APPLICATION OF IT AND INTERNATIONAL STANDARDS TO EVALUATE BUILDING ENVELOPE PERFORMANCE

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ABSTRACT

Improving thermal performance of building envelopes reduces energy consumption of residential buildings. This reduction is better fostered if the thermal analysis is included in the overall performance analysis of the building envelope or the building system. An integrated approach with IT and international standards, such as IFC, can ensure that the building envelope satisfies energy requirements as well as other requirements such as hygrothermal, acoustic, aesthetic, or economic criteria. This paper presents the concept of a building envelope performance evaluation framework which includes an IFC-compatible CAD application, a preprocessor, an application integrator, a postprocessor, etc. The proposed framework could extract the geometric data of a house from CAD drawings in IFC data model, link to performance evaluation applications, and compare evaluation results with a set of criteria. Finally, a system which partially implements the concept of this framework and a case study are also discussed.

INTRODUCTION

Since the first energy crisis in 1973, energy conservation has been considered as an important factor in the lifecycle of buildings. Thus, efforts have been made to achieve this goal by improving the thermal performance of the building envelope, e.g., the advanced house program from NRCan, better windows, and improved thermal performance of building envelopes.

According to Hydro Quebec, house characteristics in Canada are significant factors that directly influence energy consumption, especially in heating. For a residential house, a building envelope with poorly insulated walls, roofs, and foundations could cause up to 40% of total heat loss; draft can cause up to 25% of total heat loss; and low quality doors and windows can cause up to 30% of total heat loss (Hydro Quebec, 2004). Therefore, in terms of saving energy, providing housing systems, specifically building envelope subsystems, with energy conservation characteristics is one of the most critical tasks for the decision makers concerned with reducing energy consumption and lowering the lifecycle cost of houses.

In addition to saving energy, building envelope functions as a barrier or filter to protect the occupants from cold and hot weather, wind, rain, water vapor, solar radiation, outside noise, pollution, smoke and fire propagation, insects, and animals. Moreover, it must be structurally strong and stable, durable, aesthetically pleasing and economical (Hutcheon, 1963). Accordingly, in evaluating the performances of the building envelope, all these multidisciplinary and interrelated factors must be considered. For instance, after making a house more airtight to save energy, mechanical ventilation of a house may have to be introduced to provide the required fresh air to the occupants. In other words, the energy performance must be linked to the overall performance of the building, such as air tightness, moisture management performance, thermal performance, indoor air quality, structural stability, acoustic performance, fire control, etc.

In order to optimize the design and to achieve the best overall performance, energy conservation characteristics of the house should be introduced at the conceptual design stage. However, designers typically place low priority on energy performance at this stage because they believe energy is low in price, energy consumption occurs at the service stage, and no convenient tools are available to evaluate energy performance. In fact, there are many computer-based performance evaluation applications available in practice to evaluate energy consumption as well as other functions of the house. For example, HOT2000 (Buildings Group NRCan, 2004), EnergyPlus (US Department of Energy, 2004), WUFI-ORNL/IBP (ORNL/IBP, 2004), hygIRC (IRC/NRC, 2004), MOIST (BFRL/NIST, 2004), CONDENSE, and Airpak (Fluent, 2004). Since data input in these applications is complicated and time-consuming, people who run the applications need advanced computer skills and professional experience. In addition, these applications cannot read the geometry data, an important part of the data input, from CAD drawings which results in low efficiency and data input errors (Suter et al., 2004). Moreover, some of these applications are typically developed by researchers and used by researchers, and are rarely used in actual designs.

Beside evaluation applications, other Information Technologies (IT) have been widely used in

ACE/FM (Architecture, Construction, and Engineering/Facility Management), for example, CAD, structure analysis, HVAC design, cost estimation, construction management, code compliance checking etc. Unfortunately, these applications normally are developed by different individual software developers. Thus, data transfer from upstream to downstream applications often meets difficulties. Applying Industry Foundation Classes (IFC) (IAI, 2004) may be one of the best solutions to this problem.

Using performance evaluation applications aims to judge whether the building envelope comply with a specific code or standard in design or maintenance stages. Consequently, it is necessary to have a set of criteria to compare with the results from performance evaluation applications. Based on criteria developed in Canada and other countries, BEPA (Building Envelope Performance Assessment) protocol is being developed at Concordia University (Horvat and Fazio 2004, 2005). It focuses not only on the durability of building envelopes but also on energy performance of houses.

The objectives of the research described in this paper are to develop an integrated framework for building owners, manufacturers, designers, and evaluators, which could be easily used to evaluate the total performance of a housing system by integrating existing applications, such as HOT2000 and MOIST3.0, and evaluation criteria, such as BEPA protocol, with multidisciplinary knowledge, state-of-the-art IT, and IFC. Moreover, in the future, the framework can be extended to evaluate complete housing systems. Consequently, engineers and other professionals with an appropriate knowledge of building envelope could then carry out the evaluations without having to use individual simulation programs and manually match the results with the specific performance criteria.

LITERATURE REVIEW

The application of IT in AEC/FM has benefited considerably to professionals in building engineering because electronic documents are more accurate, easier to modify, and less time-consuming than hard copies. However, practitioners who are working in different fields of building engineering usually apply different computer applications separately. Thus, data within these applications cannot be shared or exchanged so as to reduce the manual re-entry of input data. In order to overcome this problem, many researchers have devoted their efforts to develop some neutral layers or information standards by which the separate computer applications could communicate with each other, for example, Initial Graphics Exchange Specification (IGES) (IGES, 2004), Standard for the Exchange of Product Model Data **(**STEP) (STEP Tool, 2004) and Industry Foundation Classes (IFC) (IAI, 2004). The IGES is the first generation of the neutral layer. After that, STEP was developed into an international standard by ISO based on IGES. IFC, also an international standard, is being developed by the IAI (International Alliance for Interoperability), based on the same schema language EXPRESS (ISO 10303 Part 11) and physical clear text format (ISO 10303 Part 21) as that of STEP.

IAI is a non-profit organization. Its IFC is a free, open standard and available to all AEC/FM software developers. Many software developers have developed their applications in a way compatible with IFC, for example, Architecture Desktop and ArchiCAD in CAD drawing; Robot with Robin Building Modeler (ISS, 2004) in structure design; EnergyPlus (US Department of Energy, 2004) and RIUSKA (Granlund, 2004) in energy simulation; AirPack (Fluent, 2004) in indoor quality control; and Timberline office (Timberline, 2004) in cost estimation.

Among these IFC-compatible applications, EnergyPlus is one of the most important simulation programs. The component related to IFC is its IFCtoIDF utility which extracts the geometric representation of building, space, envelope surface and opening object instances from an IFC data file into the Input Data Files (IDF). There is a great amount of research literature related to EnergyPlus. For instance, Bazjanac (2004) discussed a new IFC HVAC model extension (part of the BS-8 project in IAI), which has been integrated into the latest IFC version (IFC2X2). With this extension, the quality of energy performance simulation has been improved because it makes it possible to link HVAC design tools (e.g. MagiCAD) and simulation tools (e.g. EnergyPlus). Bazjanac et al. (2004) is also part of the BS-8 project in IAI. It introduced a new IFC HVAC interface to EnergyPlus which is used to translate the HVAC data from an IFC2x2 file into the corresponding definitions in IDF. It can also transfer and add HVAC data in IDF into IFC2x2 data files.

In addition to applications in energy simulation, IFC is also widely used in code compliance checking. There is an ongoing effort in Singapore to develop an IFC-based online system, Integrated Building Plan and Service (IBP/IBS) checking system, which enables the government to approve building plans submitted by architects and building services engineers on the Internet (Liebich et al., 2002). A pilot project for delivering this online code-checking service is demonstrated in Yang et al. (2004). This project applies an object-based building modeling approach and is implemented in a distributed system. Its prototype system is implemented in J2EE (Java 2 Platform, Enterprise Edition) and consists of four tiers: client tier, web tier, EJB (Enterprise Java Beans) tier, and data resources tier. The most important service in this prototype is its compliance checking which deals with the requests from clients. Moreover, this prototype includes the Java-based rule inference and IFC-based geometric reasoning (Yang et al., 2004).

OVERVIEW OF THE PROPOSED APPROACH

The research study presented in this paper is an integrated building envelope performance evaluation framework with the application of IT and IFC. The final result of this framework enables its users to evaluate the performance for the building envelope system by themselves without learning how to use each simulation program and manually matching the results with the specific performance criteria.

The Features of the Evaluation Framework

The following is the features of the proposed computer-based evaluation framework:

(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 location.

(3) Linking to application software, 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 by the internal information standard model IFC.

The Structure of the Evaluation Framework

The overview of this framework is shown is Figure 1 (at the end of the paper) and Figure 2. 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. The AutoDesk's Architectural Desktop with its IFC2x utility and Graphisoft's ArchiCAD with its add-on interface are two typical IFC-compatible CAD applications available in 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 (other than from IFC model) of a building 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. 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. They are included in Building Envelope Performance Assessment (BEPA) protocol which is under development at Concordia University (Horvat & Fazio, 2004, 2005).

(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 invoked corresponding simulation programs. As shown in Figure 2, the application integrator consists of:

- A user interface for selecting evaluation program, which is a graphic interface for user to select the simulation program corresponding to the category of evaluation performance decided by the user interface for selecting evaluation category. For instance, assessing energy performance may select HOT2000; assessing moisture management performance may select MOIST3.0; and assessing air quality may select Airpak.

- Simulation applications, such as HOT2000, MOIST3.0, CONDENSE, EnergyPlus, WUFI-ORNL/IBP, hygIRC, Airpak, and so on.

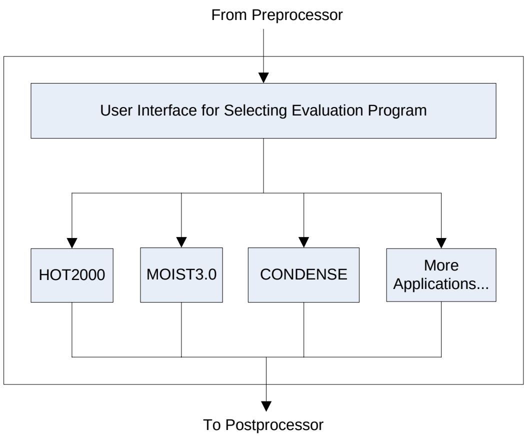

Figure 2 Application Integrator

(6) A postprocessor: It is a functional unit in the system 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 the BEPA protocol.

The Process of the 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 1, when the users initiate to assess the building envelope performances, they can input the data about the building envelope by the preprocessor. These data can be input either by the IFC processor or by the user interface for inputting data and can be mapped into the memory by the internal data structure.

Having input the data into the system, the users can select the category of the evaluation performance. In terms of generating method, there are two types of performance value: one is input by the users, 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 generating performance values manually or automatically, the system 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 comparison passes, the users can go back to the user interface to select another evaluation category, or they can select to output the final report if the users want to stop the evaluation. On the other hand, if the comparison fails, the users can revise the input data 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: one is by modifying the CAD drawing; the other is by changing the input data in the user interface for inputting data.

EVALUATION CRITERIA

The results from the evaluation applications need a set of criteria to be evaluated. Several protocols already exist to evaluate the overall or part of the performance of a house, for example, the P-mark from Sweden (SP, 2004), the Housing Quality Assurance Law (HQAL) from Japan (Eastin et al., 2000), the European Technical Approval Guidelines ETAG 007 from Europe (EOTA, 2002), and the Partnership for Advancing Technology in Housing (PATH) from the United States (PATH, 2004). In Canada, there is the R-2000 program (NRCan, 2004) and the Novoclimat from Quebec (Quebec Agency for Energy Efficiency, 2004; Horvat, 2002). To advance the concept of overall building performance, the research group on the building envelope at Concordia University first undertook the classification of the requirements and standards governing building performance resulting in the Building Envelope Performance Assessment (BEPA) protocol (Horvat & Fazio, 2004, 2005). The following functional requirements are included in this protocol: structural stability, air tightness, moisture management performance, thermal performance, energy performance, acoustic performance and fire control of the building envelope (Horvat & Fazio, 2004 & 2005).

IMPLEMENTATION

In order to implement the concept of the evaluation framework that presented in this paper, a prototype system is currently under development and is described briefly here. More details about the system can be found in Hammad et al. (2005).

At this stage, only a part of the framework has been implemented. Some components or user interfaces of the evaluation system are not fully implemented. The following is the list of the simplifications made in the implementation:

(1) The IFC processor only imports data from the IFC files and cannot modify the IFC files by the user interface for inputting data. Moreover, these imported data are limited to geometry data.

(2) The framework only evaluates the performance value which is generated automatically by the application integrator. In other words, the user interface for selecting evaluation category and the user interface for inputting performance value in Figure 1 are not implemented.

(3) The application integrator only links to two simulation programs: HOT2000 and MOIST3.0.

(4) The comparison in the postprocessor is limited to one part of BEPA protocol by extracting the rules (clauses) from the framework.

Importing IFC Files

The IFC processor can import data such as dimensions, materials, etc., from an IFC file into the framework. It accesses the IFC data file by the assistance of the Eurostep Active Toolbox, which is an Active X component that provides an interface to access IFC model data (Eurostep Group, 2004).

Figure 3 is the screen shot of importing the IFC data. It has functionalities, such as searching for IFC files from the database and transferring data from the selected IFC file into the framework. The messages that are displayed in the textbox are some geometry data, such as the total length and height of walls in each story of the building.

Inputting Data Manually

The user interface for inputting data is a graphical interface for the user to input data manually. There are two scenarios to use this interface. First, after the users have imported geometric data from an IFC file, they can use it to input data other than geometry. Second, if the users do not select importing IFC file, they can use this interface to input all data including geometric data. One of the tab pages (Step 1) in this interface is shown in Figure 4. On the left-hand side, the user can use the textboxes to input information of the building, such as location, weather area, orientation, indoor temperature and relative humidity, etc. On the right hand side, a graphical cross section of a wall is illustrated. The table in the bottom is the list of the materials which exist in the database of the framework.

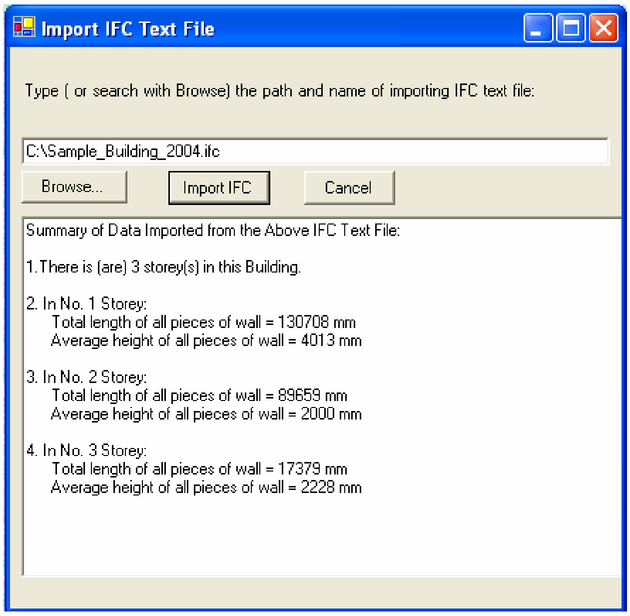

Figure 3 Importing Data From an IFC File

Application Linkage

Linking to the simulation applications needs technical support from their developers by providing APIs (Application Programming Interfaces) so that the framework could access the applications. At present, only the APIs for MOIST3.0 and HOT2000 (batch version) are available.

HOT2000 is supported by NRCan (Natural Resource of Canada) and is an energy analysis tool for low-rise residential buildings (Buildings Group NRCan, 2004). 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 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 to it in the same way as in HOT2000.

CASE STUDY

The objective of the case study is to prove that the framework can evaluate the energy consumption, thermal and moisture performance concurrently by an integrated approach. The house used in the case study is located in Winnipeg, Canada and is a single detached house with two stories and a basement. The plan shape of the house is rectangular. The front orientation is south. The building envelope surface area is 291.2 m^2. The cross section of the wall consists of four material layers: gypsum board (1.27cm), glass-fiber insulation (8.9cm), fireboard sheathing (1.27cm), and sugar pine (1.27cm). The house has been evaluated in three locations: Winnipeg, Montreal, and Vancouver. The purpose of evaluating the same house in three locations is to demonstrate that the performance values of a wall in different locations vary significantly. They may meet the requirement in one place but not in other. Table 1 lists part of the performance values calculated with the simulation applications, HOT2000 and MOIST3.0. The RSI and Moisture Content (MC) values are calculated by MOIST3.0, and the annual space heating energy is calculated by HOT2000. Moreover, these calculations are not carried out directly in HOT2000 and MOIST3.0. Instead, they are carried out in the framework by invoking these two applications. The following results are based on the analysis of the evaluation summary from the framework.

(1) Due to the difference of the annual heating degree day in the three cities (ranging from 5889 °C-days to 3007 °C-days), the values of the annual space heating energy of the same house are significantly different in the different cities. The value for Winnipeg is the highest (48127MJ) while the value for Vancouver is the lowest (19260MJ).

(2) The MC values in two wood-based layers (fireboard sheathing and sugar pine) are also significantly different. In Vancouver, the maximum MC values in these two layers are 14.7 % and 16.8 %, respectively, and are also less than the threshold 19%, mentioned in the BEPA protocol. Thus, no rot will occur in these two wood-based layers in Vancouver. However, in Winnipeg and Montreal, the maximum moisture contents in these two layers are greater than 19%. Thus, moisture damage due to condensation may occur in these layers in Winnipeg and Montreal.

(3) Since the moisture content could impact the thermal resistance of the wall, the R-values of the wall in the three cities vary slightly. The R-value of the wall in Montreal is 2.2 RSI, which is less than the 3.4 RSI, found in the BEPA protocol for Montreal. Thus, a new insulation layer with a 3.4 RSI is recommended.

Table 1
Results of Comparing 3 Locations

Location	RSI of the wall	MC (%)		AHDD (°C-days)	ASHE (MJ)
		Fireboard Sheathing	Sugar Pine		
Winnipeg	2.2	4.6~41.4	5.7~34.7	5889	48127
Montreal	2.2	4.7~26.7	6.7~24.5	4471	36841
Vancouver	2.4	5.2~14.7	7.4~16.8	3007	19260

Note: AHDD =Annual Heating Degree Day
ASHE =Annual Space Heating Energy
Unit of RSI is m^2•K/W

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 multidisciplinary knowledge, 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 data from CAD drawings with the assistance of the Eurostep toolbox. Applications such as MOIST 3.0 and HOT2000 have been successfully linked to the framework. The performance values generated from the evaluation applications have been partially compared with the developing BEPA protocol. The case study demonstrated the usefulness of the proposed system.

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REFERENCES

Bazjanac, V. (2004). Building energy performance simulation as part of interoperable software environments, Building and Environment 39

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

BFRL/NIST (2004). MOIST 3.0 http://www.bfrl.nist.gov/863/moist.html .

Buildings Group NRCan (2004). HOT2000 http://www.buildingsgroup.nrcan.gc.ca/software/hot2000_e.html.

Bradley, B. (2003). BATCH HOT2000, Draft for Version 9.2, Natural Resources Canada

Burch, D., and George T. (2001). MOIST: A numerical method for design, ASTM MNL40

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, CINTRAFOR News, Vol. 16, No.2

Eurostep Group (2004). Eurostep IFC toolbox products http://www.eurostep.com/.

EOTA (2002). Draft ETAG007 http://www.cmhcschl.gc.ca/en/homadoin/excaprex/suexin/suexin_024.cfm.

Fluent (2004). Airpak http://airpak.fluent.com/.
Granlund (2004). RIUSKA software http://www.granlund.fi/granlund_eng/ohjelmistomyynti/frameset.htm.
Hammad, A., Fazio, P., and He, H.S. (2005). Computer tool to achieve better performance and integration of building envelops with structural and mechanical systems, accepted by the 33d Annual General Conference of the Canadian Society for Civil Engineering, Toronto, 2005
Horvat, M. and Fazio, P. (2005). Comparative Review of Existing Certification Programs and Performance Assessment Tools for Residential Buildings, accepted for publication in Architectural Science Review journal, Sydney, Australia, 2005.
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, May 2-7, 2004.
Hutcheon, N.B. (1966). CBD 48: Requirement for Exterior Wall, Canadian Building Digest, NRC, DBR Ottawa, Canada.
Hydro Quebec (2004). What influences your consumption http://www.hydroquebec.com/residential/.
Horvat, M., Fazio, P. and Poliquin, L. (2002). Durability in Housing: a Review of Quality Certification Programs and Recommendations, La durabilité dans la construction domiciliaire, programmes de certification de la qualité et recommandations, report prepared for the Société d'habitation du Québec, Québec, Canada
IAI (2004). A short history of the IAI and the IFC information model http://www.iaiinternational.org/iai_international/.
IGES (2004). About IGES http://www.nist.gov/iges/.
IRC/NRC (2004). Hygrothermal modeling tool hygIRC 1-D http://irc.nrc-cnrc.gc.ca/bes/hygIRC.
ISS (2004). Robot with Robin Building Modeler http://robotstructures.com/usa/.
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 http://www.novamsc.com/news/pdf/ speeding-up_building_plan_approvals.pdf
NRCan (2004). R-2000 Standard http://oee.nrcan.gc.ca/r2000_standard_scope.cfm.
ORNL/IBP (2004). WUFI ORNL/IBP v3.0 http://www.ornl.gov/sci/btc/apps/moisture/.
PATH (2004). Partnership for advance technology in housing http://www.pathnet.org/.
Quebec Agency for Energy Efficiency (2004). Novoclimat http://www.aee.gouv.qc.ca/habitation/novoclimat/novoclimat.jsp.
Suter, G. and Mahdavi, A. (2004). Elements of a representation framework for performance-based design, Building and Environment, 39
SP (2004). SP Swedish National Testing and Research Institute http://www.sp.se/eng/spenergi/kvalitetssakring.htm.
Timberline (2004). Timberline Office http://www.timberline.com/software/estimating/.
U.S. Department of Energy (2004). EnergyPlus http://www.eere.energy.gov/buildings/EnergyPlus/.
Yang, Q.Z., Xu, X. (2004). Design knowledge modeling and software implementation for building code compliance checking. Building and Environment, Vol. 39

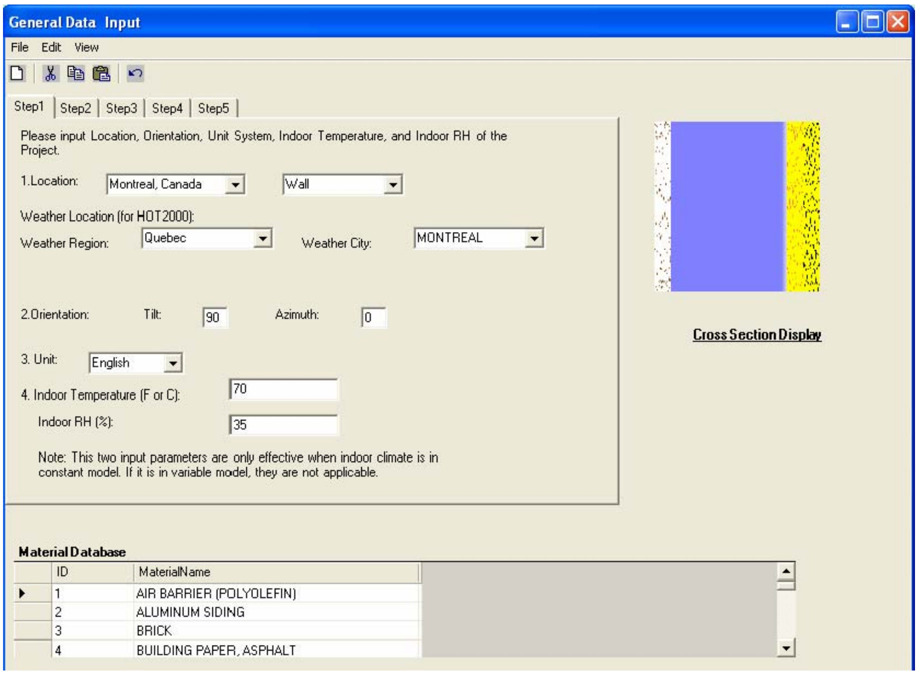

Figure 4 User Interface for Inputting Data

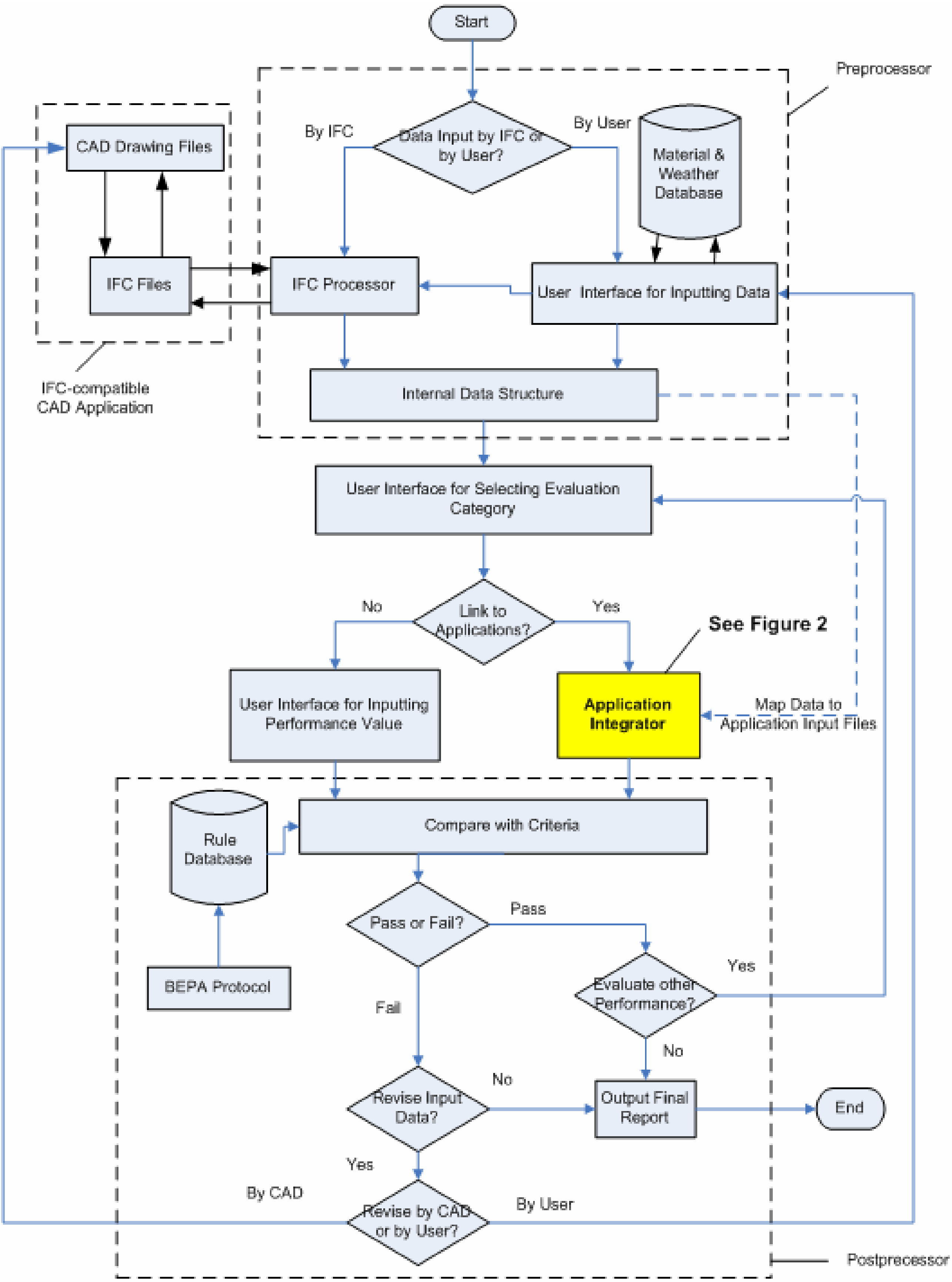

Figure 1 Overview of the Building Envelope Evaluation Framework