets (Fazio et al., 2000).

Based on these studies, a program for the performance evaluation of building envelopes has been developed at Concordia University, Montreal, entitled: Protocol and assessment tool for overall performance evaluation of light-frame building envelopes used in low-rise buildings (Horvat & Fazio, 2003, Horvat & Fazio, 2004). This protocol defines a strategy to evaluate a building envelope as an integrated sub-system of the entire building at the design stage, laboratory testing stage, execution stage, and finished stage of the building. The overall performance evaluation protocol includes the following functional requirements: air tightness, moisture management performance, thermal performance, energy consumption performance, structural stability of the building envelope, acoustic resistance, and fire

response of the building envelope. The protocol follows a performance-based concept, where each functional requirement is divided into its performance or operative requirements and their corresponding criteria and verification methods. The protocol has been designed for Montreal conditions; however, it can serve as a framework for developing similar programs in other regions.

The building envelope is an integral part of the building system and must be well integrated with the structure and the HVAC for the effective performance of the building. The envelope should be treated, therefore, as an integrated part of the building when being designed, and the performance characteristics and construction details of contiguous subsystems should be taken into consideration concurrently (Fazio, 1990). Accordingly, a holistic approach to performance evaluation will ensure that the multiple criteria of the building envelope, such as structural, thermal, integrity, moisture, acoustics, etc., are all satisfied and will ensure that compatibility among the subsystems is established, such as the envelope with the structure, the HVAC, and lighting systems of the building.

The performance of building envelopes can be evaluated through tests or computer simulation. Experimental studies can be carried out in laboratories and in the field, but they are usually more expensive and time consuming than computer simulations. Computer simulation, on the other hand, is less expensive and time consuming, but requires validation. A large number of computer-based applications are already available, e.g., HOT2000 (Buildings Group/NRCan, 2005; Buildings Group/NRCan, 1995), Energy Plus (U.S. Department of Energy, 2005), RIUSKA (Granlund, 2005), WUFI-ORNL/IBP (ORNL/IBP, 2005), hygIRC (IRC/NRC, 2005), MOIST3.0 (BFRL/NIST, 2005), CONDENSE (GES, 2005), and Airpak (Fluent Inc., 2005). However, the data input in these applications is complex and time consuming; and people who run the applications need advanced computer skills and professional experience. In addition, some of these applications cannot read the geometry data that are part of the data input from CAD drawings, which results in low efficiency and data input errors (Suter et al., 2004). Therefore, these applications are typically developed by researchers and used mainly by researchers, and are not often used in actual designs (He et al., 2005). The work presented in this paper tries to eliminate this gap between the frontline practitioners and researchers.

The objective of the research study presented in this paper aims to develop an IFC-based framework to meet the requirements of evaluating building envelope performance by integrating evaluation applications and criteria with IT (Information Technology) and IFC. The specific objectives of this research study are:

- (1) To investigate a conceptual framework for integrating tools to evaluate building envelope performance and compare this performance against established criteria.
- (2) To develop a proof-of-concept system to test and validate the conceptual framework.

Building Envelope Performance Assessment Tool (BEPAT)

The protocol developed in Horvat and Fazio (2003) and Horvat and Fazio (2004) also served as the basis for developing an assessment tool called BEPAT (Building Envelope Performance Evaluation Tool), which is a user-friendly tool developed with Microsoft Excel sheet. As shown in Figure 1, the data generated in the protocol are input manually into BEPAT. BEPAT compares these data against the benchmark values, introduces the weighting system that establishes priority between parameters and calculates the final score. Figure 2 is a fragment (Moisture management performance) of BEPAT in Excel. It shows only 2% of the total requirements of the entire Excel sheet. Data input in BEPAT could be generated by internal calculations in the Excel sheet (e.g., water vapour permeability of the assembly in Figure 2) or by other models, calculation methods and computer programs (e.g., interstitial condensation in Figure 2), More details about the protocol and BEPAT can be found in Horvat and Fazio (2004).

Integrated Framework Using Information Technology and International Standards

Although BEPAT is a useful tool, the user should perform the evaluation with each specialized application and then input the evaluation results manually into the Excel sheet (Horvat and Fazio, 2004). To solve this problem, an IFC-based integrated framework for implementing the performance evaluation protocol has been developed. It evaluates the performances of the building envelope subsystem using multidisciplinary knowledge, the state-of-the-art IT, and the international data exchange standard *Industry Foundation Classes* (IFC). With the application of IFC, the framework can import data from CAD

drawings and exchange data between the preprocessor and the simulation programs, and can interoperate with other frameworks and software using a standard data format. Its final result enables its users to carry out preliminary evaluation of the performance for the building envelope system with limited knowledge of each simulation program used in the evaluation. Engineers and other professionals with an appropriate knowledge of building envelope issues can carry out the evaluation without having to use individual simulation programs and manually match the results with the specific performance criteria. An overall rating would be obtained and, where this rating falls below expectations, corrective measures would be readily applied. The framework would extend the sphere of knowledge in the area of the building envelope and in the application of software engineering to the field of building engineering (He et al., 2005).

IFC as a Building Information Model

IFC is a building information model. It is used as data model in this research project. It is developed by the IAI (International Alliance for Interoperability), which is a non-profit organization. It is a building information model for building data sharing and exchange of AEC/FM (Architecture, Engineering, Construction/Facilities Management) objects including physical objects, e.g., walls, or abstract objects, e.g. projects (IAI, 2005). Based on EXPRESS language which is used in ISO STEP (ISO, 1999), IFC models are organized into a hierarchy structure with the object-oriented method. Furthermore, it is free, open and available to all AEC/FM software developers; thus, interoperability among AEC/FM software applications is achievable.

Current State of Application of IT and IFC in Building Engineering

IT has been widely used in ACE/FM (Architecture, Construction, and Engineering/Facilities Management). However, when practitioners use engineering software applications, they need to transfer and share data among different applications developed by different software developers. Therefore,

interoperability among them is difficult to achieve without an international standard that enables software developers to develop their software based on the same data format.

Since the release of the first IFC version, many software developers have developed their applications to be compatible with IFC, such as Architecture Desktop and ArchiCAD in CAD, Robot with Robin Building Modeler (ISS, 2005) in structural design, Energyplus (U.S. Department of Energy, 2005) and RIUSKA (Granlund, 2005) in energy simulation, AirPack (Fluent, 2005) in indoor quality control, and Timberline Office (Timberline, 2005) in cost estimation. Meanwhile, many researchers are working on advancing the methods for the application of IFC in building engineering. For example, Romberg et al. (2004) used geometric models based on IFC for the finite element analysis in structural design.

In energy simulation, Bazjanac (2004) discussed a new IFC HVAC extension schema that is integrated in the latest version of IFC (IFC2x2). He used a 3D building model of a one-story building as an example to demonstrate the usage of IFC. The model is defined using ArchiCAD and saved in IFC format. EnergyPlus then imports the building geometry data from the IFC format by using BS-Pro-COM Server. Data about HVAC system are input manually according to EnergyPlus definition. Bazjanac and Maile (2004) introduced a new IFC HVAC interface to EnergyPlus which is used to translate HVAC data from IFC2x2 file into corresponding definitions in EnergyPlus Input Data Files (IDF). Furthermore, it can also transfer and add HVAC data in EnergyPlus IDF to IFC2x2 data files. An earlier instance of energy simulation with IFC could be shown in RIUSKA software. It has an AutoCAD-based space-modeling tool called SMOG (Space Modeler by Olof Granlund Oy). It creates 3D objects of walls, windows, doors and spaces and also creates connections between these objects. It can import and export IFC1.5 files and transfer building geometry and construction data from IFC-compliant architectural software into other applications such as energy and comfort simulation, visualization and lifecycle cost analysis. Also, results calculated in RIUSKA can be exported to other IFC-compliant software (Karola et al., 1999).

In code compliance checking, CORENET (CONstruction and Real Estate NETwork) in Singapore has developed a code-checking approach based on IFC. Their Integrated Building Plan and Integrated Building Services (IBP/IBS) e-Plan Checking will enable the government to approve building plans

submitted by architects and building services engineers on the Internet (Liebich et al., 2002). This approach may be extended to offer performance-based code checking. A model-mapping engine called eThermal has been developed within the novaCITYNETS ePlanCheck framework (FORNAX™) to accomplish the task of translating CAD models to EnergyPlus model for thermal and energy simulation (WONG, 2004). IFC is an evolving international standard. With its various extension schemas developed by IFC implementers, it can describe objects in ACE/FM industry which are not included in the current IFC version. Taking the CORENET project as an example, because not all the required facilities which support automated code compliance checking within the e-Plan Checking project are included within IFC2x version, an IFC extension called IFC Extension Project CAS (Codes and Standards) is being developed. It is fully coordinated with other parts of IFC2x2, such as IAI BS8 project, which is related to building services, and IAI EL1 project, which is related to electrical services. This guarantees that the effort in developing a data model in CORENET project would be accepted internationally (Liebich et al., 2002; Yang et al., 2004).

Overview of the Evaluation Framework

The overall design of the evaluation framework is shown in Figures 3. It has the following features:

- (1) Extracting the physical properties, such as dimensions, materials, etc., from the CAD drawings in IFC model and then transferring these data into the simulation programs.
- (2) Integrating simulation programs to enable the user to easily input the characteristics of a given building envelope system and its target geographical location.
- (3) Linking to evaluation applications, such as HOT2000, to determine the performance values, such as the energy consumption of a house for a given region.
- (4) Comparing this performance value against existing criteria for that region which would be provided by the prevailing standards and codes.

(5) Interoperating, if necessary, with other systems and software using IFC.

As shown in Figure 3, the framework consists of the following components and user interfaces.

(1) An IFC-compatible CAD application. It is a CAD tool which can transfer 2D or 3D CAD drawings, files in DraWinG (DWG) or Data eXchange Format (DXF), into IFC files. It can also read IFC files and transfer them into 2D or 3D CAD drawings. Architectural Desktop (Autodesk, 2005) with its IFC2x utility and ArchiCAD (Graphisoft, 2005) with its add-on interface are two typical IFC-compatible CAD applications available on the market.

(2) A preprocessor. The preprocessor is a functional unit in the framework that processes the input data for the building envelope. It is used to access an IFC file from the CAD software; input data from end-users; store data to, and retrieve data from, the database; and build a middle layer (internal data structure) to transfer data to its receptor, the application integrator. The preprocessor consists of:

- An IFC processor, which imports data, such as dimensions, materials, etc., from an IFC file into the framework. Furthermore, it can modify the IFC files, for example, creating, retrieving, and deleting IFC instances, and setting or editing attribute values for IFC instances.
- A user interface for inputting data, which is a graphical interface for the user to input data from IFC model or manually. Moreover, the user can access the material and weather database by using this interface.
- A material and weather database, which manages the data of material and weather information in the system.
- An internal data structure, which is used to map the data from the IFC processor and the user interface for inputting data into the memory. It could be a single class or a set of classes depending on how many applications have been linked in the application integrator. It defines all the data in the framework as well as the functions that these data invoke. Moreover, it has an extensible structure which can be scaled to suit the applications that the framework includes in the application integrator.

- (3) A user interface for selecting evaluation category. This interface helps the user to select the categories of the evaluation performance included in BEPAT. These categories could be one of the following: air tightness, thermal performance, moisture management performance, energy performance, structural stability of building envelope, acoustic performance, fire control of building envelope, quality materials, quality workmanship, and maintenance.
- (4) A user interface for inputting performance value. This interface helps the user to manually input the performance value corresponding to the selected evaluation category. This interface is used when the performance value (e.g., air leakage rate) cannot be calculated automatically by the linked simulation programs.
- (5) An application integrator. The integrator is used to integrate the simulation programs such as HOT2000 and MOIST3.0. It is a linkage between the preprocessor and the simulation programs as well as a receptor for the data that are transferred from the preprocessor. Moreover, it generates performance values automatically by invoking corresponding simulation programs. As shown in Figure 3, the application integrator consists of:
- A user interface for selecting evaluation program, which is a graphical interface for user to select the simulation program corresponding to the category of evaluation performance decided by the user interface for selecting an evaluation category. For instance, HOT2000 may be selected for assessing energy performance; MOIST3.0 may be selected for assessing moisture management performance; and Airpak may be selected for assessing air quality.
 - Simulation applications, such as HOT2000, MOIST3.0, CONDENSE, EnergyPlus, WUFI-ORNL/IBP, hygIRC, Airpak, and so on.
- (6) A postprocessor. It is a functional unit in the framework that processes the performance values of the building envelope. These performance values include two categories according to their sources. One is input by the user from the user interface for inputting performance value; the other is generated automatically by simulation programs in the application integrator. The postprocessor is

used to retrieve performance evaluation criteria from the rule database, compare the performance value with the retrieved criteria, and create a final report to the user. The rule database contains rules extracted from BEPAT.

The Process of Performance Evaluation

The process of building envelope performance evaluation involves inputting data into the framework, generating performance value manually or automatically, and assessing performances against evaluation criteria.

As shown in Figure 3, when the user initiates the process to assess the building envelope performances, he/she can input the data about the building envelope using the preprocessor. These data can be input either using the IFC processor or by the user interface and can be mapped into the memory by the internal data structure.

Having input the data into the framework, the user can select the evaluation category by the user interface for selecting the evaluation category. There are two types of performance values: one is input by the user, such as air leakage rate; and the other is calculated by simulation applications, such as energy consumption from HOT2000. The first type is input manually by the user interface for inputting performance value, and the second one is calculated automatically by the application integrator.

After obtaining performance values, the framework begins to evaluate these performance values in the postprocessor. First, it retrieves criteria from the rule database according to the category of the performance values. Then, the performance values are compared with the retrieved criteria. If the result of the comparison is satisfactory, the user can go back to the user interface to select another evaluation category, or he/she can select to output the final report. On the other hand, if the comparison gives an unsatisfactory result, the user can revise the input data or the design and evaluate the performance again, or output the final report and indicate it failed the evaluation. There are two ways to revise the input data

or the design: one is by modifying the CAD drawing; and the other is by changing the input data in the user interface for inputting data.

Implementation of the Framework

In order to demonstrate the concept of the evaluation framework presented in this paper, a prototype system is currently under development (Hammad et al., 2005). At this stage, some components or user interfaces of the framework are not fully implemented. The following is the summary of the implementation:

- (1) The IFC processor in Figure 3 has several functionalities, such as searching for IFC files from the database, transferring data from the selected IFC file into the prototype system, and displaying imported data on the screen. With this IFC processor, the framework can import geometry and material layer data from the IFC model (IFC text file) using the Eurostep Active Toolbox, which is an Active X component that provides an interface to access IFC model data (Eurostep Group, 2005). The IFC text file is automatically generated by a CAD-compatible application (e.g., Architectural Desktop) from the 3D CAD model. However, at this stage, the prototype system cannot modify the IFC model by the user interface for inputting data.
- (2) Besides importing geometry and material layers' data from the IFC model, the prototype system provides the user interface for inputting data manually. Data other than geometry and material layers, such as WYEC (Weather Year for Energy Calculations) cities in MOIST3.0, weather region and weather city in HOT2000, can be input by the user manually. One of the tab pages (Layer Information) in this interface is shown in Figure 6. On the left-hand side, the user can use the textboxes and comoboxes to input layer information of a wall in a building, such as name, thickness, initial moisture content (MC), wood-based material, thermal resistance, and permeance for the layers. On the right hand side, a graphical cross section of a wall is illustrated.

- (3) Besides importing IFC data and inputting data by the user manually, the prototype system simplifies some complicated data input, such as the HVAC system of a house, by defining them using default values.
- (4) The prototype system evaluates the performance value which is generated automatically by the application integrator. The user interface for selecting the evaluation category and the user interface for inputting the performance value in Figure 3 are not implemented yet.
- (5) At this stage, the prototype system links two simulation programs: HOT2000 and MOIST3.0. It transfers input data from the preprocessor into these two programs, invokes them automatically, and overwrites their input files with the input data. In this way, the prototype system can evaluate the energy consumption of a house, and moisture and thermal performances of assemblies concurrently. The success of linking to the simulation applications HOT2000 and MOIST3.0 results from the availabilities of their APIs (Application Programming Interfaces). HOT2000 is supported by NRCan (Natural Resource of Canada) and is an energy analysis tool for low-rise residential buildings (Buildings Group/NRCan, 2005). Its Windows version could not be linked directly because it has no API. However, NRCan has provided a BATCH HOT2000 version in which both the input and output data are written in ASCII files (Bradley, 2003). Thus, the framework links and transfers input data to this application by overwriting its input and output files. MOIST3.0 was developed by NIST (National Institute of Standards and Technology) and predicts the transfer of heat and moisture in a multi-layer wall under non-isothermal conditions (Burch et al., 2001, 1997). Like HOT2000, both the input and output files in MOIST3.0 are also in ASCII format. Therefore, the framework links and transfers input data to this application in the same way as in HOT2000.
- (6) The prototype system simplifies the output data from HOT2000 and MOIST3.0 by picking up the most useful output results in the evaluation summary (e.g. annual total fuel consumptions). This would enable the user to understand the output of the simulation programs more easily.

(7) The postprocessor in the prototype system compares part of BEPAT by extracting the rules (clauses) into the system directly. Knowledge-based code compliance checking is not included in the prototype system at this moment.

Case Study

In order to test the prototype system, a typical house in Quebec is selected as a case study. The case study will demonstrate the application of IFC and the integrated evaluation approach by importing geometry and material layers' data from an IFC file with the Eurostep Active Toolbox and evaluating the hygrothermal and energy performances with the prototype system concurrently.

Case Description

The selected house is one of ten houses designed for the Advanced House Program in Canada, which showcases the Canadian innovations and affirms the commitment that fosters a greener environment. It is called the NOVTEC Advanced House and was built in the 1990's. The house is a detached single-family house with two and half stories and 3 bedrooms. It is located in Laval city, Quebec. Excluding the garage, the house has 222m² of heated floor area and total volume of 602 m³. The plan drawings of each floor are as shown in Figures 4 (a-c). Before the occupants moved in the house, the energy performance of the house had been monitored. For privacy reason, the energy consumption for Domestic Hot Water (DHW) was not monitored in the field test system. Therefore, there are no DHW data available in this case study. The data from the field tests were collected over a 21-month period from November 1993 to July 1995 (Gerbas, 2000).

Importing Geometry and Material Layer Data from an IFC File with the Eurostep Active Toolbox

In this study, the AutoDesk's Architectural Desktop 2005 with its IFC2x Utility is used as the tool to automatically generate an IFC file from the CAD drawings. A 3D model of the NOVTEC

House was created with this application as shown in Figure 4 (d), and the cross section of the exterior wall in CAD model was also created as shown in Figure 4 (e). This figure shows information about material names and layer thicknesses of the exterior walls. Figures 5 and 6 show how the prototype system handles data which are imported from the IFC model by the IFC processor. As shown in Figure 5, after a user clicks the button, “*Get Geometry Data from IFC,*” geometry data, such as total length and average height of each floor of the building, will be transferred into HOT2000 input files. In addition, as shown in Figure 6, after a user clicks the button, “*Get Layers from IFC,*” material layers’ data, such as interior and exterior finishes, material layer names, and layer thickness, will be transferred into MOIST3.0 input files.

Evaluating the Hygrothermal and Energy Performances with the Framework

In order to prove that the prototype system can evaluate the energy, thermal and moisture performance concurrently by the proposed integrated framework, the wall cross-section of the NOVTEC house was redesigned with two types: *Non-efficient Wall* and *Efficient Wall*. The purpose of selecting these types is to demonstrate the impact on the performance values by the different wall layers’ composition. The *Non-efficient Wall* is derived from the sample wall in MOIST3.0 program. The *Efficient Wall* is the same as the original exterior insulation finish system (EIFS) wall in the actual NOVTEC house. The layer information of these walls is listed in Tables 1. Figure 6 shows the user interface for inputting the layer information of the *Efficient Wall*.

Besides evaluating the house in the original weather location of Montreal (Laval is 29 km northwest of downtown Montreal), a second city, Vancouver, is also considered as evaluation location. The purpose of evaluating the same house in two locations is to demonstrate that the performance values of a wall in different locations vary significantly. The house may meet the requirements in one location but not in another. The evaluation summaries are shown in Tables 2 and 3. The performance values in these two tables are calculated by the simulation applications, HOT2000 and MOIST3.0 (The R values and MC are

calculated by MOIST3.0, and the annual fuel consumption is calculated by HOT2000). These calculations are not carried out directly in HOT2000 and MOIST3.0. Instead, they are carried out in the prototype system by invoking these two applications.

Table 2 shows the evaluation summary of the NOVTEC house with the *Non-efficient Wall* in two locations. The following is the analysis of the data in this table:

(1) Although the moisture content could impact on the thermal resistance of the wall, the R-values of the wall in the two cities vary slightly. They are 2.2, and 2.4 RSI, in Montreal and Vancouver, respectively. Moreover, the R-value of the wall in Montreal is 2.2 RSI, which is less than the 3.4 RSI, the threshold in BEPAT for Montreal. Thus, an extra insulation layer should be added.

(2) The moisture contents (MC) in the two wood-based layers (fireboard sheathing and sugar pine) are significantly different. In Vancouver, the maximum moisture contents in these layers are 14.7 % and 16.8 %, respectively and are both less than 19%, the threshold mentioned in BEPAT. Thus, no rot will occur in these two wood-based layers. However, in Montreal, the maximum moisture contents in these layers are 26.7% and 24.5%, respectively, and are greater than 19%. Moreover, the durations that the MCs are greater than 19% in these layers are 13 weeks and 12 weeks, respectively. Thus, moisture damage due to condensation may occur in these two wood-based layers in Montreal.

(3) Due to the difference of the annual heating degree-day in the two locations (ranging from 4471 to 3007 °C-days), their energy consumptions are different. The difference between the annual total fuel consumption of the NOVTEC house in Montreal (12275.1kWh) and in Vancouver (9190.2kWh) is mainly caused by the difference between the fuel consumption of heating and cooling in these two locations.

Table 3 shows the evaluation summary of the NOVTEC house with the *Efficient Wall* in two locations. The following is the analysis of the data in this table:

(1) For the same reason as in Table 2, the R-values of the wall in the two locations vary slightly. They are 5.0, and 5.2 RSI in Montreal and Vancouver, respectively. Moreover, the R-value of the wall in Montreal

is 5.0 RSI, which is greater than the 3.4 RSI, the threshold in BEPAT for Montreal. Thus, the *Efficient Wall* meets the requirement in BEPAT.

(2) The moisture contents (MC) of the wood-based layer plywood in the two locations are very similar. The maximum moisture contents in this layer are 10.3% and 9.5 % in Montreal and Vancouver, respectively and are both less than 19%, the threshold mentioned in BEPAT. Thus, no rot will occur in this wood-based layer in both locations.

(3) For the same reason as in Table 2, the values of the annual heating fuel consumption of the house are significantly different in the two locations, and their energy consumptions are different. The difference between the annual total fuel consumption of the NOVTEC house in Montreal (11176.8 kWh) and in Vancouver (8437.7 kWh) is mainly caused by the difference between fuel consumption of heating and cooling in these two locations.

By comparing the values of the hygrothermal and energy performance in Tables 2 and 3, one can conclude that the *Efficient Wall* is more suitable than the *Non-efficient Wall* in the case of Montreal. For example, in Montreal, the annual total fuel consumption of the house with the *Efficient Wall* is 11176.8 kWh, which is less than that with the *Non-efficient Wall* 12275.1 kWh. In addition, the maximum MC of the wood-based layer for *Efficient Wall* is 10.3%, which is less than that (26.7%) for *Non-efficient Wall*. Moreover, the *Efficient Wall* can be used both in Montreal and in Vancouver because no MCs in the wood-based layers are greater than 19%. However, the *Non-Efficient Wall* can only be used in Vancouver but not in Montreal because the MCs of the wood-based layers are greater than 19% (26.7% in fibre board sheathing and 24.5% in sugar pipe). Finally, in terms of cost, the cost of the *Efficient Wall* is more expensive than that of the *Non-efficient Wall* since their thicknesses are 8.5 inches (21.59 cm) and 5 inches (12.7 cm), respectively. However, in terms of lifecycle cost and environment protection, the house with *Efficient Wall* costs less in energy consumption and has less gas emissions.

The energy performance of the house had been monitored before the occupants moved in the house. Table 3 (Columns 2 and 3) compares the values of energy performance derived from the evaluation with the framework and the field test for the *Efficient Wall* in Montreal.

The differences of the values in the energy performance between the evaluation with the prototype system and field test are small. For example, the values of annual total fuel consumption derived from the evaluation and the field test are 11171 kWh and 11280 kWh, respectively, where the value in evaluation is 1% less than that in field test. Although some values such as the annual cooling fuel consumption are significantly different, they are less important in terms of energy consumption. Therefore, the results from the proposed system can be used to evaluate the energy performance of a house.

Summary and Conclusions

The research presented in this paper has established the concept for a building envelope performance evaluation framework. This framework integrates existing simulation applications and evaluation criteria with the multidisciplinary knowledge expressed in BEPAT, state-of-the-art IT, and IFC. With some simplifications, a prototype system was implemented based on the concept of the proposed framework. It applies the IFC as its data model and extracts the geometric and material layer data from CAD drawings. Applications such as MOIST 3.0 and HOT2000 have been successfully linked to the prototype system. The performance values generated from the evaluation applications have been partially compared against BEPAT. The case study demonstrated the usefulness of the prototype system.

The proposed framework can facilitate the building envelope evaluation by:

- (1) Simplifying the input and output data of the evaluation applications. These applications have many input and output files. By setting up default values in the input files and picking up the most useful output results in the evaluation summary, the user can use the applications with a minimum set of input data, such as the weather city. Moreover, she/he can check the most important evaluation results, such as the annual total fuel consumptions.

- (2) Carrying out the evaluation in short time.
- (3) Operating the system without having to learn all the details about the evaluation applications.
- (4) Establishing an extensible structure. In the long term, the framework can link more applications depending on the users' needs.
- (5) Reducing the repetitive data input. Based on the same CAD model and general manual data input, the user can use the data of a building in different applications.

Acknowledgements

Mr. Jeff Blake and Mr. Brian Bradley from Natural Resource Canada provided the API and batch version of HOT2000. Mr. Patrick Houbaux and Mr. Kari Karstila from Eurostep Group provided IFC2x2 Active Toolbox evaluation version and implementation samples. Mr. Dino Gerbasi provided data of NOVTEC Advanced House. This project is being funded by Fazio's NSERC grant no. 4770/2002 and a grant from the Faculty of Engineering and Computer Science of Concordia University.

References

- Autodesk (2005). "Autodesk Architectural Desktop."
<<http://usa.autodesk.com/adsk/servlet/index?siteID=123112&id=2956700> > (July 18, 2005).
- Anneling, R. (1998). "The P-mark system for prefabricated houses in Sweden." *CADDET Energy Efficiency Newsletter*, Newsletter No.1, pp.20-22.
< http://caddet-ee.org/public/uploads/pdfs/newsletter/981_07.pdf > (March 9, 2004)
- Bazjanac, V. (2004). "Building energy performance simulation as part of interoperable software environments." *Building and Environment*, 39, 879–883.
- Bazjanac, V. and Maile, T. (2004). "IFC HVAC interface to EnergyPlus - a case of expanded interoperability for energy." *SimBuild 2004, IBPSA-USA National Conference Boulder, CO, USA*. August 2-4, 2004

BFRL/NIST (2005). "MOIST 3.0." < <http://www.bfrl.nist.gov/863/moist.html> > (July 18, 2005).

Buildings Group/NRCan (1995). "HOT2000 Version 7 User's Manual." Natural Resource Canada, Ottawa, Canada.

Buildings Group/NRCan (2005). "HOT2000." < http://www.buildingsgroup.nrcan.gc.ca/software/hot2000_e.html > (July 18, 2005).

Bradley, B. (2003). "BATCH HOT2000, Version 9.2." Natural Resources Canada, Ottawa, Canada.

Burch, D., and George T. (2001). "MOIST: A numerical method for design." *ASTM MNL 40*. U.S.A.

Burch, D. and Chi, J. (1997). "MOIST a PC program for predicting heat and moisture transfer in building envelopes Release 3.0." *NIST Special Publication 917, National Institute of Standards and Technology*.

Eastin, I. and Boardman, P. (2000). "Regulatory Change in the Japanese Residential Construction Industry." < http://www.cintrafor.org/OUTREACH_TAB/links/FallNews00.htm#Regulatory > (July 18,2005)

EOTA (European Organization for Technical Approvals) (2001). "ETAG 007: Guideline for European Technical Approval of Timber Frame Building Kits." Edition April 2001, , Brussels, Belgium, pp.49, < <http://www.eota.be/pdf/ETAGapril01.pdf> > August 24, 2000).

Eurostep Group (2005). "Eurostep IFC toolbox products." < <http://www.eurostep.com/> > (July 18, 2005).

Fazio, P. (1990). "A case study in integrated building design Canadian." *Journal of Civil Engineering*, 17 (4), 636-642.

Fazio, P., and Poliquin, L. (2000). "Survey of Prefabricated Industry Sector – Visit of Prefabricated Companies and R&D Centers in Sweden and Finland." Concordia University and Forintek Canada Corp, April 3-8, 2000.

Fazio, P., Horvat, M., Poliquin, L., and Robichaud, F. (2000). "The Assessment of the Prefabricated Building Industry", report prepared for Société d'habitation du Québec and Canada Mortgage and Housing Corporation, Forintek Canada Corp., Eastern Division, Ste-Foy, Canada.

Fluent Inc. (2005). "Airpak." < <http://airpak.fluent.com/> > (July 18,2005).

- Gerbas, Dino (2000). "The energy performance of the NOVTEC Advanced House." Master's thesis, Concordia University, Canada.
- GES (2005). "CONDENSE." < <http://www.ges-int.com/en/> > (July 18, 2005)
- Granlund (2005). "RIUSKA software."
< http://www.granlund.fi/granlund_eng/ohjelmistomyynti/frameset.htm > (July 18, 2005).
- Graphisoft (2005). "Archicad." < http://www.graphisoft.com/products/archicad/?source=google_GSUS > (July 18, 2005).
- Hammad, A., Fazio, P., and He, H.S. (2005). "Computer tool to achieve better performance and integration of building envelopes with structural and mechanical systems." *The 33rd Annual General Conference of the Canadian Society for Civil Engineering*, Toronto, Canada, June 2-4, 2005.
- He, H.S., Hammad, A., and Fazio, P. (2005). "Application of IT and international standards to improve building envelope performance." accepted by *The Ninth International Building Performance Simulation Association Conference*, Montreal, Canada, August 15-18, 2005.
- Horvat, M., Fazio, P., Poliquin, L., and Robichaud, F. (2001). "Survey of the Canadian Prefabricated Building Industry – Findings." *International Conference on Building Envelope Systems and Technologies, ICBEST-2001*, NRCan, Ottawa, Canada, June 26-29, 2001.
- Horvat, M., Fazio, P., Poliquin, L. (2002). "Durability in Housing: A Review of Quality Certification Programs and Recommendations", report prepared for Société d'habitation du Québec, Forintek Canada Corp., Eastern Division, Ste-Foy, Canada. Also available in French under the title: La durabilité dans la construction domiciliaire - Programmes de certification de la qualité et recommandations.
- Horvat, M. and Fazio, P. (2003) Performance Evaluation Protocol for Full-Scale Wood-Frame Building Envelopes, Architectural Engineering 2003 Conference: Building Integration Solutions - proceedings, ed. by: Liu, M. and Parfitt, K. Austin, Texas, 17-20 September 2003, ASCE, Reston, VA.
- Horvat, M. and Fazio, P. (2004). "Protocol and Assessment Tool for Performance Evaluation of Light-frame Building Envelopes." *Proceedings of the CIB 2004 - World Building Congress: Building for the Future*, Toronto, Canada, May 2-7, 2004.

Horvat, M. and Fazio, P. (2005). "Comparative Assessment of Existing Certification Programs and Assessment Tools Performance Evaluation of Residential Buildings." *Architectural Science Review journal*, University of Sydney, Sydney, Australia, 48.1, 69-80.

IAI (2005). "A short history of the IAI and the IFC information model."
< <http://www.iai-international.org/About/History.html> > (July 18, 2005).

ISO (1999). "Industrial automation systems and integration -- Product data representation and exchange -- Part 225: Application protocol: Building elements using explicit shape representation." *International Standard ISO 10303-225*.

IRC/NRC (2005). "Hygrothermal modeling tool hygIRC 1-D." < <http://irc.nrc-cnrc.gc.ca/bes/hygIRC> > (July 18, 2005).

Inopso GmbH (2005). "IFC2x Utility." < <http://www.inopso.com/> > (July 18, 2005).

ISS (2005). "Robot with Robin Building Modeler." < <http://robotstructures.com/usa/> > (July 18, 2005).

Karola, A., Laine, T., Lassila, K., Lahtela, H., and Jokela, M. (1999). "Simulation data management in the design process." *Proceedings of Building Simulation' 99*, 2, 691-695
< <http://www.ibpsa.org/proceedings/bs99/papers/B-22.pdf> > (July 18, 2005).

Liebich, T., Wix, J., Forester, J. and Qi, Z. (2002). "Speeding-up building plan approvals, the Singapore e-Plan checking project offers automatic plan checking based on IFC." *The European Conferences on Product and Process Modeling (ECPPM)*, Portoroz, Slovenia, 2002.
< http://www.novamsc.com/news/pdf/speeding-up_building_plan_approvals.pdf > (July 18, 2005).

NRCan (2005). "R-2000 Standard."
< http://oe.nrcan.gc.ca/english/r2000_standard_tofc.cfm?PrintView=N&Text=N > (July 18, 2005).

Ministry of Construction Japan (2000). "Standards for Evaluation Methods under the Housing Quality Assurance Law, draft." Notification No. 1654. pp.110.

ORNL/IBP (2005). "WUFI ORNL/IBP v3.0." < <http://www.ornl.gov/sci/btc/apps/moisture/> >

(July 18, 2005).

Quebec Agency for Energy Efficiency (2005). “Novoclimat.”

< <http://www.aee.gouv.qc.ca/habitation/novoclimat/novoclimat.jsp> > (July 18, 2005).

Romberg, R., Niggel, A., van Treeck, C., and Rank, E. (2004). “Structural Analysis based on the Product Model Standard IFC.” *The 10th International Conference on Computing in Civil and Building Engineering, ICCCB E*, Weimar, June 2-4, 2004.

Suter, G. and Mahdavi, A. (2004). “Elements of a representation framework for performance-based design.” *Building and Environment*, 39, 969-988.

Timberline (2005). “Timberline Office.” < <http://www.timberline.com/software/estimating/> > (July 18, 2005).

U.S. Department of Energy (2005). “EnergyPlus.” < <http://www.eere.energy.gov/buildings/energyplus/> > (July 18, 2005).

U. S. Green Building Council (2003). “LEEDTM Green Building Rating System For New Construction & Major Renovations (LEED-NC).” *Version 2.1*, November 2002, revised March 14th, 2003, Washington, D.C., USA,, pp.75. < http://www.usgbc.org/Docs/LEEDdocs/LEED_RS_v2-1.pdf > (November 10, 2003)

Wong, N. H. (2004). “Integration of CAD and Thermal Simulation through Industry Foundation Classes (IFC) Product Model.” < http://bdg.nus.edu.sg/research/eThermal_04_017.pdf > (July 18, 2005).

Yang, Q.Z., Xu, X. (2004). “Design knowledge modeling and software implementation for building code compliance checking.” *Building and Environment*, 39, 689-698.

List of Caption of Tables

Table 1. Layer Information of the *Non-efficient Wall* and *Efficient Wall*

Table 2. Evaluation Summary of the NOVTEC House with the *Non-efficient Wall* in Two Locations

Table 3. Evaluation Summary of the NOVTEC House with the *Efficient Wall* in Two Locations and its
Field Test in Montreal

Table 1. Layer Information of the *Non-efficient Wall* and *Efficient Wall*

Wall (1)	Layer Position (2)	Material (3)	Thickness (in or cm) (4)
<i>Non-efficient Wall</i>	Interior Finish	Latex Paint	N/A
	Layer 1	Gypsum Board	0.5 (1.27)
	Layer 2	Glass Fiber Batts* (R11)	3.5 (8.89)
	Layer 3	Fibre Board Sheathing	0.5 (1.27)
	Layer 4	Sugar Pine	0.5 (1.27)
	Exterior Finish	No paint no wall paper	N/A
	Interior Finish	Latex Paint	N/A
<i>Efficient Wall</i>	Layer 1	Gypsum Board	0.5 (1.27)
	Layer 2	Glass Fiber Batts* (R14)	4 (10.16)
	Layer 3	Extruded Polystyrene (R7.5)	1.5 (3.81)
	Layer 4	Plywood	0.5 (1.27)
	Layer 5	Extruded Polystyrene (R7.5)	1.5 (3.81)
	Layer 6	Brick	0.5 (1.27)
	Exterior Finish	No paint no wall paper	N/A

*Non-storage Material: is the insulation material with low density (e.g. glass fiber blanket insulation and cellulose insulation) and cannot store heat and moisture.

Table 2. Evaluation Summary of the NOVTEC House with the *Non-efficient Wall* in Two Locations

Location		Montreal (1)	Vancouver (2)
Minimum R Value (RSI)		2.2	2.4
Wood-based layer 1 (Fibre Board Sheathing)	MC (%)	4.6 ~ 26.7	5.2 ~ 14.7
	Duration (MC>19%)	13 weeks (From the 27 th to the 40 th week)	N/A
Wood-based layer 2 (Sugar Pipe)	MC (%)	6.7 ~ 24.5	7.4 ~ 16.8
	Duration (MC>19%)	12 weeks (From the 29 th to the 41 st week)	N/A
Annual Heating Degree Day (°C-days)		4471	3007
Annual Heating Fuel Consumption (kWh)		7126.7	4491.6
Annual Cooling Fuel Consumption (kWh)		485.5	166.2
Annual Appliance Fuel Consumption (kWh)		4662.6	4532.4
Annual Total Fuel Consumption (kWh)		12275.1	9190.2
First Day of Simulation		July 1 of the first year	
Last Day of Simulation		June 30 of the second year	
Thickness of the Wall (in or cm)		5 (12.7)	

Table 3. Evaluation Summary of the NOVTEC House with the *Efficient Wall* in Two Locations and its Field Test in Montreal

Location (1)	Montreal		Vancouver Evaluation (4)
	Evaluation (2)	Field Test (3)	
Minimum R Value (RSI)	5.0	N/A	5.2
Wood-based layer (Plywood)	MC (%)	6.8 ~ 10.3	N/A
	Duration (MC>19%)	N/A	N/A
Annual Heating Degree Day (°C-days)	4471	4471	3007
Annual Heating Fuel Consumption (kWh)	5814.0	4810	3537.7
Annual Cooling Fuel Consumption (kWh)	621.1	989	254.1
Annual Appliance Fuel Consumption (kWh)	4741.7	5481	4645.8
Annual Total Fuel Consumption (kWh)	11176.8	11280	8437.7
First Day of the Simulation	July 1 of the first year		
Last Day of the Simulation	June 30 of the second year		
Thickness of the Wall (in or cm)	8.5 (21.59)		

List of Caption of Figures

Fig. 1: The Structure of the Performance Evaluation Protocol and the Building Envelope Performance Assessment Tool (Horvat & Fazio, 2004)

Fig. 2. BEPAT in Microsoft Excel format (Horvat and Fazio, 2004)

Fig. 3. Overview of the building envelope evaluation framework

Fig. 4. Plans of the (a) ground floor, (b) first floor, and (c) mezzanine floor of the NOVTEC Advanced House (Gerbasi, 2000), (d) 3D model of NOVTEC house created with Architectural Desktop 2005, (e) Cross section of the exterior wall in CAD model created by Architectural Desktop 2005

Fig. 5. Geometry data of the exterior walls in IFC model imported into the framework

Fig. 6. Material layers data of exterior walls in IFC model imported into the framework

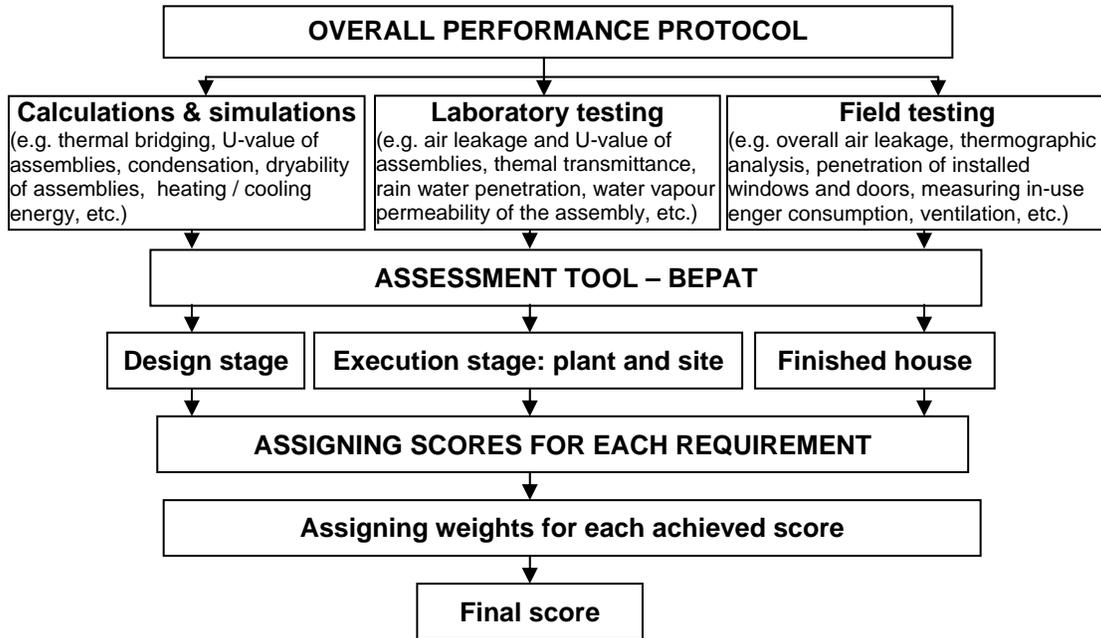


Fig.1. The Structure of the Performance Evaluation Protocol and the Building Envelope Performance Assessment Tool (based on Horvat & Fazio, 2004)

DESIGN PHASE							
FUNCTIONAL REQUIREMENT	OPERATIVE or PERFORMANCE REQUIREMENT	ACTUAL DESIGN VALUES		CRITERION	SCORE	EVALUATION METHOD(S)	
Moisture management performance	Use of kiln dried wood	Initial (construction) moisture content of structural lumber at the time of instalation	%				
			12	< 19%	2		
	Water vapour permeability of the assembly	Mandatory water vapour retarder installed on the warm side of insulation		ng/Pa·s·m ²	ng/Pa·s·m ²		
		Exterior walls: water vapour retarder component			< 45 or < 15	-2	if sheathing or cladding on the exterior side have less permeance.
		Phenolic insulation board, 50.8 mm	67				
		Exterior walls: sheathing/cladding on exterior side					
		Flakewood board (OSB), 15.3 mm	30				
		Roof: water vapour retarder component			< 45 or < 15	2	
	Polyethylene sheet 6-mil (0.15mm)	3					
	Roof: sheathing / roofing membrane						
Plywood sheathing, 9.5 mm	32						
Interstitial condensation	Water vapour movement and temperature and pressure drops across the assembly		ng/s·m ²	ng/s·m ²		Calculation by one of the following methods: 1) Dew-Point Method-ASHRAE Fundamentals, 1997 - 22.18 2) CONDENSE software	
	Calculated condensation rate across exterior walls* assembly:	2638.8		< 50,000	2		
	Calculated condensation rate across roof assembly:	3094.4		< 50,000	2		

Fig. 2. BEPAT in Microsoft Excel Sheet (Horvat and Fazio, 2004)

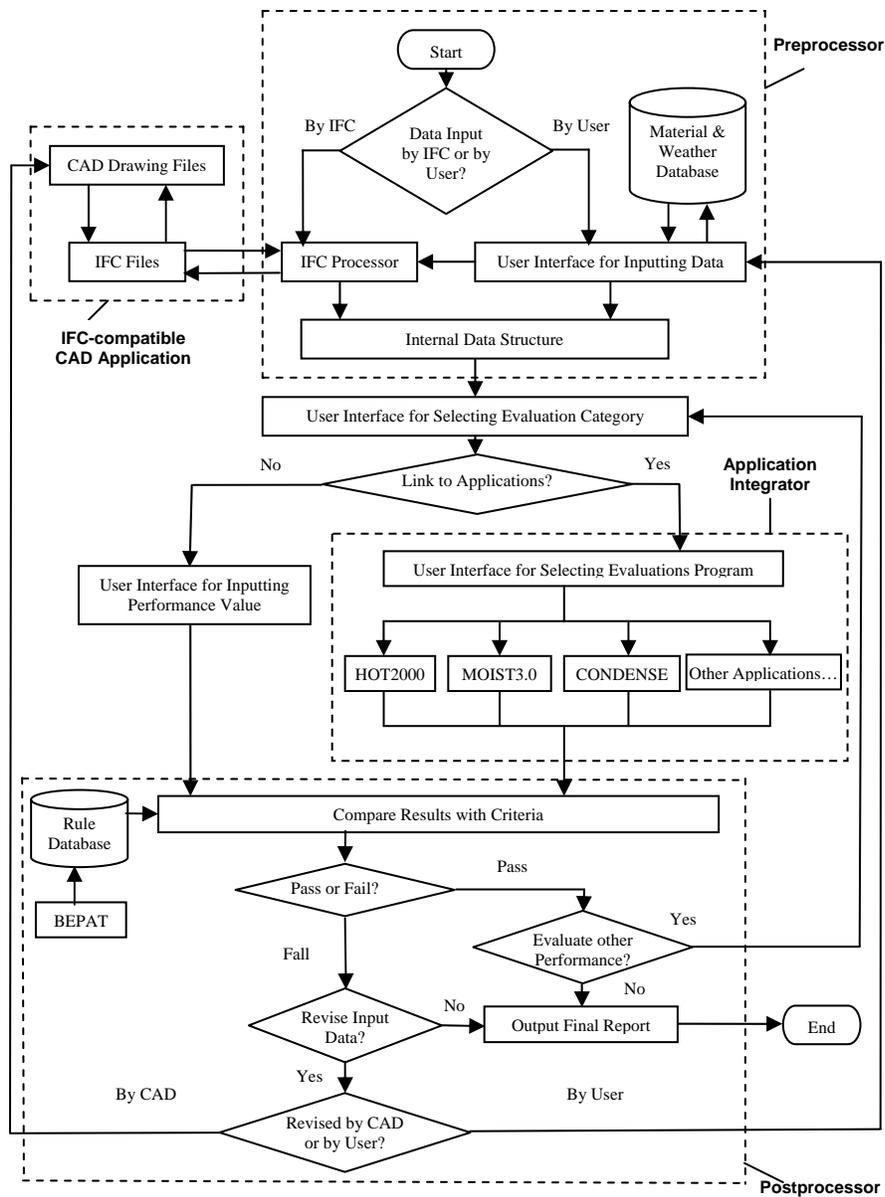


Fig. 3. Overview of the building envelope evaluation framework

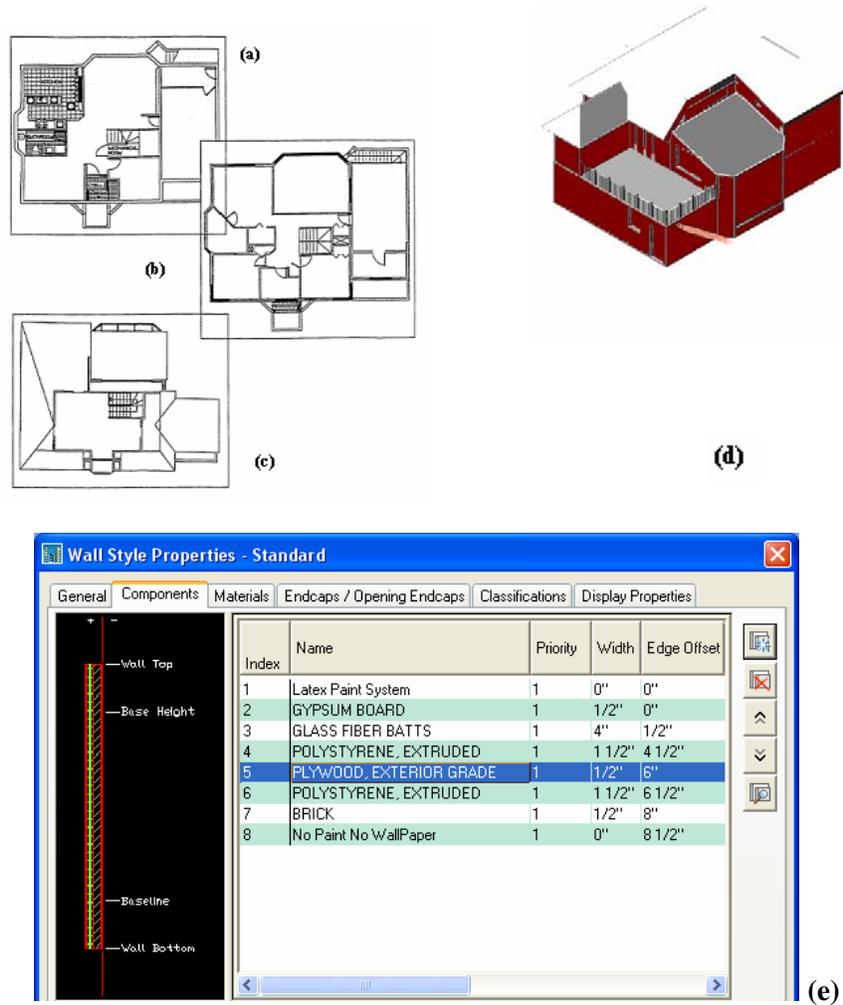


Fig. 4. Plans of the (a) ground floor, (b) first floor, and (c) mezzanine floor of the NOVTEC Advanced House (Source of NOVTEC House: Gerbasi, 2000), (d) 3D model of NOVTEC house created with Architectural Desktop 2005, (e) Cross section of the exterior wall in CAD model created with Architectural Desktop 2005

The screenshot shows a software window titled "General Data Input" with a menu bar (File, Edit, View) and a toolbar. Below the toolbar are tabs for "Location and General", "Material Database", "Geometry Data", "Layer Information", and "Save and Start". The "Geometry Data" tab is active. The form contains the following fields:

- 1. Number of Floors:
- 2. External Wall Information:
 - Floor 1:
 - Total Length (in):
 - Average Height (in):
 - Floor 2:
 - Total Length (in):
 - Average Height (in):
 - Floor 3:
 - Total Length (in):
 - Average Height (in):

At the bottom of the form is a button labeled "Get Geometry Data From IFC".

Fig. 5. Geometry data of the exterior walls in IFC model imported into the system

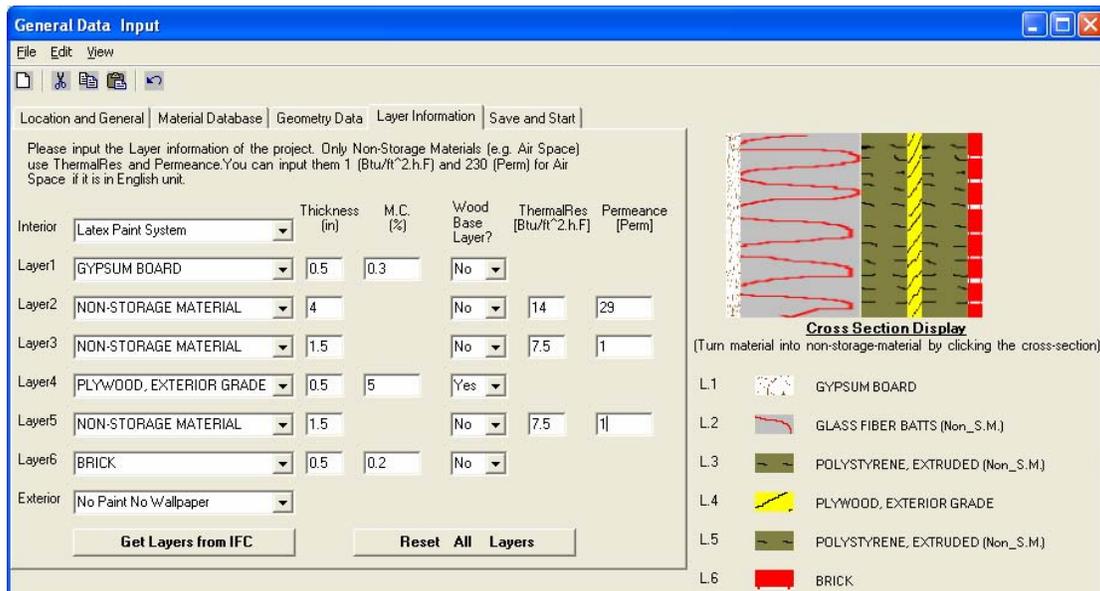


Fig. 6. Material layers data of exterior walls in IFC model imported into the system